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Toughness Requirements for Heat-Affected Zones of Welded Structural Steels for Highway Bridges

INTERIM REPORT

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CHAPTER 1
INTRODUCTION

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Background

It is well known that in a welded steel connection, the heat affected zone (HAZ) possesses the least fracture toughness. The steel for highway bridges, built according to the AASHTO specifications conform to the *AASHTO M270/ASTM 709: Standard Specification for Structural Steel for Bridges*. The fabrication processes and requirements for welded steel bridges are specified in the *AASHTO/AWS D1.5: Bridge Welding Code*, which specifies the required toughness of weld metals (WM) for the permitted welding processes for a steel grade and the applicable AASHTO temperature zones. However, the specification does not address the requirements of welding HAZ toughness, and leaves it up to the contract documents or the discretion of the Engineer. The *AASHTO LRFD Bridge Design Specifications* specify the base metal (BM) toughness requirements of various steel grades for different element thickness, member category (fracture critical vs. non-fracture critical) and service temperature zones, but not for the welding HAZ. As a result inconsistencies exist among different owner agencies regarding the requirements for welding HAZ toughness, and the toughness requirements for different welding processes, which prevent uniform and cost-effective fabrication of steel highway bridges. Research is needed to establish the HAZ toughness requirements for welded steel highway bridges designed and built according to the AASHTO specifications.

HAZ

HAZ is the un-melted region of the BM adjacent to the weld bead or nugget in a welded joint that is subjected to peak temperatures high enough to produce solid-state microstructural changes, but not high enough to cause melting. A peak temperature, up to the melting temperature, occurs in the BM at the weld interface or the fusion boundary (also called the fusion line, FL), which diffuses through the plate away from the weld. With increasing distance from the FL, the BM experiences lesser thermal cycles (peak temperature and excursion or cooling rate often defined as the time through the austenite transformation range $\Delta t_{800\text{-}500}$ or $\Delta t_{8/5}$), resulting in various precipitate reactions, phase transformations and microstructural changes. Thus, the HAZ is comprised of a metallurgical heterogeneous region that manifests as significant variability in some sensitive physical properties, such as fracture toughness (Linnert 1994).

Regions of HAZ

In ferritic steels, the HAZ of a single-pass weld typically consists of four characteristic regions depending on the peak temperature (T_p) experienced during the weld thermal cycle. The HAZ is termed as supercritical, where T_p exceeds the austenite transformation temperature Ac_3. The region closest to the weld experiences temperatures well above Ac_3, resulting in full austenitization and grain growth prior to subsequent cooling. This region consists of coarse grained structure, and is accordingly called coarse-grained HAZ (CGHAZ), with grain size progressively decreasing away from the FL. Depending on the chemical composition and the cooling rate, ferrite nucleation is delayed and lower temperature transformation products such as bainite and martensite may form. The colony size of these M-A constituents (which is the critical size for cleavage) increases with increasing grain size towards the FL, and as a result the lowest toughness is often found in the CGHAZ close to the FL. The next region away from the weld, where T_p also exceeds Ac_3 to result in austenitization, $\Delta t_{8/5}$ is not long enough for any grain growth. When the fine grained austenite cools and retransforms, multiple ferrite grains nucleate assisted by high density of grain boundary nucleation sites, and a finer grained ferrite-pearlite or bainite microstructure is formed. This region is identified as fine-grained HAZ (FGHAZ) and is the toughest part of the HAZ, often matching or exceeding the BM. The following region, called the inter-critical HAZ (ICHAZ), experiences T_p in excess of the critical temperature Ac_1 for initiating ferrite-to-austenite transformation, but less than critical temperature Ac_3, resulting in a partially transformed region with varying amounts of partial re-austenitization. In this region, the ferrite grain size remains unaltered, but higher carbon regions may diffuse during partial re-austenitization, which upon cooling can form brittle martensite islands in ferrite-pearlite matrix, resulting in reduced fracture toughness. The final region, reaching peak temperatures below Ac_1, is an over tempered region identified as sub critical HAZ (SCHAZ). In this region a number of metallurgical effects can take place depending on the T_p. At the lower end of T_p interstitial solutes can interact with dislocations giving rise to strain-age embrittlement. With increased T_p iron carbides can spheroidize and coarsen facilitating cleave fracture. With further increase in temperature, precipitation of alloy carbides can cause embrittlement (Pisarski and Pargeter 1984).

For a single-pass weld, these regions are continuous through the HAZ. For multi-pass welds, each of these regions can experience a second, third, or multiple temperature excursions, which can further alter the microstructure and introduce local embrittlement. The microstructure of the previous HAZ will have little effect on the regions of the subsequent pass HAZ that are fully reasutenized. The microstructure produced in the other lower temperature regions will depend on the initial microstructure. During the subsequent weld passes, the CGHAZ of the first pass can be either tempered, partially austenitized, or fully austenitized or retransformed. These tempering and grain refinement effects can be beneficial with respect to restoring notch toughness. However, subsequent passes can also form intermittent coarse-grained regions and intercritically and subcritically reheated regions with a microstructure of poor notch toughness. The modified CGHAZ regions that retain the coarse grained structure thus can be further sub classified as inter-critically reheated CGHAZ (ICCGHAZ) and sub-critically reheated CGHAZ (SCCGHAZ). The CGHAZ, ICCGHAZ, and SCCGHAZ are collectively termed as coarse grained (CG) region. The coarsest parts of the CG region containing M-A constituents are usually responsible for low HAZ toughness properties and are called local brittle zones (LBZ) (Satoh and Toyoda 1988; Fairchild 1990).

Microstructure of HAZ

As discussed earlier, the microstructural characteristics of the HAZ depend on both steel (chemical) composition (hardenability) and cooling rate from the peak temperature (Konkol et al. 1987). At slow cooling rates, the austenite-to-ferrite transformation occurs at a relatively high temperature, resulting in polygonal ferrite or ferrite-pearlite microstructures. As the cooling rate is increased, the transformation is depressed to lower temperatures, resulting first in coarse upper bainite, then fine lower bainite. Above a certain cooling rate, depending on the steel's hardenability, the austenite transforms to martensite. For ferrite-pearlite structures, the notch-toughness transition temperature can be relatively high (i.e., lesser toughness at lower service temperatures). Bainitic structures can exhibit a wide range of notch toughness depending on the relative amounts of upper and lower bainite. The notch toughness of an upper bainite structure is generally low, particularly for higher strength levels. The notch toughness improves as a lower bainite structure is obtained at lower transformation temperatures. Martensite is hard and brittle in the as-formed condition, except at very low carbon contents. Tempered martensite exhibits a very good toughness at lower service temperatures (i.e., low notch-toughness-transition temperature). The notch toughness generally decreases with slower cooling rate due to formation of higher temperature transformation products (upper bainite, ferrite-pearlite). The notch toughness also decreases at a very high cooling rate due to formation of un-tempered martensite or bainite in a predominantly pearlitic HAZ of typical C-Mn steels or, relatively large martensitic laths in martensitic steels.

Toughness Requirements in AASHTO Specifications

The structural steel for highway bridges are specified as per the *AASHTO M270/ASTM A709: Standard Specification for Structural Steel for Bridges*. This specification covers carbon and high-strength low allow (HSLA) steel structural shapes, plates, and bars, and quenched and tempered alloy steel for structural plates. Seven grades of steel in four yield strength levels are covered: 36, 50, 50S, 50W, HPS 50W, HPS 70 W, and HPS 100 W. Note that the numbers indicate the yield strength of the steel in ksi. Grades 36, 50, 50S and 50W conform to ASTM A36, A572, A992 and A588, respectively. Among these, grades 50, 50W and HPS 50W are most commonly used for highway bridges. Use of HPS 70W is increasing in recent years, mostly as flange plates for hybrid girders. Use of HPS (high performance steel) is preferred due to excellent combination of strength, toughness and weldability. Grade 36 steel, which used to be a staple prior to 1970s, is rarely used in modern steel bridges. Use of HPS 100W is rare. Similarly, use of grade 50S, which is a specification for steels produced out of scrap feed, is unknown.

The *AASHTO LRFD Bridge Design Specifications* specifies Charpy V-Notch (CVN) impact energy requirements for the bridge steels for various thicknesses, member category (fracture-critical vs. non-fracture critical) and service temperature zones. Three temperature zones are specified: Zone 1 [0°F (–18°C) and above]; Zone 2 [–1°F (–18°C) to –30°F (–34°C)]; and Zone 3 [–31°F (–35°C) to –60°F (–51°C)]. The plate thicknesses are limited to 4.0 in. (102 mm) Use of HPS 100W steel for thicknesses in excess of 2½ in. (64 mm) are prohibited for fracture-critical members. When specified, the bridge steels produced according to *AASHTO M270/ASTM A709* can achieve the fracture toughness requirements on the BM. The design specification doses not provide any fracture toughness requirements for weld HAZ.

The *AASHTO/AWS D1.5: Bridge Welding Code* specifies the requirements for highway steel bridge fabrication. Five welding processes: Sheilded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Gas Metal Arc Welding (GMAW), Flux Cored Arc Welding (FCAW), and narrow gap Electroslag Welding (ESW-NGI), are permitted for fabricating steel bridges. All processes, except ESW-NGI, are allowed for all grades of M 270/A 709 steels and for all applications. The use of ESW-NGI is restricted to non-fracture critical members and member components, non-HPS grades of steel, and AASHTO temperature Zones 1 and 2. The *AASHTO/AWS D1.5* specifies the CVN impact energy requirements of WM. However, no requirements are provided for weld HAZ.

Objective

The objective of this research is to develop proposed toughness requirements for the heat-affected zones of welded structural steels for highway bridges.

RESEARCH APPROACH

To achieve the project objective the research plan is divided into two phases and seven tasks. Phase I includes tasks 1 through 5. The work plan for Phase II is developed in Task 4 and included in the Interim Report. The work for Phase II will be initiated upon receiving approval from NCHRP.

Phase I:

Task 1: Literature Search

Relevant domestic and foreign literature, research findings, and information related to the toughness of HAZs of welded structural steels will be collected and reviewed. This information may be obtained from published and unpublished reports, and contacts with transportation agencies and other public and private organizations. This task will contain three subtasks: *Survey of Owners and Fabricators; Literature Survey; and Summarize Literature Search.*

Task 2: Identify Critical Factors and Acceptance Criteria

The information collected in Task 1 will be evaluated and (*1*) the factors that affect the toughness of HAZs of welded structural steels and (*2*) acceptance criteria for the HAZs of welded steel applications will be identified. This task will contain two subtasks: *Identify Critical Factors Affecting HAZ Toughness; and Identify Acceptance Criteria for HAZ Toughness.*

Task 3: Identify Relevant Factors for Steel Bridges

Relevance of the factors and acceptance criteria identified in Task 2 to the toughness of HAZs will be assessed and those most relevant to welded structural steels used in highway bridges will be identified for further consideration in this research. This task will contain two subtasks: *Evaluate Factors and Acceptance Criteria; and Assess Relevant Factors and Criteria for Steel Bridges.*

Task 4: Develop Work Plan for Phase II

Based on the findings of Task 3, a proposed plan that includes an experimental investigation to be executed in Phase II for developing toughness requirements of HAZs of welded structural steels for highway bridges will be developed. It is envisaged that Phase II will consist of two tasks, *Task 6: Execute Approved Work Plan* and *Task 7: Prepare Final Report*. Accordingly this task will contain two subtasks: Subtask 4.1: Develop Work Plan for Task 6 and Subtask 4.2: Develop Work Plan for Task 7.

Task 5: Prepare Interim Report

An interim report that documents the research performed in Tasks 1 through 4 will be prepared. Following review of the interim report by the NCHRP, the research team will make a presentation to the project panel on the interim report addressing the panel comments and discussing the work plan for Phase II. Work on Phase II of the project will not begin until the interim report is approved and the Phase II work plan is authorized by the NCHRP.

Phase II:

Task 6: Execute Approved Work Plan

The work plan approved in Task 5 will be executed. Based on this work, proposed toughness requirements for HAZs of welded structural steels for highway bridges will be developed.

Task 7: Prepare Final Report

A final deliverable that documents the entire research effort will be developed. The proposed toughness requirements for HAZs will be prepared as a stand-alone deliverable in a format suitable for incorporation in the *AASHTO/AWS D1.5 Bridge Welding Code* and *AASHTO LRFD Bridge Design Specifications*.

SCOPE OF STUDY

The research reported herein summarizes the finding of tasks 1 to 4.

CHAPTER 2
RESEARCH FINDINGS

TASK 1 – LITERATURE SEARCH

This task comprised reviewing relevant domestic and foreign literature, research findings, and industry specifications related to the toughness of HAZs of welded structural steels obtained from published manuscripts and reports, specifications of professional organizations and regulatory agencies for different industries, and surveys of the state departments of transportation and steel bridge fabricators. This task contains three subtasks: *Survey of Owners and Fabricators; Literature Survey; and Summarize Literature Search*

Review of Literature

An extensive review of published literature and relevant specifications of professional organizations and regulatory agencies across different industries and from both domestic and foreign sources was carried out. Detailed reviews of some of the most relevant literature are provided in APPENDIX A for ready reference.

The reviewed literature broadly covered four different aspects of HAZ toughness. A significant number of the literature discussed the metallurgy of weld HAZ, including the mechanisms of different microstructure transformation, the effects of different alloying components and welding processes on the microstructure, and the effects of different alloying elements on the HAZ fracture toughness for steels with wide range of application encompassing bridges, offshores, ships, pipe lines and pressure vessels. Many of these literature discussed improvements of welding procedures for enhancing HAZ fracture toughness. While almost all the literature discussed results of experimental evaluation of HAZ fracture toughness by small scale testing, a few presented large scale test results, including comparison among various test methods. Development of test protocols for HAZ fracture toughness that are included in the specifications of different regulatory agencies was discussed in some literature. Another group of reviewed literature consisted of domestic and international specifications pertaining to different industries encompassing bridge, offshore, ship building, pipe line and general structures. Additional review consisted of standards on different fracture toughness testing methods, and literature on fracture mechanics parameters relevant to the HAZ fracture toughness testing, and correlations between different fracture toughness characterizations. The literature review is summarized in the following along these major areas.

Large Research Programs on HAZ Fracture Toughness

UK Offshore Steel Research Project Phase I. One of the early comprehensive research on HAZ fracture toughness conducted in the 1970s for offshore structures under the UK Offshore Steel Research Project Phase I (UKOSRP I) on: C-Mn steel plates, 2.0 in. (50 mm), 3.0 in. (75 mm) and 4.0 in. (100 mm) thick, conforming to BS4360 Grades 40E and 50D and investigating: variations of three welding processes, SMAW, FCAW, and MIG; single and multipass welds with different heat input (HI); post-weld heat treatment (PWHT); and influence of Nb by CTOD and CVN testing concluded that the HAZ fracture toughness for the subject steels was adequate and fracture was unlikely above –4°F (–20°C). For avoidance of brittle fracture from HAZ, PWHT of plates up to 3¼ in. (83 mm) was unnecessary. In PWHT condition, some degradation in HAZ toughness was noted for steels alloyed with Nb. It was determined that the adequate HAZ toughness was achieved for hardness less than 380 HV. This and another contemporary study by Det Norske Veritas (Eide 1980, reported by Webster 1987) involving CTOD tests carried out on 2.0 in. (50 mm) to 4.0 in. (100 mm) thick steel plates used in offshore construction and welded using heat input up to 102 kJ/in. (4 kJ/mm) led to the conclusion that HAZ toughness of contemporary C-Mn killed offshore steels produced by fine grain practices and welded with heat input between 38 kJ/in. (1.5 kJ/mm) and 102 kJ/in. (4.0 kJ/mm) (irrespective of the welding processes) was satisfactory. Accordingly, the HAZ toughness requirements in the 1977 version of the *UK DOE's Guidance Notes* on the design and construction of offshore installations, and in the *BS6235: 1982 Code of Practice for Fixed Offshore Structures* was quite lax. The *Guidance Notes* required CVN energy of 25 ft-lb (34 J) at –13°F (–25°C), and 20 ft-lb (27 J) at –4°F (–20°C) for stress relieved (PWHT) and as-welded conditions, respectively. The *BS6235* did not require any HAZ testing provided the heat input was between 25 kJ/in. (1.0 kJ/mm) and 114 kJ/in. (4.5 kJ/mm). Irrespective of the requirements, a common trend in the offshore industries had been to require a much stringent universal criterion of 0.01 in. (0.25 mm) minimum CTOD at 14°F (–10°C) for all parts of the structure, although many experts across owners, steel produces and certifying agencies considered that such a requirement could not be guaranteed (Bateson et al. 1988).

Additional UK Offshore Steel Research. During the early-mid 1980's, a group sponsored large research program was performed in the UK (Webster 1987; Bateson et al. 1988; Webster and Walker 1988; Pisarski and Jutla 1989) in response to the increased frequency of low CTOD values [<0.004 in. (0.1 mm)] and low CVN test values in the HAZ of some low-carbon, micro-alloyed offshore steels that were developed in the previous decade. Although no evidence of offshore structure failure could be associated with low HAZ fracture toughness, examples of such failure were reported for other industries (Harrison 1983). To determine the cause of the low HAZ fracture toughness, and the impact of these on large structures the program systematically studied: (*a*) correlation of small and large HAZ fracture tests; (*b*) influence of amount of CGHAZ on the observed fracture properties; (*c*) comparison of through-thickness and surface notched CTOD specimens; (*d*) comparison of CTOD and CVN test results; and (*e*) the effect of PWHT on HAZ fracture toughness. Although, the changes in steel chemistry and manufacturing were initially suspected, a separate limited research program at the British Steel Corporation (Bateson et al. 1988) demonstrated that older steels also exhibited low levels of CTOD (<0.004 in. (0.1 mm) at 14°F (–10°C)], when tested according the more stringent CTOD testing methodology developed within the previous decade, including a more realistic heat input for specimen preparation. The group test program investigated 50 mm thick plates of low carbon normalized steel conforming to BS4360 Grade 50E, butt-welded with a half K-joint preparation using a submerged arc welding (SAW) process with a heat input of 114 kJ/in. (4.5 kJ/mm). Two weld procedures were used that produced along the vertical edge of the weld preparation (adjacent to the FL) 30% CGHAZ through the thickness, and 10% CGHAZ distributed at quarter plate thickness (Pisarski and Harrison 1989). The PWHT was performed at 1110°F (600°C) for 2 hours.

All together 236 CVN tests were performed (including retests) as per the UKDOE guidelines. The specimens were sampled from the vertical HAZ in the plate thickness direction, at subsurface and at plate centerline, and within the HAZ at FL, at FL+0.08 in. (2 mm), and at

FL+0.2 in. (5 mm). At least three replicates were tested at each sampling location. The CVN tests performed at –40°F (–40°C) or above met the requirements of UK DOE guidelines.

Altogether 198 CTOD specimens were tested in three point bending according to *BS5762: Methods for Crack Opening Displacement*: *1979*. In addition 20 wide plate (WP) tests were conducted to determine the effect of the structure size. Three of these specimens were welded using V-bevel joint preparation and normal welding procedure without any particular effort for controlling the CGHAZ. The WP specimens were 35.4 in.×39.4 in. (900 mm×1000 mm), welded along the shorter length, and had a semi-elliptical surface notch in the HAZ. The specimens were tested in tension normal to the weld axis at 14°F (–10°C).

All tests except 10% CGHAZ at 50°F (10°C) and TT notch with 10% CGHAZ at –22°F (–30°C) produced a minimum CTOD value less than 0.004 in. (0.1 mm). No clear trend could be discerned between the SN and TT specimens, as both specimens produced similar minimum values. The post-test metallographic studies revealed that the low toughness values were associated with fracture initiation at the grain coarsened HAZ in the ICCGHAZ and SCCGHAZ regions, or LBZ, with a coarse grain greater than 0.003 in. (80 μm) (ASTM 4). Significant scatter was noted in the toughness results; the location of the fatigue crack tip with respect to the FL and the microstructure adjacent and slightly ahead of it were the major factors contributing to the variation in the CTOD values. The minimum CTOD values, measured in AW and PWHT conditions, were similar, although at lesser frequency for the PWHT condition. A reduction in the amount of grain coarsening from nominally 30% to 10% did not significantly affect the minimum CTOD values, although their frequency reduced, suggesting that LBZ was responsible for the observed low fracture toughness. The CTOD values were not sensitive to the actual amount of coarse grain sampled; however, at higher temperature pop-in seemed to occur with larger amount of coarse grain, and low toughness fracture could be prevented with small amount of coarse grain. Sampling of coarse grains at the fatigue crack tip alone, however, did not always result in lower toughness. Ductile tear prior to cleavage contributed to higher CTOD values, even in presence of coarse grains [as high as 0.004 in. (100 μm) or ASTM 3] at some part of the crack front. As such, crack tip location relative to the FL was also found to be an important factor for observed fracture behavior. A small deviation of the notch location away from the FL severely reduced the frequency of low CTOD results, although the minimum value did not alter significantly.

The aspects of fracture initiation in WP tests were similar to those in the CTOD tests, for both AW and PWHT conditions. The minimum fracture toughness, corresponding to the lowest global strain in the plates, was similar to that obtained from the CTOD tests, when the fatigue crack sampled relatively long lengths of coarse grain. The depth of the CGHAZ sampled by the fatigue crack did not seem to be critical. Although, more WP test results on specimens sampling the lowest toughness HAZ would have been desirable for a meaningful comparison, the results indicated that the small scale CTOD tests could be considered as representative of fracture behavior in WP tests. The WP test results also demonstrated that in addition to the sampled microstructure by the fatigue crack, the relative yield strength of the BM, the WM and the HAZ, together with the presence of residual stresses had an impact on the fracture behavior. The yielding of lower strength BM would protect the strain distribution around the FL. With reduction in WM yield strength by PWHT compared to the BM, local strains at the FL concentrated more rapidly for PWHT specimens, which contributed to greater frequency of fractures in this condition compared to AW condition. Comparison of the CTOD and the WP test results, performed using an Universal Assessment Diagram that combined the consideration of both fracture and plastic collapse, also showed that the two testing methods could be correlated for CTOD values less than 0.004 in. (0.1 mm), i.e., when the lowest toughness microstructure or local brittle zone was sampled by the fatigue crack tip. Of the three tests on bevel welded plates, fracture initiated only in one plate but was arrested in the BM, suggesting that the effect of low HAZ fracture toughness due to LBZ was not significant for large structures having sufficient crack arrest toughness for the BM.

FHWA Study on Tolerable Flaw Sizes in Full Size Welded Bridge Details (1977). One of the first studies indirectly assessing fracture toughness of HAZ in weldments of steel highway bridges was performed at Lehigh University (Roberts et al. 1977), where the smallest tolerable flaws size that is stable in a particular weldment at the lowest service temperature was investigated. Twenty-four full size beams with welded details were fabricated from A36, A588, and A514 steels which met the 1975 AASHTO toughness specifications. For each type of steel two beams were fabricated for each type of detail. The types of details tested were cover-plates (Category E), lateral attachments (Category E), transverse stiffeners (Category C), and flange thickness transitions (Category B), all of which were susceptible to fatigue crack growth from the weld toe. These beams were cyclically loaded to initiate fatigue cracking at room temperature and then cyclically loaded at temperatures –40°F (–40°C) and lower until rapid fracture occurred (crack growth became unstable). The specimens were cooled by liquid nitrogen by completely enclosing the sections of interest in a Styrofoam box.

The web-to-flange longitudinal fillet welds were made by an automatic continuous SAW process. The groove welded lateral attachment and flange splices were fabricated by semi-automatic SAW processes. The fillet welds at the cover plates, overlapped lateral attachments and transverse stiffeners were manually made. All specimens were fabricated by the Bethlehem Steel Corporation at their Bridge Division Fabrication Plant in Pottstown, PA using prevalent fabrication and inspection practices.

All details were subjected to at a stress range level above their respective fatigue limit. Although the tests did not explicitly investigate the effects of HAZ toughness on unstable crack growth, repeated attempts to fracture the specimens at smaller fatigue cycles, while fatigue cracks were small and still within the stress concentration of the detail, were unsuccessful. For all specimens, unstable crack growth at low temperature was experienced after 2 million cycles, at sections where the fatigue crack grew significantly through the section (as great as the section thickness.)

All fractures in the groove welded lateral attachment precipitated from an edge crack. In the overlapped fillet welded attachments, the fatigue cracks initiated at the transverse fillet weld toe, but led to fracture when multiple surface cracks coalesced as a large elliptical crack and eventually a corner crack and an edge crack. In the cover plate details the fatigue cracks initiated at the cover plate terminations and led to fracture when the crack significantly grew through the flange thickness or grew to a corner crack and eventually an edge crack. All fractures in flange thickness transitions precipitated from fatigue cracks that initiated at a corner and turned into an edge crack through significant portion of the section. At the fractured transverse stiffener details, the fatigue cracks initiated at the stiffener-to-flange weld toe and at fracture had grown through the flange thickness as an elliptical crack, or a corner crack or an edge crack.

FHWA Study on Fracture Toughness and Weldability Tests for SAW Joints (1987) The first and the most comprehensive study on fracture toughness of weld HAZ in bridge steels was conducted at the US Steel (Konkol et al. 1987), where optimum test and test procedures for measuring the fracture toughness of WM and HAZ was evaluated for A514 and A588 steels meeting AASHTO Zone 2 and Zone 3 fracture toughness requirements. The study primarily considered SMAW and SAW processes with several variations of welding energy, preheats and weld inter-pass temperature. In addition, special welding processes such as 2-wire SAW, long-stickout SAW and FCAW processes were also investigated. Two types of steels, one produced by conventional steel making practice, and the other by a sulfide-shape-control (SCC) practice, were investigated. All weldments were made using double V-groove weldments in 2.0 in. (51 mm) thick plates. The consumables used were those permitted by the AWS Structural Welding Code for A514 and A588 steels (exposed bare application) and typically used in bridge fabrication.

Fracture toughness was evaluated using both CVN and CTOD tests. Both the last pass HAZ (CGHAZ) and the HAZ tempered by a subsequent weld pass (ICCGHAZ) were of interest. However, due to the difficulty in accurately placing the pretest fatigue crack tip in the HAZ for the CTOD tests, and the erratic scatter in the CVN test results due to variation in in HAZ microstructure in the notch root or crack path that affect the absorbed energy, the specimen orientation was changed from surface-notched to edge-notched (through thickness) configuration. Accordingly, all but a few of the tests were conducted for a HAZ influenced by subsequent weld passes. The toughness of this HAZ was expected to provide low toughness. Typically, CVN tests were performed at five temperature levels [–60°F (–51°C), –30°F (–34°C), 0°F (–17°C), 40°F (4°C), and 70°F (21°C)] to determine the complete fracture toughness response. Three replicates were tested at each temperature level.

The CTOD tests employed simple end bend (SEB) specimens of $B \times B$ configuration. Two sets of three specimens each were tested at two temperature levels under a 1.0 sec loading rate (considered to be bridge loading rate). Both CTOD and CVN tests were conducted on all SMAW weldments and weldments made by the special welding processes; however, since sufficient data was available for a CTOD-CVN correlation, CTOD tests were conducted on only four of the 16 weldments made in the SSC steels. The yield strength of the HAZ was estimated from Vickers Hardness readings of the HAZ, and using the same yield-to-tensile strength ratio as the BM.

For both SMAW and SAW weldments in A588 steel, 50% of the HAZ exceeded a minimum (estimated from the measurements) CVN of 25 ft-lb (34 J) at –20°F (–29°C). However, none of the HAZ of SAW weldments in A514 steel achieved a minimum (estimated) CVN of 35 ft-lb (47 J) at –30°F (–34°C), but all HAZ of SMAW weldments in A514 steel did. The limits were based on the prevalent AASHTO fracture critical criterion for weldments.

The limiting value of plane strain for a 2.0 in. (51 mm) thick plate was taken as the criterion for evaluating the CTOD values. The CTOD values were taken as the minimum measurements corresponding to the AASHTO Zone 3 service temperature of –30°F (–34°C) and an intermediate (1.0 sec) loading rate. For the A514 weldments, only three HAZ measurements met the criterion. For A588 steel, only two HAZ measurements for SAW weldments exceeded the criterion, whereas all HAZ measurements for SMAW weldments exceeded the limit.

For the HAZ, the minimum CTOD and CVN values did not exhibit any correlation that exists for BM between plane strain fracture toughness and CVN values at the lower shelf (Barsom and

Rolfe 1999). This lack of apparent correlation was attributed to the consideration of the minimum CTOD values that represent crack extension from small embrittled region along the fatigue crack front. In contrast, the CVN values represent energy absorbed in initiating and propagating a crack over a much larger region of the weldment. A good correlation was indicated when maximum CTOD values were compared with the corresponding average CVN values.

The study noted the limitations of the toughness measurements of the weldments, which in many instances suggested potentially brittle performance in service. In view of the satisfactory performance in service of many structures built with similar steels and weldments it was suggested to verify the impact of local low HAZ toughness by full scale testing of bridge connection details. In addition, the study identified the need to determine the loading rate effect (temperature shift) on the CTOD ductile-to-brittle transition temperature.

FHWA Study on HAZ Fracture Toughness of Narrow Gap Electroslag Welds (1994) Another study of the HAZ fracture toughness was carried out at the Oregon Graduate Center (OGC) (Wood and Devletian 1987), as part of the development of Narrow Gap Electroslag Welding (ESW-NGI) process (Atteridge et al. 1994). The Fracture toughness of weldments including the WM and the HAZ was determined for both A36 and A588 steel of 2.0 in. (51 mm) and 3.0 in. (76 mm) thicknesses. Three conditions were studied: (*a*) a standard gap practice (SG); (*b*) an OGC modified narrow gap practice (NG); and (*c*) an OGC narrow gap weld and metal alloy practice. A fourth condition (NG, ST2), derived from the third condition by increasing WM alloy content to reduce heat input and faster welding, was also studied. Since only the improved narrow gap practice is permitted by the current *AASHTO/AWS D1.5*, the results related to the HAZ of the (NG), (NG,ST) and (NG,ST2) processes are discussed in the following.

The HAZ toughness was determined by CVN tests, sampled at the mid-thickness in the CGHAZ. The notch of the specimens was located within 0.06 in. (1.5 mm) from the fusion line. The surfaces of the CVN specimen blanks were ground and etched to identify the proper notch location. Tests were performed at several temperatures to establish the entire transition curve. At least two replicates were tested at each temperature, and six replicates were tested at 0°F (–17°C). The measurements showed that the HAZ of the NG-ESW-NG weldment in a 3.0 in. (76 mm) thick A36 steel plate exhibited a toughness of 20 ft-lb (27 J) at 40°F (4°C). For an A588 steel plate the HAZ toughness fell between 15 ft-lb (20 J) and 20 ft-lb (27 J). For NG-ESW-NG process, the HAZ is the most critical region.

The HAZ toughness was also evaluated by plane strain fracture toughness test as per *ASTM E399* for 3.0 in. (76 mm) thick plates. The tests were conducted at 0°F (–17°C) and 20°F (–7°C) and at quasi-static and intermediate (2.0 sec to failure) loading rates. The tests showed better toughness than the CVN tests, probably due to the mixed zone presence over the full thickness, which exhibited an average toughness rather than a very narrow low toughness zone sampled by a smaller CVN specimen.

Under the same program, fatigue performance of flange splices made by ESW-NGI was evaluated in six full scale A588 built-up I-girders, each having two details. Six details were fabricated with SG, and the other six details were fabricated using NG. All tests were performed at a stress range of 18 ksi (124 MPa) at the splices. None of the specimens developed fatigue cracking from the ESW-NGI welds. The first two specimens developed fatigue cracking from a residual tack weld that was placed on the outside edge of the run-in block. Nevertheless, the crack did not propagate into the ESW-NGI or the HAZ. One of these beams exceeded 7 million cycles and the other one endured about 2 million cycles. Rest of the specimens endured between 2 and 4 million cycles and the tests were terminated for other reasons.

HAZ Microstructure, Steel Chemistry and Welding Procedures

Numerous studies have discussed the effects of chemistry, manufacturing process and welding procedures on HAZ fracture toughness of structural steels (Banks 1974; Dolby 1979; Bowker et al. 1983; Grong and Akselsen 1986; Pisarski and Pargeter 1984; Thaulow et al. 1987; Haze and Aihara 1988; Amano et al. 1989; Wang et al. 1990; Fairchild et al. 1991; Tronskar 1993; Kasuya et al. 1995; Gianetto et al. 1997; Liao et al. 1998; Jang et al. 2008; Chiba et al. 2010; Lee et al. 2012; Yuga et al. 2013).

Fracture in HAZ of as-welded joints can occur mostly by cleavage (brittle) or microvoid coalescence (ductile). Occasionally intergranular fracture is found in the HAZ of low-alloy steels. HAZ fracture toughness can be lower than the BM depending on the steel type and the welding procedure. Typically HAZ of fine grained C-Mn and low alloy steels exhibit lower toughness, and HAZ of C or lean C-Mn steels that are not grain refined produce similar or higher toughness (Dolby 1977; Dolby 1979). For C-Mn steels, low fracture toughness (due to cleavage) can occur at lower temperature, irrespective of the weld heat input, initiating at the fully transformed HAZ. At higher heat input [~635 kJ/in. (25 kJ/mm)] the slow cooling rates produce coarse microstructural constituents including coarser prior austenite grains, grain boundary ferrite, ferrite side plates and ferrite interphase carbides resembling pearlite, and exhibit lower cleavage resistance despite low HAZ hardness. At lower heat input [<178 kJ/in. (7 kJ/mm)], the lower toughness is due to relatively hard microstructure (~350 HV10) containing mixed ferrite martensite constituents produced by fast cooling rates. At lower temperature, the weld HAZ toughness in C and C-Mn steels are not affected by the hardness or the proportion of martensite, when the IIW carbon equivalence (CE) is greater than about 0.35. For lesser CE, the HAZ toughness can increase and the hardness can decrease significantly with small changes in steel chemistry.

At low heat inputs [<51 kJ/in. (2 kJ/mm), $\Delta t_{800\text{-}500}$ < ~30 sec], C-Mn microalloyed steels or high strength low alloy (HSLA) steels with C greater than 0.12% and containing small amounts of Nb and V show similar or improved toughness compared to steels free of Nb or V and having comparable C and Mn content. Nb and V form precipitates of Nb(C,N) and V(C,N) respectively during rolling or normalization of steels, which retard the recrystallization and grain growth, At higher heat input [> 89 kJ/in. (3.5 kJ/mm)], however, the HAZ fracture toughness drops rapidly in these steels. In Nb microalloyed steels, the low HAZ toughness at higher heat input is attributed to Nb promoting ferrite plate microstructures and harder CGHAZ that is 20-40 HV10 harder than comparable Nb-free steels.

For C-Mn microalloyed steels with C less than 0.12%, improved HAZ fracture toughness can be obtained for heat input as high as 178 kJ/in. (7 kJ/mm). At very low ($\Delta t_{800\text{-}500}$ < 10 sec) and high cooling rates or heat inputs ($\Delta t_{800\text{-}500}$ > ~50 sec) the HAZ toughness deteriorates because of the same reasons discussed with respect to C-Mn steels. Lowering carbon content reduces the M-A constituents. Suitable addition of Mn helps to improve toughness by reducing the ferrite grain size. These low carbon steels are also more tolerant to high levels of microalloying with respect to HAZ toughness. Depressing the γ-α transformation by suitable alloying such with Mo, Cu and Ni can minimize the precipitation hardening potential through Nb, and increase tolerance to higher % Nb with no adverse effect on toughness. However, only slight improvement of the

HAZ toughness has been reported with small additions of Nb at low heat input or cooling rate ($\Delta t_{8/5}$ < 40 sec) due to reduced size of sideplates and carbide aggregates by pinning effects of Nb(C,N) precipitates. Moderate alloying with V does not have any significant effect on HAZ toughness, but V and Nb in combinations, even in small concentrations, are detrimental to HAZ fracture toughness. Alloying by Mo, Cu and Ni also enhances the HAZ toughness by general refinement of the microstructure. Addition of Cr suppresses the formation of ferrite side plates through the pinning effects of chromium carbide precipitates. Similar to Nb, Al helps by reducing austenite grain growth in the CGHAZ only below 2010°F (1100°C). At higher temperatures [2460°F (1350°C)], small amounts of Ti prevent coarsening of prior austenite grains close to the FL by forming stable nitrides (TiN). Use of Ti to prevent HAZ grain growth is limited to continuously cast and controlled rolled steels. Excess Ti to N ratio could enable austenite grain growth through coarsening of TiN, and hence reduced HAZ toughness. In coarse grained region close to FL, B not exceeding 10-15ppm can improve the HAZ toughness by suppressing the formation of ferrite sideplates and ferrites. In excess, however, B would cause embrittlement of the HAZ. The HAZ toughness of the HSLA steels is further benefitted by thermomechanically controlled processing that promotes refined microstructure, and homogenization of possible Mn solidification segregations (or banding) through diffusion.

In low alloy steels, carbon contents are typically in the range of 0.15-0.25%. With total alloy contents of 2-6%, these steels are of higher hardenability than the other steels discussed above, and accordingly higher proportion of martensite is developed in the HAZ. In AW condition, HAZ toughness reduces with increasing heat input due to increase in prior austenite grain size and martensitic structure, and progressive introduction of bainite in the martensitic microstructure. For these steels, HAZ hardness usually is not indicative of its toughness, because the softer microstructure is produced by higher proportion of bainite, which is of lower toughness.

Due to similar CGHAZ microstructure, the HAZ toughness of high strength steels having yield strength of 50-70 ksi (350-500 MPa) and produced by QT or TMCP processes, is not significantly different than normalized microalloyed steels of similar chemical composition.

In case of C, C-Mn and microalloyed steels, embrittlement of subcritical and intercritical HAZ can occur respectively due to dynamic strain aging and presence of martensitic islands in pearlite colonies. The degree of embrittlement is influenced by the welding procedure and appears to be more severe at lower heat inputs. Typical fine grained C-Mn and C-Mn microalloyed or low alloyed steels, which are Al treated, contain negligible interstitial N and supplied in normalized and QT conditions, have high resistance to subcritical HAZ embrittlement.

The principal metallurgical factor controlling the HAZ fracture resistance against mocrovoid coalescence for all types of steels is the cleanliness with respect to non-metallic inclusion.

One specific study related to HAZ fracture toughness of A709 steels was performed by Biswas et al. (2012) on simulated HAZ of grade HPS 100W, which is a low C and Cu age-hardening steel, alloyed in addition with Ni, Cr, Mo, Nb, and V. The HAZ simulations were performed at T_p of 1560°F (850°C), 2010°F (1100°C), 2370°F (1300°C) and 2460°F (1350°C). Fine grained ferritic and bainitic microstructures, finer than the base material, were observed at lower T_p due to successive phase transformations from ferrite to austenite and then back to ferrite without enough time for substantial grain growth. At higher T_p of 2370°F (1300°C) and 2460°F

(1350°C), the microstructure was mainly bainitic with some martensite with extensive grain growth. The HAZ microstructures at all T_p showed Ti, Nb, and V carbide, nitride and carbonitride precipitation within and at the grain boundary. At higher T_p of 2370°F (1300°C) and 2460°F (1350°C), the precipitates were elongated along the martensite lath boundaries and at the prior austenite grain boundaries, which could be detrimental to fracture toughness. The martensite laths were not present at lower T_p. The CVN results showed an increase in the toughness for all the HAZ microstructures compared to that of the BM, which was attribute to: coarsening of carbide and carbonitride precipitates at T_p of 1560°F (850°C); refinement of grain size and re-precipitation of finely distributed Cu following dissolution at T_p of 2010°F (1100°C); very fine low carbon bainitic and matensitic structure and re-precipitation of dissolved Cu with high density at a relatively faster cooling rate at T_p of 2370°F (1300°C) and 2460°F (1350°C). All the simulated microstructures exhibited toughness higher that required for AASHTO zone 3 service conditions, 35ft-lb (48 J).

Subcritical post weld heat treatment (PWHT) at temperatures around 1110°F (600°C) is beneficial for HAZ toughness of C-Mn steels welded with low heat input, as it helps in tempering martensite and reduces HAZ hardness (Pisarski and Pargeter 1984). Similar treatments are also effective in removing strain aging damage in SCCHAZ. For low alloy steels, PWHT is normally beneficial to HAZ fracture toughness in situations where precipitation hardening effects are small. On the other hand, PWHT of microalloyed steels containing Nb, V, and Cu that are capable of precipitation hardening during heat treatment can degrade HAZ fracture toughness. Steels with high V and Cu contents can produce secondary (precipitation) hardening in the HAZ with reduced toughness, particularly at high C levels, depending on the other alloying elements. Additional embrittlement by PWHT can occur due to segregation of P at the prior austenite grain boundaries. Large prior austenite grain boundaries are more susceptible to phosphorous embrittlement which is boosted by raising the concentrations of either Mn or Si in low carbon microalloyed steels. The HAZ toughness rapidly decreases with increase in phosphorous content. Overall, PWHT helps by reducing residual stresses and consequent defect tolerance, even if the HAZ toughness is slightly reduced.

In addition to heat input, the weld travel speed influences the HAZ fracture toughness. Higher travel speeds facilitate reduction in prior austenite grain size and increased HAZ toughness. Controlling weld bead size and placement influence HAZ fracture toughness. Smaller weld bead size, particularly in the capping layer, increases the potential for lower HAZ toughness arising from extremely low heat input and small hydrogen cracks. In multipass welds, increasing proportion of HAZ refinement enhances toughness by arresting any crack initiated from LBZ. This can be accomplished by closely overlapping weld beads, which is enabled by low angle of the electrode with the work piece. Welding in the flat and overhead positions create the lowest angles, whereas horizontal and vertical positions create the higher angles. Adjusting the weld procedure during welding is another approach to increasing grain refinement in the HAZ, which has been mostly used for weld repairs. This can be accomplished by: (*a*) adjusting the welding parameters during subsequent passes; (*b*) grinding of the first layer to predefined depth before depositing second layer; (*c*) increasing the weld interpass temperature. In addition, temper bead technique can be used to refine the HAZ of the capping layer, however, it is extremely difficult to control.

Characterization of HAZ Fracture Toughness

Pisarski and Pargeter (1984) have provided the rationale behind the philosophy of characterizing HAZ fracture toughness in terms of fracture initiation as determined by CTOD tests, although in-service performance of offshore structures, WP tests in the laboratory representing large structures, and Engineering Critical Assessments (ECA) have demonstrated that the lower fracture toughness of the HAZ associated with initiation at the LBZ may not be significant for the structure's integrity as the cracks are often arrested by tougher grain refined HAZ and the BM surrounding the LBZ. However, fabrication and service induced micro-discontinuities often lie in the HAZ adjacent to the FL, which is also the region of high stress concentration at the weld toe notch and high tensile welding residual stresses, collectively favoring the condition for cleavage fracture initiation. Whether the fracture, once initiated at the LBZ is arrested or continues to propagate depends on the arrest toughness of the surrounding fine grain HAZ and the BM (if the crack propagates out of the HAZ). Although the arrest toughness of the fine grain HAZ and the BM can be higher than fracture initiation toughness of LBZ enabling crack arrest, in most structural steels the necessary arrest toughness may not be achievable for the high stress and/or low temperature applications. Moreover, consistent determination of crack arrest toughness of HAZ is extremely challenging.

Malik et al. (1996) investigated the potential for arrest of a through-thickness HAZ crack running parallel to the FL using compact plain strain (*ASTM E1221*) and plane stress crack arrest tests on HAZ having inadequate toughness against fracture initiation. The results indicated that crack arrest toughness was not influenced by the presence of LBZs; rather by the fine grain HAZ present along the fracture path surrounding the LBZ. In view of the difficulty of performing a valid crack arrest test, the study alluded at the possibility of obtaining HAZ crack arrest toughness from the CVN test results.

In view of the improved HAZ toughness of modern steels with optimized chemistry, improved welding processes, and enhanced probability of detecting defects in the HAZ, the significance of HAZ toughness testing by deep notched CTOD specimens for line pipes as recommended by the offshore industry specifications have been critically reviewed over the past decade (Liessem and Erdelen-Peppler 2004) and more pragmatic test protocols that match the full scale test results simulating lower constraints (than deep notched CTOD specimens) representative of typically small flaws that may remain undetected in the HAZ have been suggested. The constraint at a crack tip depends on a number of factors, including crack depth, mode of loading and crack shape (Pellini 1973). Loss of constraint for a shallow notched specimen with respect to a deep notched specimen has been assessed by Dodds et al. (1991). Use of a single edge notch tension (SENT) specimen for CTOD testing that provides a lower level of crack trip constraint and more closely matches flaw in a pipeline has been developed (MacDonald 2011; Moore et al. 2012) and incorporated in *DNV-RP-F108:2006: Fracture Control for Pipeline Installation Methods Introducing Cyclic Plastic Strain*. Evaluating varying degrees of constraint, scale and loading mode through single edge notched bend and tension specimens as well as surface notched tension specimens with varying crack depth, Amadioha et al. (2011) demonstrated in a statistical manner that the reduced constraint specimens provide a more realistic HAZ toughness.

Testing Methods for HAZ Fracture Toughness

Primarily two experimental approaches have been followed for studying HAZ fracture toughness, where testing has been conducted on specimens containing HAZ microstructures produced either by weld thermal simulators, or by a physical welding process. The tests results on HAZ produced by weld simulators are questionable for several reasons (Dolby 1979; Grong and Akselsen 1986). For an identical thermal cycle, the weld simulator tends to promote larger austenite grains because of the absence of a steep temperature gradient as in a physical weld. Adjusting the peak temperature downwards for matching the austenite grain size, can affect the dissolution of carbides and second phase particles, which may produce a different transformed microstructure in the HAZ. The CVN tests on HAZ produced by thermal simulators tend to produce higher transition temperature due to more homogeneous microstructure sampled by the fracture path (Dolby 1979) compared to a weld HAZ. Nevertheless, most of the Japanese, North European, and other studies on HAZ fracture toughness have been performed on microstructures produced by a weld simulator, which have provided significant insight into the metallurgical and microstructural effects on HAZ toughness.

Depending on the function, several test methods can be used for assessing HAZ fracture toughness (Denys and McHenry 1988). The studies on HAZ fracture toughness reported in the literature have mostly employed and CVN impact tests and CTOD tests. A few studies have employed WP tests for assessing the significance of HAZ fracture toughness obtained from small scale specimens on the integrity of large structures. Majority of these studies have used 1.0 in. (25 mm) thick plates with ½ K- or K-joint configuration for the groove weld, where the HAZ on the vertical side of the joint has been investigated. A handful of studies have investigated joints with a V- (Webster and Walker 1988) or a double U- (Konkol et al. 1987) configuration where the crack initiating in the CGHAZ have deviated into the BM, confounding the HAZ fracture toughness results.

The CVN tests have been performed at subsurface and/or specific locations through the thickness of the plate with notches placed at specified distances from the FL. Typically the notches have been located at the FL, at 0.08 in. (2 mm) from FL, and at 0.2 in. (5 mm) from FL. The tests have been performed at multiple temperatures, mostly as per the practice of the respective industry. While most studies have used full size Charpy specimens, some have used sub-size specimens when plate thickness was not sufficient for a full size specimen. Subsized CVN specimens have been used by Malik et al. (1996) to determine local dynamic fracture toughness through the plate thickness.

Fracture mechanics tests such as CTOD testing has been widely used to assess the weld HAZ toughness against crack initiating at the LBZ, but with varying success. Most of these studies have employed a single edge notched bend specimen (SENB) of $B \times B$ or $B \times 2B$ cross section with through thickness (TT) deep notch (a/W~0.5) at the CGHAZ adjacent to the FL. The validity of the tests has been assessed by post-test metallography and fractography, including examination of the microstructure at the point of fracture initiation, and the microstructures sampled by the fracture. For realistic assessment of fracture initiation from CGHAZ of the cap layer, both shallow (a/W~0.06-0.3) and deep surface notched (SN) specimens, with the notch in the CGHAZ parallel to the FL have been investigated and compared with deep notched TT specimens (Thaulow et al. 1987; Pisarski and Jutla 1989; Amadioha et al. 2011). These studies have demonstrated that the lower bound toughness is not significantly affected by the notch orientation (TT vs. SN). The shallow notched specimens, however, provided significantly higher fracture toughness. The CTOD tests have been performed under slow (static) loading rate.

To demonstrate the insignificance of occasional low HAZ fracture toughness on the structural integrity, several studies have utilized WP tests (Denys 1987; Webster and Walker

1988; Watanabe et al. 1988; Pussegoda et al. 1992) with varied success. These tests have involved custom sized groove welded plates containing fatigue pre-cracked notches of semi-elliptical shape in the HAZ and loaded in tension normal to the crack plane. The tests required special apparatus of extremely high loading capacity. No standard exists for WP tests and the results depends on several factors including the notch location, weld orientation with respect to the loading direction, under-matched vs. over-matched welds. Although appears to be simple, the WP tests require elaborate fixtures for the required high force level. In addition, placing the notch in the CGHAZ is extremely difficult, as it can be only located by macro-etching the plate edges. Due to the variation in the FL there is little certainty in the outcome, and significant scatter exists in the test results.

Standards for Fracture Toughness Testing

Several domestic and international standards for fracture toughness testing were reviewed and assessed for application to this research project, as summarized in the following.

ASTM E23-12c: Standard Test Methods for Notched Bar Impact Testing of Metallic Materials provides requirements of Charpy (simple beam) test and Izod (cantilever-beam) test. As noted earlier, Charpy notched bar impact test is universally used for evaluation of weld HAZ fracture toughness. This test is also universally used for evaluation of BM and WM.

ASTM E436-03: Standard Test Method for Drop-Weight Tear Tests of Ferritic Steels provides a test method for determining the appearance of propagating fractures in plain carbon or low-alloy pipe steels [yield strength less than 120 ksi (827 MPa)], $^1/_8$ in. to $^3/_4$ in. (3.2 mm to 19 mm) thick, over the brittle-ductile transition temperature range. The test involves a single edge notch beam specimen that is impact loaded in three-point bending over a 10 in. (254 mm) span in a pendulum or drop-weight type machine. The drop-weight tear test (DWTT) is evaluated by the percent shear area of the fracture surface, which can provide a measure of fracture propagation transition temperature (FPTT).

ASTM E604-83: Standard Test Method for Dynamic Tear Testing of Metallic Materials provides a test method for dynamic tear (DT) test of specimens $^3/_{16}$ in. to $^5/_8$ in. (4.8 mm to 16 mm) thick. The test involves a single edge notch beam specimen that is impact loaded in three-point bending over a 6.5 in. (165 mm) span in a pendulum or drop-weight type machine. The test provides the total energy required to fracture the specimen (DT energy), which is a measure of resistance to rapid progressive fracturing. The test is designed for applications where the enhanced resistance to fracture during about one plate thickness of crack extension from a sharp notch is of interest.

ASTM E1820-13: Standard Test Method for Measurement of Fracture Toughness covers procedures and guidelines for the determination of fracture toughness of metallic materials under the opening mode (Mode I) at slow loading (0.3 to 3 minutes to maximum force). Fracture toughness is measured using parameters of J-integral (J) and crack tip opening displacement ($CTOD$, δ). Evaluation of plain strain fracture toughness K_{Ic} is not included in this specification. The standard test method covers only deep notched specimen which the initial crack length (a_o) between $0.45W$ and $0.7W$, where W denotes the depth of the specimen. Single-edge bend [SE(B)] (same as SENB specimens), compact tension [C(T)], and disk-shaped compact tension [DC(T)]. The specification also covers two additional test methods for: (*a*) loading rate exceeding the slow loading rate noted earlier; and (*b*) precracked Charpy-type specimens at impact loading rates. In addition, as a nonmandatory information, guidelines for measuring fracture toughness using shallow notched SE(B) specimens is provided, where the initial crack can range between $0.05W$ and $0.45W$.

ASTM E1921-13a: Standard Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range covers determination of a reference temperature which characterizes the fracture toughness of ferritic steels, having yield strength ranging between 40 and 120 ksi (275 to 825 MPa), at the onset of cleavage cracking at elastic or elastic-plastic instabilities K_{Jc} or both. Fatigue precracked SE(B), C(T) or DC(T) specimens are allowed. The test method ues a statistical analysis to establish a K_{Jc} value from J_c test results at a reference temperature T_o at which the K_{Jc} value is 90.9 ksi$\sqrt{in}$ (100 MPa$\sqrt{m}$). Knowing the reference temperature, a master curve describing the median K_{Jc} over the transition temperature range can be established. A lower bound fracture toughness can then be determined taking into account the variability of the test results.

BS7448 Part 1: Method for Determination of K_{Ic}' Critical CTOD and Critical J values of Metallic Materials covers procedures and guidelines for the determination of critical fracture toughness of metallic materials, which are mostly identical to *ASTM E1820* and *E399*, excpt for minor details. However, guidance for fracture toughness testing under dynamic loading rate and testing of shallow notched specimens with notch depth less than $0.45W$ are not provided.

BS EN ISO 15653:2010 Metallic Materials - Methods of Test for the Determination of Quasistatic Fracture Toughness of Welds is an international standard that provides guidelines for for determining point values of fracture toughness in WM and HAZ. The fracture toughness is determined in terms of stress intensity factor (*K*), crack tip opening displacement (*CTOD, δ*), and experimental equivalent of *J*-integral (*J*). The methods use fatigue precracked specimens that have been notched in a specific target area. The specification allows both CT and SENB specimens, which are identical to the specimen recommended by *ASTM E1820*. Both through thickness and surface notch are allowed. The specification provides detailed guidelines for notch placement in the HAZ, specimen preparation, and post test metallographic and fractographic analysis of the microstructure sampled by the crack. The specification also provides informative guidelines for testing shallow notched specimens with the crack length ranging between *0.1W* to *0.45W*. Additional information on this specification is presented in APPENDIX A.

DNV-RP-F108: Fracture Control for Pipeline Installation Method Introducing Cyclic Plastic Strain is an international standard that provides guidance for fracture resistance testing and tolerable flaw size analysis for both pipe and girth welds including HAZ, using Single Edge Notched Tension (SENT) specimens. The SENT specimen is normally designed with a surface notch (SN) and loaded in axial tension. Compared to traditional deep single edge notched tension specimens, a SENT specimen with shallow surface notch more accurately represents both the tensile loading mode and a lower crack tip constraint. The SENT testing is to be performed according to general fracture toughness testing standards such as *BS7448-1* or *ASTM E1820*. Fracture resistance of the SENT specimen is characterized by *J-R* (or CTOD-*R*) curves. The recommendations are applicable only when a maximum load plateau or a stable crack extension of at least 0.06 in. (1.5 mm) occurs before initiation of brittle fracture. Further details are provided in APPENDIX A.

Specifications Related to HAZ Fracture Toughness

Several specifications and regulatory guidance in the United States and other countries related to bridge, offshore, ship building, pressure vessel and pipeline industries were reviewed for requirements on HAZ toughness. These specifications are tabulated in Table 1. A preliminary review of the specifications for nuclear pressure vessels indicated a fracture toughness requirement in the upper shelf (ductile tear mode) to address irradiation embrittlement. Since the service condition and toughness requirements (in the lower shelf) for bridge steels are significantly different, the specifications for pressure vessels were not pursued further.

AASHTO/AWS D1.5: Bridge Welding Code does not provide any mandatory requirements for weld HAZ toughness. Article 5.4.3.3 of the specifications recommends CVN testing for measuring the coarse grained area of the HAZ when specified in the contract document. The specifications, however, provide requirements for CVN testing of WM as part of qualification of weld procedure specification (WPS). Five CVN specimens are required to be tested for each test weld made by SMAW, SAW, FCAW or GMAW. For ESW-NGI welds eight specimens are required for each test weld. The specimens are required to be extracted from the mid-thickness of the test plate. The tests must satisfy the requirements shown in Table 2. In addition, AWS D1.5 provides provisions related to: (a) preheat and interpass temperature for different welding processes, A709 steels and plate thicknesses; (b) methods of determining alternate preheat for preventing HAZ cold cracking; and (c) heat input (including controls of voltage, current and travel speed), with the objective of producing welds and HAZ of adequate mechanical properties.

The *AWS D1.1: Structural Welding Code – Steel* provides guidance for testing both WM and HAZ toughness for CJP groove welds in tubular structures, when required by the contract document as part of the WPS qualification. The notch location for the CVN testing is recommended at FL+0.04 in. (1 mm), and FL+0.2 in. (5 mm), and at sub-surface and mid-thickness. The test with notch location at FL+0.04 in. (1 mm) is only recommended for the sub-surface location. Minimum three and maximum five specimens are recommended at each test location. The recommended minimum absorbed energy for HAZ of different grades of steel as provided in the commentary of the code is presented in Table 3. It may be noted that in the main body of the code, the recommended test temperature is left to the contract document. For critical welded connections, the commentary suggests sampling the HAZ at 0.016 in. (0.4 mm), 0.08 in. (2 mm), and 0.2 in. (5 mm) from the FL for increased likelihood of finding LBZ. Alternatively, the commentary suggests prequalifying the steels for producing acceptable HAZ toughness through CVN and CTOD testing. Other suggestions provided for addressing LBZ are to: use steels with moderate crack arrest capability; overmatching to provide higher strength WM and HAZ than the BM; designing such as to let the fatigue crack grow out of the HAZ; promote grain refinement by controlling weld layer thickness and heat input; and controlling alloy contents of steels such as reduced V and N, and increased Ti.

The other reviewed specifications related to offshore (API, DNV, BS), ship building (ABS), and pipe line (API, DNV) industries include toughness requirements for weld HAZ. In all of these specifications, the HAZ toughness is to be evaluated by CVN testing. These test requirements, including the sampling location, notch location, number of replicates, test temperature etc., are tabulated in Table 4. The CVN sampling locations, as required by different specifications, are also depicted graphically in Table 5 for clarity. Most of these specifications require multiple CVN specimens through thickness (depending on the plate thickness) with the notch located at FL and at various distances with respect to the FL. Most specifications require testing at 0.04 in. (1 mm) or 0.08 in. (2 mm) and 0.2 in. (5 mm) from the FL. The ABS specification in addition requires testing at 0.4 in. (10 mm) from FL for higher heat input (>127 kJ/in. or 5 kJ/mm), where a larger HAZ is expected. Most specifications require three replicates.

The HAZ toughness requirements in terms of CVN impact energy for *AWS D1.1*, *ABS*, *API-5L* and *ISO 3183*, and *DNV-OS-C401* are tabulated in Tables 3 and 6 through 8, which vary depending on the steel grade (type and strength) and plate thickness.

For comparison, the Charpy impact energy required for the BM by several specifications including *AWS D1.1*, *AWS D1.5/AASHTO LRFD BDS*, *ABS*, *API-5L* and *ISO-3183*, and *DNV-OS-B101* are presented in Tables 9 to 14. Most fracture toughness requirements for the HAZ is less than the BM.

In addition, some specifications, mostly in the offshore industry, require CTOD or other similar fracture mechanics parameter based testing (such as K_{Ic}, J_{Ic}, J) of the HAZ. Depending on steel grade, plate thickness, and heat input *API RP 2Z: Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures* provides detailed requirements for prequalification of steel plates by CTOD testing of HAZ. The details of the specifications are provided in APPENDIX A and in Tables A-8 and A-9. Another specification *DNV-OS-C401: Fabrication and Testing of Offshore Structures* require a minimum CTOD value of 0.006 in. (0.15 mm) at a temperature less than 14°F (–10°C) for submerged structures, and at temperature lower than the service temperature for other structures. These specifications also specify CTOD testing of the BM, with a higher requirement than the HAZ. The comparison of fracture mechanics test requirements in the HAZ according to various specifications, including fracture toughness parameter, test temperature, test procedure, specimen type and geometry, notch orientation and location, and number or replicates is tabulated in Table 15.

Correlation between Fracture Mechanics and CVN Testing

Another focus of the literature survey was on correlation of HAZ fracture toughness obtained by CTOD and CVN testing. Many such correlations have been proposed in the literature for steel BM of different grades used in different industries (Barsom and Rolfe 1970; Wallin 1989; Bannister 1998). Konkol et al. (1987) investigated existence of such correlation following the two stage model proposed by Barsom and Rolfe (1970) for BM between plane strain fracture toughness and CVN values at the lower shelf. For the HAZ, however, the minimum CTOD and CVN values did not exhibit any correlation. This lack of apparent correlation was attributed to the consideration of the minimum CTOD values that represent crack extension from small embrittled region along the fatigue crack front. In contrast, the CVN values represent energy absorbed in initiating and propagating a crack over a much larger region of the weldment. A good correlation was indicated when maximum CTOD values were compared with the corresponding average CVN values.Using subsize CVN tests at different depths through the plate thickness, Malik et al. (1996) have alluded at a possible correlation between the plain strain dynamic fracture toughness (K_{Id}) and CVN results in an average sense for weld HAZ, since crack arrest toughness was not influenced by the presence of LBZs; rather by the fine grain HAZ present along the fracture path surrounding the LBZ.

Survey of State Departments of Transportation

The survey sent by the research team to the state DOTs, as well as the results of the survey are provided in APPENDIX B. Altogether 40 agencies responded to the survey. The responses were followed-up by further email and/or telephone interview.

About 50% of the responding states specify special welding guidelines in their state standard specifications, in addition to *AASHTO/ AWS D1.5: Bridge Welding Code*. Weld preheat temperature is the most frequently specified welding parameter in state specifications. The other supplementary weld parameter often specified is the weld interpass temperature. Only two states (NY and WY) provide additional requirements for post-weld heat treatment. None of the states have any special requirements for weld heat input, welding speed and cooling rate.

About 56% of the responding states use *AWS D1.1: Structural Welding Code* for welding tubular members for ancillary items in steel bridges, pedestrian bridges, and cantilever sign structures.

In the responding states, most of the steel bridge fabrication is performed by SAW process, although all processes (except ESW-NGI) are allowed for welding all plate thicknesses and for all steel grades. The FCAW and SMAW are the next most commonly used process. GMAW and ESW-NGI are not used by most states. The maximum plate thickness used for each welding process ranged between 3.0 in. (76 mm) and 4.0 in. (102 mm), and the minimum plate thickness for each welding process mostly ranged between $^{1}/_{8}$ in. (3.2 mm) and $^{3}/_{8}$ in. (9.5 mm). The maximum and minimum thickness as "per AWS D1.5" represent the restrictions noted in *AASHTO/AWS D1.5,* which includes a minimum plate thickness of $^{1}/_{8}$ in. (3.2 mm), and the maximum plate thickness as demonstrated by weld PQR.

The steel bridges built since 2005 have mostly used Grade 50 and 50 W steels. Grades HPS 50W and HPS 70W have also been used but at a lesser frequency. Grade HPS 100W has been rarely used. For these bridges, most states used a maximum plate thickness of 3.0 in. (76 mm) to 4.0 in. (102 mm) and a minimum plate thickness of $^{5}/_{16}$ in. (7.9 mm) to $^{3}/_{8}$ in. (9.5 mm). Usage of grades 50, 50W, HPS 50W and HPS 70W are noted at both ends of the plate thickness spectrum, although use of HPS 70W is more frequent than HPS 50W, particularly at greater thicknesses. Grade HPS 100W has been occasionally used for plates as thick 3.0 in. (76 mm) and 3.5 in. (89 mm) Commonly specified thickness transitions are between 1.0 in. (25 mm) and $1^{1}/_{2}$ in. (38 mm), $1^{1}/_{2}$ in. (38 mm) and 2.0 in. (51 mm), and 2.0 in. (51 mm) and $2^{1}/_{2}$ in. (64 mm). Where the thickness transition by more than $^{1}/_{2}$ in. (13 mm), the ratio of thinner and thicker plate is mostly limited to 1:2 with a 1:2.5 slope.

Charpy V-notch (CVN) testing for HAZ is not specified by any responding states, but State of Washington required HAZ CVN test for a particular project. Although toughness testing for HAZ is not required, cracking and low toughness in HAZ were experienced by about 27% and 11% of the responding states. The reasons for having adverse effects in HAZ was lack of preheat or using ESW-NGI. Cracking and low toughness in the HAZ of the ESW-NGI process has been cited by some states as the reason for prohibiting ESW-NGI.

Survey of Steel Bride Fabricators

A survey was sent by the research team to 14 steel bridge fabricators around the country to gather pertinent information from steel bridge fabricators on specific topics including: commonly used materials for highway steel bridges; experiences with HAZ and its toughness on performance; special provisions for HAZ toughness; preferred welding processes; and quality control procedures. Five fabricators responded to this survey, and the responses were followed-up by further email interview. The survey as well as the results are provided in APPENDIX C. The responses of the fabricators were in line with the response of the state departments of transportation.

Out of five responding fabricators, four follow special welding guidelines such as the state DOT standard specifications or internal guidelines, in addition to *AASHTO/AWS D1.5: Bridge Welding Code*. Only one fabricators uses *AWS D1.1: Structural Welding Code* in addition to *AWS D1.5*, for welding tubular or ancillary/miscellaneous products. Most fabricators use SAW and FCAW for fabrication of steel bridges. Three fabricators (AFCO, Hirschfeld and High) have used ESW-NGI process for steel bridge fabrication. The maximum thickness fabricated is about 4.0 in. (102 mm) for SMAW, SAW, FCAW and GMAW processes, and 5.5 in. (140 mm) for ESW-NGI process. The minimum fabricated plate thickness for the welding processes (except ESW-NGI) mostly ranged betweem $^1/_8$ in. (3.2 mm) and $^1/_2$ in. (13 mm). The minimum fabricated thickness using ESW-NGI process ranged between $^7/_8$ in. (22 mm) and 1.5 in. (38 mm). The responding fabricators have mostly used Grade 50 and Grade 50W steels for fabricating steel bridges since 2005. Use of HPS grades has been much less. All responding fabricators have performed HAZ fracture toughness testing using CVN specimens. Both cracking and low toughness associated with HAZ was experienced respectively due to lack of adequate heat input, and the low toughness was , and with ESW-NGI process or SAW process on HPS steel.

TASK 2 – IDENTIFY CRITICAL FACTORS AND ACCEPTANCE CRITERIA

Based on the analysis of survey results, review of information collected in in Task 1, and the general understanding of HAZ fracture toughness, the critical factors that affect the fracture toughness of structural steels and the acceptance criteria for HAZ fracture toughness in other industries are identified in this task.

Identify Critical Factors Affecting HAZ Toughness

The HAZ toughness depends on its microstructure, which results from a complex interaction between the BM chemical composition and the cooling rate ($\Delta t_{8/5}$) as the two primary variables. In addition, specific weld fabrication practices such as hydrogen control can affect the HAZ fracture toughness.

For a given steel composition, the cooling rate is the most important factor affecting the toughness (microstructure) of weld HAZ. The cooling rate further depends on the welding procedure and the thickness of the welded component (plate). The aspects of the welding procedure influencing the thermal cycle in the HAZ, including the peak temperature and the duration, are: gross energy input (heat input), the efficiency of energy transfer from the arc to the weldment, preheat/interpass temperature, extent of preheat, and post-weld heat treatment (PWHT). The heat input for a welding process is a function of the welding voltage, current, and travel speed.

For a given welding process, lesser arc energy, increased welding speed (for a particular heat input), increased plate thickness and reduced preheat/interpass temperature increases cooling rate. Similarly, for a particular welding process the cooling rate for a plate thickness increases as the heat input increases.

The HAZ microstructure depends on the steel composition and the rate of cooling. The size of the grain in the CGHAZ is an important parameter that influences the fracture toughness of the HAZ. Due to the high temperature of welding, the existence of CGHAZ is unavoidable. In addition to the rate of cooling, however, the width of weld HAZ and its grain size can be controlled by welding position and weld bead size and placement. The weld bead size increases with the heat input. Closely overlapped weld beads can improve the HAZ notch toughness, resulting from refinement by subsequent weld passes.

The effects of steel composition on the fracture toughness of welding HAZ are not well established (Pisarski and Pargeter 1984). Typically, traditional C-Mn steels that are not grain refined tend to produce HAZ as tough as the BM. Both at high and low heat input, the HAZ toughness of these steels reduce significantly. When the CE is greater than about 0.35, the influence of hardness on the HAZ toughness at low temperatures cannot be differentiated. The HAZ toughness of C-Mn microalloyed steels (HSLA steels) with C > 0.12% and small amount of Nb and V degrade at higher higher (> 90 kJ/in. or 3.5 kJ/mm). These steels with C < 0.12%, however are more tolerant of Nb or V alloying at heat input as high as 175 kJ/in. or 7 kJ/mm. However, only slight improvement in HAZ toughness is noted at a moderately low cooling rate ($\Delta t_{8/5}$ < 40sec), and at very low and very high cooling rates the HAZ toughness deteriorates. Other alloying elements such as Mo, Cu, Ni, Cr, Al and Ti can also improve HAZ toughness. Boron, less than 10-15 ppm, has beneficial effects on HAZ toughness, but can be detrimental in excess. In low alloy steels, with carbon contents typically in the range of 0.15-0.25% and total alloy contents of 2-6%, the HAZ toughness in as-welded condition reduces with increasing heat input.

PWHT at temperatures around 1110°F (600°C) is beneficial for HAZ toughness of C-Mn steels welded with low heat input. Similar treatments are also effective in addressing dynamic strain aging. For low alloy steels, PWHT is normally beneficial to HAZ fracture toughness in situations where precipitation hardening effects are small. On the other hand, PWHT of microalloyed steels containing Nb, V, and Cu that are capable of precipitation hardening during heat treatment can degrade HAZ fracture toughness. Additional phosphorus embrittlement by PWHT can occur at large prior austenite grain boundaries. Overall, PWHT helps by reducing residual stresses and consequent defect tolerance, even if the HAZ toughness is slightly reduced.

In addition, controlling weld fabrication defects in the HAZ such as hydrogen cracking and under-bead cracking can enhance the HAZ fracture toughness. These are influenced by combined effects of chemical composition of steel, cooling rate (heat input), and weld fabrication practices including adequate hydrogen control, hardness control, joint restraint (including geometry), and pre/post weld heat treatment for hydrogen diffusion.

The HAZ fracture toughness in terms of CVN impact energy for a few HSLA steels reported in the literature are presented in Figures 1 to 4. The chemical composition of these steels are tabulated in Table 16. The results show significant scatter in the test results, however a few generic observations can be made. As is seen, the HAZ fracture toughness was primarily influenced by heat input. The fracture toughness of all HAZ was similar for a heat input less than about 140 kJ/in. (5.5 kJ/mm). Significant reduction in the toughness was noted at heat input of 203 kJ/in. (8 kJ/mm). The influence of CE, on the HAZ toughness was not significant. However, the HAZ toughness was more sensitive to C- and Mn-content. The HAZ toughness reduced with increasing C-content; but increased with increasing Mn-content. Such influence of these alloying elements was also noted in the literature.

Identify Acceptance Criteria for HAZ Toughness

The domestic and foreign regulatory agencies in the offshore, pipeline, and ship building industries that specify HAZ toughness evaluation require CVN testing. The AASHTO design and fabrication specifications do not have any HAZ fracture toughness requirements for the bridge steels. The AASHTO specifications, however, require fracture toughness evaluations for the BM and the WM by CVN testing. AWS D1.1: Structural Welding Code provides requirements for HAZ fracture toughness evaluation by CVN testing. The test requirements from different agencies, including the sampling location, notch location, number of replicates, test temperature etc., are tabulated in Table 4. The HAZ toughness requirements in terms of CVN impact energy are tabulated in Tables 3 and 6 through 8, which vary depending on the steel grade (type and strength), plate thickness and application. Most fracture toughness requirements for the HAZ are less than the BM

TASK 3 – IDENTIFY RELEVANT FACTORS FOR STEEL BRIDGES

The factors affecting the HAZ fracture toughness as identified in Task 2 are also expected to affect the bridge steels. These include the chemical composition, the weld heat input (or cooling rate), the welding procedure, the thickness of the welded component, preheat/interpass temperature, and PWHT.

The material for steel bridges conforms to *AASHTO M270/ASTM A709: Standard Specification for Structural Steel for Bridges*, which cover carbon and HSLA structural shapes, plates and bars and QT alloy steel for structural plates. All steels are killed. The chemical composition of the steels are listed in Table 17 along with their CE based on the maximum allowable element content. Out of the seven grades covered by the specification, Grade 36 is the traditional C-Mn steel, having C $\leq \sim$0.27%, and Mn in the range of about 0.80-1.20% for plate thicknesses ¾-4 in, and Cu $\geq$ 0.2% if specified. The Grades 50, 50W and 50S are HSLA steels, having C > 0.12%. The Grade 50 contains small amounts of columbium (also known as niobium), and V and possibly N along with Ti. The Grades 50S may contain Ni, Cr and Mo in addition to Cb (or Nb) and V. This steel is produced by a practice such that N is contained to less than 0.012%. The Grade 50W is alloyed with Ni, Cr, and V and is produced by a fine grain practice. The grades HPS 50W, 70W can be classified as HSLA steels with C $\leq$ 0.11%. These steels are produced using a low H practice such as vacuum degassing and a fine grain practice. These steels can also be furnished as-rolled, control-rolled, TMCP (with or without accelerated cooling) and QT. They are alloyed with Ni, Cr, Mo, V, and Al, and may contain N $\leq$ 0.015%. The grade HPS 100W is QT alloy steel having C $\leq$ 0.08%, produced using a low heat practice. It is alloyed with Ni, Cr, Mo, V, Nb, and Al, and may contain N $\leq$ 0.015%. All the HSLA and QT steels are also alloyed with Cu.

The steel bridge fabrication code *AASHTO/AWS D1.5* allows SMAW, SAW, GMAW, FCAW, and ESW-NGI processes. All processes, except ESW-NGI, are allowed for all grades of M 270/A 709 steels and for all applications having a plate thickness of at least $^1/_8$ in. The use of ESW-NGI is restricted to AASHTO temperature Zones 1 and 2, non-fracture critical members and member components, and for non-HPS grades. Within the limitations of the specifications, the process that can most efficiently weld a particular thickness is selected for bridge fabrication. As was revealed from the survey responses of the state department of transportation and fabricators, SAW process is most frequently used for steel bridge fabrication in the United States. This is probably due to the convenience of splicing plates and making web-flange welds by this process. FCAW and SMAW processes are the next most frequently used process, for welding that cannot be easily accomplished by SAW process. GMAW and ESW-NGI processes are rarely used. The SMAW, GMAW and FCAW are comparatively low heat input processes [typically between 20 kJ/in. (0.8 kJ/mm) and 50 kJ/in. (2 kJ/mm)], and are preferred for welding components of smaller thickness, although their use for welding thicker flange plates [as large as 3.0 in. (76 mm)] is not uncommon. Using these processes for larger thicknesses [typically greater than 1.0 in. (25 mm)] would require a large number of passes and would be time consuming (not cost-effective). Among these, SMAW is the manual process (stick welding) and is the least efficient. On the other hand, GMAW and FCAW are semi-automated processes and can provide better efficiency. The single wire SAW (typically 50 to 70 kJ/in. or 2 kJ/mm to 2.8 kJ/mm), multi-wire SAW (~ 180 kJ/in. or 7 kJ/mm) and ESW-NGI (typically 250 to 600 kJ/in. or 10 to 25 kJ/mm) are higher heat input processes that are typically suitable for thicker components, although use of SAW for thinner plates (such web splice and web-flange welds) is not uncommon. Both these processes are semi-automatic. The ESW-NGI is the most efficient for groove welded splices in thicknesses greater than 2.0 in. (51 mm), as it can be performed through-thickness in one single pass. Accordingly, the heat input for the ESW-NGI process is the maximum.

The chemical composition of the bridge steels are consistent the C-Mn and HSLA steels reported in the literature (Dolby 1979) for offshore structures and pressure vessels, and are therefore expected to demonstrate similar HAZ toughness characteristics (as reported) depending on the cooling rate from peak temperature (or heat input associated with the accepted welding processes). For a faster cooling rate (or lower heat input), a degradation of the HAZ fracture toughness is possible due to formation of hard microstructure containing mixed M-A constituents such as un-tempered martensite or bainite in a predominantly pearlitic HAZ of typical C-Mn steels or relatively large martensitic laths in martensitic steels, assuming that the heat input is high enough to avoid hydrogen cracking. At slower cooling rate (or higher higher heat input), degradation of HAZ toughness could occur due to formation of coarse microstructural constituents including coarse prior austenite grains, grain boundary ferrite, ferrite sideplates. For a welding process the cooling rate depends on the heat input and the weld preheat, and weld interpass temperature. For SMAW, GMAW, FCAW and SAW processes, *AWS D 1.5* specifies minimum preheat/interpass temperature depending on the steel type and the component thickness to prevent too fast a cooling rate. The specification also provides limits on maximum preheat/interpass temperature to prvent too slow a cooling rate and grain growth in the CGHAZ that could affect the mechanical properties of the weldment. High weld heat input and associated slow cooling rate is of particular concern for mechanical properties of QT steels due to graing growth in the HAZ, and/or precipitation hardening.

For steel bridge fabrication, stress relieving PWHT to improve WM and HAZ properties is rarely performed and is mostly unnecessary. Sometimes post heating is performed at temperatures below 500°F (260°C), mostly for repair welds, for hydrogen diffusion and preventing weld cracking associated with lamellar tearing. These treatments are not considered as PWHT. Typically PWHT for stress relieving involves heating at a uniform rate above 900°F (480°C) holding for a certain time and then cooling at a specific rate, all of which are proportional to the plate thickness. Such treatment of QT steels can also degrade their toughness and strength.

The three primary conditions that affect the fracture toughness requirements of material are the loading rate, the service temperature and the constraint (plane stress vs. plane strain). The constraint condition is primarily controlled by the plate thicknesses used for design (thicker plates tend to have less fracture toughness than thinner plates). Thus, in addition to affecting the fracture toughness of welding HAZ by affecting the cooling rate (and therefore the microstructure), the plate thickness can also affect the fracture toughness requirement due to the constraint condition.

The loading rate for steel bridges is close to static loading condition (loading over 1.0 sec.), and therefore the fracture toughness requirements for bridge steels are less severe than what is required for impact resistance, but more severe than what is required for offshore structures (which are essentially subjected to static loading rate). Plates as thick as 4 in. (102 mm) are used in steel bridges, which are significantly larger than those used in offshore structures, and therefore would have different toughness requirements. The fracture toughness is a function of the service temperature, which for the specific applications within the AASHTO specifications would require different levels of fracture toughness of the welding HAZ for different service zones, and therefore would be relevant for the current research.

TASK 4 – DEVELOP WORK PLAN FOR PHASE II

A detailed work plan for Phase II was developed in this task which is presented in the following. The Phase II will consist of two tasks, *Task 6: Execute Approved Work Plan* and *Task 7: Prepare Final Report*. A work plan for both tasks is developed under this task. The work plan for Task 6 depicts the experimental investigations for developing HAZ toughness requirements of welded steel highway bridges. The work plan for Task 7 addresses preparation of final report including development of specification recommendations. The work plan for Task 6 and Task 7 is developed based on the approved project work plan, which is further modified, updated and expanded in view of the findings of Tasks1 through 3.

Develop Work Plan for Task 6

In Task 6, the fracture toughness requirements will be experimentally determined for weld HAZ in various grades of *AASHTO M270/ASTM A709* steel plates, where the weldment are made according to the welding processes of *AASHTO/AWS D1.5*. The *AASHTO M270/ASTM A709* covers seven grades of steel in four yield strength levels: 36, 50, 50S, 50W, HPS 50W, HPS 70W, and HPS 100W. The steel bridge fabrication code *AASHTO/AWS D1.5* allows SMAW, SAW, GMAW, FCAW, and ESW-NGI processes. All processes, except ESW-NGI, are allowed for all grades of M 270/A 709 steels and for all applications. The use of ESW-NGI is restricted to AASHTO temperature Zones 1 and 2, non-fracture critical members and member components, and for non-HPS grades. As was identified in Task 3, the steel grade (chemical composition), the welding process (cooling rate), and the component thickness are the primary factors affecting the weldment HAZ fracture toughness in bridge steels. Experiments are designed using these variables, based on the rationale discussed in the following.

Design of Experiments

As was revealed by the survey (conducted in Task 1) of the state departments of transportation and the steel bridge fabricators, M 270/A709 Grades 50 and 50W have been mostly used for fabricating steel bridges since 2005. Use of HPS grades have increased in recent years because of their excellent combination of strength, toughness, and weldability. Grade HPS 70W is more frequently used compared to HPS 50W, as thicker flange plates for hybrid girders, which can provide a cost-effective solution by optimum combination of strength and toughness. It should be noted that the specified chemical composition of HPS 50W and HPS 70W are identical. Grade HPS 100W has been rarely used. Also, grade 36 steel is rarely used in modern steel bridges. Use of grade 50S, which is a specification for steels produced out of scrap feed, is unknown. Thus, it is proposed to evaluate HAZ fracture toughness of highway bridge steels on Grades 50, 50W, HPS 70W and HPS 100 W. Since the specified chemical composition of Grades HPS 50W and HPS 70W are identical, their HAZ microstructures are expected to be similar. Evaluation of the higher strength steel is proposed because of any possible adverse effect of higher strength on toughness, and more frequent use in service. Most of the HAZ fracture toughness evaluation will focus on Grades 50, 50W and HPS 70W; a limited study will be performed on HPS 100W for completeness.

As was noted in Tasks 2 and 3, for a grade of steel (or chemical composition), the HAZ fracture toughness of a weldment depends on the cooling rate in the HAZ, which is a function of the heat input, preheat/interpass temperature, and the component thickness. The cooling rate decreases with increasing heat input and preheat/interpass temperature,but increases with the component thickness. Too fast and too slow cooling rates can adversely impact the HAZ fracture toughness. Within the limitations of *AWS D1.5* specifications, the process that can most efficiently weld a particular thickness is selected for bridge fabrication. The SMAW, GMAW and FCAW are comparatively low heat input processes, typically between 20 and 50 kJ/in. (0.8 and 2 kJ/mm)]. Welding larger thicknesses typically greater than 1.0 in. (25 mm) by these processes for would require a large number of passes and would be time consuming (not cost-effective). Among these, SMAW is the least heat input process, and being a manual process (stick welding) is also the least efficient. On the other hand, GMAW and FCAW are semi-automated processes and can provide better efficiency for smaller thicknesses. The SAW process, typically 50 to 70 kJ/in. (2 to 2.8 kJ/mm) is a higher heat input processes that is efficient for continuous long welds in both thinner and thicker plates. The ESW-NGI uses a much higher heat input, typically 250 to 600 kJ/in. (10 to 23.6 kJ/mm), and is the most efficient for groove welded splices in thicknesses greater than 2.0 in. (51 mm), as it can be performed through thickness in one single pass. Both SAW and ESW-NGI processes are semi-automatic.

For SMAW, GMAW, FCAW and SAW processes, *AWS D 1.5* specifies minimum preheat/interpass temperature depending on the steel type and the component thickness to prevent too fast a cooling rate, which can promote a hardenable HAZ microstructure, cold cracking, and lower fracture toughness. For the typical heat input associated with these processes, at a specific preheat/interpass temperature the maximum possible component thickness will produce the fastest cooling rate, when a weld procedure with the minimum possible heat input and other appropriate parameters (such as current, travel speed etc.) for an acceptable weld quality is used. On the other hand, the maximum possible heat input subject to an acceptable weld quality and the minimum possible component thickness for a specific preheat/interpass temperature will slow down the cooling rate, and can produce a coarser HAZ adjacent to the FL. The high heat input associated with ESW-NGI process produces a slow cooling rate, which generates a much larger HAZ with coarse microstructural constituents and lower HAZ fracture toughness. Because of the high heat input, no preheat is necessary for this process. It may be noted that the heat input associated with ESW-NGI increases with increased component thickness as the welding is performed through thickness in one pass, and the heat dissipation is mostly limited to convection through the cooling shoes on the component surface, and conduction through the component. It is thus apparent that the thickest component and the least possible heat input and preheat/interpass temperature, as well as the thinnest component with largest possible heat input and preheat/interpass temperature, both can produce the critical HAZ toughness.

The survey of state departments of transportation and steel bridge fabricators performed in Task 1 revealed that the SAW process is mostly used for steel bridge fabrication, although all processes, except GMAW and ESW-NGI, are allowed by all states for welding all plate thicknesses greater than $^1/_8$ in. (3.2 mm) in all steel grades. The next two commonly used processes are FCAW and SMAW. The SAW process is used for both thinner and thicker plates. The FCAW, SMAW, and GMAW processes are more frequently used for thinner plates, although their use for thicker plates as large as 4.0 in. (102 mm) has been reported. The larger plate thicknesses most frequently used for steel bridge fabrication are 3.0 in. (76 mm) and 4.0 in. (102 mm) of Grades 50, 50W, HPS 70W and HPS 50W (although use of HPS 50W is less frequent than HPS 70W).

In view of the above, it is proposed to evaluate the HAZ in M270/A709 steels of Grades 50, 50W, HPS 70W, and HPS 100W for SMAW, GMAW, FCAW, SAW, and ESW-NGI welding processes, and in three plate thicknesses of 1.0 in. (25 mm), 2.0 in. (51 mm), and 4.0 in. (102 mm). Not all combinations of steel grades, welding processes and plate thicknesses are considered, however; only the plate thicknesses for a particular welding process that are prevalent in steel bridge fabrication practices are considered to accomplish the project objective.

Three plate thicknesses, 1.0 in. (25 mm), 2.0 in. (51 mm), and 4.0 in. (102 mm) are proposed, for Grades 50, 50W,and HPS 70W. If 4.0 in. (102 mm) plates are not readily available, they will be replaced with 3.0 in. (76 mm) thick plates, which are also frequently used for steel bridge fabrication. Only 1.0 in. (25 mm) thick plate is considered for HPS 100W, although this steel grade is reported to be used for plates as thick as 3.5 in. (89 mm). Due to rare use of HPS 100W, this material is not readily available, and may be more difficult to find in larger thicknesses. The 1.0 in. (25 mm) thick plate in HPS 100W is considered for the sake of completeness of the study. It may be noted that for multipass welds the most critical CGHAZ is produced by the capping pass. A suitable weld procedure with appropriate heat input and preheat/interpass temperature may be developed for the 1.0 in (25 mm) thick HPS 100W plate to reproduce the critical HAZ condition of the multipass weld in a plate as thick as 3.5 to 4.0 in. (89 to 102 mm), without affecting the research outcome.

Noting that currently the ESW-NGI process is not allowed by many states and the relatively new technology is not available with most steel bridge fabricators, a limited study on HAZ of this process is proposed involving only 4.0 in. (102 mm) thick plates, as this process is more efficient for through thickness splicing of thicker plates and uses larger heat input for larger thicknesses. Although, not allowed by *AASHTO/AWS D1.5* specifications, it is proposed to evaluate this process for HAZ toughness in HPS 70W, since this steel is becoming more popular for bridge fabrication, particularly for thicker flange. The moratorium of using ESW-NGI on HPS 50W and HPS 70W grades may be removed if adequate HAZ toughness can be verified by this study, which appears to be a possibility based on recent unpublished studies.

The HAZ of SAW process is proposed to be evaluated on 1.0 in. (25 mm), 2.0 in. (51 mm), and 4.0 in. (102 mm) thick plates of Grades 50, 50W and HPS 70W, and on 1.0 in. (25 mm) thick plate of Grade HPS 100W. The HAZ of FCAW process is proposed to be evaluated on 1.0 in. (25 mm) and 2.0 in. (51 mm) thick plates of Grades 50W and HPS 70W, on 2.0 in. (51 mm) thick plate of Grade 50, and 1.0 in. (25 mm) thick plate of Grade HPS 100W. Although GMAW process is typically not efficient for thicknesses beyond $^5/_8$ in. (16 mm), it is proposed to be evaluated on 1.0 in. (25 mm) thick plates as an extreme condition for all considered steel grades.

For steel bridge fabrication, stress relieving PWHT to improve WM and HAZ properties is rarely performed and is mostly unnecessary. Sometimes post heating is performed at temperatures below 500°F (260°C), mostly for repair welds, for hydrogen diffusion and preventing weld cracking associated with lamellar tearing. These treatments are not considered as PWHT. The survey of state departments of transportation and the steel bridge fabricators revealed that such treatments are rare and only used for highly restrained joints. Typically PWHT for stress relieving involves heating at a uniform rate above 900°F (480°C) holding for a certain time and then cooling at a specific rate, all of which are proportional to the plate thickness. Such treatment of Q&T steels can also degrade their toughness and strength. Accordingly, it is proposed to assess the effect of post-weld heat treatment (PWHT) on 4.0 in. (102 mm) thick plates of Grades 50 and 50W, and 2.0 in. (51 mm) and 4.0 in. (102 mm) thick plates of HPS 70W, for SAW and ESW-NGI processes.

The influence of plate thickness transition is proposed to be evaluated by full scale tests using ESW-NGI process. The surveys of state departments of transportation, and the steel bridge fabricators showed that thickness transition of 1.0 in. to 1.5 in. (25 to 38 mm), 1.5 in. to 2.0 in. (38 to 51 mm) and 2.0 in. to 2.5 in. (51 to 64 mm) are more common. Accordingly, a thickness transition of 2.0 in. to 3.0 in. in grade 50W has been proposed.

For each combination of investigated steel grade, welding procedure, and thickness, the HAZ toughness will be measured by CVN tests and will be verified by limited CTOD tests. For each combination these tests will be performed at multiple temperatures, and for each temperature at multiple locations in the HAZ with replicates for each location. The test matrices for CVN and CTOD testing are shown in Tables 18 & 19 and are further discussed later in the text.

In addition, it is proposed to verify the fracture toughness of HAZ of all welding processes in Grade 50W steel by full scale tests, under the most severe temperature conditions. The purpose of these tests is to determine the significance of the weld HAZ fracture toughness as determined from the small scale tests. These tests are discussed in detail under Subtask 6.4. The test matrix is presented in Table 20.

Vickers hardness (HV10) of the BM, HAZ and the WM of each CVN and CTOD specimens will be measured at locations schematically identified in Figure 5. The yield strength of the BM, HAZ and the WM will be estimated based on the hardness measurements. In addition, the chemical composition of the BM for each plate material will be analyzed.

Specimen Designs for CVN and CTOD Testing

The CVN and CTOD test specimens will be machined from a groove-welded plate. All welding related to the specimens will be performed by a certified steel bridge fabricator.

For GMAW, FCAW, SMAW, and SAW processes, a K-joint configuration will be used for the groove welded plate to obtain a vertical HAZ at the vertical edge of the joint preparation. As reported under Literature Review in Task 1, this joint configuration has been mostly used by other researchers to obtain a HAZ normal to the plate surface that has a higher likelihood of being sampled by the specimen notch and the fracture path. It may be noted that a prequalified double-bevel-groove weld butt joint, similar to the proposed K-joint, exists in the *AWS D1.5* for SMAW (joint designation B-U5a), and GMAW and FCAW (joint designation B-U5-GF) processes with unlimited BM thickness. This joint configuration will have to be qualified for the SAW process and the considered plate thicknesses.

For ESW-NGI, a square joint preparation will be used, which naturally provides a HAZ normal to the plate surface. The CVN and CTOD specimens will be provided with a surface notch in the HAZ, normal to the plate surface and oriented in the thickness direction of the plate. The HAZ will be identified by polishing and etching the side faces of the welded plate before locating the notch, following the process recommended by *BS EN ISO 15653:2010.*

Plan of CVN Testing

The CVN tests will be conducted at subsurface (SS), and at mid-thickness (MT) of the plates. The SS tests will be performed both at top and bottom surfaces. At MT location, the CVN tests can only be performed for 2.0 in. (51 mm) and 4.0 in. (102 mm) thick plates. For typically narrow HAZ produced by SMAW, GMAW, FCAW and SAW processes, at SS locations the notches will located in the HAZ, within 0.02 in. (0.5 mm) of the FL (identified as FL+0.5mm), and at about 0.2 in. (5 mm) from the FL (identified as FL+5mm); at MT location, the test will be performed with the notch at FL+5mm. The tests with notch at FL+0.2 in. (0.5 mm) are devised to capture the effect of LBZ in the CGHAZ adjacent to the FL, which is most severe within the HAZ of the capping pass for a multipass weld. The tests with notch at the FL+0.2 in. (5 mm) are to capture any possible embrittlement in the SCHAZ that has been reported in the literature. Three replicates will be tested at each location. Since ESW-NGI process produces a relatively wider HAZ associated with the high heat input, and the FL tends to bulge out in the mid thickness due to unequal rate of cooling, the CVN notch will be located in the HAZ at about 0.08 in. (2 mm) from the FL (identified as FL+2mm), and at about 0.4 in. (10 mm) from the FL (identified as FL+10mm)

Most specifications require three replicates for CVN testing at each sampling loction (Table 4). The *AASHTO/AWS D1.5* specifications recommend five replicates for CVN testing of weldments, but at only one thickness position. Since all thicknesses are being sampled at two thickness positions, three replicates for each position would be sufficient for a statistically significant evaluation of fracture toughness. This approach is also consistent with other previous research.

In addition to providing replicates, the CVN tests at multiple locations through the thickness of the plate can provide a through thickness variation in dynamic fracture toughness of the CGHAZ, as was suggested by Malik et al. (1996). The CVN tests will be performed at three temperatures, consistent with the *AASHTO LRFD Bridge Design Specifications* for the different grades of steel. The test matrix for CVN testing is shown in Table 18. The CVN testing will be performed according to *ASTM E23*. In addition, the microstructure at the notch location and on the fracture surface will be evaluated by post-test metallography and fractography.

Plan of CTOD Testing

The CTOD tests will be conducted using a single edge notch bend specimen (SENB) with a shallow surface notch (a/W~0.15) and $B\times B(=W)$ or $B\times 2B(=W)$ configuration, where W is the full plate thickness, a is the notch depth, and B is the width of the specimen. The SENB with a shallow SN is proposed as it more realistically represents the constraint condition of a likely flaw in the HAZ. The notch will be located at 0.02 in. (0.5 mm) from the FL for SMAW, GMAW, FCAW and SAW processes. For ESW-NGI process, the notch will be located at 0.08 in. (2 mm) from the FL. The test matrix for CTOD testing is shown in Table 19. Only a limited number of CTOD tests will be performed at 1.0 sec. loading rate (considered as the bridge loading rate) and dynamic loading rates(time to maximum load of 0.001 sec.) The purpose of the CTOD testing is to determine the fracture toughness of the LBZs, and to determine the loading rate effects on the HAZ fracture toughness. For the BM, several correlations between the plane strain fracture toughness at the slow loading rate and the CVN toughness under dynamic loading are available in the literature (Bannister 1998). This limited exercise is to verify if similar relationship can be established for the HAZ. Two replicates will be tested for each combination, each at two temperatures. The tests will be performed according to *BS EN ISO 15653:2010* and *ASTM E1820-13*. The notch depth, the microstructure at the fracture initiation, and the validity of the tests will be determined by post-test metallography and fractography. All CTOD tests will be performed under three point bending. The tests under bridge loading rate will be performed in a MTS 810 material testing system. The dynamic tests will be performed in a drop weight testing apparatus.

The work plan for Task 6 will be divided into five subtasks as described in the following.

Subtask 6.1: Pilot CVN and CTOD Testing of HAZ

A pilot study will be conducted to develop the welding procedures for all considered steel grades and plate thicknesses that would produce the most critical HAZ within the specifications of *AWS D1.5*, and to establish the CVN and CTOD test protocols. The weld procedure qualification records (PQR) will be developed for GMAW, FCAW, SMAW, and SAW processes using the proposed K-joint configuration. For each process, two procedures will be considered to produce the fastest and the slowest cooling rates.

The weld procedure qualifications will be performed according to *AWS D1.5*. Details of the WPS qualification test plates, identifying the various specimens required for the qualification tests, are shown in Figures 6 and 7. The test plate follows the recommendations of *AWS D1.5*. Since the primary purpose of this pilot study is to develop a weld procedure that produces the most critical HAZ, CVN and CTOD testing of the HAZ has also been included.

The weld procedures will be qualified for the maximum and the minimum possible heat input for a particular welding process and plate thickness, and the maximum and minimum preheat/interpass temperature to produce the slowest and the fastest cooling rate in the WM and the HAZ. The welding will be performed in 1G position. To produce the largest possible arc angle with the vertical face of the joint for maximizing the HAZ, the plates will be tilted by 45 degrees with respect to the horizontal as shown in Figure 8.

To optimize the research output, it is proposed to test during the pilot studies a subset of the full CVN and CTOD test matrices (presented in Tables 18 and 19), taking advantage of the PQR tests plates. The subset is identified by the number of replicates shown in parentheses, and reproduced separately in Tables 21 and 22, respectively for the CVN and CTOD testing of the HAZ. The thickness of the PQR test plates has been selected accordingly to investigate the most critical HAZ. It may be noted that *AWS D1.5* requires a minimum 1.0 in. (25 mm) thick PQR test plate for FCAW, GMAW, SMAW, and SAW processes.

The CVN samples for WPS qualification will be obtained from the mid-thickness of the WM as recommended by *AWS D1.5*. Five CVN tests will be conducted per PQR plate at the test temperature for AASHTO service Zone 3 (see Table 23)

The CVN and CTOD testing of the weld HAZ will be performed as discussed earlier. Altogether 450 CVN and 44 CTOD specimens will be tested. The protocols for conducting and evaluating the CVN and the CTOD tests will be established in this subtask. In addition, the critical weld procedures will be identified for each process, steel grade and plate thickness.

Subtask 6.2: CVN Testing of HAZ

In this subtask, CVN testing of weld HAZ will be performed based on the protocols established in Subtask 6.1. The critical weld procedures developed in Subtask 6.1 for each weld process and plate thickness will be considered. The test matrix for the CVN testing is presented in Table 18. Each cell of the matrix shows the replicates to be tested for the particular condition at each test temperature. The values in the parentheses represent the tests conducted in the pilot study under Subtask 6.1. Altogether 1152 CVN testing will be performed.

Subtask 6.3: CTOD Testing of HAZ.

In this subtask, CTOD testing of weld HAZ will be performed based on the protocols established in Subtask 6.1. The test matrix for the CTOD testing is presented in Table 19. Each cell of the matrix shows the replicates to be tested for the particular condition at each test temperature. The values in the parentheses represent the tests conducted in the pilot study under Subtask 6.1. The CTOD specimens will be produced from the same welded plates used for the CVN testing in Subtask 6.2.

Subtask 6.4: Testing Full Scale Specimens.

The HAZ fracture toughness, determined in the previous subtasks, will be verified by testing full scale plate specimens under axial loading. These specimens will employ a T-section consisting of a part web and a part flange of a full size girder as shown in Figure 9. The flange of the T-specimens will include two groove welded splices. A full size girder, sans the T-section will be fabricated as a fixture (Figure 10). The T-specimens will be attached to the fixture girder using bolted splices, and the composite girder will be tested under flexure as shown in Figure 11 subjecting the groove welded splices in the flange of the T-specimens to axial/in-plane membrane stresses normal to the welds. Three replicates each of the T-specimens containing SAW, FCAW, GMAW, SMAW and ESW-NGI splices in 2.0 in. (51 mm) flange plates will be tested. In addition, three replicates of a T-specimen containing a flange thickness transition from 2.0 in. (51 mm) to 3.0 in. (76 mm) and fabricated using ESW-NGI process will be tested. Thus, six replicates of each weld process/configuration will be tested. All welding will be performed according to the WPS' used for Subtasks 6.2 and 6.3, and all splices will be provided with a reinforcement to promote crack growth at the weld toe. For ESW-NGI, a modified shoe will be considered to create this reinforcement. The T-specimens and the fixture girder will be fabricated using Grade 50W steel. The test matrix is shown in Table 20.

The specimens will be tested under cyclic loading to promote fatigue crack growth into the CGHAZ from the toe of the weld reinforcements. The fatigue tests will be conducted at a stress range of about 20 ksi (138 MPa), which exceeds the fatigue threshold for the splice details (AASHTO Category B). The splice details will be cooled down to –60°F (–51°C), the service temperature for AASHTO Zone 3, at regular interval, and the cycling testing will be performed for a predetermined number of cycles to promote brittle fracture from any fatigue crack growth into the CGHAZ. It is envisaged that the specimens will be cooled by liquid nitrogen flowing through a pipe network having a closed loop temperature control. The welded details will be frequently inspected non-destructively for fatigue cracking using techniques such as magnetic particle and dye penetrant testing. In addition, Phased Array Ultrasonic Testing (PAUT) will be tried due to its sensitivity to smaller flaws. In case a fatigue crack is detected, which would not cause ustable fracture under the cyclic loading, efforts will be made to promote unstabe crack growth under a higher static loading not exceeding the nominal yield stress (50 ksi or 350 MPa) in the flange. The testing will be continued until brittle fracture could be developed in the specimen or until the specimen develops large fatigue crack that prevents continued testing. Upon test termination all specimens will be destructively evaluated. The fracture surfaces will be exposed and the crack at the initiation of the brittle fracture will be characterized.

Subtask 6.5: Develop Proposed Toughness Requirements

Based on the findings of the experimental studies, the fracture toughness requirements for the HAZ will be developed. The CVN and CTOD results will be plotted over the range of test temperatures. The effect of loading rate will be evaluated, and the correlation between CVN test results and the fracture toughness at the bridge loading rate will be established. The HAZ fracture toughness will be verified against the full scale test results. In addition, the fracture toughness will be correlated with the hardness measurement of HAZ. Effects of BM physical and chemical properties and the weld procedures on the HAZ toughness and hardness will be assessed. The fracture toughness demands or the stress intensity factors will also be estimated analytically based on published formulae or Finite Element Method. Further, the significance of the measured HAZ fracture toughness on the integrity of the full scale structures may be addressed by Engineering Critical Assessment (ECA) calculations utilizing the Failure Assessment Diagram in accordance with *BS7910:2005* Level 2. It is anticipated that the fracture toughness requirements will be defined in terms of energy absorbed in CVN testing, consistent with the AASHTO specifications for BM and WM.

It is estimated that 1152 CVN specimens, 120 CTOD specimens and 18 full scale specimens will be tested. The proposed experimental studies have been adequately budgeted including cost of specimens, laboratory supplies and use fees, as presented in section 8 of the proposal. The research team will seek material donations from steel producers, the American Iron and Steel Institute (AISI) and AISC, and plate droppings from bridge fabricators, and hopes to procure the specimens for the research at cost from the bridge fabricators. This will help in optimizing the research output.

Develop Work Plan for Task 7

The Task 7 will consist of preparation of the final report and development of specification recommendations. The final report will contain all relevant findings from the literature review, the surveys, as well as from the experimental studies. The report will also discuss the interpretation, appraisals and application of the results in practice. Recommendations for future research will be made where appropriate.

A draft of the proposed requirement for HAZ toughness along with commentary will be developed as a standalone document in a format suitable for incorporation into the *AASHTO/AWS D1.5 Bridge Welding Code* and *AASHTO LRFD Bridge Design Specifications.*

TABLES

Table 1 Specifications Reviewed for Different Industrial Applications

Specifications	Titles	Applications
ABS	Rules for materials and Welding -Part 2	Ship building
API RP 2Z	Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures	Offshore plates
API 2B	Specification for the Fabrication of Structural Steel Pipe	Structural steel pipe
AWS D1.1	Structural Welding Code -Steel	General Welding
AWS D1.5	Bridge Welding Code	Bridge steels welding
BS EN 10225	Weldable Structural Steels for Fixed Offshore Structures — Technical Delivery Conditions	Fixed offshore structures
DNV-RP-F108	Fracture Control for Pipeline Installation Methods Introducing Cyclic Plastic Strain	Pipeline installation
DNV-OS-C401	Fabrication and Testing of Offshore Structures	Offshore structures
DNV-OS-F101	Submarine Pipeline Systems	Submarine Pipeline Systems
ISO 3183	Petroleum and natural gas industries—Steel pipe for pipeline transportation systems	Pipelines for petroleum and natural gas

Table 2 CVN Requirements for Weldments in AWS D1.5

		CVN, ft-lb (J) AASHTO Temperature Zones	
Grade of Steel	**Welding Process**	**I and II**	**III**
50, 50W, HPS 50W	SMAW	Prequalified - Exempt from Test	
	SAW, GMAW, FCAW	20 @ 0°F (27 @ –20°C)	20 @ –20°F (27 @ –30°C)
HPS 70W	SMAW	Prequalified - Exempt from Test	
	SAW, GMAW, FCAW	25 @ –10°F (34 @ –25°C)	25 @ –25°F (34 @ –30°C)
HPS 100W over $2^1/_2$ in. (60 mm) thick	SMAW	Prequalified - Exempt from Test	
	SAW, GMAW, FCAW	20 @ –40°F (27 @ –40°C)	As approved by engineer

Table 3 HAZ CVN Requirements (*AWS D1.1*)

Relevant Steel Grades	Yield Strength, ksi (MPa)	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J)
ASTM A 709 Grades 50T2, 50T3	50 (350)	40 (4)	15 (20)

Table 4 HAZ CVN Toughness Test Requirements for Different Specifications

Specification	Test Specification	Sampling Locations				Number of Samples	Test Temperature, °F (°C)
		Heat Input	Plate Thickness	Specimen Location in Thickness[7,8]	Notch Locations		
ABS	*ISO 148*	≤ 127 kJ/in. (5 kJ/mm)	≤ 2 in.	1-2 mm from surface [5]	FL FL+2 mm	3	Varies with steel grade
			> 2 in.	1-2 mm from surface	FL FL+2 mm	3	
				At the root (for single V groove only)	FL	3	
		>127kJ/in. (5 kJ/mm)	≤ 2 in.	1-2 mm from surface [5]	FL FL+ 2mm FL+5 mm FL+10 mm	3	
			> 2 in.	1-2 mm from surface	FL FL+2 mm FL+5 mm FL+10 mm	3	
				Root	FL (only for single V groove) FL+2 mm	3	

Table 4 *Continued*

Specification	Test Specification	Sampling Locations: Heat Input	Plate Thickness	Specimen Location in Thickness[7,8]	Notch Locations	Number of Samples	Test Temperature, °F (°C)
API RP 2Z	—	—	—	$^1/_4$t Root	Unaltered CGHAZ Unaltered SCHAZ	3 (for each temperature in transition curve)	8 temperatures points required in each transition curve
API 2B	*ASTM E23* *ASTM A370*	—	≤ 0.5 in.	Root	FL+5mm	3 or 5	Same as *AWS D1.1*
			> 0.5 in.	> $^1/_4$t	FL+1mm FL+5mm	3 or 5	Same as *AWS D1.1*
API 5L	*ASTM A370* *ISO 148-1*	—	—	Root	FL	3	32 (0)
AWS D1.1	*ASTM E23* *ASTM A370*	—	≤ 0.5 in.	Root	FL+5mm	3 or 5	Contract documents or specifications
			> 0.5 in.	> ¼ t	FL+1mm FL+5mm	3 or 5	Contract documents or specifications

Table 4 ***Continued***

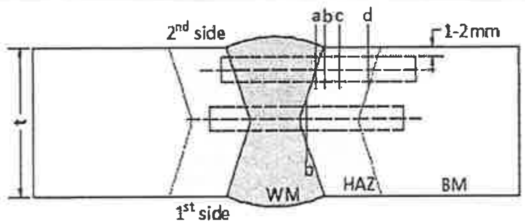
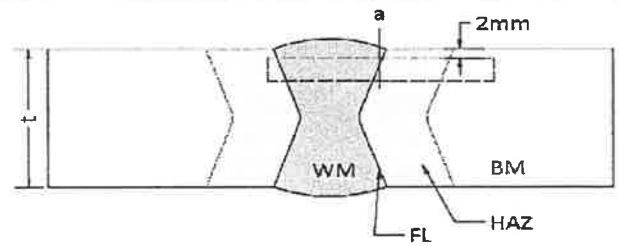
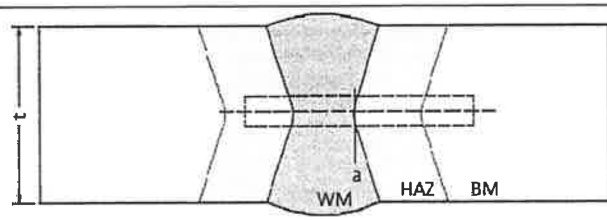
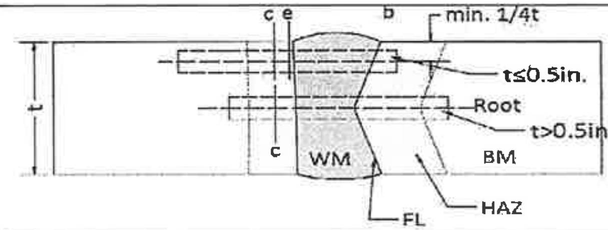
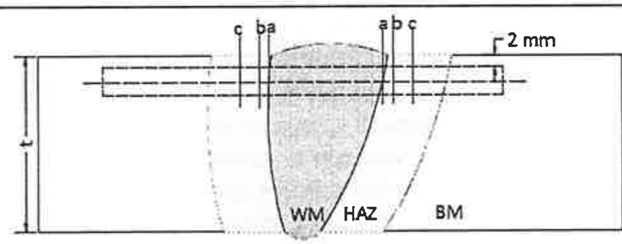
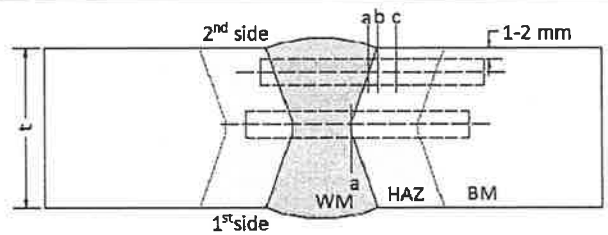
Specification	Test Specification	Sampling Locations: Heat Input	Sampling Locations: Plate Thickness	Sampling Locations: Specimen Location in Thickness[7,8]	Sampling Locations: Notch Locations	Number of Samples	Test Temperature, °F (°C)
BS EN 10225	*EN 10045-1.*	—	≤ 1.5 in.	At weld cap, < 2 mm from surface	FL FL+2mm FL+5mm	3	–40 (–40)
			> 1.5 in.	At weld cap, < 2 mm from surface	FL FL+2mm FL+5mm	3	–40 (–40)
DNV-OS-C401	*ISO 148*	—	≤ 2 in.	2 mm from surface	FL FL+2mm FL+5mm	3	Varies with steel grade
			> 2 in.	< 2 mm from surface	FL FL+2mm FL+5mm	3	
				Root	FL	3	
DNV-OS-F101	*ISO 148-1*	—	≤ 1 in.	At weld cap, < 2 mm from surface	FL FL+2mm FL+5mm	3	Varies with steel grade
			> 1 in.	At weld cap, < 2 mm from surface	FL FL+2mm FL+5mm	3	
			—	Root	FL	3	

		Sampling Locations					
Specification	**Test Specification**	**Heat Input**	**Plate Thickness**	**Specimen Location in Thickness**[7,8]	**Notch Locations**	**Number of Samples**	**Test Temperature, °F (°C)**
ISO 3183	*ASTM A370* *ISO 148-1*	—	—	Root	FL	3	32(0)

Notes:

1. 1.0 in. = 25.4 mm
2. Specimen orientation: longitudinal centerline of the specimen perpendicular to weld axis
3. Notch orientation: perpendicular to plate surface
4. Specimen size: 10 mm×10 mm (sub size allowed depending on plate thickness)
5. Testing in multiple HAZ locations is optional and locations vary with heat input
6. On the second side of weld for double V groove
7. 1-2 mm from surface corresponds to the position of top face of the specimen.
8. Root, $^1/_4$t, $^1/_2$t correspond to the position of the centerline of the specimen.
9. According to *API 5L* and *ISO 3183 HAZ*, CVN testing is required only for PSL2 pipes.

Table 5 CVN Specimen Sampling Locations for Different Specifications

Specification	HAZ Test Notch Locations	Specification	HAZ Test Notch Locations
ABS		API 2B	
ISO 3183, API 5L		AWS D1.1	
BS EN 10225		DNV-OS-C401 DNV-OS-F101	

Notes:
1. 1.0 in. = 25.4 mm
2. Legend:
   a = FL;
   b = FL + 2 mm
   c = FL + 5 mm
   d = FL + 10 mm
   e = FL + 1 mm
   t = thickness

Table 6 HAZ CVN Requirements of *ABS*

Relevant Steel Grades	Yield Strength, ksi (MPa)	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J)	
			Manual and Semiautomatic Welding Processes	Automatic Welding Processes and Vertical Position
AH36	51 (355)	32 (0)	25 (34)	25 (34)
DH36	51 (355)	32 (0)	35 (47)	25 (34)
EH36	51 (355)	–4 (–20)	35 (47)	25 (34)
FH36	51 (355)	–40 (–40)	35 (47)	25 (34)

Table 7 HAZ CVN Requirements of API 5L and ISO 3183

Relevant Steel Grades	Yield Strength, ksi.	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J)	
			D[3] < 56 in.	D[3] ≥ 56 in.
≤ X60 or L415	≤ 60	32 (0)	20 (27)	30 (40)
> X65 or L450 and ≤ X70 or L485	>65 and ≤ X70	32 (0)	20 (27)	30 (40)
> X90 or L625 and ≤ X100 or L690	> 90 and ≤ 100	32 (0)	30 (40)	30 (40)

Notes:
1. 1.0 in. = 25.4 mm
2. 1 ksi = 6.89 MPa
3. D = pipe outer diameter
4. Permissible range of pipe wall thickness varies with pipe diameter

Table 8 HAZ CVN Requirements of *DNV-OS-C401*

Relevant Steel Grades	Yield Strength, ksi	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J)			
			t[3] ≤ 2 in.	2 in. < t[3] ≤ 3 in.	3 in. < t[3] ≤4in.	t[3] ≤ 6 in.
NV A36	51	32 (0)	17.5 (23.8)	(21) 28.7	(25.9) 35	—
NV D36	51	−4 (−20)	17.5 (23.8)	(21) 28.7	(25.9) 35	—
NV E36	51	−40 (−40)	17.5 (23.8)	(21) 28.7	(25.9) 35	—
NV A500	71	32 (0)	—	—	—	24 (33)
NV D500	71	−4 (−20)	—	—	—	24 (33)
NV E500	71	−40 (−40)	—	—	—	24 (33)

Notes:
1. 1.0 in. = 25.4 mm
2. 1 ksi = 6.89 MPa
3. t = thickness

Table 9 Base Metal CVN Requirements of *AWS D1.1*

Relevant Steel Grades	Yield Strength, ksi (MPa)	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J)
ASTM A 709 Grades 50T2, 50T3	50 (350)	Lowest anticipated service temperature	25 (34)

Table 10 LRFD CVN Requirements for ASTM A709 Steel Grades

Grade (Y.P./Y.S.)	Thickness (in.)	Min. Test Value Energy (ft-lbs.)	Fracture-Critical Zone 1 (ft-lbs.@°F)	Fracture-Critical Zone 2 (ft-lbs.@°F)	Fracture-Critical Zone 3 (ft-lbs.@°F)	Nonfracture-Critical Zone 1 (ft-lbs.@°F)	Nonfracture-Critical Zone 2 (ft-lbs.@°F)	Nonfracture-Critical Zone 3 (ft-lbs.@°F)
		20	25 @ 70	25 @ 40	25 @ 10	15 @ 70	15 @ 40	15 @ 10
50/50S/50W	$t \leq 2$	20	25 @ 70	25 @ 40	25 @ 10	15 @ 70	15 @ 40	15 @ 10
	$2 < t \leq 4$	24	30 @ 70	30 @ 40	30 @ 10	20 @ 70	20 @ 40	20 @ 10
HPS 50W	$t \leq 4$	24	30 @ 10	30 @ 10	30 @ 10	20 @ 10	20 @ 10	20 @ 10
HPS 70W	$t \leq 4$	28	35 @ −10	35 @ −10	35 @ −10	25 @ −10	25 @ −10	25 @ −10
HPS 100W	$t \leq$ 2-1/2	28	35 @ 30	35 @ 0	35 @ −30	25 @ 30	25 @ 0	25 @ −30
	2-1/2 $< t \leq 4$	36	45 @ 30	45 @ 0	not permitted	35 @ 30	35 @ 0	35 @ −30

Table 11 Minimum Service Temperatures for Different Service Zones According to LRFD

Minimum Service Temperature (°F)	Temperature Zone
0 and above	1
−1 to −30	2
−31 to −60	3

Table 12 Base Metal CVN Requirements of *ABS*

Relevant Steel Grades	Yield Strength, ksi (MPa)	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J): $t \leq 2$ in. L	$t \leq 2$ in. T	2 in. $< t \leq 2.8$ in. L	2 in. $< t \leq 2.8$ in. T	2.8 in. $< t \leq 4$ in. L	2.8 in. $< t \leq 4$ in. T
AH36	51(355)	32 (0)	25(34)	17 (24)	30 (41)	20 (27)	37 (50)	25 (34)
DH36	51(355)	32 (0)	25(34)	17 (24)	30 (41)	20 (27)	37 (50)	25 (34)

EH36	51(355)	–4 (–20)	25(34)	17 (24)	30 (41)	20 (27)	37 (50)	25 (34)
FH36	51(355)	–40 (–40)	25(34)	17 (24)	30 (41)	20 (27)	37 (50)	25 (34)

Notes:
1. 1.0 in. = 25.4 mm
2. Legend:
   t = thickness
   L = Longitudinal to plate rolling direction
   T = Transverse to plate rolling direction

Table 13 Base Metal CVN Requirements of *API 5L* and *ISO 3183*

Relevant Steel Grades	Yield Strength, ksi.	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J)	
			$D^3 < 56$ in.	$D^3 \geq 56$ in.
≤ X60 or L415	≤ 60	32 (0)	30 (40)	30 (40)
> X65 or L450 and ≤ X70 or L485	>65 and ≤ X70	32 (0)	40 (54)	50 (68)
> X90 or L625 and ≤ X100 or L690	> 90 and ≤ 100	32 (0)	50 (68)	70 (95)

Notes:
1. 1.0 in. = 25.4 mm
2. 1 ksi = 6.89 MPa
3. D = pipe outer diameter
4. Permissible range of pipe wall thickness varies with pipe diameter

Table 14 Base Metal CVN Requirements of *DNV-OS-B101*

Relevant Steel Grades	Yield Strength, ksi	Test Temperature, °F (°C)	Minimum Impact Energy, ft-lb (J)			
			$t^3 \leq 2$ in.	2 in. $< t^3 \leq 3$ in.	3 in. $< t^3 \leq 4$in.	$t^3 \leq 6$ in.
NV A36	51	32 (0)	25 (34)	(30) 41	(37) 50	—
NV D36	51	–4 (–20)	25 (34)	(30) 41	(37) 50	—
NV E36	51	–40 (–40)	25 (34)	(30) 41	(37) 50	—
NV A500	71	32 (0)	—	—	—	24 (33)
NV D500	71	–4 (–20)	—	—	—	24 (33)
NV E500	71	–40 (–40)	—	—	—	24 (33)

Notes:
1. 1.0 in. = 25.4 mm
2. 1 ksi = 6.89 MPa
3. t = thickness

Table 15 Comparison of Fracture Mechanics Test Requirements in HAZ According to Different Specifications

Specification	Fracture Toughness Parameter	Test Temperature °F(°C)	Test Procedure	Specimen Type	Cross Section Geometry	Specimen Orientation	Notch Orientation	Notch Location	No. of Samples
ABS[2]	K_{IC} J_{IC} CTOD	—	ISO 12135, ASTM E1820, ISO 15653	SENB	B×B or B×2B	—	—	—	3
				CT	B×2B	—	—	—	3
API 5L, ISO 3183[3]	CTOD	As stated in purchase order	BS 12135 ASTM E1290	—	—	—	—	HAZ	—
API RP 2Z	CTOD	14 (–10)	BS7448 Parts 1&2 or ASTM E1290	—	B×2B	Transverse to DOR	TT	HAZ	See Table A-8
BS EN 10225	CTOD	14 (–10)	ISO 12135	SENB	B×B for t ≥ 3 in. and B×2B for t < 3 in.	Transverse to DOR	TT	CGHAZ (<FL+ 0.5mm) or SCHAZ or ICHAZ boundary	3
DNV-OS-C401[4]	CTOD	≤ 14(–10) for submerged structures and ≤ Service temperature for other structures	ISO 15653	SENB	B×B for t ≥ 3.1 in. and B×2B for t < 3.1 in.	NP	TT	HAZ	3

Table 15 ***Continued***

Specification	Fracture Toughness Parameter	Test Temperature °F(°C)	Test Procedure	Specimen Type	Cross Section Geometry	Specimen Orientation	Notch Orientation	Notch Location	No. of Samples
DNV-RP-F108	J, CTOD	Highest and lowest anticipated service temperatures	DNV-RP-F108 ASTM E 1820	SENT	W $\leq$B $\leq$ 2W	NQ	SN	At the weld cap in HAZ or at FL	Minimum 6 valid specimens

Notes:

1. 1 in. = 25.4 mm
2. Fracture mechanics tests according ABS are carried out only when specified mandatory
3. API 5L, ISO 3183 specifications require CTOD testing in HAZ only for PSL 2 pipes
4. DNV-OS-C401 specifies 0.15mm as the critical CTOD value
5. Legend:
    - B = Specimen thickness
    - W = Specimen width
    - TT = Through thickness notch
    - SN = Surface Notch
    - CT = Compact tensile test
    - SENB = Single edge notch bend test
    - SENT = Single edge notch tension specimen
    - NP = Specimen normal to weld axis and crack plane parallel to weld axis
    - NQ= Specimen normal to weld axis and crack plane along the thickness
    - DOR = Direction of rolling

Table 16 Chemical Compositions of Various HSLA Steels

Authors	Applications	Steel Types	C	Mn	Si	P	S	V
Banks	General	Semikilled grade of steel equivalent to ASTM A36	0.16	0.90	0.032	0.005	0.010	—
		Semikilled grade of steel equivalent to ASTM A441	0.17	1.38	0.065	0.014	0.015	—
Bowker et al.	Ship	V-bearing microyalloy ship-plate steel	0.16	1.35	0.300	0.010	0.010	0.090
Gianetto et al.	Offshore	TMCP steel	0.10	1.50	0.180	0.010	0.004	—
Yuga et al.	Offshore	API 2W Gr.50	0.07	1.49	0.130	0.005	0.001	—
		API 2W Gr.60	0.07	1.55	0.100	0.005	0.001	—
Jang et al.	Pressure Vessel	SA-516 Gr.70	0.18	1.15	0.300	0.014	0.030	0.026
Lee et al.	Ship / Construction	SM490B	0.15	1.32	0.230	0.023	0.003	—
		SM570-TMC	0.07	0.91	0.300	0.015	0.004	—
Fairchild et al.	Offshore	BS4360 Gr.50E	0.14	1.43	0.240	0.012	0.004	0.060
Chiba et al.	Building	SM490A	0.14	1.29	0.260	0.014	0.006	—

Table 16 *Continued*

Authors	Ni	Cr	Al	Nb	Cu	N	Mo	Ti	CE
Banks	0.024	0.008	0.002	<0.001	0.016	—	—	—	0.31
	0.026	0.035	0.005	0.024	0.035	—	—	—	0.41
Bowker et al.	0.9	0.11	0.035	—	0.24	0.005	—	—	0.50
Gianetto et al.	0.68	0.02	0.04	0.027	0.18	<0.0025	0.003	0.006	0.41
Yuga et al.	—	—	0.029	—	—	—	—	—	0.35
	—	—	0.028	—	—	—	—	—	0.42
Jang et al.	0.31	0.02	—	0.016	0.17	—	0.098	—	0.43
Lee et al.	—	—	—	—	—	—	—	—	0.37
	—	—	—	—	—	—	—	—	0.22
Fairchild et al.	0.24	0.04	0.018	0.019	0.01	0.0078	—	0.005	0.42
Chiba et al.	—	—	—	—	0.16	—	—	—	0.41

Table 17 Chemical Compositions of AASHTO M270/ASTM A709 Structural Steels

Elements	Types	C, %	Mn, %	S, %	P, %	Si, %	Ni, %	Cr, %	Mo, %	V, %	Cu, %	Nb, %	Al, %	N, %	Ti, %	CE[7], max %
Grade 50	Type 1	0.23, max	0.8 – 1.35	0.05, max	0.04, max	0.15 –0.4	—	—	—	—	0.2, min[1]	0.005 – 0.05	—	—	—	0.46
	Type 2	0.23, max	0.8 – 1.35	0.05, max	0.04, max	0.15 –0.4	—	—	—	0.01 – 0.15	0.2, min[1]	0.005 – 0.05	—	—	—	0.49
	Type 3	0.23, max	0.8 – 1.35	0.05, max	0.04, max	0.15 –0.4	—	—	—	0.01 – 0.15[2]	0.2, min[1]	0.005 – 0.05[2]	—	—	—	0.49
	Type 5	0.23, max	0.8 - 1.35	0.05, max	0.04, max	0.15 –0.4	0.003 – 0.015	—	—	0.06, max	0.2, min[1]	—	—	—	0.006 – 0.04	0.47
Grade 50W	Type A	0.19, max	0.8 – 1.25	0.05, max	0.04, max	0.3 – 0.65	0.4, max	0.4 – 0.65	—	0.02 – 0.1	0.25 – 0.4	—	—	—	—	0.60
	Type B	0.2, max	0.75 – 1.35	0.05, max	0.04, max	0.15 – 0.5	0.5, max	0.4 – 0.7	—	0.01 – 0.1	0.2 – 0.4	—	—	—	—	0.65
Grade 50S	—	0.23, max	0.5 – 1.6[3]	0.045, max	0.035, max	0.4, max	0.45, max	0.35, max	0.15, max	0.15, max[4]	0.6, max	0.05, max[4]	—	—	—	0.70
Grade HPS 50W, 70W	—	0.11, max	1.1 – 1.35[5] or 1.1 – 1.5[6]	0.006, max	0.02, max	0.3 – 0.5	0.25 – 0.4	0.45 – 0.7	0.02 – 0.08	0.04 – 0.08	0.25 – 0.4	—	0.01 – 0.04	0.015, max	—	0.56[5] or 0.59[6]
Grade HPS 100W	—	0.08, max	0.95 – 1.5	0.006, max	0.015, max	0.15 – 0.35	0.65 – 0.9	0.4 – 0.65	0.4 – 0.65	0.04 – 0.08	0.9 – 1.2	0.01 – 0.03	0.02 – 0.05	0.015, max	—	0.75

Notes:
1. Applicable when copper is specified
2. Nb+V = 0.02% – 0.15%
3. Ratio of Mn to S is not less than 20 to 1
4. The sum of Nb+V $\leq$ 0.15%
5. Thickness of 2.5 in. (65 mm) and under
6. Thickness over 2.5 in. (65 mm)
7. IIW Carbon Equivalence, CE = $CE = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$, computed for maximum alloy content

Table 18 Test Matrix for CVN Testing

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes						
							SAW		ESW-NGI	
				GMAW	FCAW	SMAW	As-welded	PWHT	As-welded	PWHT
50	1.0	SS-1	FL+0.5mm	(3)	3	—	3	—	—	—
			FL+5mm	(3)	3	—	3	—	—	—
		SS-2	FL+0.5mm	3	3	—	3	—	—	—
	2.0	SS-1	FL+0.5mm	—	(3)	(3)	3	—	—	—
			FL+5mm	—	(3)	(3)	3	—	—	—
		MT	FL+5mm	—	(3)	(3)	3	—	—	—
		SS-2	FL+0.5mm	—	3	3	3	—	—	—
	4.0	SS-1	FL+0.5mm	—	—	—	(3)	3	3	3
			FL+5mm	—	—	—	(3)	3	3	3
		MT	FL+5mm	—	—	—	(3)	3	3	3
		SS-2	FL+0.5mm	—	—	—	3	3	3	3
50W	1.0	SS-1	FL+0.5mm	(3)	3	—	3	—	—	—
			FL+5mm	(3)	3	—	3	—	—	—
		SS-2	FL+0.5mm	3	3	—	3	—	—	—
	2.0	SS-1	FL+0.5mm	—	(3)	(3)	3	—	—	—
			FL+5mm	—	(3)	(3)	3	—	—	—
		MT	FL+5mm	—	(3)	(3)	3	—	—	—
		SS-2	FL+0.5mm	—	3	3	3	—	—	—
	4.0	SS-1	FL+0.5mm	—	—	—	(3)	3	3	—
			FL+5mm	—	—	—	(3)	3	3	—
		MT	FL+5mm	—	—	—	(3)	3	3	—
		SS-2	FL+0.5mm	—	—	—	3	3	3	—

Table 18 *Continued*

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes						
							SAW		ESW-NGI	
				GMAW	FCAW	SMAW	As-welded	PWHT	As-welded	PWHT
HPS 70W	1.0	SS-1	FL+0.5mm	(3)	3	—	3	—	—	—
			FL+5mm	(3)	3	—	3	—	—	—
		SS-2	FL+0.5mm	3	3	—	3	—	—	—
	2.0	SS-1	FL+0.5mm	—	(3)	(3)	3	3	—	—
			FL+5mm	—	(3)	(3)	3	3	—	—
		MT	FL+5mm	—	(3)	(3)	3	3	—	—
		SS-2	FL+0.5mm	—	3	3	3	3	—	—
	4.0	SS-1	FL+0.5mm	—	—	—	(3)	3	3	3
			FL+5mm	—	—	—	(3)	3	3	3
		MT	FL+5mm	—	—	—	(3)	3	3	3
		SS-2	FL+0.5mm	—	—	—	3	3	3	3
HPS 100W	1.0	SS-1	FL+0.5mm	(3)	(3)	(3)	(3)	—	—	—
			FL+5mm	(3)	(3)	(3)	(3)	—	—	—
		SS-2	FL+0.5mm	3	3	3	3	—	—	—

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at each test temperature; the numbers in the parentheses to be tested in Pilot Study
3. Tests to be performed at following temperatures:
   Grade 50,50W: 10°F (–12°C), 40°F (4°C), and 70°F(21°C)
   Grade HPS 70W: –10°F (–23°C), 10°F (–12°C), and 40°F (4°C)
   Grade HPS 100W: –30°F (–34°C), -10°F (–23°C), and 10°F (–12°C)
4. Legend:
   SS = sub-surface
   MT = mid-thickness

Table 19 Test Matrix for CTOD Testing

Steel Grade	Thickness (in.)	Welding Processes									
		GMAW		FCAW		SMAW		SAW		ESW-NGI	
		Loading Rate		Loading Rate		Loading Rate		Loading Rate		Loading Rate	
		Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic
50	1.0	—	—	—	—	—	—	2	—	—	—
	2.0	—	—	—	—	—	—	2	—	2	2
	4.0	—	—	—	—	—	—	—	—	2	2
50W	1.0	(2)	—	—	—	—	—	2	2	—	—
	2.0	—	—	—	—	(2)	(2)	2	2	2	2
	4.0	—	—	—	—	—	—	(2)	2	2	2
HPS 70W	1.0	(2)	(2)	—	—	—	—	—	—	—	—
	2.0	—	—	(2)	(2)	—	—	—	—	—	—
	4.0	—	—	—	—	—	—	2	2	2	2
HPS 100W	1.0	—	—	(2)	(2)	—	—	(2)	—	—	—

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at each test temperature; the numbers in the parentheses to be tested in Pilot Study
3. Tests to be performed at following temperatures:
   a. For Bridge loading rate: –60°F (–51°C) and 0°F (–18°C)
   b. For Dynamic loading rate:
      Grade 50/50W: 10°F (–12°C) and 70°F (21°C)
      Grade HPS 70W: –10°F (–23°C) and 40°F (4°C)
      Grade HPS 100W: –30°F (–34°C) and 10°F (–1°C)

Table 20. Test Matrix for Full Scale Girder Test

Flange Thickness, in.	Welding Process	Number of Replicates
2.0	SAW	3
	FCAW	3
	GMAW	3
	SMAW	3
	ESW-NGI	3
2.0 to 3.0	ESW-NGI	3

Notes:
1. 1.0 in. = 25.4 mm
2. Test temperature = –60°F (–51°C)

Table 21 Test Matrix for CVN Testing in the Pilot Studies

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Welding Processes			
			GMAW	FCAW	SMAW	SAW
50	1.0	SS	3	—	—	—
	2.0	SS	—	3	3	—
		MT	—	3	3	—
	4.0	SS	—	—	—	3
		MT	—	—	—	3
50W	1.0	SS	3	—	—	—
	2.0	SS	—	3	3	—
		MT	—	3	3	—
	4.0	SS	—	—	—	3
		MT	—	—	—	3
HPS 70W	1.0	SS	3	—	—	—
	2.0	SS	—	3	3	—
		MT	—	3	3	—
	4.0	SS	—	—	—	3
		MT	—	—	—	3
HPS 100W	1.0	SS	3	3	3	3

Notes:

1. 1.0 in. = 25.4 mm
2. Each of the cases shown in test matrix is tested at 3 temperatures
   Grade 50,50W: 10°F (–12°C), 40°F (4°C), and 70°F(21°C)
   Grade HPS 70W: –10°F (–23°C), 10°F (–12°C), and 40°F (4°C)
   Grade HPS 100W: –30°F (–34°C), 0°F (–18°C), and 30°F (–1°C)
3. SS = sub-surface
4. MT = mid-thickness
5. Each of the cases shown in test matrix is tested at 2 notch locations: FL+0.5mm (CGHAZ) and FL+5mm (SCHAZ)

Table 22 Test Matrix for CTOD Testing in the Pilot Studies

Grade of Steels	Thickness, in.	Welding Processes							
		GMAW		FCAW		SMAW		SAW	
		Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic
50	1.0	—	—	—	—	—	—	—	—
	2.0	—	—	—	—	—	—	—	—
	4.0	—	—	—	—	—	—	—	—
50W	1.0	2	—	—	—	—	—	—	—
	2.0	—	—	—	—	2	2	—	—
	4.0	—	—	—	—	—	—	2	—
HPS 70W	1.0	2	2	—	—	—	—	—	—
	2.0	—	—	2	2	—	—	—	—
	4.0	—	—	—	—	—	—	—	—
HPS 100W	1.0	—	—	2	2	—	—	2	—

Notes:
1. 1.0 in. = 25.4 mm
2. Each of the cases shown in test matrix is tested at two temperatures.
   a. Bridge loading test: –60°F (–51°C) and 0°F (–18°C)
   b. Dynamic loading test:
      Grade 50/50W: 10°F (–12°C) and 70°F (21°C)
      Grade HPS 70W: –10°F (–23°C) and 40°F (4°C)
      Grade HPS 100W: –30°F (–34°C) and 30°F (–1°C)
3. $a/W = 0.15$

Table 23 Weld Metal Requirement for WPS in *AWS D1.5*

		CVN, ft-lb (J) AASHTO Temperature Zones	
Grade of Steel	**Welding Process**	**1 and 2**	**3**
50, 50W, HPS 50W	SMAW	Prequalified - Exempt from Test	
	SAW, GMAW, FCAW	20 @ 0°F (27 @ –20°C)	20 @ –20°F (27 @ –30°C)
HPS 70W	SMAW	Prequalified - Exempt from Test	
	SAW, GMAW, FCAW	25 @ –10°F (34 @ –25°C)	25 @ –25°F (34 @ –30°C)
HPS 100W over $2^1/_2$ in. (60 mm) thick	SMAW	Prequalified - Exempt from Test	
	SAW, GMAW, FCAW	20 @ –40°F (27 @ –40°C)	As approved by engineer

FIGURES

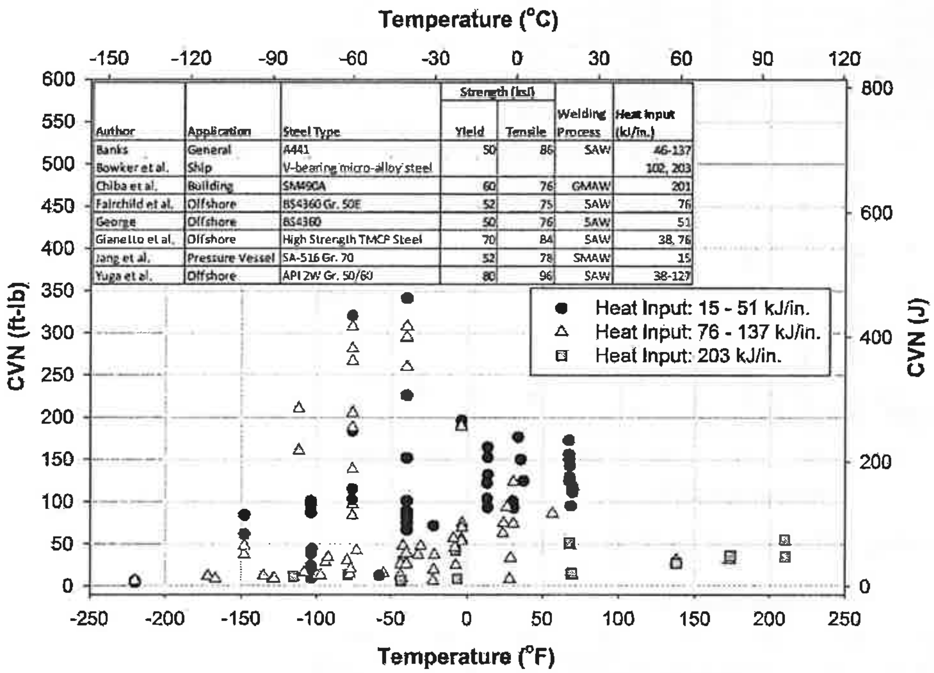


Figure 1 **Comparing influence of heat input**

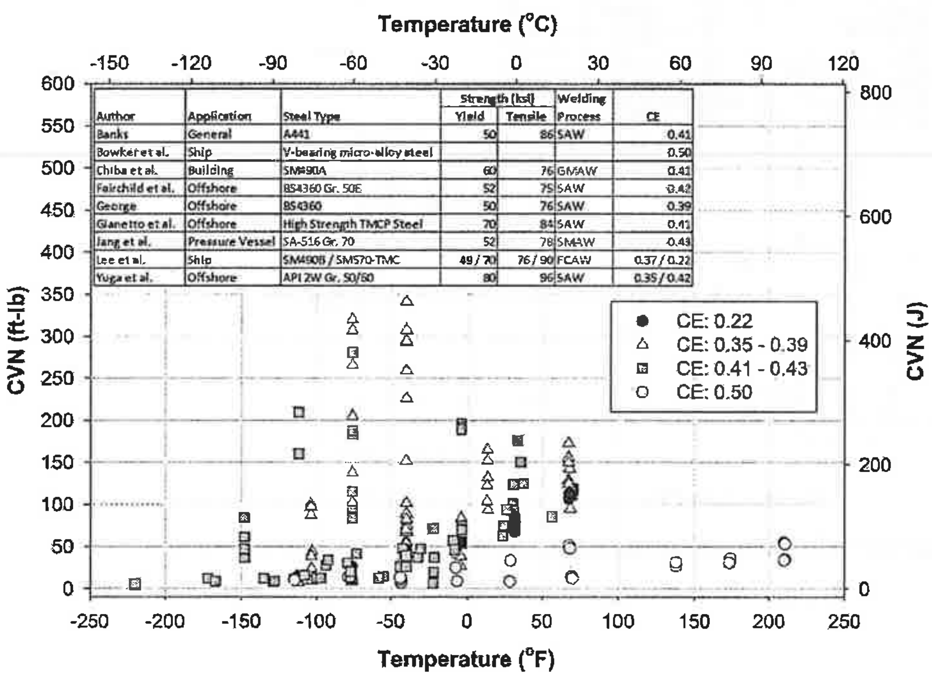
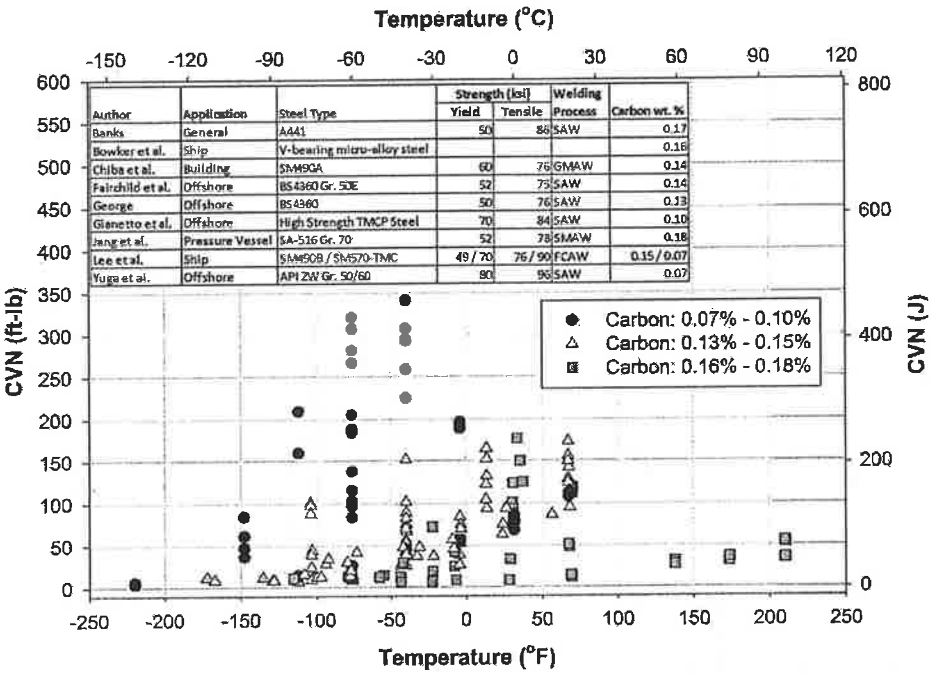
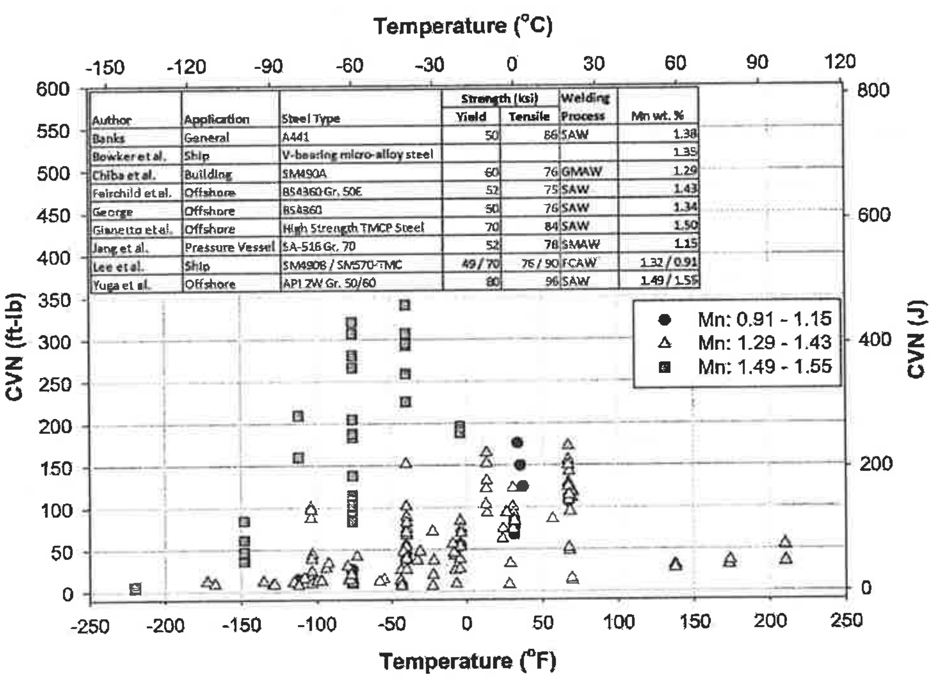


Figure 2 **Comparing influence of carbon equivalence**



Author	Application	Steel Type	Strength (ksi) Yield	Tensile	Welding Process	Carbon wt. %
Banks	General	A441	50	86	SAW	0.17
Bowker et al.	Ship	V-bearing micro-alloy steel				0.16
Chiba et al.	Building	SM490A	60	76	GMAW	0.14
Fairchild et al.	Offshore	BS4360 Gr. 50E	52	75	SAW	0.14
George	Offshore	BS4360	50	76	SAW	0.13
Gianetto et al.	Offshore	High Strength TMCP Steel	70	84	SAW	0.10
Jang et al.	Pressure Vessel	SA-516 Gr. 70	52	78	SMAW	0.18
Lee et al.	Ship	SM490B / SM570-TMC	49 / 70	76 / 90	FCAW	0.15 / 0.07
Yuga et al.	Offshore	API 2W Gr. 50/60	90	96	SAW	0.07

Figure 3 Comparing influence of carbon content



Author	Application	Steel Type	Strength (ksi) Yield	Tensile	Welding Process	Mn wt. %
Banks	General	A441	50	86	SAW	1.38
Bowker et al.	Ship	V-bearing micro-alloy steel				1.35
Chiba et al.	Building	SM490A	60	76	GMAW	1.29
Fairchild et al.	Offshore	BS4360 Gr. 50E	52	75	SAW	1.43
George	Offshore	BS4360	50	76	SAW	1.34
Gianetto et al.	Offshore	High Strength TMCP Steel	70	84	SAW	1.50
Jang et al.	Pressure Vessel	SA-516 Gr. 70	52	78	SMAW	1.15
Lee et al.	Ship	SM490B / SM570-TMC	49 / 70	76 / 90	FCAW	1.32 / 0.91
Yuga et al.	Offshore	API 2W Gr. 50/60	80	96	SAW	1.49 / 1.55

Figure 4 Comparing influence of manganese content

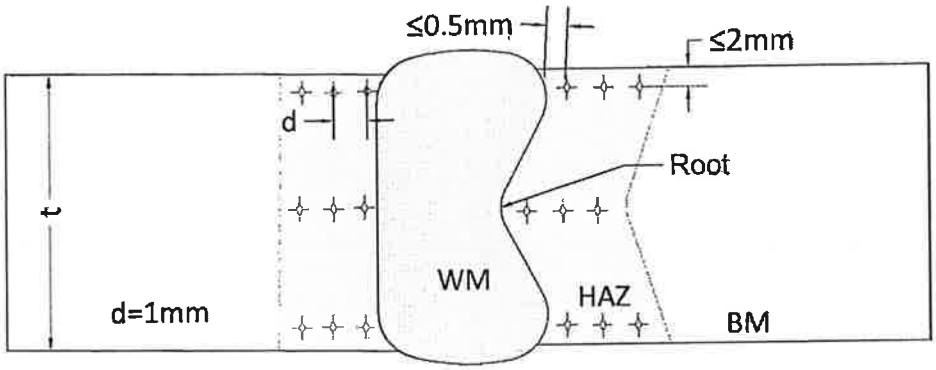
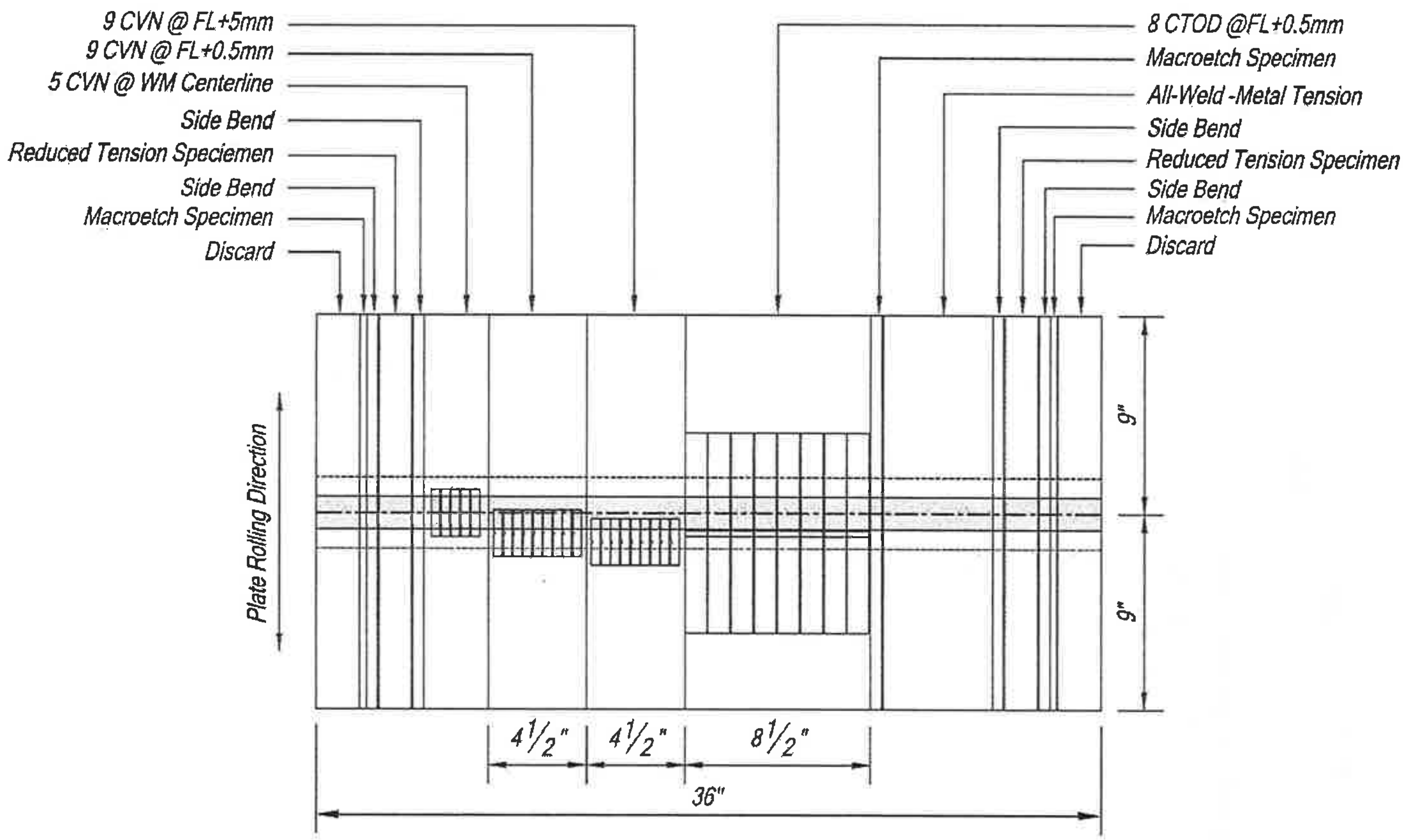
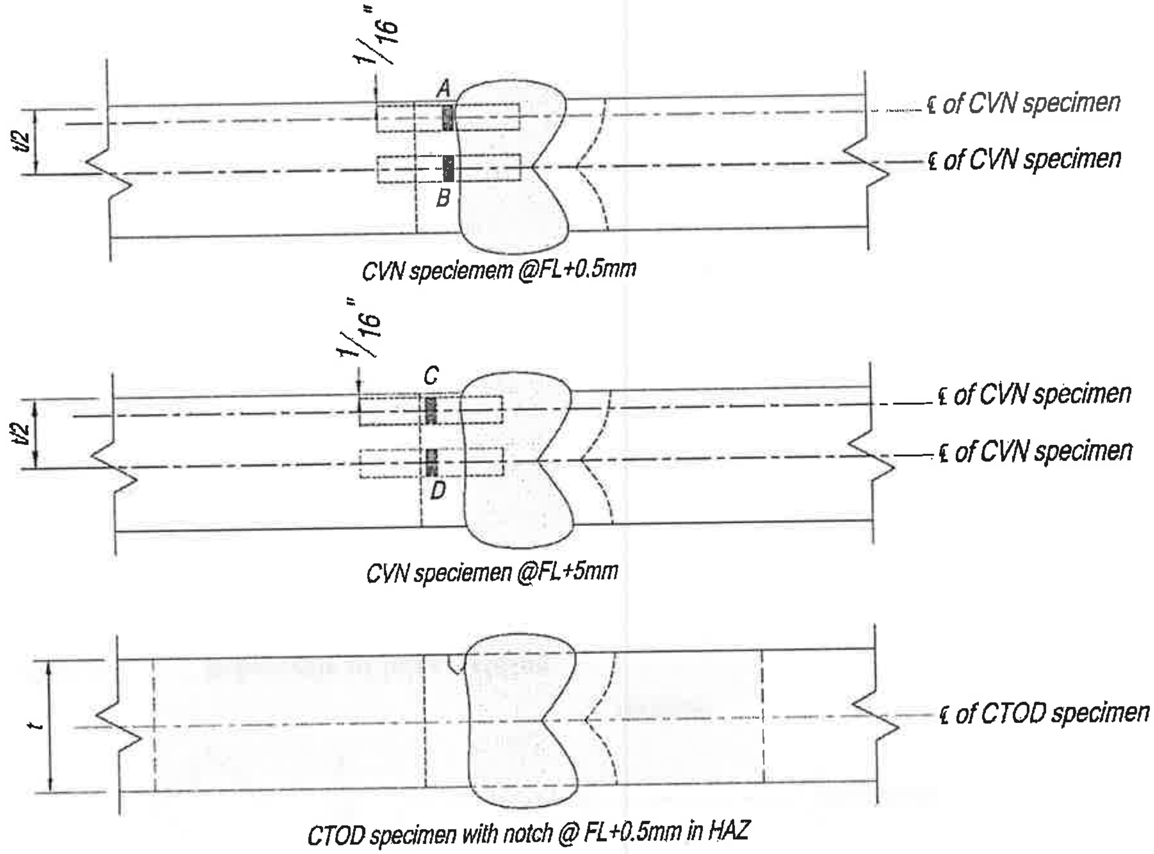


Figure 5. **Locations for hardness measurements**



Note:
1. Specimen dimensions not shown in the figure are according to AWS D1.5:2010
2.. FL = Fusion Line
3. WM = Weld Metal

Figure 6. **Details of WPS qualification plates (plan view)**



A - FL+0.5mm in HAZ @Plate subsurface
B - FL+0.5mm in HAZ @Plate mid-thickness
C - FL+5mm in HAZ @Plate subsurface
D - FL+5mm in HAZ @Plate mid-thickness
t = Plate thickness

Figure 7 **Locations of CVN and CTOD specimens for WPS qualification plates (section view)**

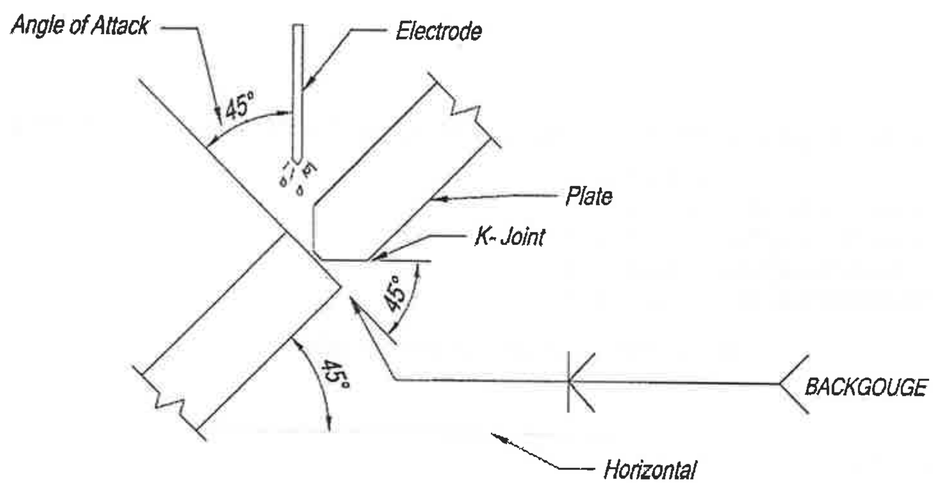


Figure 8 Schematic of joint welding

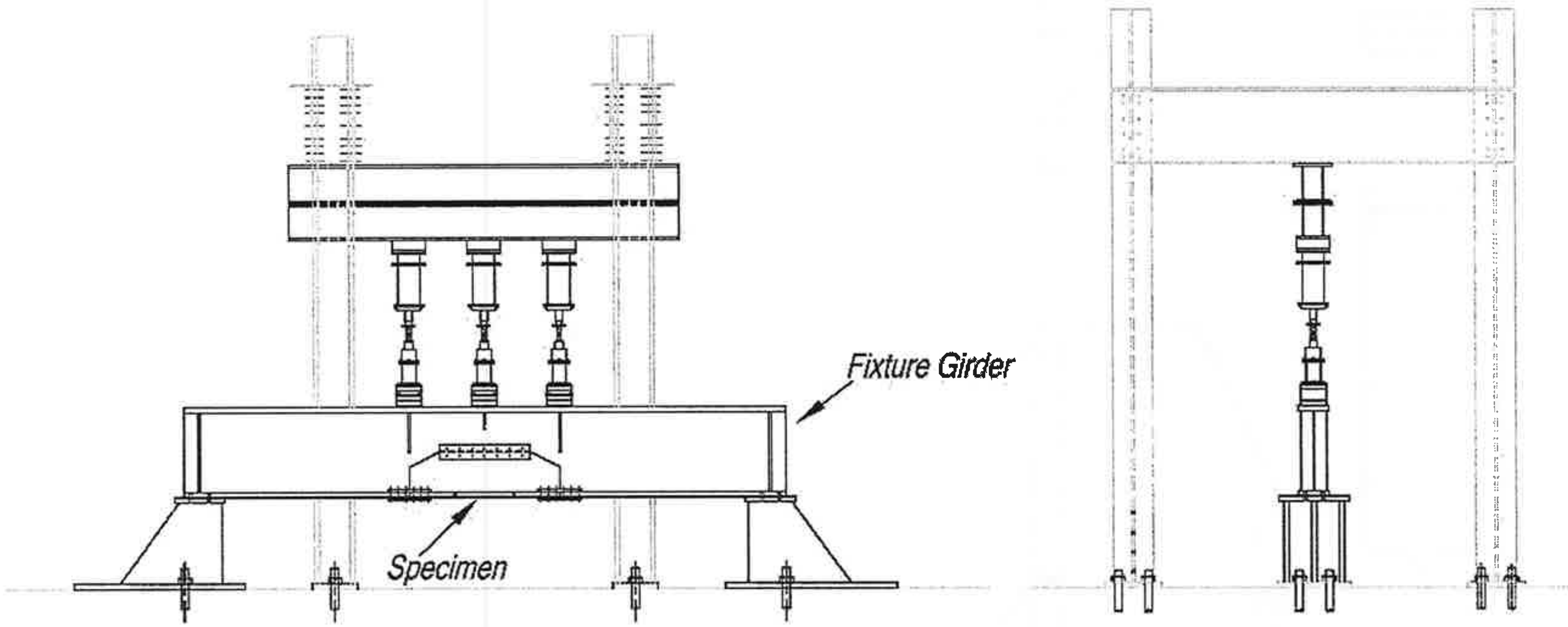


Figure 9 Overview of girder testing setup

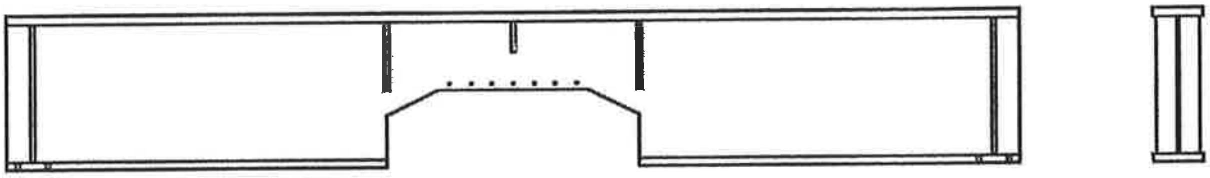


Figure 10 **Fixture girder**

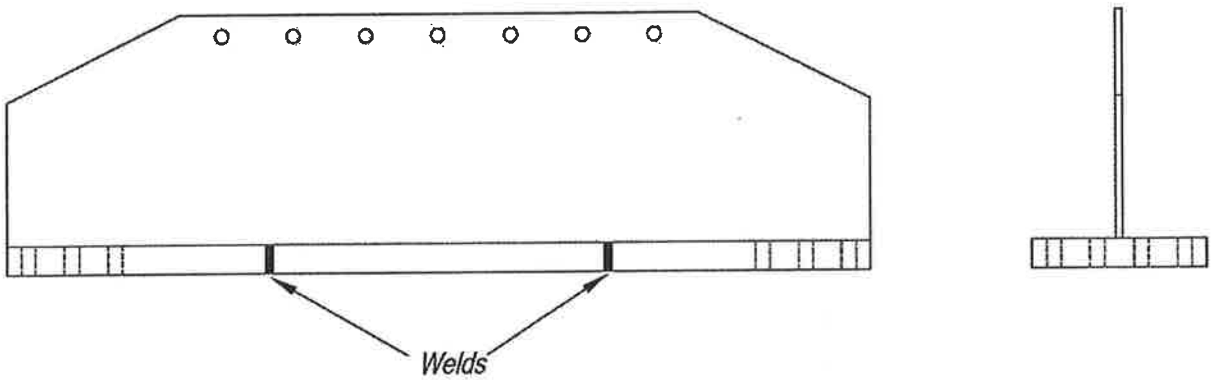


Figure 11 **T-specimens**

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APPENDIX A

LITERATURE REVIEW

Research under UK Offshore Steel Research Project Phase I (UKOSRP I)

Pisarski (1981), Webster (1987), Bateson et al. (1988), Webster and Walker 1988

With growth of the offshore industry in the North Sea, concerns about safe operation of welded fixed offshore oil production platforms in the arduous conditions led to one of the early studies on fracture toughness of weld HAZ in steels for offshore structures under the UKOSRP I in the 1970s. Typical killed C-Mn normalized structural Steel plates conforming to BS4360 grades 40E and 50D, produced using a fine grain practice, and with thicknesses of 2 in. (50 mm), 2.8 in. (70 mm), 3 in. (76 mm), 4 in. (100 mm), and $5^1/_4$ in. (134 mm) were considered. The grades 40E and 50D had nominal yield strengths of 33.3 ksi (230 MPa), and 49.3 ksi (340 MPa) respectively. The grade 50D steel was considered with and without niobium. These steels had very low Sulphur (<0.005%).

Seven SMA consumables, two self-shielded FCAW wires, and MIG with 80%A/20%CO2 shielding and one solid wire were investigated. Single and multi-pass welds were carried out for heat input (HI) of 38-114 kJ/in. (1.5-4.5 kJ/mm). Single pass welds were considered as they represent the final run in capping the weld which is not tempered in any subsequent passes.

The plate thicknesses of 2 in. (50 mm), 3 in. (75 mm) and 4 in. (100 mm) were considered for the HAZ toughness studies. The welds in the 4 in. (100 mm) plate were post-weld heat treated (PWHT) at 1076-1112°F (580-600°C) for 4 hours [1 hour per 1 in. (25 mm) thickness]. The HAZ toughness was evaluated by crack tip opening displacement (CTOD) testing. Strain embrittlement in transformed HAZ was assessed using a single pass weld in which a fatigue crack tip was located in the HAZ, and a second bead was deposited over the first to induce dynamic strain aging.

Recognizing the need for a straight HAZ normal to the plate surface for consistent CTOD testing, a straight side K-joint preparation was adopted. To obtain a straighter HAZ, all the weld preparations were "buttered" using a low heat input process. Although the effect of this experimental technique disregarding the effect of heat input on grain coarsening in the HAZ is not known, it is unlikely that the tested HAZ was representative of realistic high heat input welding processes.

The CTOD specimens were of $B \times B$ configuration (where B is the plate thickness) and were tested in triplicate. The fatigue pre-cracked notches were located in the CGHAZ close to the FL. The ratio of crack depth to plate thickness (a/W) was 0.3 for multipass welds, and ranged between 0.1 and 0.2 for single pass welds. Majority of the tests were conducted at 14°F (–10°C). After testing, all specimens were sectioned and examined to determine if the fatigue crack tip was correctly located in the transformed HAZ.

Total 183 specimens were tested, out of which 20 were discarded as the notch tip was incorrectly sited, and another 95 did not fracture. Remaining 76 specimens initiated a fracture in the HAZ, and 74 of these exhibited CTOD greater than 0.008 in. (0.2 mm). Six of the fractures were outside of the CGHAZ, but in the SCHAZ. All but 18 specimens exhibited CTOD values greater than 0.022 in. (0.55 mm). In all but one specimens cleavage fracture was preceded by tearing. For the specimen that exhibited no tearing, the measured CTOD value was 0.0055 in. (0.14 mm). This was a multi-pass welded specimen made at a HI of 38 kJ/in. (1.5 kJ/mm). Additional tests were conducted on 3 in. (75 mm) thick grade 50D, grade 50D with Nb, and grade 40E steels to determine the transition curve relative to 14°F (–10°C). It was apparent that for all three steels fracture was unlikely above –4°F (–20°C).

Although no effect of Nb was apparent at 14°F (–10°C), additional tests were conducted at lower temperatures to determine any detrimental effect of Nb on HAZ toughness at high HI. The CTOD transition curves were obtained for as-welded multipass weld HAZs in grade 50D steels with and without Nb respectively for 3 in. (75 mm) and $3^{1}/_{4}$ in. (83 mm) thick plates, made at 102 kJ/in. (4.0 kJ/mm). To investigate the potential problem with Nb due to carbides precipitation after PWHT, additional tests were conducted on 4 in. (100 mm) thick grade 50D with and without Nb, and grade 40E steels. These HAZ were due to single pass welds made at 102 kJ/in. (4.0 kJ/mm) and subsequently PWHT. The test results indicated that in AW condition the HAZ toughness apparently reduced due to increased HI. In PWHT condition, some degradation in HAZ toughness could be attributed to Nb. The strain-age embrittlement tests were unsuccessful due to incorrect notch position. In addition to the toughness the HAZ hardness was also investigated as part of the study, which showed that the hardness ranged from 200-380 HV2.5. Since the HAZ toughness at 14°F (–10°C) was satisfactory, it was concluded that hardness was not a concern unless higher than 380 HV.

In summary, the study showed that for avoidance of brittle fracture from the HAZ, PWHT of plate thicknesses up to $3^{1}/_{4}$ in. (83 mm) was unnecessary. It was also demonstrated that 4 in. (100 mm) to $5^{1}/_{4}$ in. (134 mm) thick plates had adequate toughness. Additional Charpy V Notch testing of multipass welds for all steels studied showed impact toughness in excess of UK DOE requirements. Accordingly it was recommended that HAZ toughness testing was unnecessary for steels which were killed, aluminum treated and conformed to BS4360, provided the HI was between 38 kJ/in. (1.5 kJ/mm) and 102 kJ/in. (4.0 kJ/mm).

This and another study by Det Norske Veritas (Eide 1980) led to the conclusion that weld metal (WM) was the region of lowest toughness in a welded joint, whereas the toughness of the base metal (BM) and the HAZ were satisfactory. Accordingly, the HAZ toughness requirements in the 1977 version of the UK Department of Energy's Guidance Notes on the design and construction of offshore installations, and in the BS6235: 1982 Code of practice for fixed offshore structures were quite lax. The Guidance Notes required Charpy energy of 25 ft-lb (34 J) at –13°F (–25°C), and 20 ft-lb (27 J) at –4°F (–20°C) for stress relieved (PWHT) and as-welded conditions, respectively. The BS5235 did not require any HAZ testing provided the heat input was between 25 and 114 kJ/in. (1.0 and 4.5 kJ/mm). Irrespective of the requirements, a common trend in the offshore industries had been to require a much stringent universal criterion of 0.01 in. (0.25 mm) minimum CTOD at 14°F (–10°C) for all parts of the structure, although many experts across owners, steel produces and certifying agencies considered that such a requirement could not be guaranteed (Bateson et al. 1988).

Eide (1980)

Eide analyzed 230 CTOD tests carried out on steels used in offshore construction and welded using HI up to 102 kJ/in. (4 kJ/mm). The tests were performed in the temperature range of 14°F (–10°C) to 32°F (0°C), with thicknesses between 2 in. (50 mm) and 4 in. (100 mm). The lowest

CTOD recorded in the as-welded condition was 0.006 in. (0.15 mm). All values attributed to "pop-in" were excluded from the analysis.

Group Sponsored Research Program in UK

Webster (1987), Bateson et al. (1988), Webster and Walker (1988), Pisarski and Jutla (1989), Pisarski and Harrison (1990)

In the mid 1980's, frequent occurrence of low CTOD values [0.004 in. (<0.1 mm)] and low Charpy impact test values in the HAZ noted during weld procedure evaluation for offshore steel structures led to a group sponsored large research program in the UK to investigate the cause and the risk of such low fracture toughness. The research was primarily sponsored by UK Department of Energy. Other contributors were: British Gas; British Petroleum; Britoil; British Steel Corporation (BSC); Esso Exploration and Production (UK); Marathon; Philips Petroleum; Shell Expro; and Statoil. The research was performed jointly by the BSC Swinden Laboratories and The Welding Institute (TWI). In view of no evidence of field fractures associated with the low toughness of the HAZ, the research program tested Charpy V Notch (CVN), CTOD and wide plate (WP) specimens to systematically study: (a) the correlation of small scale fracture tests with the large scale surface notch specimens; (b) the influence of the amount of coarse grain upon observed fracture properties; (c) the comparison of through thickness and surface notch CTOD specimen tests; (d) the comparison of CTOD and CVN test results for the same test weldments; and (e) the effect of PWHT on small and large scale fracture behavior.

Since the occurrence of the low toughness results coincided with the steel making practice, initially it was considered that the change in chemistry and steel making that took place in the 1970s, although beneficial to the plate properties and weldability, may have adversely affected the HAZ toughness. It was suggested that the cleaner modern steels did not effectively have sufficient grain boundary pinning agents that could effectively control the austenite grain growth adjacent to the fusion line during the welding process. A limited research program at the BSC, however, demonstrated that older open-hearth type steels also exhibited low levels of CTOD [0.004 in. (<0.1 mm) at 14°F (–10°C)], eliminating changes in steel making as a contributor to the observed low HAZ toughness.

The group research program investigated 2 in. (50 mm) thick plates of low carbon normalized steel conforming to BS4360 Grade 50E. The nominal yield strength of the material was 59 ksi (406 MPa). The plates were produced by continuous casting in basic oxygen steelmaking (BOS) furnace. The chemical composition of the steel and comparison with ASTM A709 Grade 50 and 50W is shown in Table A-1.

Recognizing the need for a straight HAZ through the plate thickness, the plates were butt welded with a half K joint preparation. All welding was carried out parallel to the plate rolling direction using single $^{1}/_{8}$ in. (3.25 mm) wire submerged arc welding (SAW) with a HI of 114 kJ/in. (4.5 kJ/mm). Two weld procedures were used that produced two levels of CGHAZ refinement along the vertical edge of the weld preparation representing typical range of HAZ in structural steels. The lower refinement procedure was designed to provide approximately 30% CGHAZ adjacent to the columnar weld metal along the vertical edge of the weld preparation. The higher refinement procedure was designed to provide approximately 10% CGHAZ distributed at quarter plate thicknesses. The PWHT was performed at 1112°F (600°C) for 2 hours.

The CVN tests of the weld HAZ were carried out as per the UK DOE guidelines. As per the requirement, testing was required in the plate thickness direction at subsurface and at plate centerline, and within the HAZ at FL, at FL+0.08 in. (2 mm), and at FL + 0.2 in. (5mm). At least three replicates were required at each sampling location for each test condition. Retest was required if the average impact energy was less than 27 ft-lb (36 J) or, individual impact energy was less than 20 ft-lb (27 J) at the qualifying the test temperature (shown in Table A-2) The test program is shown in Table A-3. All together 236 CVN tests were performed (including retests), where the specimens were sampled from the vertical HAZ. The notch location was verified by post-test metallography. Majority of the CVN test results that failed to meet the specified impact energy, were obtained at a test temperature less than –40°F (–40°C). The impact energy of tests performed at –40°F (–40°C) or above met the requirements of UK DOE guidelines. The lowest test result obtained from a subsurface specimen with the notch located in the 30% CGHAZ at the FL was 21 ft-lb (28 J) at –40°F (–40°C) in as-welded condition, and the corresponding average impact energy for the three replicates was 73 ft-lb (99 J).

The CTOD test program is shown in Table A-4. Altogether 198 CTOD specimens were tested in three point bending according to BS5762: Methods for Crack Opening Displacement, 1979. The surface notched (SN) specimens were tested in $B \times B$ ($W = B$) configuration [i.e., 2 in. × 2 in. (50 mm×50 mm) cross section], having a nominal notch depth of $a/W = 0.3$. The through thickness specimens were tested in $B \times 2B$ ($W = 2B$) configuration [i.e., 2 in. × 4 in. (50 mm × 100 mm) cross section], having a nominal notch depth of $a/W = 0.5$. The 10% CGHAZ was tested only in as-welded (AW) condition. All tests except 10% CGHAZ at 50°F (10°C) and TT notch with 10% CGHAZ at –22°F (–30°C) produced a minimum CTOD value less than 0.004 in. (0.1 mm). The later result was confusing, since CTOD less than 0.004 in. (0.1 mm) was found for a similar specimen when tested at a higher temperature of 14°F (–10°C). Overall the occurrence of low CTOD in the more refined (10%) CGHAZ was much less than the 30% CGHAZ, due to the chance of sampling a coarse grained area. However, at 14°F (–10°C) and below, the minimum CTOD values were very similar irrespective of the CGHAZ refinement, suggesting that the fracture was triggered by LBZ. Comparing the CTOD data for PWHT and AW 30% CGHAZ it was evident that the minimum CTOD value was similar between the conditions, although the occurrence was lower for the PWHT condition. Thus, LBZ was still present in PWHT specimens, however, the martensitic islands in the ICCGHAZ were tempered, increasing fracture resistance (reduced probability of sampling LBZ). For 30% CGHAZ, the test pieces showing low CTOD value completely fractured at –22°F (–30°C), whereas only “pop-in” was noted at 50°F (10°C), with crack arrest. Although the 10% CGHAZ exhibited increased toughness at 50°F (10°C), similar increase in toughness for 30% CGHAZ would occur at temperatures beyond 50°F (10°C). No clear trend could be discerned between the SN and TT specimens, as both specimens produced similar minimum values.

The study on CTOD tests determined that the location of the fatigue crack tip with respect to the FL and the microstructure adjacent and slightly ahead of it were the major factors controlling the CTOD values. Detailed post-test evaluations revealed that a low CTOD value was obtained when the fatigue crack sampled a coarse grain > 3.1×10^{-6} in. (80 μm) (ASTM 4), leading to both complete fracture and pop-in. The lowest values were measured in the ICCGHAZ and SCCGHAZ regions, and were similar for AW condition. Higher CTOD value was obtained when tearing from the original crack tip was involved prior to intercepting the coarse grain. The CTOD values were not sensitive to the actual amount of coarse grain sampled; however, at higher temperature pop-in seemed to occur with larger amount of coarse grain, and low toughness fracture could be prevented with small amount of coarse grain. Sampling of coarse grains at the fatigue crack tip alone did not always resulted in lower toughness. High CTOD values were noted in some instances when ductile tear through coarse grains [as high as 0.004 in. (100 μm) or ASTM 3] at some part of the crack front preceded the fracture initiation. Crack tip location relative to the FL was also found to be an important factor for observed fracture behavior. A crack located slightly in WM would tear into the CGHAZ and initiate fracture. A crack located in HAZ would tear away from FL and will be arrested unless brittle regions are present at crack tip. A small deviation of the notch location away from the FL severely reduced the frequency of low CTOD results, although the minimum value did not alter significantly.

The WP test specimens were 35.4 in. × 39.4 in. (900 mm × 1000 mm), and welded along the shorter length. A surface notch was introduced in the weld HAZ from the weld root or the weld cap sides using a 0.006 in. (0.15 mm) wide cutter, which was further fatigue cracked to nominal 0.47 in. (12 mm) deep and 5 in. (125 mm) long semi-elliptical shape. Based on the macro-etched section on each edge of the plate, the crack tip was aimed at regions of CGHAZ located between 0.4 in. (10 mm) and 0.8 in. (20 mm) from the plate surface. The fatigue crack growth was measured by AC potential drop based instrumentation or by time-of-flight based ultrasonic testing. The specimens were welded in a 8800 kip (4000 ton) WP test machine, and were tested at 14°F (–10°C), loaded in tension normal to the weld. The WP test summary is shown in Table A-5. The specimens were monitored during testing using strain gauges, liner voltage differential transformers (LVDT), clip gauges, and thermocouples. The instrumentation plan is shown in Figure A-1. The tests were terminated when the plates fractured or the overall strain exceeded 3%.

The test results were grouped into high and low strain fractures based on 0.5% overall strain as the divider. For straight-sided joint preparation (½ K) in as-welded condition, two out of six plates each with 30% and 10% CGHAZ refinements fractured, and each fracture within each subset occurred at greater and less than 0.5% overall strain. In PWHT condition all five plates (with 30% CGHAZ refinement) fractured. Of the three tests on bevel welded plates, fracture initiated only in one plate. This fracture was arrested in the BM and did not reinitiate, allowing the overall strain to exceed 3%.

The aspects of fracture initiation in WP tests were similar to those in the CTOD tests. All the AW and majority of the PWHT fractures initiated from a grain size > 3.1×10^{-6} in. (80 μm) (ASTM 4). Varying amount of coarse grained areas was present ahead of the fatigue crack tips in the fractured specimens; the depth of the CGHAZ sampled by the fatigue crack did not seem to be critical. The lowest strain fracture providing the lowest CTOD occurred in WP9, where less than 0.1 in. (2.5 mm) coarse grain existed ahead of a 0.4 in. (10 mm) deep fatigue crack, but almost 3.1 in. (80 mm) of the crack length was located in the coarse grain in excess of 0.004 in. (100 μm). This specimen fractured at an applied nominal stress of 49.3 ksi (340 MPa), which was less than the yield strength of the material. Overall the lowest strain fractures occurred when the cracks sampled relatively long lengths of coarse grain. The dominant influence of coarse grain in initiating fracture was also demonstrated by the location of the initiation sites, which in a number of tests were at crack depths shallower than the maximum but at the intersection of coarse grains. A number of tests showed that for fracture initiation a crack or a tear had to actually intercept a coarse grain and not merely be adjacent to it.

The WP test results also demonstrated that in addition to the sampled microstructure by the fatigue crack, the relative yield strength of the BM, the WM and the HAZ, together with the presence of residual stresses have an impact on the fracture behavior. The measured strains in the BM and the WM showed that specimens notched from the cap side had fastest rise in local strain and consequently more rapid strain concentration. This was due to the bowing (welding distortion) of the plate towards the cap and therefore higher bending strain in this area when axially loaded. The average local strain in the WM was always lower than the average nominal strain over the 27.6 in. (700 mm) gauge length. In general, the rise in the level of strain in the WM was less steep than in the BM, and increased when the lower strength BM yielded. The strain at the FL was lower than the strains in the BM and the WM. It was apparent that the strain distribution around the FL was protected by the yielding of lower strength BM. It was also apparent that in similarly notched specimens, local strains concentrated more rapidly in relation to the strains for PWHT specimens, which contributed to greater frequency of fractures in this condition compared to AW condition. This implied that the reduction in the WM yield strength and/or absence of residual stresses due to PWHT promoted conditions for local yielding in the ligament below the crack tip. This local straining could be discerned in CTOD values, but not in the global strain at fracture. Indeed, with reduction in WM yield strength by PWHT the ratio of WM to BM yield strength decreased from 1.28 to 1.07.

The CTOD results generated at 14°F (–10°C) were further analyzed along with the WP test results. One hundred eight CTOD tests were performed at 14°F (–10°C), out of which 36 were on 30% CGHAZ with PWHT. The CTOD results for both SN and TT specimens, where the fatigue crack tip in the CGHAZ sampled a grain size ≥ 0.002 in. (50 μm) (<ASTM 5), were grouped further as the test program had shown this to be characteristic of the lowest toughness region. The amount of sampled CGHAZ was not a criterion, however, for TT specimens the HAZ in the central 80% of the thickness was sampled. The smaller data sets for each of AW and PWHT conditions were combined further, when standard statistical tests such as the t-test and the Kruskal Wallis test indicated no difference. Consistent with the selection criteria for the CTOD data, only in three WP tests (WP2, WP9, and WP17) the fatigue crack tip sampled the CGHAZ and the columnar weld metal adjacent to the FL such that the crack tip was not more than 0.006 in. (0.15 mm) if in WM, or 0.014 in. (0.35 mm) in CGHAZ [with a grain size ≥ 0.002 in. (50 μm)]. The sorted CTOD test results exhibited a lognormal distribution; however, the all fractured WP test results when plotted on the lognormal plot did not conform to this distribution. Although, more WP test results on specimens sampling the lowest toughness HAZ would be desirable for a meaningful analysis, the results for AW condition indicated that the lower tails were similar for both tests. Thus, CTOD tests could be considered as representative of fracture behavior in WP tests.

Further comparison of the CTOD and the WP test results were performed using an Universal Assessment Diagram that combined the consideration of both fracture and plastic collapse. The analysis also showed that the two testing methods could be correlated for CTOD values less than 0.004 in. (0.1 mm), i.e., when the lowest toughness microstructure or local brittle zone was sampled by the fatigue crack tip.

Pisarski and Harrison, 1990

Recognizing the need for optimum sampling of CGHAZ during CTOD testing to determine the lower bound HAZ fracture toughness, several weld procedures were developed at the Welding Institute that would consistently produce realistic HAZ with specific degree refinement [defined as % of coarse grain ≥ 0.002 in. (50 μm) present at the notch section]. Most of these procedures were devised for 2 in. (50 mm) thick sections using single wire SAW at HI between

76 kJ/in. (3 kJ/mm) and 127 kJ/in. (5 kJ/mm). A single bevel (½ K) joint preparation with vertical side was used for all development.

In the initial development using 76 kJ/in. (3 kJ/mm) HI, welding was performed in a flat position carefully stacking weld beads adjacent to the vertical preparation directly on top of each other. The centerline of the weld beads was approximately 0.16 in. (4 mm) from the wall. The weld assemblies were heavily restrained to minimize distortion. The procedure produced consistent levels of sidewall penetration and straight HAZ, however, resulted in an almost complete refinement of the coarse grained region, which was metallurgically unrealistic. Similar results were observed for higher and lower HI and with tandem wire SAW process.

To prevent complete refinement of the coarse grained region, the weld beads in each layer adjacent to the vertical preparation were offset relative to the same bead in the layers above and below, within the practical limits of ability to wet the side wall and directly arcing the side wall. It was determined that offsetting the weld beads in each layer 0.16 to 0.24 in. (4 to 6 mm) from the side wall, the CGHAZ of the 0.16 in. (4 mm) bead would remain unrefined for a 76 kJ/in. (3kJ/mm) HI and 45 degree bevel; but, the % of CGHAZ was low. Preparation angle and weld bead shape, however, had more pronounced effect on the % of CGHAZ with the same HI. Decreasing the bevel from 45 to 10 degree and maintaining the deliberate bead staggering approach [alternately 0.16 to 0.24 in. (4 to 6 mm) from sidewall] significantly increased % CGHAZ to <10%. Further modification of the bead stacking sequence by alternating the bead at 0.16 in. (4 mm) from the wall in every 4 layers produced 20-50% CGHAZ.

At higher HI 114 and 127 kJ/in. (4.5 and 5 kJ/mm), simple 2 layer repeat with alternate beads in the stacking sequence at 0.16 in. (4 mm) and > 0.24 in. (6 mm) from the vertical wall produced approximately 30% CGHAZ. It was noted that increasing depth-to-width aspect ratio of the weld bead, avoiding solidification cracking, could change the amount of CGHAZ by 20%. The factors that produced the high aspect ratio and the highest CGHAZ are: (a) higher current (for same voltage increasing the current from 500 A to 600 A increased CGHAZ by 10%; increasing to 700 A bordered solidification cracking); (b) lower voltage; (c) smaller diameter wire; (d) DC+ polarity; (e) small wire stick-out; and (f) welding away from earth connections.

Factors that consistently produced CGHAZ are: (a) welding in flat position; (b) heavy restraint of weld panels; (c) use of small preparation angle; (d) machined but not flame-cut edge preparation; (e) welding as far from the earth connection as possible; (f) high aspect ratio beads; and (f) accurately controlled bead placement, including staggered stacking.

Another technique was developed for producing small regions of CGHAZ at specific positions through the thickness of the plate. Using a mixed HI with a ½ K joint preparation, two regions of approximately 0.1 in. (2.5 mm) high CGHAZ were produced at ¼ and ¾ thickness of a 2 in. (50 mm) plate, generating 10% CGHAZ. All passes adjacent to the vertical side were stacked the same way and welded at 114 kJ/in. (4.5 kJ/mm) except at the ¼ and ¾ plate thicknesses, where the beads were deposited at 76 kJ/in. (3 kJ/mm), which did not completely refine the larger beads produced by the 114 kJ/in. (4.5 kJ/mm). The other weld parameters were generally similar as the procedure producing the coarser HAZ, with the exception of a reduced bead aspect ratio, which was accomplished by a 0.16 in. (4 mm) wire, reduced current, and increased voltage, keeping the travel speed unchanged.

Banks (1974)

Fracture toughness properties of the subcritical and transformed HAZ for widely used two structural steels were investigated. The testing results regarding the toughness of SCHAZ was not discussed. Measured toughness in SCHAZ was very low because the size of the initial crack was too large. As such, alternate testing method was proposed.

Two 1.0 in. (25 mm) thick semikilled grades of steels were prepared which were equivalent to ASTM A36 and A441 steels. The yield strength of A36 and A441 steels were 36 ksi (248 MPa) and 50 ksi (345 MPa), respectively. Chemical compositions of both steel indicated that A441 steel had higher alloy content than A36 steel.

Several different types of welding was used for half K-joint preparation. Submerged arc welding and ESW-NGI were used for A36 steel and only SAW was used for A441 steel. The heat inputs of each welding process were 45 kJ/in. (1.8 kJ/mm), 90 kJ/in. (3.6 kJ/mm), and 135 kJ/in. (5.4 kJ/mm) for SAW and 1000 kJ/in. (40 kJ/mm) for ESW-NGI.

Charpy impact and COD tests were conducted over wide range of temperatures. Overall test results indicated that the toughness in transformed HAZ of the conventional low alloy steels examined in this study presented fairly high level of toughness even with the high heat input.

Increasing heat input decreased fracture toughness for both steels except the heat inputs below 90 kJ/in. (3.6 kJ/mm) for A36 steel, which produced even greater fracture toughness than base metal. Metallographic examination of the HAZ microstructure for both steels revealed that the ferrite/pearlite microstructures for A36 steel were coarser for less tough cases. Therefore, HAZ microstructures were refined as preceding welds with heat input below 90 kJ/in. (3.6 kJ/mm), but as the heat input was increased, the refinement effect diminished. On the other hand, similar effect was not pronounce for A441 steel. It was probably because higher content of Mn and/or Nb formed upper bainite type microstructure in HAZ, which was known to be less tough.

CVN test result presented that the fracture toughness in HAZ for both steels were greater than the base metal irrespective to the heat inputs. It is contrary to the COD test results, which is more realistic test method. The examination on the fractured Charpy specimen indicated that the fracture path tended to deviate from the HAZ and run into the weld metal or the base metal. As a result, it was recommended that Charpy specimens were not recommended to use Charpy impact testing for assessing comparative study on HAZ fracture toughness.

Barsom et al. (1975)

The variation of fracture toughness of with strain rate and temperature was studied for A36 and A572 Grade 50 bridge steels. There exist steels that have sufficient fracture toughness to perform in low service temperatures, but are expensive. The useful life does not entirely dependent on the notch toughness of the material. It also depends on magnitude and number of stress cycles the structural component undergoes at low stress intensity factors until crack initiation and propagation are completed. Therefore specification of fracture toughness levels required to ensure a satisfactory performance at reasonable cost is necessary. Fracture mechanics parameter K_{Ic} was chosen for the measurement of fracture toughness.

K_{Ic} is an inherent material property that changes with temperature and loading rate. Therefore it is necessary to determine this fracture toughness property for the bridge steels at relevant service temperatures and loading rates. Data for various steels showed that transition of K_{Ic}

occurred with temperature change but was independent of specimen geometry. The rate of change of K_{Ic} was not uniform. It was low before and after transition, with high rate at the transition temperature, changing the mode of fracture initiation from cleavage to ductile tear during the transition.

Increase in loading rate shifts the transition temperature towards higher temperatures. This shift for steels of different yield strengths was related to room temperature yield strength as follows.

$$T_{shift} = 215 - 1.5\sigma_y, \text{ for } 36 \text{ ksi} < \sigma_y < 140 \text{ ksi}$$

$$T_{shift} = 0.0 \qquad , \text{ for } \sigma_y > 140 \text{ ksi}$$

where, T_{shift} is absolute magnitude of shift in transition temperature between slow bend loading and impact loading in Fahrenheit and σ_y is a room temperature yield strength.

The shifts in transition temperatures for strain loading rates $10^{-5}sec^{-1}$, $10^{-3}sec^{-1}$, and $10sec^{-1}$(slow bend load, intermediate strain rate load, and dynamic load respectively) were found to be close to –160°F (–107°C), –120°F (–84°C), 0°F (–18°C) respectively for A36 and –160°F (–107°C), –120°F (–84°C), 10°F (–12°C) for A572 Grade 50 steels. It should be noted that temperature shifts are possible only for loading rates below impact loading. K_{Ic} value depends on the size of the plastic zone at the crack tip which increases asymptotically with temperature for a given loading rate. Due to the asymptotic nature it is not possible to measure the K_{Ic} value after a certain temperature. Considering the above effects, specification of loading rates for the bridge steels is as essential as that of specifying member thickness and service temperatures. In general bridge loading times are greater than 1.0 sec that is the strain rates are less than $10^{-3}sec^{-1}$ (conservative) close to slow bending than to impact loading. For A36 and A572 grades when tested at $10^{-3}sec^{-1}$ strain rate, plain-stress condition was observed at the crack tip, at test temperatures lower than minimum service temperatures. Thus grades, A36 and A572 were verified to show sufficient ductility at minimum service temperatures and stresses in actual bridges independent of geometry.

Determining Fracture mechanics parameter, K_{Ic}, is not only an arduous process but also expensive for routine quality control tests. On the other hand, the CVN test (dynamic test) is economic and parallels the effects of temperature and loading rate on the fracture toughness with a temperature shift according the preceding discussion. However, CVN tests are qualitative to determine the toughness requirements directly. Reviewing the available literature, it was concluded that the effects of temperature and rate of loading are same on CVN and K_{Ic} values. Which implies that test results for CVN and K_{Ic} values at a given temperature and strain rate can be correlated. The following correlation was used to for the correlation.

$$\frac{K_{Ic}^{\ 2}}{E} = A(CVN)$$

The correlation constant (A) was found to be 5.0 for the bridge steels at both slow bend and impact loading rates. CVN values were predicted using the above correlation for the K_{Ic} values and compared with experimental CVN values for bridge steel grades under study, which were found to be in good agreement with. Thus, $K_{Ic,}$ values can be obtained at any strain rates from the impact CVN values shifted to the corresponding lower temperatures.

Simulated nonredundant bridge members of A36 and A572 grades of steel were tested for most severe combinations of strain rate, temperature, and structural detail that could possibly occur in actual highways bridges in the United States. The members depicted sufficient fracture toughness to withstand most severe service conditions of AASHTO.

Development of AASHTO toughness requirements for bridge steels

Fracture toughness specifications should ensure the adequacy of the respective material to withstand the intended service conditions. The preceding results of temperature transitions and correlation between CVN and K_{Ic} values were applied to develop fracture toughness requirements of bridge steels. The requirements were developed in terms of CVN parameter that is energy absorbed as K_{Ic} tests are tedious and expensive. The following procedure was adopted for this purpose. Initially fracture toughness transition temperature for the (for K_{Ic} corresponding to yield strength at room temperature) bridge steels was obtained at intermediate loading rate. Beyond this temperature, fracture in the member did not occur under plane-strain condition. The lowest service temperatures for all zones were verified to be above the intermediate strain rate transition temperature. Then, energy absorption values of CVN tests at the same temperatures and loading rate were obtained. Temperatures corresponding to CVN impact test were computed using the temperature shift equations. At this temperature, for the same energy absorption as for the intermediate loading, the impact loading fracture toughness of the material is not in plane strain condition. Hence, this energy at the dynamic loading transition temperature was taken as the toughness requirement of the corresponding steel grade.

The toughness requirements derived for the bridge steels were approved by the Federal Highway Administration (FHWA) and by American Association of State Highway Transportation Officials (AASHTO). They were declared mandatory on all Federal aided Highway programs in United States.

Dolby (1979)

This study presented steel selection and welding procedural control measures summarizing the results of previous studies to produce weldments of improved HAZ toughness of C, C-Mn, microalloyed and low-alloyed steels. In addition to this, guidance in HAZ toughness testing was provided in order to reduce the need for expensive mechanical testing.

The following recommendations were summarized by the study for effective steel selection to obtain improved HAZ fracture toughness. For C, C-Mn and microalloyed steels with C greater than 0.12%, low C and CE content produced with fine grain practice and treated with Al were recommended. Additions of Nb and V to these steels whose weldment were subjected to heat input greater than 89 kJ/in. (3.5 kJ/mm) reduced the HAZ toughness. For microallyed steels with C less than 0.12% additional alloying was advised to improve HAZ toughness in the presence of Nb or V for moderate or high heat input weldments. Low Ni content, higher base metal toughness, low impurity content, low S content, and inclusion of shape control additives were further recommended for improved HAZ toughness.

Subcritical post weld heat treatments (PWHT) at temperatures around 1112°F (600°C) were found to increase the HAZ toughness. But this may prove to be detrimental in the presence of elements causing precipitation hardening such as V, Nb and Cu. However the reduction in tensile residual stresses can improve the overall toughness. For low alloy steels, the steels with high V and Cu content, can result in secondary hardening effects. As allowable V and Cu contents depend on the other allying elements these contents should be carefully chosen for each of the steels. Faster cooling rates from PWHT temperatures is beneficial to minimize the austenite grain growth.

Very low heat inputs and very high heat inputs during welding lead to lower HAZ fracture toughness. Higher weld deposition rates and higher travel speeds give better HAZ as the lower retention time at martensite-austenite transformation temperatures retards the austenite grain growth.

CVN and COD HAZ toughness test values can be improved by maximizing the proportion of HAZ refined by subsequent weld passes. The study suggests the following approaches to achieve this. The first approach is to increase the weld bead overlap by reducing the angle of attack (between the electrode and the work piece). The second approach suggested is to maximize the grain refinement of HAZ. The study summarizes the following ways to achieve this from previous literature available. Refining HAZ of first layer of the welds by grinding or cutting off the first layer and applying another weld layer. Increasing the weld interpass temperatures can increase the proportion of grain refined HAZ. Unreheated regions such as weld toes are often treated using temper bead technique which requires high precision of bead placement to achieve required results avoiding creation of new coarse grain regions.

It was outlined that the CVN and COD specimen to be tested in HAZ should be notched to represent actual constraint, defect size, orientation as that encountered in the actual weldments. Use of rounded slots instead of fatigue cracks is suggested for the exact location of crack tip in the fracture toughness test specimens, except that the effect of round root radius on the fracture toughness should be accounted for. The long-term nitrogen aging of the weldments should be simulated before testing using heat treatments.

Bowker et al. (1983)

The coarse and fine grain regions of HAZ of a V-bearing microalloy ship-plate steels were tested. The purpose of this study was to determine the effect of high heat input on coarse and fine grain HAZ of a microalloy V-bearing steel widely used for ship building.

Standard Charpy specimens were prepared from 1.0 in. (25 mm) thick plate. The coarse and fine grain regions of the HAZ was simulated by thermal cycling of the blank specimen to peak temperatures of 1830°F (1000°C) and 2460°F (1350°C) using Gleeble 1500, a weld thermal simulator, to simulate FGHAZ and CGHAZ, respectively. Cooling times from 1470°F (800°C) to 930°F (500°C) of 42 seconds and 200 seconds were chosen to represent heat inputs of respectively 102 kJ/in. (4 kJ/mm) and 203 kJ/in. (8 kJ/mm) on 1.0 in. (25 mm) plate. The notch was located in L-T direction.

Charpy impact testing was conducted over the temperature range of –112°F (–80°C) to 212°F (100°C) using three samples per temperature. After the Charpy impact testing was competed, metallographic sections were prepared from the broken Charpy samples. Toughness results for each HAZ region and heat input were examined by analyzing microstructures using scanning electron microscope (SEM) and transmission electron microscope (TEM).

Coarse grain HAZ was obtained from the peak temperature of 2460°F (1350°C) and FGHAZ was obtained from that of 1830°F (1000°C). No evidence of difference in the toughness in CGHAZ for two heat inputs. From FGHAZ, lower toughness obtained from lower heat input caused by the presence of a significant volume fraction of coarse bainite compare with a low volume fraction of pearlite in the case of the higher heat input condition.

Grong and Akselsen (1986)

This article provides a comprehensive review of the HAZ toughness of low carbon (0.06 - 0.12%C) micro-alloyed offshore steels, having yield strength ranging between 43.5-72.5 ksi (300-500 MPa) depending on the plate thickness, with respect to HAZ transformation behavior, welding procedures, alloying components, and post-weld heat treatment (PWHT).These steels were developed primarily to improve weldability, particularly with respect to HAZ stress corrosion and cold cracking. However, in contrast to traditional C-Mn steels, these low carbon microalloyed steels tend to form brittle zones of ferrite sideplates in coarse grain region close to fusion line adversely affecting the HAZ toughness, which could not be easily improved by PWHT. For the subject steels, the combined effects of peak temperature determining the austenite grain size and the cooling time from 1470-930°F (800-500°C) through the transformation temperature range of the austenite ($\Delta t_{8/5}$) on the HAZ transformation behavior show that the coarse grained region close to the fusion line transformed at a much slower rate compared to the grain refined region. The toughness of the CGHAZ deteriorates with increasing heat input (decreasing cooling rate), as the microstructure shifts from auto-tempered martensite (at low $\Delta t_{8/5}$) to predominantly ferrite side plates (at medium and high $\Delta t_{8/5}$).

The effect of different thermal parameters of welding on the HAZ toughness for the subject steels were determined by thermally simulation technique and CVN specimens. Embrittlement in the CGHAZ close to the FL was observed due to formation of low toughness microstructure such as ferrite side plates. The grain refined region of the HAZ showed satisfactory toughness because of characteristic fine polygonal ferrite microstructure. The intercritically heated region showed a reduced cleavage resistance at around peak temperature of 1340°F (730°C), as at lower heat the carbon rich austenite formed by decomposition of carbon rich pearlite retransformed into a high carbon (twinned) martensite upon cooling.

Several improvement possibilities for HAZ toughness were discussed. Improved HAZ toughness at higher heat input was noted for steels produced by new technology, where strength, toughness and ductility were achieved by balanced addition of Al, Ti, and B, in combination with accelerated cooling subsequent to controlled rolling. It was postulated that the observed improvements were due to general refinement of the microstructure, reduction in free N, and addition of Ti, which acted as favorable nucleation sites for polygonal ferrite through intragranular precipitation of coarse titanium nitride.

Improvement of HAZ toughness through reduction in austenite grain size could be achieved by increased welding speed because of decreased excursion time at elevated temperatures. In addition, for multi-pass welds, increase in HAZ toughness was possible by maximizing HAZ refinement from subsequent weld passes. This could be achieved by ensuring a high degree of bead overlapping i.e., keeping the angle of attack of the electrode with the work surface as low as possible, and increasing the penetration of the follow on layer HAZ by adjusting the welding parameters and/or the weld interpass temperature. Deposition of temper beads, although extremely difficult, could also reduce HAZ hardness of weld toes and cap layers.

The alloying elements in these micro-alloyed steels have a significant impact on the HAZ toughness. The volume fraction of martensite formed in the coarse grained region monotonically increase with CE, which reduce the fracture toughness. But the grain refined region exhibits satisfactory impact toughness. The effects of individual alloying elements are further elaborated in the following:

Carbon: Lowering the carbon content improves HAZ toughness by smaller fraction of martensite/ austenite (M-A) constituents, and increased martensite autotempering with increased Martensite start temperature (M_s). But this reduction in carbon content needs to be compensated by equivalent alloying elements to avoid formation of coarse sideplate microstructures and improved HAZ toughness.

Manganese: Manganese improves the HAZ toughness by reducing the ferrite grain size (lowering austenite to ferrite transformation temperature). However, Mn addition should be balanced to minimize solidification segregation and microstructural banding in hot rolled/normalized steel plates that lead to anisotropy in base metal and large fluctuation in HAZ microstructure and toughness. The detrimental effects of Mn can be reduced by thermomechanically controlled processing that promotes homogenization of segregations through diffusion.

Molybdenum, copper, nickle and chromium: Mo promotes formation of martensite/austenite constituent by suppressing ferrite formation. Cu and Ni affect steel transformation behavior by lowering austenite transformation temperature. In addition to general refinement of microstructure, they inhibit precipitation of Nb(C,N) particles. Balanced addition of Mo, Cu, and Ni separately or in combination improve HAZ toughness of normalized low C steels by producing desired microstructure.

Chromium suppresses the formation of ferrite sideplates through the pinning effects of chromium carbide precipitates.

Vanadium, niobium, aluminum, and titanium: Niobium and Vanadium form precipitates of Nb(C,N) and V(C,N) respectively during rolling or normalization of steels which retard the recrystallization and grain growth. The extent of Nb and V effects on HAZ toughness depend on the C content and transformation behavior of BM. Small additions of Nb slightly improves the HAZ toughness of low carbon steels (C < 0.12 %) at low heat input or cooling rate ($\Delta t_{8/5} < 40$ sec) due to reduced size of sideplates and carbide aggregates by pinning effects of Nb(C,N) precipitates. Moderate alloying with V does not have any significant effect on HAZ toughness. Small amounts of Ti prevent coarsening of prior austenite grains close to the FL by forming stable nitrides (TiN) at higher temperatures [2460°F (1350°C)]. Use of Ti to prevent HAZ grain growth is limited to continuously cast and controlled rolled steels. Excess Ti to N ratio could lead austenite grain growth through coarsening of TiN, and hence reduced HAZ toughness. Certain combinations of microallying elements could be detrimental to HAZ toughness.. Simultaneous presence of Nb and V, even in small concentrations, is detrimental to HAZ toughness. Molybdenum inhibits the formation of beneficial Nb(C,N) precipitates that prevent austenite grain growth.

Boron: This element suppresses the formation of ferrite sideplates and ferrites by raising the energy barrier for ferrite nucleation at the austenite grain boundaries improving the HAZ toughness. Boron in excess would pose an embrittlement problem in HAZ. In order to avoid embrittlement, boron content in low carbon microallyed steels should not exceed 10-15ppm in coarse grain region close to fusion line.

Effects of Impurities: HAZ fracture toughness by microvoid coalescence is influenced by the volume fraction, shape and distribution of non-metallic inclusions. In Al-killed steels, Type II MnS and elongated stringers of Al_2O_3 are of primary concernnucleating at inclusions such as Al_2O_3 and TypeII MnS. This can be controlled by addition of Ca, Zr, Ti or REM to liquid steel. The free nitrogen content should be minimized to reduce the susceptibility of strain aging and solid solution hardening.

Effects of PWHT: Offshore steels with thickness greater than 2.0 in. (50 mm) are often subjected to PWHT in the temperature range of 1020°F (550°C) to 1200°F (650°C), to improve the HAZ resistance to brittle fracture. Though PWHT has additional benefits of reducing residual weld stresses and removal of strain aging damage, the original purpose of improving HAZ toughness is entirely dependent on temperature and chemical composition and only a reduced the toughness was observed in most of the cases. The reasons for reduced toughness are given as follows. As explained earlier simultaneous presence of V and Nb leads to the precipitation of V(C,N) and Nb(C,N) respectively at PWHT temperatures, which is detrimental to the HAZ toughness. The second reason is the segregation of impurity elements especially phosphorus at the prior austenite grain boundaries, which leads phosphorous embrittlement in HAZ after PWHT. Large prior austenite grain boundaries are more susceptible to phosphorous embrittlement which is boosted by raising the concentrations of either Mn or Si in low carbon microalloyed steels. HAZ toughness was found to rapidly decrease with increase in phosphorous content.

It was concluded that the HAZ toughness cannot be reliably predicted by the base metal chemistry and welding parameters alone without the actual testing of HAZ.

Konkol et al. (1987)

The study included an extensive experimental program to achieve the following objectives. The first was to arrive at an optimum test to assess the susceptibility of the structural steel to welded metal and HAZ cracking. Second was to obtain optimum procedures to measure fracture toughness of weldments. And third was to come up with an optimum welding procedure to minimize cracking and maximizing fracture toughness of weld metal and HAZ A514 and A588 bridge steels, which could not be accomplished.

Fracture toughness measurement is possible in both direct and indirect ways. Indirect methods such as CVN Test, Nil-Ductility-Transition (NDT) Test and Dynamic Tear (DT) measure parameters such as angle of bend, deflection, lateral contraction, temperature at crack arrest, energy absorbed in fracture, and the percent-shear for qualitative assessment of fracture toughness. Direct tests such as Plane-Strain-Fracture toughness (K_{Ic}) test, Elastic-Plastic-Fracture toughness (J_{Ic}) test and CTOD test directly measure the actual elastic or elastic-plastic fracture toughness. CTOD and CVN tests were conducted to come up with an optimized fracture toughness test method. Figure A-2 shows different regions in a typical weldment. Weld region R and HAZ region B at the root were identified to be the most critical regions to be tested.

Double-V groove weldments were chosen to the testing instead of K weld or a single bevel with a straight edge in order to represent the service conditions. Narrow groove was used for the low energy input weldments and double-V wide groove was used high energy input weldments. A groove angle of 20° was used in both cases. Four combinations heat input and preheat temperatures were used for each of A514 and A588 steels to develop weldments used in toughness test development.

Initially several CTOD specimens were tested in the surface notch orientation. Fatigue crack tip sampling the target HAZ highly unsuccessfully due to the bowed fatigue crack tip and the irregular HAZ profile. Fracture toughness in the critical last pass HAZ (region A) was tested through shallow surface notched CTOD tests where crack depth was much lower than that allowed by *BS5762:1979* (a/W = 0.45-0.55). This made it impossible to calculate the CTOD from the test results. Due to above reasons edge notch orientation was adopted. Though edge notch orientation is easy to sample, results are conservative as the fatigue crack tip samples regions all along the edge. Root HAZ (region B) and the weld root region (region R) selected to be sampled require a crack depth up to mid thickness (a/W=0.5). The specimens were chosen to be $B\times B$ [2 in.×2 in. (51 mm×51 mm)] geometry or $B\times 2B$ [1 in.×2 in. (25 mm×51 mm)] geometry (subsized in edge notched orientation due to the insufficiency of plate material). The specimen geometries were adopted according to *BS5762:1979*.

A notch was machined into the specimens up to 0.6 in (15 mm) and the fatigue crack was extended to further 0.4 in (10 mm) by cyclic loading. Residual stresses were relieved in edge notched specimens by local compression as per the recommendations. Required compression was applied on the sides of the notch before fatigue precracking for each of the steels. An automatic control was setup to stop the test after desired depth of fatigue crack is attained. A silver paint circuit that breaks off when with fatigue crack was employed for this purpose. After fatigue precracking, the specimens were held at desired test temperature for 20 minutes prior to CTOD test. The specimens were loaded to failure in about 1 second (corresponding to a crack-tip strain rate of about 10^{-3} sec^{-1} i.e. at an intermediate loading rate). The load versus crack mouth opening were plot. For each case a total of six CTOD tests were conducted of which the first three at –30°F (–34°C), AASHTO Zone 3, and the next three at either –18°F (–28°C) or at –60°F (–51°C) in case the average of the first three CTOD values was greater than 2 mils (0.05 mm).

Weldments of A514 and A588 steels by two different producers were prepared by different weld processes such as SAW, SMAW. Special welding processes such as 2-wire SAW, Long stick Out SAW(LSO SAW), and FCAW with high deposition rates at low heat input were also studied to assess their effects on HAZ toughness. Different combinations of energy input, preheat and interpass temperatures, cooling times were used to produce the weldments. Each combination was given a code from 1 to 14. CVN and CTOD tests were conducted in different regions of these weldments. A total of 163 CTOD and 277 CVN tests on A514 weldments and 123 CTOD and 253 CVN tests on A588 weldments were conducted for different temperature ranges in regions A and B. It should be noted that the tests and results from the weld root region are not discussed in here as only HAZ toughness is focused in this study.

Test records were evaluated according to the rationale developed in the study, following different standards. The requirements for a valid CTOD record include: (*a*) a straight crack front satisfying the specifications of *BS5762:1979*; (*b*) the ratio of loads at a valid CTOD and subsequent load drop should be less than 1.1; (*c*) a crack extension due to the load drop at CTOD should be limited to the size of plastic zone at the tip of the crack; (*d*) slope of the load-displacement curve with subsequent reloading should be greater than 90% of the slope prior to valid CTOD; and (*e*) the load at valid CTOD must be the maximum load in the record. The CTOD values from the valid results were calculated according to *ASTM E399*. Yield strength for CTOD calculations at HAZ was deduced from the tensile strength from hardness tests in HAZ, using the base metal ratio for yield to tensile strength. Both CVN and CTOD tests were conducted at each of the regions in the weldments. Only surface notched tests were conducted in A and C regions where as only edge notched specimens were tested for region W. All the cases were tested for B and R regions. The observations from only HAZ regions A and B are further discussed.

The significance of difference in CTOD values comparing $B \times B$ and $B \times 2B$ geometry as observed in Figure A-3 was neglected and it was concluded by the author that specimen geometry did not affect the fracture toughness. It should be noted that $B \times 2B$ specimen with lower constraint gave higher CTOD values. This could have been established with sufficient data.

The last pass region HAZ CVN toughness in surface notched specimens of A514 steels was found to increase with test temperature and increase with input energy as shown in Figure A-4. However, this was not clear in case of A588 as low CVN values were observed even at lower energy input. This was attributed to the variations in the HAZ microstructure at surface notch root effecting the CVN toughness.

Only one of the shallow surface notched specimens had its final crack tip in the last pass region, A. As the crack depth was less than the a/W range of 0.45 to 0.55 as specified in *BS5762:1979*. CTOD values were not calculated. With no significant effect of $B \times 2B$ geometry identified by the author on the specimen toughness and a higher probability of sampling desired location with edge notched specimen, $B \times B$ geometry with an edge notch orientation was adopted in the further tests.

Effect of welding parameters on HAZ CVN toughness

HAZ CVN values were in general found to increase with a lower input energy for A514 and A588 steels in Region B as shown in the Figures A-5 and A-6, respectively. At respective AASHTO Zone 3 temperatures the root HAZ CVN toughness results were compared with facture critical criterion for base metals, that is 35 ft-lb (47 J) at –30°F (–34°C) for A514 steels and 25 ft-lb (34 J) at –20°F (–29°C) for A588 steels (see Figures A-7 and A-8). This comparison was supported by the argument that the soundness of HAZ is likely to be that of the base metal. A higher number of lower input energy weldments SAW [50kJ/in (2 kJ/mm)] and SMAW [50, 25 kJ/in (1 kJ/mm)] satisfied the AASHTO Zone 3 CVN criterion in A588 steels (tougher steels) compared to A514 steels. Most of the high energy input weldments such as did not satisfy the AASHTO Zone 3 CVN criterion. A general trend of decreasing CVN toughness with increasing cooling rate [from 1470°F (800°C) to 930°F (500°C)] was observed from the CVN values in HAZ. A cooling time less than 16 seconds was found to satisfy the AASHTO Zone 3 CVN requirements of 35 ft-lb (47 J) at –30°F (–34°C) for A514 and 25 ft-lb (34 J) at –20°F (–29°C) for A588 steels in region B (see Figures A-9 and A-10) .

A general trend similar to CVN was observed with respect to test temperature and input energy as shown in Figure A-11. The limiting CTOD values (δ_{lps}) were calculated using the yield strength and the flow strength of each of the steels as 1.4 mils (0.036 mm) for A514 and 2.2 mils (0.056 mm) for A588 at –30°F (–34°C) at an intermediate loading rate. These were considered as criterion for evaluation of CTOD values was taken as, limit of plane strain for 2.0 in. (51 mm) thick plate. This implies that a CTOD less than δ_{lps} indicates fracture. In addition to this the elastic-plastic criterion δ_{ep} was calculated as 50 percent greater than δ_{lps} that is 2.1 mils (0.053 mm) for A514 steels and 3.3 mils (0.084) for A588 steels. Lower energy input weldments [less than 50 kJ/in. (2 kJ/mm)] tested at AASTHO Zone 3 service temperatures showed higher number of CTOD values that exceeded both the limiting values (see Figures A-12 and A-13). Weldments with lower cooling rates exhibited lower CTOD values in agreement with the effects cooling rates on HAZ, as explained previously. Any consistent effects of sulphide shape control (SSC) were not observed from the CTOD test results by the author. The minimum CTOD values of most of the high energy input weldments did not satisfy the critical CTOD limits. This was not in agreement with the actual performance of the bridge steels. It was concluded that the significance of low CTOD values obtained in laboratory via high constraint CTOD tests such are bend tests representing the 'worst case scenario' unlike the actual service conditions in bridge steels must be investigated. In addition, the effect of loading rate on the behavior of crack propagation in actual bridge details must be investigated.

It was assumed that CVN-K_{Ic} correlation for base metals as given in the literature (Barsom and Rolfe 1970) was also applicable to HAZ and the weld metal. The temperature shifts between the CTOD (intermediate) and CVN (dynamic) test loading rates were obtained for A514 and A588 steels. The CVN (dynamic test) values were obtained at the shifted temperatures and were compared with CVN values corresponding to the K_{Ic} calculated from the limit δ_{lps} but were found to be inconsistent. It was justified that the dynamic CVN tests represent both crack initiation and crack propagation whereas, the CVN values obtained as explained above represent only crack propagation.

HV 10 Hardness tests were conducted on each of the weldments tested for CVN and CTOD. Full plate thickness metallographic specimens were saw cut and the surface was ground, etched and polished. Indentations were made at every 0.05 in. (1.3 mm) across the root and the last pass regions [$^1/_{16}$ in. (1.6 mm) below the surface]. Figure A-14 shows the hardness profile across the weldment in root region (B) for A514 and A588 weldments, on the either side of the weld centerline. The profile manifests higher hardness just beyond the fusion line FL (marked by a diagonal segment), indicating reduced toughness in the HAZ regions. Also hardness was observed to be lower in A588 steel (tougher) compared to A514 steel. Figures A-15 and A-16 show that hardness decreased with increase in cooling time [1470°F (800°C) to 930°F (500°C)] for both A514 and A588 steels. This contradicts the observed CVN trend and the agreed CVN relation with the hardness. It was justified that weldments with lower cooling times had considerable amounts of martensite causing higher hardenability.

Wood and Devletian (1987)

The advantages of electroslag welds were overlooked by the industry and specifications, due to the wide regions of low toughness heat affected zones (HAZ) that occur as result of high heat input of this welding process. A project was drafted to improve the reliability, integrity and mechanical behavior of electroslag welds in type A36 and A588 bridge steel alloys. The research focused on the fundamental relationships between process variables, microstructure, and properties of electroslag welds. One of the objectives of the program was to improve the fracture toughness properties of the electroslag weldments by enhancing the microstructure and improving Charpy V-notch impact values above minimum requirement of Zone 2 AASTHO service temperatures. Improved electroslag weld procedures developed by OGC (Oregon Graduate Center) and Battelle Pacific Northwest Laboratory (PNL) were employed for this purpose. Other objectives included plane strain fracture toughness (K_{Ic}) assessment, and comparison of fatigue behavior of the improved electroslag weldments with the conventional electroslag weldments through full-scale tests of I beam girders.

Optimum electroslag weld parameters and alloy additions were determined from the results of approximately 500 CVN tests on the trial combinations of weld procedures and steels. Each of the alloys A36 and A588 and plate thicknesses 2.0 in. (51 mm) and 3.0 in. (76 mm) were tested for the following four optimized weld conditions: (*a*) a standard gap [1 1/4 in. (32 mm) practice with highest heat input (SG); (*b*) an OGC -modified narrow gap [3/4 in. (19 mm)] practice with low heat input (NG); (*c*) an OGC narrow-gap weld and metal alloy addition practice (NG, ST) with lower heat input; and (*d*) condition3 with a reduced heat input (lowest) (NG, ST2). The first two conditions employed standard wires of respective alloys, while Stoody tubular wire (ST) was used in the third and fourth conditions with reduced heat input. Mechanical property weldments for the above optimized conditions, alloys, and thicknesses were prepared in the laboratory with minimal imperfections. These weldments were tested for CVN and K_{Ic}.

Charpy V-notch Tests

The impact tests were conducted according to *ASTM E23*. Each of the weldments mentioned above were impact tested with surface notches at quarter and mid-thickness at weld centerline and at mid-thickness between 0.04 in. (1 mm) to 0.06 in. (1.5 mm) from the fusion line in the is CGHAZ. A total of 46 transition curves with 8 temperatures each were obtained from the above mechanical property weldments for temperatures ranging from –100°F (–73°C) to 150°F (65°C). Each CVN values in the transition curve is an average of two or three samples and six samples at 0°F (–18°C). The test matrix for CVN testing is shown in Table A-6.

A separate series of CVN tests were conducted to investigate toughness variation in HAZ region. Notches were placed in between fusion line and 0.16 in. (4 mm) from fusion line. These tests were performed on 2.0 in. (50 mm) thickness welds of A588 alloy made using the tubular alloyed electrode practice. Huge drop in the toughness was observed from base metal through HAZ but leveled off from 0.06 in. (1.5 mm) from fusion line as shown in the Figure A-17. So, this region which is, about three grains from fusion boundary was identified to be suitable for coarse grain HAZ testing. It should be noted that size of this region is dependent on the weld parameters such as heat input. The average CVN toughness values at CGHAZ region from six tests at 0°F (–18°C) and 39°F (4°C) for different welding conditions as shown in Table A-7. Values at CGHAZ were considerably low for highest heat input welding procedures SG, 25P and SG, WS. The key levels of CVN toughness values [15 ft-lb (20 J), 20 ft-lb (27 J), and 25 ft-lb (34 J)] were achieved at higher test temperatures in CGHAZ compared to other locations. The above observations strongly indicate the necessity of different toughness requirements in the HAZ region than base metal or weld metal.

Plane strain fracture toughness test (K_{Ic})

CVN tests provide only localized toughness values in the weldments. In order to estimate the toughness of full thickness of the weldments at a higher constraint, plane strain fracture toughness K_{Ic} was measured. ASTM test method for plane strain fracture toughness of metallic materials (*ASTM E399-83*) was used. Four compact tensile K_{Ic} specimens were machined in each of the full thickness weldments [3 in. (76mm)]. Chevron notches were placed parallel to welding direction at the weld centerline and in CGHAZ for each of the welding conditions as shown in Figure A-18. The specimen were pre-cracked according to *ASTM E399-83*. The tests were conducted at 0°F (–18°C) and 10°F (–7°C). The fracture toughness test results were evaluated according to *ASTM E 399-83*. The ratio P_{max}/P_Q is considered as one of the measures to validate the test record. P_{max} is the maximum force recorded in the force displacement test record. P_Q is also obtained from the test record according to *ASTM E 399-83*. If the ratio P_{max}/P_Q less than 1.1 then K_Q calculated.

If $2.5(K_Q/\sigma_{YS})^2$ is less than ligament of the specimen (W-a), then $K_Q = K_{Ic}$. Otherwise test is not a valid K_{Ic} test. Valid plane strain K_{Ic} indicates brittle fracture and the lower toughness of the material. From the Table A-8, it can be observed that higher number of valid K_{Ic} samples were observed high heat input weld procedures (SG, 25P; SG WS), intermediate loading rate (I), at lower test temperature, 0°F (–18°C), and for a higher strength alloy. Valid load displacement curve for the plane strain fracture toughness could be obtained only for the higher strength alloy A588, at 0°F (–18°C). This manifests high toughness properties of the lower strength alloy. As mentioned earlier, the CVN tests could capture more localized toughness of very narrow CGHAZ regions in comparison to the full thickness tests where the toughness obtained from the full thickness specimens can only be an average of neighboring higher toughness zones (including HAZ) sampled by the crack tip. As a result, the full thickness specimens did not show low toughness values in the CGHAZ region and were not consistent with CVN tests.

I-beam girder fatigue tests

Fatigue tests were conducted with a purpose to evaluate fatigue behavior of OGC modified electroslag weldments. Fatigue tests for 12 I-beam girders were planned. Six girders were to represent optimized OGC electroslag weld processes that were welded using narrow-gap wing-type guide tube and a reduced heat input. Another 6 were fabricated with a conventional round guide tube to compare with former. The I-beam girders for the fatigue tests were designed at Lehigh University. The central part of the lower flange consisted of two electroslag welds as shown in the Figure A-19. The electroslag welds were manufactured under carefully controlled conditions and were finally ground and flushed. The central part was connected to the outer portions of the lower flange through submerged arc welds. The flanges were welded to the web. In order to check for any imperfections that could induce early fatigue cracks or accelerated rates in these weldment, the electroslag and the submerged arc welds were ultrasonically tested. With minimal imperfections, the welds represent electroslag welds manufactured under good practices making them very much suitable for testing inherent fatigue behavior of electroslag welds. With no crack initiation sites such as lack of fusion, slag entrapment or hot cracks, no fatigue cracks developed in the electroslag welds even at number of cycles greater than thrice of the required number for category B beams, under the stress range tested [17.3-18.7 ksi (120-130 MPa)]. With no fatigue cracks developed, additional sets of standard gap and narrow gap reduced heat input electroslag welds were tested to reaffirm the data. Repeated tests demonstrated fatigue cracks that developed at defects in residual tack welds or submerged arc welds whereas the electroslag welds were found to be intact. It can be summarized that the electroslag welds for the category tested have excellent fatigue behavior.

The following observations can be made from the test results of the project: (*a*) CVN impact testing is not entirely reliable as it provides only localized fatigue behavior instead of instead of overall behavior as that of a full thickness specimen; (*b*) CGHAZ has the lowest toughness in the HAZ region and its size is dependent upon the weld parameters such as heat input; (*c*) full thickness tests such as KIc provide only an average toughness value of the surrounding regions when tested for CGHAZ. As a result, higher toughness values may be obtained than the actual CGHAZ toughness values; (*d*) low CVN values of CGHAZ at given temperature indicate that a different set of toughness requirements need to be established for HAZ instead of comparing with base metal or weld metal requirements; and (*e*) I-beam fatigue tests did not indicate the wide HAZ of electroslag welds as a crack initiator or a weak zone through which already initiated cracks propagate.

Denys (1990)

Wide plate testing was initially developed with the discovery of brittle fractures in welded ships and oil tanks. Brittle fractures originated at weld flaws or section discontinuities and failures occurred at stresses below the yield strength of the materials. The main purpose of wide-plate testing (WPT) was intended to rectify the drawbacks of small scale toughness testing by providing a full scale alternative that could simulate the service performance of base metals and weld configurations. Hence in WPT size of the test specimens and test variables must be representative of the service conditions. The testing process was eventually extended to visible HAZ in addition to weld metal by Kihara and Masubuchi (1959). Notch design was no longer restricted V shape and through thickness and surface and edge notches were used. WPT includes the effects of interaction of HAZ, weld metal, base metal unlike small scale testing which tends to focus on a particular area. WPT being an expensive test can be used as a primary investigative test for the toughness requirements rather than as a routine test.

Weldments WPT in a series of articles was reviewed in detail. Developments in WPT procedures for the evaluation of HAZ toughness in steel weldments were reviewed in the part III of the series. WPTs were used to evaluate the structural significance of Local Brittle Zones (LBZ), as the LBZs resulted in CTOD values lower than 0.004 in. (0.1 mm). As the strength of weld metal is influential in the interactions previously mentioned, that effect the fracture behaviour of HAZ, consumable must be carefully chosen.

Design of a WPT test specimen is not standard but depends on the structural detail being simulated and the capacity of the test apparatus. LBZs are the low toughness regions that occur due to the presence of CGHAZ, ICCGHAZ and SCCGHAZ in multi-pass welds. The size and distribution of LBZs varies in the weld direction (along length), in the transverse direction (width) and in the through thickness direction. The probability of occurrence of straight fatigue crack in CGHAZ is very low. WPTs are loaded transversely to the direction of weld and the fatigue pre-crack three or four point loading. This enhances the chances of sampling desired microstructures. The cracks that occur in the real weldments are generally surface breaking and irregular in shape. Hence in order to sample representative portions of LBZ the defect or starter notch for the fatigue pre-cracking along the weld can be designed in two other ways instead of a straight notch. The zig-zagging or staggering are less than 0.06 in. (1.5 mm). Multiple starter notches are used to produce an irregular crack front. Locating crack tip in the desired microstructure is throughout the width of the specimen is a problematic task. The area of the coarse grain region for notch position in the central portion of the plate is unknown. A detailed metallographic examination is performed for each of the cut-off macro-specimens taken at the sides of the weld plate. Charts for the microstructures of both locations are prepared to identify the regions of LBZs. These are usually located towards the straight edge of the weld. These regions are located within outer 15-20% percent of the specimen thickness. These locations are extracted to the surface and joined along the fusion line. The starter notches are then machined with respect to this line.

Acceptability of the WPT for HAZ is based on the following criteria: (*a*) Straining capacity; (*b*) Valid crack tip location; and (*c*) Microstructures of the regions neighboring crack tip. The wide plate are principally loaded either up to fracture or 2% strain rate whichever occurs first. Acceptability of the test result is based on the purpose of the test. Either to corroborate results of a small scale test or to assess fitness for purpose directly that if the preset strain requirements are achieved. Diversified views are expressed in for the acceptability of HAZ /LBZ tests. One of the views is that adequate ductility can be demonstrated in the base metal if the overmatched weld metal exhibits a 0.5% strain. Other view is that gross yielding of the section can guarantee a ductile fracture in HAZ region. For comparison of the wide plate test results with that of CTOD, both the tests should sample same microstructures. After completion of the test the plate specimen should be sectioned and subjected to detailed micrograph and macrograph analysis in order to verify if the crack tip has successfully sampled the desired microstructure. As the crack front length is long a number of micrographic sections are required. Sectioning of the tested specimens is performed differently for fractured and fractured specimens.

Though wide plate testing is advantageous in cases of realistic testing, post weld heat testing, determining effect of residual stresses, the reliability of the test is questionable if yield tresses are greater than 350 ksi (2413 MPa).

Fairchild (1990)

This paper provides an overview of the local brittle zones (LBZs) in the HAZ of welded steels on its fracture toughness, the fracture mechanism of the LBZ, and the fatigue crack sampling requirement for evaluating the lower bound HAZ fracture toughness by CTOD testing.

A data set of 485 HAZ CTOD tests was obtained and statistically analyzed. Medium-strength structural steels generally used in offshore structures with 45 ksi (310 MPa) to 75 ksi (517 MPa) yield strength were chosen for investigation. Multiple pass welding HAZ regions of previous pass are overlapped and hence reheated by successive passes. These multiple thermal cycles result in spatially varying microstructures that result in varying fracture toughness of the HAZ, and sensitivity to such variation leads to scatter in low toughness values in HAZ. In medium-strength offshore steels toughness degradation in HAZ is generally observed in subcritical HAZ (SCHAZ), intercritical HAZ (ICHAZ) and other coarse grain regions. The coarse grain regions consist of unaltered coarse grain HAZ (CGHAZ), and for multi pass welding, intercritically reheated CGHAZ (IRCG) and subcritically reheated CGHAZ (SRCG) from subsequent weld passes. Out of these degraded regions, only the coarsest portions with 70-80 μm grain size account for LBZs, which typically exhibit CTOD less than 0.004 in. (0.1 mm). The low toughness of the LBZs can be attributed to upper bainite microstructure, microalloy precipitation, and large prior austenite grain size and martensite islands.

The mechanism of fracture initiation and propagation in a region of high stress around a crack tip (also called the process zone) in the presence of LBZs were explained based on a weak link theory. Nearing the limit stress, small micro cracks develop in the process zone either due to decohesion of martensite islands from the surrounding ferrite matrix or cleavage of constrained ferrite in between martensite islands under triaxial stress state.

At the critical event (corresponding to the critical CTOD), one of the brittle cracks start propagating through coarse grain region. With sufficient dynamic energy, the crack would propagate uninhibited across the surrounding fine grain region and cause complete fracture. Otherwise, it would be arrested in the fine grain region resulting in a "brittle pop-in". Such crack propagation mechanism is feasible only if the fatigue crack tip is close enough and favorably oriented to the critical microcrack, which acted as the weakest link within the LBZ. Under a different set of welding conditions such as PWHT or in different steels, other metallurgical subfeature such as precipitate cluster could be the weak links to initiate fracture.

Since only the coarsest regions in HAZ, when sampled by a fatigue crack tip result in low toughness, it is important for realistic assessment of HAZ toughness testing to verify fatigue-crack sampling (FCS) of CG microstructure. Otherwise, events such as deviation of fatigue crack from target microstructure might mislead to higher HAZ toughness values, by sampling weld metal, fine grain HAZ or other tougher regions. FCS involves: (*a*) cross sectioning of the specimen ahead of the fatigue crack; (*b*) photographing the section; (*c*) magnifying the photograph; (*d*) identifying the CG regions; and (*e*) measuring the lengths of CG regions intercepted by the fatigue crack. The fraction of the intercepted length of CG regions with respect to the total fatigue crack is called "%CG regions". As the weak links triggering the fracture are often found in CG regions, the %CG regions was argued as a direct indicator of the lower bound HAZ toughness. In order to establish a minimum % CG for valid lower bound HAZ fracture toughness, FCS data was generated from 485 CTOD tests of 13 normalized and nine thermo-mechanically-controlled-processed (TMCP) medium-strength [45 ksi (310 MPa) to 75 ksi (517 MPa)] steels used in offshore platform at 14°F (–10°C). The CTOD test specimens from 2 in. (51 mm) to 3.5 in. (89 mm) thick plates were sampled including both $B \times B$ and $B \times 2B$ geometries with a through thickness crack depth of a/W ~0.5. The specimens included both K- and half K-joint preparations, made with SAW process using approximately 76 kJ/in. (3 kJ/mm) and 127 kJ/in. (5 kJ/mm) heat input and were tested in both as-welded (AW) and post-weld heat treated (PWHT) conditions. The welding procedures including joint design, bead placement, and HAZ overlap did not necessarily represent the fabrication practice; rather was developed to produce sufficient CG regions for the experimental study.

Statistical analyses of the CTOD test results demonstrated that the probability of a lower bound CTOD increased as the fatigue crack sampled more CG. Apparently a limiting maximum probability of low CTOD was obtained for about 25% CG region (see Figure A-20). Thus FCS after CTOD testing should provide a significant percentage of CG for obtaining a lower bound fracture toughness with sufficient confidence.

Wang et al. (1990)

This study is an excerpt from an extensive research performed by the Welding Institute Canada for evaluating HAZ fracture toughness of construction steels. This study focuses on understanding the individual and combined effects of Vanadium (V), Niobium (Nb) and Titanium (Ti) on fracture toughness of HAZ in HSLA construction steels. Also, their effects on Silicon (Si) and Carbon(C) contents with different heat inputs was studied. For this purpose steel plates with combinations of, [V,Nb,Ti], [Nb,Ti], [V,Ti], V, Ti and Nb, were prepared in highly controlled process in the laboratory. Also Ti steels with increased Silicon content and reduced Carbon content were prepared. Submerged arc weldments were produced for varying heat inputs of 76 kJ/in. (3 kJ/mm), 102 kJ/in. (4 kJ/mm), 127 kJ/in. (5 kJ/mm), and 152 kJ/in. (6 kJ/mm) with cooling times $\Delta_{t8/5}$ of 16.9 sec, 28.9 sec, 42.4 sec, and 55.6 sec, respectively. CTOD tests were conducted on the above weldments to obtain 0.004 in. (0.1 mm) CTOD transition temperatures. The specimens were tested at –94°F (–70°C), –58°F (–50°C), –22°F (–30°C), and 23°F (–5°C) with three to five specimens at each temperature to obtain transition curves and the nature of fracture was noted for each case. The CTOD specimens were 0.4 in.×0.4 in.×2.0 in. (10 mm×10 mm×51 mm) obtained from 1.0 in. (25 mm) thick plates. The notch from weld root side was precracked such that final crack tip samples HAZ with a final crack length of a/W=0.5. In addition to CTOD tests, 20 hardness samples (VH 1000 gf scale) were also taken in HAZ of each of the weldments. A detailed examination of microstructures in the HAZ followed by microstructural classification were performed for each weldment.

The results obtained from the above tests were used to study the effect of microalloy content on 0.004 in. (0.1 mm) CTOD transition temperatures for different heat inputs mentioned above. Also, the grain size and hardness values obtained from the metallogrphy and the hardness tests were compared in each case. Form the 0.004 in. (0.1 mm) CTOD transition temperatures, it was concluded that [V,Nb,Ti] steels had detrimental effects on the HAZ fracture toughness. Ti only steels with increased silicon content and reduced carbon content showed detrimental effects on fracture toughness at lowest [76 kJ/in. (3 kJ/mm)] and highest [152 kJ/in. (6 kJ/mm)] respectively. Increasing heat input for V, Ti steels reduced their HAZ toughness by replacing acicular ferrite microstructure with coarse equiaxed ferrite. The steel with highest V content, 0.093% had lower toughness with increased heat input as the material was hardened.

Verma (1996)

This paper describes a comprehensive research and development project in progress by FHWA to introduce 'Narrow-Gap Improved Electroslag Welding' (ESW-NGI) process for production welding for steel bridges. The ESW-NGI is an improved version of the Elctroslag welding (ESW) process, which in addition to high productivity rate and cost effectiveness is also enhanced with higher fracture toughness in welds and the heat affected zone. This process offers higher freedom from fusion weld defects and cracking. It is envisioned to pass on the ESW-NGI procedure to the Departments of transportations (state DOTs), bridge fabricators, contractors and others in the bridge industry.

Through this research efforts were made to understand the relationships between the welding variables, grain structure, microstructure and toughness and were controlled. The ESW-NGI adopts a narrower root opening which provides more uniform distribution of heat and increased welding speed due to reduced requirement of filler material. New types of consumable guides and tubular powder metal-cored wire are introduced to reduce the sensitivity to weld defects and improve microstructures. The low-carbon material used in the consumable guide reduces the susceptibility to hot cracking. The rectangular shape of the guide introduced in this process promotes uniform lateral distribution of heat and avoids the possibility of incomplete fusion. An increased cross-sectional area of this type of guide increases the productivity. Electrode of Nickel-molybdenum alloy wire composition is developed to meet the weld metal composition and tubular electrode reduces sensitivity to hot cracking and increase productivity. The tubular electrode in increases width to depth ratio of the weld pool which is known to mitigate the hot cracking. Neutral fused fluxes with optimized oxygen content (180-200 ppm) are used to avoid microcracks. Also the new ESW-NGI process improves the weld toughness through: (*a*) higher cooling rate due to lower heat input; and (*b*) formation of microstructures with higher toughness such as acicular ferrite due to higher cooling rate.

The new ESW-NGI process is found to facilitate an improved Chary V-notch toughness and excellent weld fatigue resistance. Also extensive field tests and testing during the demonstration of the new process established that acceptable toughness of elctroslag welds can be achieved on regular basis. One of the objectives of this technology demonstration project DP-102, that is compilation of comprehensive specifications and guides for technical, procedural, and training information on ESW-NGI, which are to be included in the *ANSI/AASHTO/AWS D1.5* bridge welding code.

Liao et al. (1997)

Heat affected zone fracture toughness properties of SQV-2A pressure vessel steel were investigated using thermal simulation technique. SQV-2A is a low alloy steel with a chemical composition as shown in Table A-9. Though the steel exhibits very good low-temperature toughness as suitable for pressure vessels, the high heat input required to join very thick pressure vessel plates is apprehended to cause low toughness in the HAZ. The CGHAZ and ICCGHAZ are anticipated to exhibit lowest toughness. With an overall objective to provide a guidance for the correct choice of welding parameters, the effect heat input on CGHAZ toughness and tempering thermal cycles on intercritically reheated CGHAZ (ICCGHAZ) toughness were studied. The effects of post weld heat treatments (PWHT) on toughness were also determined.

Weld CGHAZ and ICCGHAZ regions were simulated in the 8.0 in. (200 mm) thick quenched and tempered plates using thermal/mechanical simulator Gleeble 1500. Simulations were performed on specimens of 2.2 in.×0.4 in.×0.4 in. (55 mm×10 mm×10mm) sampled at ¼*t* and ¾*t* of the plate with longest dimension of the specimen is along the plate rolling direction, where *t* is the plate thickness. Single thermal cycles with peak temperatures reaching 2460°F (1350°C) with the cooling times, $\Delta t_{8/5}$ varying between 6.0 sec and 1000 sec were used to simulate CGHAZs with varying heat inputs for a given welding process. A second thermal cycle with peak temperatures ranging between 1110°F (600°C) and 1530°F (830°C) to simulate ICCHAZs. The cooling times $\Delta t_{8/5}$ for second thermal cycle were varied between 6.0 sec and 40 sec. PWHT was performed at 1150°F (620°C) on CGHAZ simulated by single thermal cycle. All the above simulated full size CVN samples were tested at 32°F (0°C). Metallography and fractography were performed on the tested CVN samples.

Based on the M-A constituents and toughness values obtained from the CVN tests the following conclusions were summarized. The CGHAZ toughness of SQV-2A plates at high heat input that is cooling time between 6.0 sec and 12 sec had exhibited high toughness along with very high hardness (greater than 400 HV). Suitable PWHT was found to significantly reduce the toughness and lowered hardness. Optimum welding and PWHT parameters were suggested for improved toughness greater than 148 ft-lb (200 J) and a reduced hardness less than 350HV.

Liessem et al (2004)

The study reviews various specifications and previous investigations to understand the significance of HAZ toughness testing in the welding of offshore pipes. The study provides an overview of HAZ microstructures in longitudinal submerged arc welded (LSAW) pipelines in offshore steels. Methods to reduce the brittle or low toughness microstructures through welding procedures and chemical composition. Inappropriate acceptance criteria for offshore steels with respect to HAZ toughness was pointed out and explained.

LASW is a high heat input welding process and the cooling conditions in two pass LSAW remain constant irrespective of pipe wall thickness which leads to the formation of low toughness upper bainite microstructures containing M-A constituents. This can be regulated through altering steel chemical composition, so that a positive influence on the FATT and upper shelf energy to restrict austenite grain coarsening and hardenability of the steel microstructures. Reduction of C and CE content, limiting Nb, controlled use of Ti, addition of Ni, and low percentages of S, P and O are some of the ways to achieve this. In spite of proper application of these methods in steel making, toughness less than that required by standards is still experienced when notched in the CGHAZ LBZs.

HAZ toughness in SAWL 450, $1^{3}/_{8}$ in. (35 mm) WT weldments were tested for CVN at *DNV-OS-F101*, notch locations, FL, FL+0.08 in. (2 mm) in HAZ at –4°F (–20°C). The results showed toughness values higher than required minimum that is, 27 ft-lb (36 J) at –4°F (–20°C) in both the notch locations. But the toughness values at FL+0.08 in. (2 mm) in HAZ were higher due to lesser amount of CGHAZ sampled away from the fusion line. Associating increased heat input with increased wall thickness, CVN tests were conducted to examine the dependency of HAZ toughness on heat input/wall thickness. X65/X70 steels of varying thickness were tested at –22°F (–30°C), with CVN notch locations at FL, FL+0.08 in. (2 mm), FL+0.2 in. (5 mm) according to test and acceptance criteria of *Statoil Specification RSP-230*. Average CVN toughness values were higher than the minimum average requirement as per *RSP-230*, 33 ft-lb (45 J) at –22°F (–30°C) and minimum individual CVN toughness did not meet the requirement of 25 ft-lb (34 J) at –22°F (–30°C) only for FL notch location. The toughness values were found to be higher for thickness less than 1.0 in. (25 mm) due reduced heat input. Failure at FL increases by 3% with increased thickness. No failures were reported for FL+0.2 in. (5 mm) notch location as, the notches were almost located in base metal for smaller thickness.

An extensive review of literature and previous tests, the reason for the discrepancy between fracture toughness tests, wide plate tests and actual structures was explained as follows. Fracture toughness tests like CTOD do not reflect the actual conditions in structures. The effects of low constraint in surface cracks, low probability of exact crack placement in low toughness regions simultaneously at higher loads are overlooked which leads to conservative toughness requirements such as 0.008 in. (0.2 mm) CTOD which is frequently specified.

The relationship among critical defect size, toughness, and load was investigated according to *BS 7919* using crackwise computer program. A critical flaw sizes for toughness varying from 0.0004 in. (0.01 mm) to 0.004 in. (0.1 mm) CTOD and ligament length were calculated for X80 grade steel assuming a load of 70% SMYS as the internal pressure in the pipeline. The lower CTOD values represented higher constraint in terms of higher wall thickness. The critical flaw size was found to increase with increase in ligament length and CTOD fracture toughness values.

Bennett et al (2009)

The Electroslag welding (ESW-NGI) process was investigated for use in welding grade HPS 70W steel for bridges. Specifically, the fatigue resistance of butt-splice connections fabricated using the ESW-NGI process were tested. At the time of this publication, the AASHTO specifications did not permit the use of ESW-NGI for welding high performance steel (HPS) grades and if test results were sufficient the authors sought to recommend the allowance of using ESW-NGI with HPS grades in bridge construction. HPS 70W has become an attractive alternative to traditional steel grades due to its higher yield strength [70 ksi (482 MPa)], increased ductility, superior fracture toughness, weldability, and weathering properties.

The experimental test results would dictate whether or not it the authors felt it would be appropriate to include the ESW-NGI for use with HPS 70W steel as an addendum to the *AASHTO/AWS D1.5*. Also, another objective of the research was to determine whether or not

HPS 70W butt splices fabricated using the ESW-NGI procedure would be acceptable for use with fracture-critical bridges. As a comparison to the ESW-NGI process the same number of specimens was to be fabricated using SAW. The goal of the research was not to determine the more effective welding process between ESW-NGI and SAW but rather to test if the ESW-NGI specimens performed at least as well as the already proven SAW process.

The test specimens were fabricated from both $^{7}/_{8}$ in. (22 mm) and 2.0 in. (51 mm) thick HPS 70W steel plates. Two of the 2.0 in. (51 mm) plates were welded by the SAW process using a $^{3}/_{32}$ in. (2.4 mm) diameter LA85 electrode. The other plates were joined by the ESW-NGI process and a ¾ in. (19 mm) gap and a shoe speed of 1.5 in. (38 mm) per minute. The specimens were then machined from the welded plate, five using the SAW process and five from the ESW-NGI process. The machining was performed so that the butt weld area was located in the middle of each specimen.

Following preparation, the specimens were tested in a universal testing machine and slightly preloaded to ensure that they were initially in tension. Three target stress ranges were used: 22.3 ksi (154 MPa) and 23.5 ksi (162 MPa) for only one SAW specimen each and 29.2 ksi (201 MPa) for all ESW-NGI and the remaining SAW specimens. The authors noted that these tested ranges were significantly higher than those used for design of steel bridges. All ten specimens achieved a run-out after the initial two million cycles of fatigue testing. Two specimens of each welding type were then subjected to an additional three million cycles. Both ESW-NGI specimens achieved over five million cumulative cycles without failure. One of the SAW specimens failed at over three million cumulative cycles due to a fracture in the base metal at the fillet transition from the reduced section to the wider grip section. The remaining SAW specimen achieved over six million cumulative cycles without failure.

Based on the results, the authors concluded that it was reasonable to state that the ESW-NGI specimens performed at least as well as the SAW specimens when subjected to extended fatigue testing. The performance overall was an improvement over the predicted fatigue life determined using the fatigue life equation in the AASHTO specifications. Although more extensive research would lead to further detailed test results and a potentially larger dataset the authors recommended the ESW-NGI process for use with HPS 70W steel and fracture-critical bridge members.

Based on the outcomes of this research it may be worth further research to determine the fracture and fatigue performance of other HPS steel grades. Since AASHTO does not currently permit the use of the ESW-NGI process for use with any HPS steel, similar tests performed by Bennett et al may be significant for HPS 50W and HPS 100W. Also, the authors did not subject the specimens to extreme temperatures which are known to be a factor in determining the toughness and therefore fatigue resistance of steels.

Amadioha et al (2011)

Realistic assessment of HAZ toughness of line pipe seam welds by constraint corrected small scale shallow edge notch tension specimens was investigated. The study was motivated by occasional low outliers with respect to the specified CTOD of 0.01 in. (0.25 mm) at 14°F (–10°C) observed from highly constrained single edge notched bend (SENB) specimens, which were due to the crack front intercepting the LBZ in CGHAZ with low probability; these low outliers were demonstrated to be structurally insignificant by large scale structurally-representative wide plate tests.

The effects of varying degrees of constraint, scale and loading mode were evaluated on more than 50 single edge notch bending (SENB), single edge notch tension (SENT) and surface notched tension (SNT) specimens with varying crack depths.

The specimens were machined from the two pass SAW seam weldments of a 1.2 in. (31 mm) thick Grade X65 U-O-E TMCP pipe. The specimens were tested as-welded. A baseline data was generated representing high constraint fracture toughness tests for the pipeline weldments. For this ten full wall thickness, gull-winged SENB specimens of $B \times B$ configuration were machined and notched in NP orientation in the seam welds of the pipe with CGHAZ as the target microstructure to be sampled. CTOD and J tests according to *BS7448-2*, were conducted at 14°F (–10°C) on the specimens at a high constraint of a/W of 0.5. A cumulative probability of 60% was observed for the CTOD of the baseline test specimens to cross 0.01 in. (0.25 mm).

Lower constraints were achieved by reducing the notch depth (a/W), variation of loading mode (SENT), increased ligament length ($B \times 2B$ or $5B$) and reduced thickness (sub-sized specimens). Table A-10 gives the test matrix different low constraint tests performed for CGHAZ to compare with the conservative baseline data. All bend specimens in the test matrix were tested for CTOD and J according to *BS7448-2*, at 14°F (–10°C), and the results were evaluated using *ISO15653*. Orientation and notch positioning of the bend specimens were same as the baseline tests. Sub-sized SENT through thickness, deeply notched (a/W=0.5) and shallow notched (a/W=0.2) specimens as shown in the same table, were tested for CTOD and evaluated according to *DNV-RF-108*.

The following observations were using the data from SENB and SENT tests, shown in Figure A-21. Deep notched SENB tests are more conservative compared to deep notched SENT tests. SENT tests yielded higher cumulative probability of toughness (CTOD) in the SENB specimens (full thickness or sub-sized specimens). Higher ligament length did not have much effect on the toughness. Shallow notched specimens showed the highest toughness in both SENB and SENT specimens where shallow notched SENT specimens showed the highest overall toughness.

Surface-notched tensile (SNT) plate tests: To represent the surface cracking defects in the pipelines and to test the effects scale on HAZ toughness, three surface notched tensile plate tests were conducted for the pipeline seam welds. The SNT test specimens were 0.79 in. (20 mm) thick and 3.9 in. (100 mm) wide seam weld coupons, with a total parallel gauge length of 15.7 in. (400 mm) providing a ($B \times 5B$) specimen size. The plates were notched at CGHAZ/FL with semi elliptical notches of 20mm long and 4 mm deep with 0.1 notch root radius. Tests were conducted at -10°C. All three specimens attained CMOD/CTOD of approximately 3mm at maximum load. Strains in the specimens at failure were much higher than the material strain capacity. Toughness values of HAZ in surface notched specimens thus indicated higher toughness performance compared to the high constraint specimens.

Engineering Critical Assessment (ECA): The significance of seam weld HAZ toughness in the structural integrity of UOE pipelines was investigated using ECA. ECA was performed for surface breaking, external, axial flaws with depths of 8%, 20% and 50% of pipe wall thickness according to *BS7910:2005*. The minimum of three equivalent (MOTE) CTOD were input as obtained from the tests. ECA employs the 'failure assessment diagram' (FAD), to predict the safety the structure for a given flaw size, material properties, and fracture toughness values input.

ECA analysis gave conservative results for the fracture toughness values from high constraint tests such as SENB through thickness deep and shallow notched cases compared to SENT and SNT specimens. High conservatism of FAD based ECA was attributed to the assumptions such as usage of full yield stress magnitude residual stress, fracture toughness of deep notched, high constraint specimens.

In summary, the study focused on understanding the significance of occasional low HAZ toughness values encountered in high constraint fracture toughness tests of pipeline seam welds. For this purpose SENT, SENB and SNT tests were carried out representing varied constraints and scales. SNT tests at FL showed very high toughness at realistic constraints as the material at the notch failed by plastic collapse achieving strains greater that 2.5%. It was deduced that, for the occasional low toughness outliers of HAZ to not significantly lower the overall fracture toughness values, reduced or realistic constraints must be used in the tests.

Biswas et al (2012)

An experimental program was conducted for microstructural characterization of heat affected zone of HPS 100 W steel simulated using Gleeble 3500 at different peak temperatures of 1560°F (850°C), 2010°F (1100°C), 2370°F (1300°C), and 2460°F (1350°C) for 51 kJ/in. (2 kJ/mm) heat input. In addition to this Charpy impact toughness tests were conducted according to *ASTM E23* at AASHTO service temperatures of different zones, that is 0°F (18°C), –30°F (–34°C) and –50°F (–46°C). Three samples were tested at each test temperature for each of the simulated HAZ microstructures at above mentioned temperatures.

The Charpy impact toughness results showed an increase in the toughness of all the HAZ microstructures compared to that of the base metal. This was justified as follows for each of the cases: The increase in toughness for 1560°F (850°C) and 2010°F (1100°C) peak temperature microstructures was attributed to the formation of carbide, crabonitride and Copper precipitates and grain refinement. The increase in toughness for microstructure with 2370°F (1300°C) and 2460°F (1350°C) peak temperatures was justified that the toughness increased due to formation of very fine low carbon bainitic martensitic structures. All the simulated microstructures exhibited toughness higher that required for AASHTO Zone 3 service conditions, 35 ft-lb (48 J).

Collins (2014)

As part of Transportation Pooled Fund Project 5-238 (TPF 5-238), *Design and Fabrication Standards to Eliminate Fracture Critical Concerns in Steel Members Traditionally Classified as Fracture Critical*, the fracture behavior of steels used in bridge application was examined.

Investigation on HPS and conventional steels were performed on several topics. Those were: (*a*) fracture toughness data of bridge steels was compiled and reanalyzed using master curve methodology; (*b*) currently available methods for correlating CVN-toughness was examined using the compiled data of bridge steels; (*c*) characteristics of modern high performance steels (HPS) was investigated; (*d*) dynamic fracture toughness performance for HPS was examined; (*e*) crack arrest test for HPS was conducted; and (*f*) fracture toughness performance of conventional steel was examined using master curve methodology.

Fracture toughness data of bridge steels was compiled and re-analyzed by applying plasticity correction to estimate elastic-plastic fracture toughness. Due to high ductility and toughness in structural steels for bridge application, considering plasticity in fracture is critical. Fracture behavior of the bridge steels in ductile-brittle transition region was characterized using master curve methodology. The results indicated that the scatter of the fracture toughness data in ductile-brittle transition region is statistically characterized and the master curve methodology could be used to accurately describe the temperature dependence in fracture toughness.

This study also analyzed the all available methods correlating CVN impact energy to fracture toughness using fracture toughness data of bridge steels. The predicted and actual fracture toughness values were analyzed for the master curve reference temperature, T_o and compared. From the comparison, the temperature shift in Barom-Rolfe Two Stage method, which have been used by current AASHTO material specification, can lead to unconservative estimates of intermediate and static loading rate fracture toughness. The overall comparison results indicated that none of the methods acted as a true predictor of the reference temperature because the dispersion of the predicted reference temperatures were too large. The reason for large dispersion was because the correlation methods were developed to provide conservative toughness values.

Although application of modern high performance steel (HPS) in new steel bridge construction have been increased, little investigation have been done to characterize the fracture toughness of HPS. As a result, current material specification do not take advantage of the improved fracture performance of HPS. Fracture toughness testing and analysis for HPS steels were conducted. Total eight HPS steel plates were prepared. Five plates of HPS 70W steels had four different thickness and two different heat number with the same plate thickness. Three plates of HPS 100W steel had three different plate thicknesses. The thicknesses of the plate were varied from $^3/_4$ in. (19 mm) to 2 in. (51 mm). From the eight plates, 246 CVN specimens and 144 precracked SE(B) specimens were prepared and tested. The results indicated that the fracture toughness of HPS was much higher than the required toughness in ASTM A709-13 and for AASHTO Zone 3 temperature.

The result of dynamic fracture testing of eight HPS steel plates found that rate adjustment recommended by ASTM 1921 predicting dynamic fracture toughness from the static fracture toughness could estimate unconservative dynamic fracture toughness for HPS 70W steel.

Crack arrested testing for HPS and fracture toughness testing for conventional steel were not successful to obtain enough valid data. As such, no conclusion was made.

ABS Steel Vessel Rules - Rules for Materials and Welding - Part 2

American Bureau of Shipping (ABS), through this standard provides rules for testing and certification of materials and welding procedure qualifications for materials used in ABS classed vessels, other marine structures and their associated machinery units. Guidelines for fracture mechanics testing, impact testing and hardness testing of weldments for the ordinary-strength structural steels and higher-strength structural steels that are widely used in the form of plates in hull construction are also included.

Materials and the weldments are to be tested for fracture toughness in HAZ only when specified. One of the facture toughness properties of K_{Ic}, J_{Ic} and δ may be tested for. Three specimens are to be sampled and tested at each of the weldments. Specimen geometry, notch orientation and load type (bend or tension) should be in conformity with *BS7448 Parts 1 and 2*, *ASTM E1823* or any other recognized standard. The specimen are not allowed to be stress relieved unless, specially permitted in the ABS-approved material and product manufacturing procedure specifications. If required, straightening of the specimen can be carried out under the slowest possible loading rate, at a compressive load not exceeding the compressive yield stress of the material. Fatigue pre-cracking and the tests are to be carried out according to *BS7448 Parts 1 and 2, ASTM E1823* or any other recognized standard. The results from the post-test analysis should meet all the established validity criteria of *BS7448 Parts 1 and 2, ASTM E1823* or any other recognized standard.

If the fracture toughness parameter is CTOD (δ_c, δ_u or δ_m), lowest value of the three samples tested at a location should be greater than 70% of the average value of the set and greater than equal to the minimum required CTOD specified for the material at that location. Then this value is considered as characteristic CTOD. If the above conditions are not satisfied three additional specimens are tested for the same location. The second lowest of all the six values if greater than the minimum specified CTOD value for the material at that location by ABS-approved material and fabrication specifications is considered as the characteristic CTOD for that location.

Charpy V-notch impact test is specified for the welding procedure approval in case of higher-strength steels, electroslag welding, one-side welding, etc. For ordinary-strength and higher-strength structural steels used for hull construction, the impact test specimen should be oriented such that longitudinal axis of the specimen is parallel to the plate rolling direction and transverse to the weld direction. Whereas, in case of quenched and tempered steels the specimen is in transverse direction to the plate rolling direction and the weld. The notch line is perpendicular to the plate surface. The sampling locations in a butt weld plate for impact testing in HAZ are shown in Figure A-22. Three samples are to be tested at each location. For Butt welds or single sided welds with heat input less than equal to 20 kJ/in. (5 kJ/mm), the Charpy impact specimens are sampled at less than 0.08 in. (2 mm) from plate surface and V-notches are to be placed at fusion line (FL), FL+0.08 in. (2 mm) and FL+0.2 in. (5 mm) in HAZ for. If the plate thickness greater than 2 in. (51 mm) additional samples must be tested at FL near the weld root. For weldments with heat input greater than equal to 20 kJ/in. (5 kJ/mm) additional samples are to be tested at FL+0.4 in. (10 mm) near the surface for plates of any thickness at additional locations near the root for plate thickness greater than 2 in. (51 mm) as shown in the Figure A-22.

Acceptance criteria for CVN Impact tests are described as follows. The CVN test at a location is considered to be valid only if the average is greater than the average required at that location and not more than one value in the set is less than the required average. Also no value in the set should be less than 70% of the required average given by the standard. If the above conditions are not satisfied, then three additional samples are tested close to the same location. Out of the six samples not more than two samples shall have a value less than the required average and not more than one shall have a value less than 70% of the required average. Else, the material is rejected. CVN impact energy requirements for ABS steels are as given in Table A-11.

Hardness tests are required if the specified minimum yield strength (σ_y) greater than 51 ksi (355 MPa). Vickers hardness HV 10 tests are to be conducted according to *ISO 6507/1*. At least two rows of indentations are to be carried out on a weld as shown in Figure A-23. A minimum three indentations are to be made in HAZ on both sides of the weld in each row. A minimum distance of 1 mm should be maintained between adjacent indentations. Additional row of indentation is required for double sided welds. Hardness limits for hull construction and marine steels is given in Table A-12.

API RP 2Z: Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures

One of the first standards detailing recommendations for HAZ fracture toughness of offshore structures was issued by the American Petroleum Institute (API). This document provides recommended welding practices and mechanical testing methods for the qualification of steel plates prior to fabrication. These recommendations are intended to minimize the time and testing necessary to prepare and certify fabrication welding procedures with particular attention to HAZ toughness.

The HAZ regions that are referred to in this document are described as follows for the unbeveled plate edge of a single bevel groove weld. Typically a weld pass metallurgically transforms the base metal from fusion line into the base metal. Figure A-24 shows the HAZ regions in case of Single-pass, Bead-on-plate weld. The microstructure in these regions depends on the peak temperature respective region experiences during welding. The region adjacent to the weld metal is called CGHAZ, as it experiences the highest peak temperature and results in coarse grain formation. The regions further away from the boundary experience lower peak temperatures resulting in FGHAZ, ICHAZ, and SCHAZ in order. In a multi-pass weld these regions are overlapped by subsequent passes which further modifies their microstructures. As seen in Figure A-25, the CGHAZ of the previous pass is reheated by the subsequent pass to intercritical and subcritical temperatures depending on their proximity from weld boundary. This results is intercritically reheated coarse grain region (IRCG) and subcritically reheated coarse grain region (SRCG). The region that lies between visible etched HAZ and a parallel boundary delineated at a distance of 0.02 in. (0.5 mm) into the base metal [0.01 in. (0.3 mm) for the lowest heat input weld] is called etched HAZ boundary material. This region contains unaltered SCHAZ.

Pre-qualifications tests for HAZ toughness: Three butt welds of test plates configured with either a K-bevel or single-bevel joint type shall be made using the submerged arc welding (SAW) process, but other processes may be used for root pass and lowest heat input welds. The welds are to be placed parallel to the final rolling direction of the steel at the middle of the plate width and shall be performed on the maximum plate thickness intended for pre-qualification. The heat input shall range from 21 kJ/in. (0.8 kJ/mm) to 114 kJ/in. (4.5 kJ/mm) unless further restrictions are introduced by the fabricator. The first weld shall use the lowest heat input and a preheat/interpass temperature of 212°F (100°C); the second shall use the maximum heat input with a preheat/interpass temperature of 482°F (250°C) or higher; and the third shall use a heat input of 76 kJ/in. (3.0 kJ/mm) with the maximum preheat temperature of 482°F (250°C).

At the time this document was published, CTOD testing of the HAZ was to be in accordance with either ASTM E1290 or BS 7448 Parts 1 and 2 at the option of the manufacturer. These specifications have since been superseded by ASTM E1820 and BS EN ISO 15653 respectively. For specimens of plate thickness thickness,T greater than 2.5 in. (63 mm), a specimen geometry of $T \times T$ shall be adopted, instead of $T \times 2T$ that is prefeerred for lower thickness .

It should be made sure that the weld metal's CTOD when tested at 14°F (–10°C) at distance of 0.04 in. (1 mm) to 0.08 in. (2 mm) from the fusion line into the weld metal, is at least 0.005 in. (0.013mm) greater than that of the required CTOD at HAZ region. The weld metal hardness should be equal or exceeding the hardness of the base metal. This is to ensure that, crack propagation into the soft weld metal during the HAZ CTOD testing is prevented. A minimum of eight and five valid CTOD specimens is required for the lowest and highest heat inputs respectively and all tests must be performed at either 14°F (–10°C) or the lowest intended service temperature. The length direction of the specimen must be perpendicular to the weld and final rolling direction. HAZ toughness for each of the three test weldments is to be tested by CVN and CTOD tests.

The vertical boundary of the weld must be straight enough to allow for the placement of a through-thickness notch normal to the plate surface. Prior to testing it should be checked that the notch is able to sample at least 75% of the etched HAZ, within the middle two-thirds of the plate thickness when etched. The weldments should be notched such that the notches of at least six, three, and three specimens from the lowest, high and highest heat input weld categories respectively must intersect the maximum amount of CGHAZ. The notches of at least two specimens from each of the three heat input welds must intersect the etched HAZ boundary.

A lower bound of crack inclusion is recommended to increase the probability of the crack front sampling the CGHAZ. If the CGHAZ is not totally homogenous, a crack entering the region may not sample an LBZ and overcompensation of the CGHAZ behavior may result. After CTOD test according to the specified standard, metallographic investigation is to be performed to locate the fatigue crack with respect to HAZ. Metallographic requirements of fatigue precrack position are given in Table A-13. Also, the acceptable CTOD test results for different plat thicknesses can be found in Table A-14.

CVN testing includes development of transition curves for coarse grain HAZ and unaltered SCHAZ locations at both root and quarter thickness regions of the weldment. Each of the four transition curves should contain at least eight tests. The specimens are to be notched through thickness and the dynamic crack should propagate along the weld length.

API Specification 5L – Specification for Line Pipe

The specification provides requirements for the manufacture of two product specification levels, PSL1 and PSL2 of seamless and weld steel pipes used in transportation systems of the petroleum and natural gas industries.

Heat affected zone in the welds when tested for guided bend tests are not allowed to reveal any cracks or ruptures longer than $^1/_8$ in. (3.2 mm) or deeper than 12.5% of the specified wall thickness. The test pieces preparation and test shall be carried out according to *ISO 7438* or *ASTM A370*.

Three CVN samples are to be tested in HAZ of seam welds of SAWL or COWL and SAWH or COWH pipes. The notch shall be placed as close to the fusion line as possible as shown in Figure A-26, outside the weld bead and the specimen shall be sampled closet possible to the pipe outer surface. CVN specimen preparation and testing shall be according to *ASTM A370*. When tested for CVN at 32°F (0°C) or any lower temperature the HAZ requirements are as given in the Table A-15.

Seam-heat-treated welds should be verified for full wall thickness treatment. When heat treatment is not required, the welds should be verified for the presence of untampered martensite remains. These verifications are to be performed by metallographic testing of HAZ.

When ordered for sour service, the PSL2 pipes are subjected to additional provisions according to Annex H of *API 5L*. Hardness testing in HAZ shall be carried out according to *ISO 6507-1* or *ASTM E384*. Hardness test traverses are made across the visible HAZ, only at mid-thickness for pipes with thickness less than 0.16 in. (4 mm) and only within 0.06 in. (1.5 mm) from inner and outer surfaces for the pipes with thickness varying between 0.16 in. (4 mm) and 0.24 in. (6 mm) as shown in Figure A-27. In no case the HAZ hardness shall be less than 250 HV10 when tested at mid-thickness and 275 HV10 when tested near the surface.

PSL2 pipes when ordered for offshore service, are subjected to additional provisions according to Annex J of *API 5L*. HAZ shall be tested for CVN, CTOD and Hardness. Hardness testing follows the same procedure as that of sour service pipes given above. HAZ hardness values shall not exceed 270 HV10 for steel grades less than or equal to 450 or X65, 300 HV10 for steel grades greater than L450 or X65 and less than equal to 555 or X80, and 325 HV10 for steel grades greater than L555 or X80. Sample preparation and test procedure for CTOD test shall be performed according to *ASTM 1290*, *BS7448*. The CTOD test temperature shall be as specified in the purchase order. three CVN samples are to be tested in HAZ of seam welds of SAWL pipes and in seam weld and strip/ plate end weld in SAWH pipes.

ASTM E399: Standard test method for linear-elastic plane-strain fracture toughness K_{Ic} of metallic materials

ASTM E399 covers the determination of fracture toughness (K_{Ic}) of metallic materials under predominantly linear-elastic plane-strain conditions. Until the publication of ASTM E1820, testing method of ASTM E399 had been used for evaluating K_{Ic}. As such, the evaluation of K_{Ic} has been removed from ASTM E1820 to avoid duplication. Recommended requirements for testing apparatus, testing procedure, specimen types, and specimen dimensions are identical to ASTM E1820. In addition, arc-shaped tension [A(T)] and arc-shaped bend [A(B)] specimens are also recommended for K_{Ic} testing.

ASTM E436: Standard Test Method for Drop Weight Tear Tests of Ferritic Steels

This specification provides a test method for drop weight tear tests (DWTT) on ferritic steel specimens $^1/_8$ in. to ¾ in. (3.2 mm to 19 mm) thick. The method is used to determine the appearance of propagating fractures in plain carbon or low-alloy pipe steels (yield strength less than 120 ksi (827 MPa) over the brittle-ductile transition temperature range. The test involves a single edge notch beam specimen that is impact loaded in three-point bending over a 10 in. (254 mm) span in a pendulum or drop-weight type machine. The specimen is 3 in. (76.2 mm) deep and of full plate thickness. A 0.2 in. (5.1 mm) deep notch of 0.01 in. (0.25 mm) root radius is pressed by a sharp tool chisel. The specimen is to be fractured in a single impact. The specimens are evaluated by determining the percent shear area of the fracture surface, neglecting the fracture surface for a distance of one specimen thickness from each end. The data (percent shear area) is a qualitative measure, and not amenable to any meaningful analysis. Correlating the full-scale pipe tests with DWTT results, however, it is observed that the transition in the fracture propagation appearance (% shear area) remote from the initiation region in both specimens occur at the same temperature. Thus, the DWTT can define a fracture propagation transition temperature (FPTT).

ASTM E604: Standard Test Method for Dynamic Tear Testing of Metallic Materials

This specification provides a test method for dynamic tear (DT) test of specimens $^3/_{16}$ in. to $^5/_8$ in. (5 mm to 16 mm) thick. The test involves a single edge notch beam specimen that is impact loaded in three-point bending over a 6.5 in. (165 mm) span in a pendulum or drop-weight type machine. The test provides DT energy, which is the total energy required to fracture the DT specimen. The DT energy value is a measure of resistance to rapid progressive fracturing. The test is designed for applications where the enhanced resistance to fracture during about one plate thickness of crack extension from a sharp notch is of interest. Accordingly, a sufficiently long fracture path is provided. The specimen depth in the direction of impact or the notch, W, is 1.6 in. (41 mm). A notch depth, a, of approximately 0.475 in. (12 mm) is machined to provide a fracture path of 1.125 in. (29 mm), which results in a/W close to 0.3. The notch is sharpened by a pressed knife of maximum 0.001 in. (0.025 mm) notch radius. Accordingly, the test process is restricted to materials with a hardness level of 36 HRC, which is approximately correlated to a tensile strength of about 170 ksi (1170 MPa) and yield strength of 120 ksi (827 MPa). The test method is useful for: evaluating the effects of metallurgical variables or fabrication processes; establishing the suitability of a material for a specific application in service, where a correlation between the DT energy and service performance is known; and for quality control.

ASTM E1221-12a

This standard test method employs a side-grooved, crack-line-wedge-loaded specimen to obtain a rapid run-arrest segment of flat-tensile separation with a nearly straight crack front. This test method provides a static analysis determination of the stress intensity factor, K_{Ia}, at a short time (1 to 2 ms) after crack arrest by measuring the arrested crack size and the crack mouth opening displacement prior to initiation and shortly after crack arrest. A nominal stress intensity factor at a crack initiation, K_o, can be also determined based on measurements of machined notch size and the crack-mouth opening displacement at initiation of rapid running crack. Specimen size requirements are provided to allow the specimen to be modeled by linear elastic analysis and obtain plane-strain condition crack-arrest toughness. The requirements depend on the crack arrest toughness and yield strength of the material. For example, the ratio between specimen width (W) and thickness (B) is recommended to be between 2.0 and 8.0 ($2B \leq W \leq 8B$). Once the test is completed, validity of the test results should be confirmed. The validity requirements consider the length of unbroken ligament, specimen thickness, and length of rapid crack propagation.

ASTM E1820: Standard Test Method for Measurement of Fracture Toughness

ASTM E1820 covers procedures and guidelines for the determination of fracture toughness of metallic materials under the opening mode (Mode I) of slow loading (0.3 to 3 minutes to maximum force). Fracture toughness is measured using parameters of J-integral (J) and crack tip opening displacement ($CTOD$, δ). Evaluation of plain strain fracture toughness K_{Ic} is not considered in this document and is covered by ASTM E399.

As per these standard test methods, fracture toughness could be measured in a point value or the continuous fracture toughness versus crack extension relationship (R-curve) format based on the response type. A point value measurement could be done when fracture instability occurs before stable tearing. When fracture instability occurs after stable tearing, R-curve is used to evaluate fracture toughness.

The standard test method covers only deep notched specimen which the initial crack length (a_o) is between $0.45W$ and $0.7W$, where W denotes the depth of the specimen (Figure A-28). Recommended specimens for the test methods are single-edge bend [SE(B)], compact tension [C(T)], and disk-shaped compact tension [DC(T)] specimens. For each specimen type, requirements for test apparatus, specimen dimensions, testing procedures, and fracture toughness calculation are provided. Also, data qualification methods are recommended to ensure plane-strain fracture toughness.

In addition to the standard test method, two additional test methods for special conditions are provided. Those are: (*a*) requirements for the test which loading rate exceeds allowed loading rate; (*b*) requirements for the tests at impact loading rates using precracked Charpy-type specimens.

As a nonmandatory information, a guidelines for measuring fracture toughness of shallow notched single-edge bend specimen [SE(B)] is provided. Recommended size of the initial crack is between $0.05W$ and $0.45W$. It is commented that the fracture toughness evaluated by shallow notch specimens is usually non-conservative compared to the toughness using deep notch specimens and may exhibit larger scatter, especially in the ductile-to-brittle transition region for ferritic steels.

BS7448 Part 1: Method for Determination of K_{Ic}', Critical CTOD and Critical J values of metallic materials

BS 7448 Part 1 covers procedures and guidelines for the determination of critcal fracture toughness of metallic materials, which are similar to *ASTM E1820* and *E399*. Overall specimen and test apparatus requirements, testing procedures, fracture toughness calculations, and qualification of data are almost identical to *ASTM E1820* and *E399* except some minor details. However, guidance for fracture toughness testing under dynamic loading and testing of shallow notched specimens with notch depth less than $0.45W$ are not provided.

BS EN ISO 15653:2010 Metallic Materials - Methods of Test for the Determination of Quasistatic Fracture Toughness of Welds

This international standard specifies methods for determining point values of fracture toughness in weld metal (WM) and heat affected zone (HAZ). The fracture toughness is determined in terms of stress intensity factor (K), crack tip opening displacement *(CTOD, δ)*, and experimental equivalent of J-integral (J). The methods use fatigue precracked specimens that have been notched in a specific target area. This standard is complementary to *ISO 12135: Metallic Materials – Unified method of test for the determination of quasistatic fracture toughness* (almost same as *BS7448 part 1*). Only the procedures relevant to HAZ testing are reviewed in the following.

The specimens are required to have one dimension equal to the full thickness of the parent metal adjacent to the weldment to be tested. The specification allows compact tension (CT) and single-edge-notched bend (SENB) specimens, plain-sided or side-grooved, as defined in *ISO 12135*. Both through thickness notched specimens (TT), notched into the plate thickness, and surface notched specimens (SN), notched into the planar surface of a plate, are allowed. The recommendations for a typical SENB specimen are shown in Figure A-28 and it is identical to the SE(B) specimen recommended by *ASTM E1820*.

The specification identifies the target area for fracture toughness in relation to either a weld feature of interest referred to as "weld positional"(WP) or, a microstructure of interest referred to as "specific microstructure"(SM). For HAZ, the notch target area can either be WP or SM.

The recommendations are elaborated based on SENB configuration. The specification provides elaborate guidance on typical notch locations in SENB specimens. The crack plane orientations in Table A-16 are designated according to directions in Figure A-29. The first letter of the designations in the table indicates direction normal to the crack plane that is the direction of longitudinal axis of the specimen and the second letter indicates the intended direction of crack propagation. The first two cases in the table depict the notch locations for WP, whereas the last two for SM that is to sample a specific microstructure in HAZ.

Recommended pretest requirements and procedures

(*a*) For SM, target microstructure is to be determined on polished and etched macrosections normal to the weld axis prior to machining. In case of TT specimens the notch should be located such that the crack tip is likely to reside in the target area within the central 75% of the thickness. The macrosection should contain the desired microstructure within central 75% of its thickness in sufficient quantities for the fatigue crack to sample and a successful test. In case of a SN specimen, the notch should be sited such that the crack is no more than 0.5 mm from the target area and the target microstructure is present within the range $0.45 \leq a_o/W \leq 0.7$, where a_o is the notch depth.

(*b*) Notch placement procedure: The specification provides guidance for notch placement in HAZ for TT (crack plane orientation NP) and SN (crack plane orientation NQ) specimens. The specimens are recommended to be notched along an approximate position that is likely to increase the sampling probability the desired target area. The procedure for a through thickness notch is illustrated as follows. Reference lines are scribed along the target area on both thickness faces of the specimen, normal to the specimen axis as shown in Figure A-30. Each of these lines are extended to the opposite side such as to form planes normal to the specimen axes. A plane equidistant to these planes, delineates the intended plane of notch to be machined. A similar procedure is recommended by the standard for a surface notched specimen.

(*c*) Specimen Preparation: The specification provides specimen and notch dimensions, tolerances for specimen distortion and guidance for specimen straightening. The specification cites *ISO 12135* for notch machining, side grooving, and fatigue precracking. The specification recommends Stepwise High R-ratio for fatigue precracking. The fatigue precracking force F_f and the maximum stress intensity factor K_f in case of HAZ are to be based on the tensile properties of the adjacent material with lowest tensile properties.

(*d*) Residual stress modification: The specification provides guidelines to relieve residual stresses by local pre compression of the free surfaces around the notch tip before fatigue precracking to prevent uneven fatigue crack front in as-welded and partially stress relieved specimens.

The standard refers to ISO 12135 for test apparatus andrequirements and procedures for K_{Ic}, CTOD, and J testing.

Post-test Analysis

The specification recommends post-test verification of requirements by detailed metallographic examination: (*a*) to verify the acceptability of final crack tip location, and the microstructure sampled by the fracture; and (*b*) to assess the significance of a pop-in, if identified in the force-displacement plot of the test.

The specification requires verification of the significance of pop-ins by fractographic and metallographic procedures. The specimen is required to be sectioned along the plane of fatigue crack and examined for the presence of brittle crack extension, Da_{pop} at the point of fracture initiation. With evidence of an arrested brittle crack along fatigue crack plane, the specimen is to be further evaluated metallographifcally by sectioning along a plane through the fracture initiation point normal to the crack plane (see Figure A-31). These sections are then analyzed as for a TT specimen, where d_1 is the length of target microstructure sampled by the fatigue crack in the region of fracture initiation and d_2 is the maximum length of similar microstructure in central 75% of B. If d_2 is greater than d_1 in a TT specimen or d_1 greater than Da_{pop} in a SN specimen, then pop-in is considered significant. Also the percentage drop in force at constant displacement must be greater than 5% in both TT and SN specimens for the pop-in to be significant.

The specification recommends considering higher of parent and weld metal strengths for the HAZ.

For the fracture toughness test result of a TT specimen to qualify, the fatigue crack front should sample both designated target area and, where specified, designated lengths (λ_i) of the specific microstructure within the central 75% of the specimen thickness. A schematic showing the macrosection of the crack plane with the designated lengths of microstructure mapped are presented in Figure A-32.

The percentage of specified microstructure sampled over middle 75% thickness is calculated as: $\frac{\sum_{\lambda_1}^{\lambda_n} \lambda}{0.75B} \times 100$. This percentage should meet the requirements of respective specifications

For a surface notched specimen the distance between fatigue crack tip and the target microstructure S_1 and the distance between fatigue crack plane and the target microstructure S_2 (see Figure A-33) should be less than 0.02 in. (0.5 mm).

Fracture toughness evaluation from test results: Interpretation of test results and estimation of K_{Ic}, δ, and J are to be performed according to *ISO 12135*.

Provision for Shallow Notched Specimen Testing:

Specifications allows testing of for shallow notched bend specimen for CTOD and J. Shallow notched specimen testing is convenient in case of testing a specific microstructure close to surface or when the specimens are required to represent a low constraint case such as a shallow surface crack. In this case the specification allows a crack length of $a_o = 0.1W$ to $0.45W$ in the specimen. The specimen configuration is similar to that of a deep notched specimen. Local compression is recommended before fatigue precracking the specimen, as it gets difficult to achieve the specified crack front straightness requirements of the fatigue precrack as a_o/W approaches 0.1. Unlike deep notched specimens, procedures for determination of δ and J in shallow notched specimens are provided in Appendix E of the specification.

DNV OS-C401: Fabrication and Testing of Offshore Structures

The standard consists of requirements for fabrication and testing of offshore structures involving units and installations specified in *DNV-OSS-101* and *DNV-OSS-10*. The standard includes welding procedure qualification tests for C-Mn steel and low alloy steels that are specified in *DNV-OS-B101: Metallic materials.*

Charpy V-notch impact tests

The standard provides Charpy impact test requirements and guidelines for high, normal, extra high strength steels and improved weldability steels that are used in the offshore structures. It is recommended that normal and high strength steel grades shall be impact tested in the longitudinal direction, the butt weld of the test assembly is perpendicular to the rolling direction of the two plates. Whereas extra high strength steel grades shall be impact tested in transverse direction. V notch shall be perpendicular to material surface in both the cases. It is recommended to have plate size that can simulate the heat transfer during production welding.

For the impact tests, three samples should be taken at teach of the following locations in HAZ, 0.08 in. (2 mm) below the plate surface: (*a*) FL; (*b*) FL+0.08 in. (2 mm); and (*c*) FL+0.2 in. (5 mm) as shown in Figure A-34. If thickness of the plate is greater than equal to 2.0 in. (50 mm), two additional sets of tests are to be conducted for at the root area of FL and WM.

Test temperatures and average energy absorption requirements for FL and HAZ for extra high strength steels is same as that of base material in transverse direction. For normal and high strength steels, 70% of the base metal requirements in longitudinal direction.

Acceptability of impact test results

At each of the notch locations the average impact requirements shall be satisfied. However, one of the values of the three specimen at a notch location is allowed to be less than that of the average but not less than 70% of the required average. Where the above requirements are not met, an additional set of three impact test specimens may be taken. The results obtained shall be combined with the original results, and the new average formed shall not be less than the required value. Additionally, not more than two individual values of the combined set, shall be less than the required average value, and of these, not more than one shall be less than 70% of the average required value.

Fracture Mechanics Testing (CTOD)

When the units described in *DNV-OS-C101* or *DNV-OS-C201* are intended to operate continuously for five years in the same location, their welding procedure qualification tests for joints should include fracture mechanics testing under any of the following conditions: (a) design temperature is lower than 50°F (10°C); (*b*) joint is in a special area; or (*c*) at least one of the adjoining members is fabricated from steel with a specified minimum yield strength (SMYS) greater than equal to 61 ksi (420 MPa). The Fracture mechanics test in HAZ is be conducted according to *BS7448 part 2*. Through thickness tests shall be carried out on K or single V-penetration butt welds.

If nominal thickness of the plates is less than 3.1 in. (80 mm), $B\times 2B$ specimen is to be used. Otherwise $B\times B$ specimen is to be used. It mandatory that the joints submerged under water should be tested at temperatures lower than 0°F (–18°C) where as other joints cab be tested at their respective service temperatures. Three specimens along the heat affected zone of one of the vertical legs of the weld shall be tested as shown in Figure A-35.

Post-test sectioning of HAZ-CTOD specimens

Metallographic section shall be prepared according to *BS7448 part 2*, section 11.2. The exact location of the fatigue pre-crack shall be obtained by sectioning on both sides of the pre-crack. The faces of the metallographic sections shall not be taken deeper than the deepest point of the fatigue pre-crack and not more than 0.12 in. (3 mm) from the deepest point of the fatigue pre-crack. The lengths of the areas with fatigue pre-crack distance from fusion line (d_f) less than equal to 0.02 in. (0.5 mm) shall be identified within the central 75% of the plate thickness and measured as λ_i, as shown in Figure A-36. The following criteria should be satisfied for the results from the test to be valid for given plate thickness (t):

$$\sum_N \lambda_i \geq 3 \text{ mm for } t \leq 20 \text{ mm}$$

$$\geq 0.15t \text{ for } 20 < t < 80 \text{ mm}$$

$$\geq 12 \text{ mm for } t > 80 \text{ mm}$$

where N is number of areas with d_f less than 0.02 in. (0.5 mm). None of the specimens shall have a critical CTOD less than 0.006 in. (0.15 mm), otherwise additional tests may be carried out. In such a case, the characteristic value of CTOD for that location, considering results of all the valid CTODs is according to Table A-17. If the characteristic value as obtained according to is larger than 0.006 in. (0.15 mm) an ECA (Engineering critical assessment) may be carried out.

Hardness tests

Minimum three indentations shall be made in HAZ of single sided welds, at 0.04 in. (1 mm) below the surface of the plate starting close to the fusion line. Additional row of indentations shall be made at the weld root for double sided welds as shown in the Figure A-37. The hardness tests shall be conducted according to *ISO 6507-1* or equivalent using Vickers method (VH10). HAZ hardness values shall be less than equal to 350 HV10 for steel with yield strength less than 60 ksi (414 MPa) and less than equal to 420 HV10 for steel with yield strength greater than 60 ksi (414 MPa).

Offshore Standard DNV-OS-F101: Submarine Pipeline Systems, 2012

This offshore standard provides criteria and recommendations on concept development, design, construction, operation and abandonment of submarine pipeline systems that are used in petroleum and natural gas industries. The specification covers C-Mn steel linepipe generally conforming to *ISO 3183* Annex J, with modifications and amendments. Material grade is limited to X80 (including). Other applications covered are: Corrosion Resistant Alloy (CRA) linepipe with specific requirements to 22Cr and 25Cr steel and 13 Cr martensitic steel and clad and lined linepipe. Supplementary requirements are provided for sour service, fractures arrest properties, plastic deformation, dimensional tolerances and high utilization.

Section 7 of the specification provides requirements for construction of linepipes made of C-Mn steel, clad or lined steel, corrosion resistant alloys (CRA) including ferritic-austenitic (duplex) stainless steels, austenitic stainless steels, martensitic stainless steels (13Cr), other stainless steels and nickel based alloys.

C-Mn linepipes are permitted to be manufactured as seamless, High Frequency Welded (HFW) and Submerged Arc Welded (SAW). The SAW is used for pipes manufactured by forming from strip or plate and with one longitudinal (SAWL) or helical (SAWH) seam, with at least one pass made on the inside and one pass from the outside of the pipe. C-Mn steel pipeline fabricated according to this standard generally conform to *ISO 3183* Annex J: PSL

DNV-RP-F108: Fracture Control for Pipeline Installation Method Introducing Cyclic Plastic Strain

This recommended practice provides guidance for fracture resistance testing and tolerable flaw size analysis for both pipe and girth welds using Single Edge Notched Tension (SENT) specimens. The above methods or procedures were developed based on experience from practice, tests and finite element analysis. These recommended practices are applicable to materials with properties close to linepipe steels of type *API 5L* X52 to X65 [0.6 in. (15 mm) to 1.0 in. (25 mm) wall thickness and yield strength of 52 ksi (359 MPa) to 65 ksi (448 MPa)] welded by well proven welding methods giving ductile weldments.

During installation, the girth welds in pipelines are predominantly subjected to tensile stresses even if the pipe is subjected to global bending. Moreover, typical flaw sizes of interest are 0.08 in. (2 mm) to 0.24 in. (6 mm), which represent low constraint. Estimation of fracture resistance in such cases using deep notched SENB or CT specimens yields conservative results because of higher constraints at the notch tip.

The SENT specimen is normally designed with a surface notch (SN). Compared to traditional deep single edge notched tension specimens, a SENT specimen with shallow surface notch more accurately represents both the tensile loading mode and a lower crack tip constraint. The SENT testing is to be performed according to general fracture toughness testing standards such as *BS7448-1* or *ASTM E1820*. Fracture resistance of the SENT specimen is characterized by *J-R* (or CTOD-*R*) curves. The recommendations are applicable only when a maximum load plateau or a stable crack extension of at least 0.06 in. (1.5 mm) occurs before initiation of brittle fracture.

For testing HAZ fracture toughness the surface notch crack plane should intersect the fusion line extending from the weld metal on the cap side into the HAZ (see Figure A-38).

The recommended width for SENT specimen, $B = 2W$, where W is the pipe wall thickness (t) after machining to prepare the specimen. The width of the specimen may be reduced, if $W < 0.85t$, however, $B \geq W$. The precracked notch depth allowed for SENT clamped specimen is $0.2 \leq a/W \leq 0.5$.

The SENT tests shall be conducted for as welded condition at lowest and highest anticipated temperatures (to check for the lowered tearing resistance at higher temperatures). The SENT specimen can either be clamped or pin loaded except that the clamped specimen experiences higher constraint to bending. For the clamped specimens, the length between clamps or "day-light", (H) should be at least $10W$ (See Figure A-39). *J-R* (or CTOD–*R*) curves are to be established using at least six valid test results. These test results should correspond to specimen loaded to tearing lengths between 0.008 in. (0.2 mm) to 0.12 in. (3 mm) (including crack blunting), with a majority of these values should falling in between 0.02 in. (0.5 mm) to 0.06 in. (1.5 mm). The recommended practice includes formulae for calculation of J for SENT specimens.

Table A-1 Chemical requirements of BS4360 Grade 50E and ASTM A709 Grade 50 steels

Elements	C, %	S, %	P, %	Si, %	Mn, %	Ni, %	Cr, %	Mo, %	V, %	Cu, %	Nb, %	Al, %	N, %
BS4360 Grade 50E	0.16, max	0.012, max	0.025, max	0.1-0.45	1.1-1.15	0.2, max	0.2, max	0.08, max	0.02, max	0.2, max	0.04, max	0.05, max	0.01, max
ASTM A709 Grade 50	0.23, max	0.05, max	0.04, max	0.15 - 0.4	1.35, max	–	–	–	0.15, max	–	–	–	–
ASTM A709 Grade 50W Type A	0.19, max	0.05, max	0.04, max	0.3 – 0.65	0.8 – 1.25	0.4, max	0.4 – 0.65		0.02 – 0.1	0.25 – 0.4			
ASTM A709 Grade 50W Type B	0.20, max	0.05, max	0.04, max	0.15 – 0.5	0.75 – 1.35	0.5, max	0.4 – 0.7		0.01 – 0.1	0.2 – 0.4			

Table A-2 CVN Test Results at –40°C[1]

CGHAZ Refinement, %	Heat Treatment	Through Depth Notch Location	Absorbed Energy, J[2] FL	FL+2mm[3]	FL+5mm
30	AW	Surface	28	84	152
			132	165	110
			136	223	44
		Average	**99**	**157**	**102**
		Mid-thickness	63	258	150
			105	260	112
			192	270	77
		Average	**120**	**263**	**113**
	PWHT	Surface	132	239	134
			178	228	135
			163	132	164
		Average	**158**	**200**	**144**
		Mid-thickness	62	127	35
			111	125	80
			152	152	64
		Average	**108**	**135**	**60**
10	AW	Quarter-thickness	42	288	210
			192	187	168
			198	220	168
		Average	**144**	**232**	**182**
	PWHT	Quarter-thickness	177	199	159
			229	218	156
			152	216	142
		Average	**186**	**211**	**152**

Notes:
1. –40°C = –40°F
2. 1 in. = 25.4 mm
3. 1 J = 0.74 ft-lb

Table A-3 CVN Test Matrix

CGHAZ Refinement, %	Heat Treatment	Through Depth Notch Location	Notch Positions	Test Temperature,°C[1]	Number of Repeats
10	AW, PWHT	Quarter-thickness	FL, FL+2mm[2], FL+5mm	–20, –40, –60	3
30	AW, PWHT	Surface, Mid-thickness	FL, FL+2mm, FL+5mm	–20, –40, –60	3

Notes:
1. –20°C = –4°F, –40°C = –40°F, –60°C = –76°F
2. 1 in. = 25.4 mm

Table A-4 CTOD Testing Matrix and Results

CGHAZ Refinement, %	Heat Treatment	Test Temperature, °C[1]	Notch Orientation	Number of Repeats	Lowest CTOD, mm[2]	Number of Samples (CTOD < 0.1mm)
10	AW	–30	SN	10	0.008	1
			TT	10	0.120	0
		–10	SN	22	0.029	4
			TT	20	0.029	2
		10	SN	10	0.830	0
			TT	10	0.580	0
30	AW	–30	SN	10	0.025	3
			TT	10	0.024	6
		–10	SN	10	0.021	4
			TT	20	0.014	8
		10	SN	10	0.025	3
			TT	10	0.030	5
30	PWHT	–30	SN		Not Tested	
			TT	10	0.036	3
		–10	SN	12	0.015	3
			TT	24	0.021	2
		10	SN		Not Tested	
			TT	10	0.093	1

Note:
1. –30°C = –22°F, –10°C = 14°F, 10°C = 50°F
2. 1 in. = 25.4 mm

Table A-5 Wide Plate Test Matrix and Results

Joint Preparation	Heat Treatment	CGHAZ Refinement, %	Wide Plate ID	Crack Dimensions, mm[1]	Measured CTOD: Fractured: Final Overall Strain >0.5%	Measured CTOD: Fractured: Final Overall Strain <0.5%	Measured CTOD: Not Fractured	Final Overall Strain, %	CGHAZ Original Crack Tip Intercepted by Fractured in Wide Plate Tests
Half K-Joint	AW	30	1	16.5×147.3			4.400	3.150	
			2	14.7×148.0		0.220		0.365	2 regions, 39 and 30 mm in CGHAZ > 100 μm, 47.9% of total defect length 22 mm in weld metal adjacent to CGHAZ
			3	15.0×150.0	1.540			2.000	No fatigue crack in CGHAZ 130 mm (90%) of crack in weld metal adjacent to 100 μm HAZ
			4	16.5×142.0			2.000	2.980	
			5	13.1×124.0			2.800	3.030	
			6	14.9×136.0			2.950	3.760	
		10	7	14.×145.6			3.100	5.760	
			8	16.5×149.1	1.780			0.800	40 mm in > 100 μm HAZ, 27% of total crack length 40 mm in 50-100 μm HAZ
			9	10.1×125.3		0.064		0.190	80 mm in > 100 μm HAZ, ~60% of total crack length 25 mm in 50-100 μm
			10	11.4×125.0			0.800	1.090	
			11	19.3×150.0			3.560	3.330	
			12	11.3×150.0			2.410	3.070	

Table A-5 *Continued*

Joint Preparation	Heat Treatment	CGHAZ Refinement, %	Wide Plate ID	Crack Dimensions, mm	Measured CTOD: Fractured: Final Overall Strain >0.5%	Measured CTOD: Fractured: Final Overall Strain <0.5%	Measured CTOD: Not Fractured	Final Overall Strain, %	CGHAZ Intercepted by Original Crack Tip in Fractured Wide Plate Tests
Half K-Joint	PWHT	30	13	17.9×170.7	1.880			0.530	40 mm in 100 μm HAZ, 23% of total crack length 25 mm in 50-100 μm
			14	15.5×148.3	1.870			0.780	30 mm in 50-100 μm HAZ, 20% of total crack length 75 mm of crack in weld metal - not adjacent to CGHAZ
			15	17.2×146.4		1.870		0.430	~117 mm in weld metal adjacent to CGHAZ, ~80 mm, 80% of total crack length
			16	17.4×148.0	3.500			2.130	All fatigue crack > 1. mm HAZ0 mm from fusion line in 10-20
			17	21.7×148.0		0.960		0.300	78 mm in > 100 μm HAZ, 46% of total length 22 mm in 50-100 μm HAZ
Single V-Joint[2]	AW	—	18	NA			4.000	NA	
			19	NA	0.490[3]			NA	145 mm of fatigue crack in weld metal, 0.1/0.2 mm from fusion line, adjacent to > 100 μm CGHAZ
			20	NA			4.000	NA	

Notes:
1. 1 in. = 25.4 mm
2. No particular effect was done to develop CGHAZ
3. Final overall strain was not provided

Table A-6 CVN Test Matrix (Wood et. al., 1987)

Purpose of Impact Tests	Steel Grades	Plate Thickness, t, in. (mm)	Test Temperatures	Number of Samples at Each Temperature	Notch Location	Weld Designation[1]
Transition curves for optimized elcetroslag welds (8 tests each)	A36, A588	2.0 (51), 3.0 (76)	−100°F (−73°C) to 150°F (65°F)	2 or more @ each temperature in the transition curve, 6 @ 0°F	CGHAZ (@ 1/2 t[3])	SG, 25P , NG,25P , NG,ST

Notes:
1. NG, ST2 is also employed for A588
2. Full size CVN Specimen are employed in all CVN tests
3. Plate thickness

Table A-7 Average CVN Values in CGHAZ for Different Welding Conditions

Steel Grade	Plate Thickness, in. (mm)	Welding[1] Procedure	CVN Values in CGHAZ @ -0°F (18°C), ft-lb	CVN Values in CGHAZ @ 39°F (4°C), ft-lb
A36	2.0 (51)	SG,25P	10	30
		NG,25P	12	34
		NG,ST	12	36
	3.0 (76)	SG,25P	10	16
		NG,25P	12	35
		NG,ST	8	18
		NG,ST2	10	14
A588	2.0 (51)	SG,WS	4	10
		NG,WS	8	13
		NG,ST	15	23
	3.0 (76)	SG,WS	2	3
		NG,WS	2	4
		NG,ST	3	5
		NG,ST2	8	18

Notes:
1. 1.0 ft-lb = 1.35 J
2. Welding procedures are described in the text

Table A-8 Compact tension Fracture Toughness (K_{Ic}) Tests for CGHAZ for Optimized Electroslag weldments

Steel Grades	Plate thickness, in. (mm)	Plate Weld Designation	Number of Samples	Test Temperatures, °F (°C)	Loading Rate[1]	Number of Samples per Loading Rate	Number of Valid K_{Ic} Samples
A36	3.0 (76)	SG, 25P	4	0 (-18)	S	2	2
		NG, 25P	4	0 (-18)	S	2	2
		NG, ST2	4	0 (-18)	S	2	2
		SG, 25P	4	19 (-7)	S	2	1
		NG, 25P	4	19 (-7)	S, I	1	0
		NG, ST2	4	19 (-7)	S, I	1	0
A588	3.0 (76)	SG, WS	4	0 (-18)	S	2	1
		NG, WS	3	0 (-18)	I	1	0
		NG, WS	3	0 (-18)	S	2	1
		NG, ST2	4	0 (-18)	S	2	2
		SG, WS	4	19 (-7)	S, I	2	2
		NG, ST2	4	19 (-7)	S, I	1	1 (I)

Note:
1. Legend:
S= Quasi Static loading Rate
I= Intermediate Loading rate

Table A-9 Chemical Composition of SQV-2A

Element	C	Si	Mn	P	S	Ni	Mo
% by mass	0.19	0.24	1.48	<0.01	<0.01	0.62	0.56

Table A-10 Test Matrix of Amadioha et al. (2011)

Test Type	Specimen Thickness	Specimen Size	Notch Orientation[3]	*a*/*W*	No. of Replicates
SENB[2]	Full thickness	$B \times B$ ($W = B$)	TT	0.5	10
SENB	Full thickness	$B \times 2B$ ($W = 2B$)	TT	0.5	6
SENB	Full thickness	$B \times B$ ($W = B$)	TT	0.2	12
SENB	Sub-size	$B \times B$ ($W = B$)	TT	0.2	10
SENT	Sub-size	$B \times B$ ($W = B$)	TT	0.5	6
SENT	Sub-size	$B \times B$ ($W = B$)	TT	0.2	3
SENT	Sub-size	$B \times B$ ($W = B$)	SN	0.2	6
SNT	Sub-size	$B \times 5B$ ($W = 5B$)	SN	0.2	3

Note:

1. Legend:
   - B = Thickness of the specimen
   - W = Width of the specimen
   - t_T = Through thickness notch
   - SN = Surface notch
   - a = Notch depth
   - Sub-size = 0.79 in. (20 mm)
   - Full thickness =1.2 in. (30 mm)

Table A-11 ABS CVN Impact Energy Requirements

		Minimum Impact Energy Requirements, ft-lb (J)	
ABS Steel Grades	Temperatures, °F (°C)	Manual and Semiautomatic Welding Processes	Automatic Welding Processes and Vertical Position
AH36	32 (0)	25 (34)	25 (34)
DH36	32 (0)	35 (47)	25 (34)
EH36	-4 (-20)	35 (47)	25 (34)
FH36	-40 (-40)	35 (47)	25 (34)

Table A-12 Hardness limits for VH10 tests for hull construction and marine steels

Specified minimum yield strength σ_y, ksi (MPa)	Hardness Limit
60 (420) or lower	350 HV10
60 (420) < σ_y < 100 (690)	420 HV10

Table A-13 API RP 2Z CTOD Testing Requirements

Criteria	Welding Conditions to be Tested for		
Heat Input	20 kJ/in. (0.8 kJ/mm)	76 kJ/in. (3.0 kJ/mm)	114 kJ/in. (4.5 kJ/mm)
Preheat and Interpass Temperature Range	≤ 212 °F (100 °C)	212 °F(100 °C) - 482 °F (250 °C)	≥ 482 °F (250 °C)
Minimum Number of Valid CTOD Tests Required for Notch in			
HAZ Region in general	8	5	5
CGHAZ	6	3	3
Etched HAZ Boundary Material (SCHAZ)	2	2	2
Precrack Position: Metallurgical Requirements			
General HAZ Region	Precrack should be able to intersect the etched HAZ for at least 75% of the central $^{2}/_{3}$ specimen thickness		
For CGHAZ specimens	1) at least 15% precrack in the central $^{2}/_{3}$ of the specimen thickness should be in the CGHAZ region		
	2) The 15% must be with in within 0.01 in.(0.3 mm) from fusion line	2) The 15% must be with in within 0.02 in. (0.5 mm) from fusion line	2) The 15% must be with in within 0.02 in. (0.5 mm) from fusion line
	3) Minimum 6 valid specimens	3) Minimum 3 valid specimens	3) Minimum 3 valid specimens
	or Best effort to locate notch in CGHAZ		
For Etched HAZ Boundary Specimens	1) In minimum 2 valid specimens, at least 50% precrack in the central 2/3 of the specimen thickness should be in the etched HAZ boundary region		
	2) The 50% must be with in within 0.01 in.(0.3 mm) from fusion line	—	—
	or Best effort to locate notch in etched HAZ boundary		

Table A-14 Accepted CTOD Values for All Three Weld Conditions in API RP 2Z

Steel Grade	Plate Thickness, in. (mm)	Accepted CTOD
50	≤ 3.0 (76)	≥ 0.01 in. (0.25 mm)
50	> 3.0 (76)	≥ 0.015 in. (0.38 mm)
60	≤ 3.0 (76)	≥ 0.012 in (0.30 mm)
60	> 3.0 (76)	To be agreed
stronger than 60	—	To be agreed

Table A-15 CVN Impact Energy Requirements in API 5L

Steel Grades	Test Temperature, °F (°C)	Minimum Impact Energy Requirements, ft-lb (J)	
		D[1] < 56 in. (1.422mm)	D ≥ 56 in. (1.422mm)
≤ L555 or X80	32 (0) or lower	20 (27)	30 (40)
>L555 or X80	32 (0) or lower	30 (40)	30.(40)

Table A-16 Typical Notch Locations for Testing HAZ with Through Thickness and Surface Notched Specimens in *ISO15653*

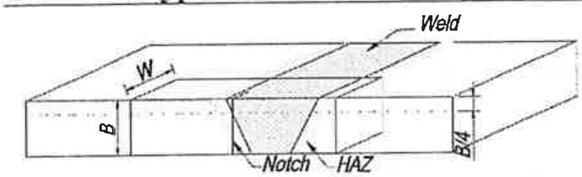
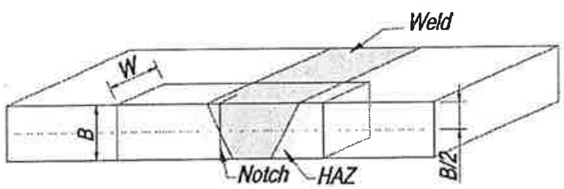
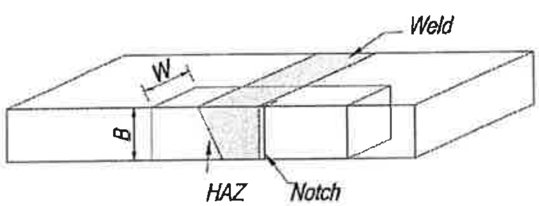
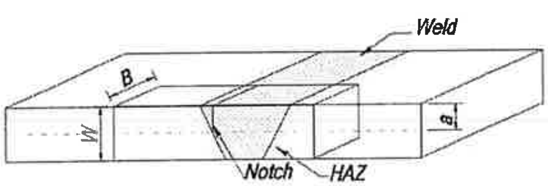
Typical Notch Locations	Notch Location	Specimen Size	Crack Plane Orientation
	HAZ with notch intersecting fusion line at quarter thickness	$B \times B$ ($W=B$)	NP
	HAZ with notch intersecting fusion line at mid thickness	$B \times B$ ($W=B$)	NP
	Crack front to sample a specific region within HAZ	$B \times B$ ($W=B$) or $B \times 2B$ ($W=2B$)	NP
	CGHAZ adjacent to columnar weld metal	$B \times B$ ($W=B$) or $B \times 2B$ ($W=2B$)	NQ

Table A-17 Characteristic value of CTOD

Number of valid tests	Characteristic value
3 to 5	Lowest value
6 to 10	Second lowest value
11 to 15	Third lowest value

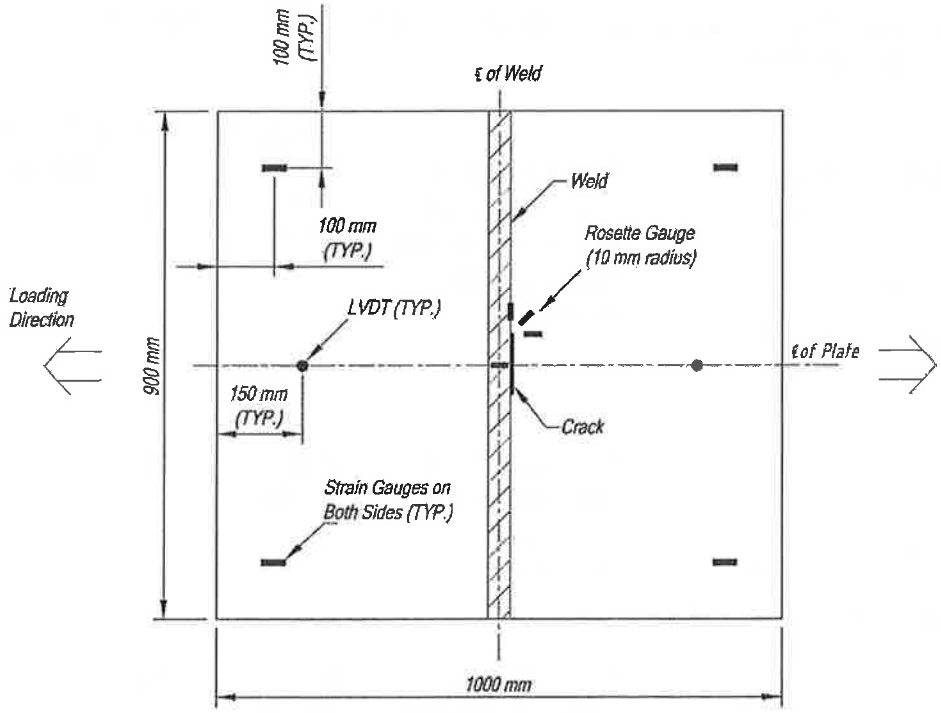
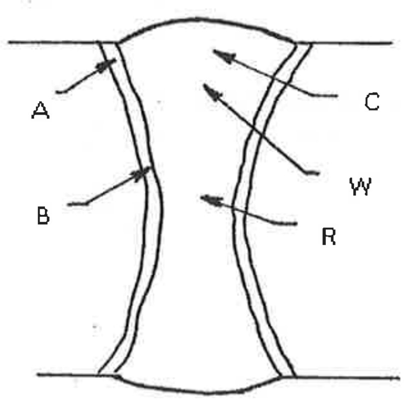


Figure A-1 Wide plate test instrumentation plan



A= Last-Pass HAZ
B= HAZ Tempered form Subsequent Weld Passes
C= Last-Pass Weld Metal
W= AASHTO Weld-Metal CVN Location
R= Weld Root

Figure A-2 Regions to be tested in Weldments

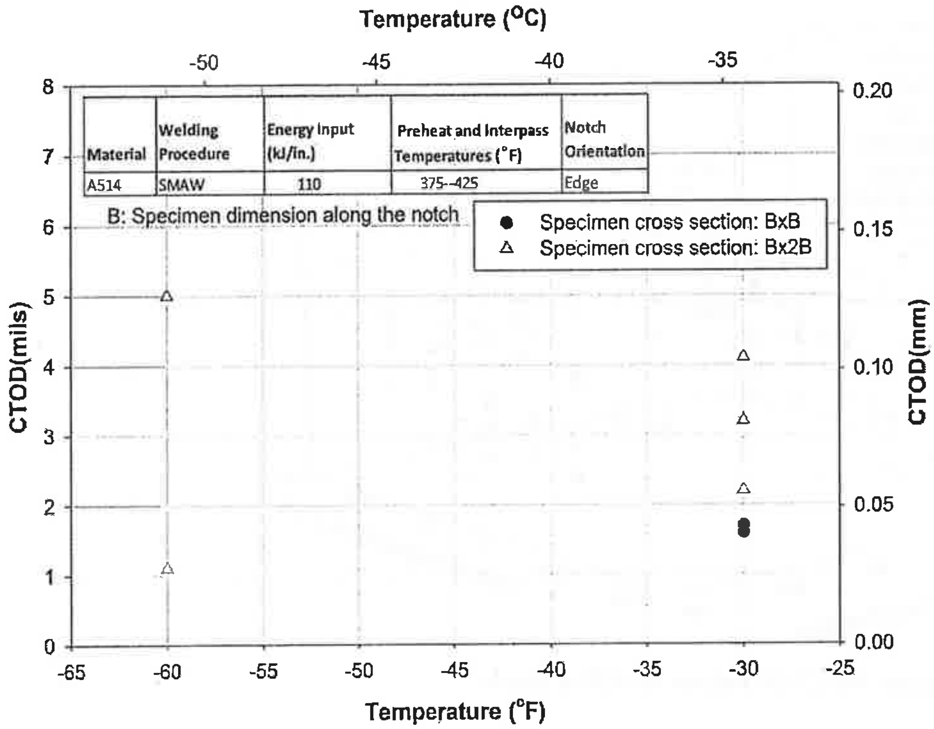


Figure A-3 CTOD values for BXB and BX2B geometries for edge notched specimens

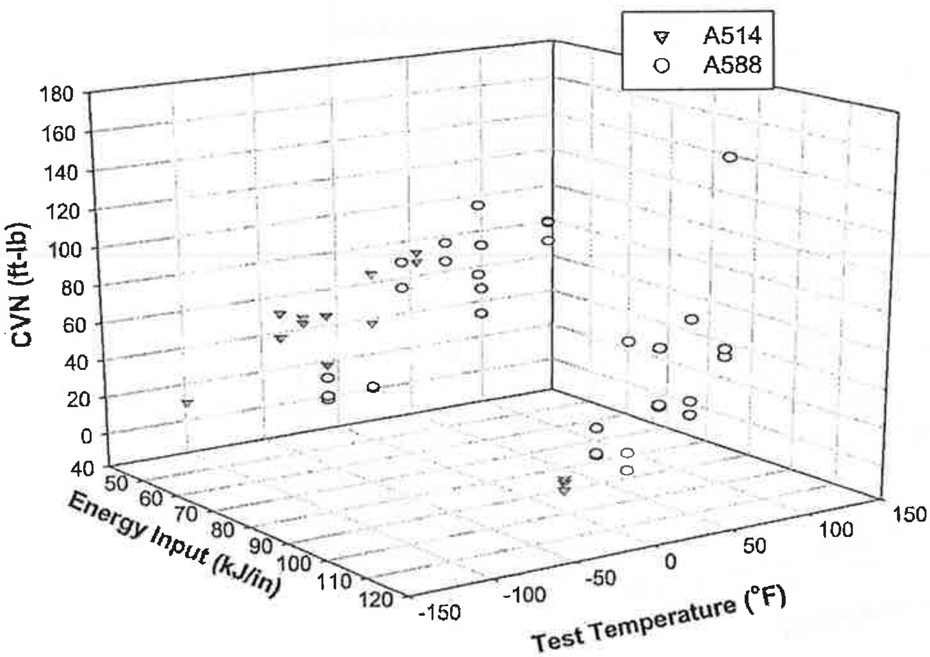


Figure A-4 Surface notched last pass HAZ (region A) CVN values for different energy inputs for A514 and A588 steels

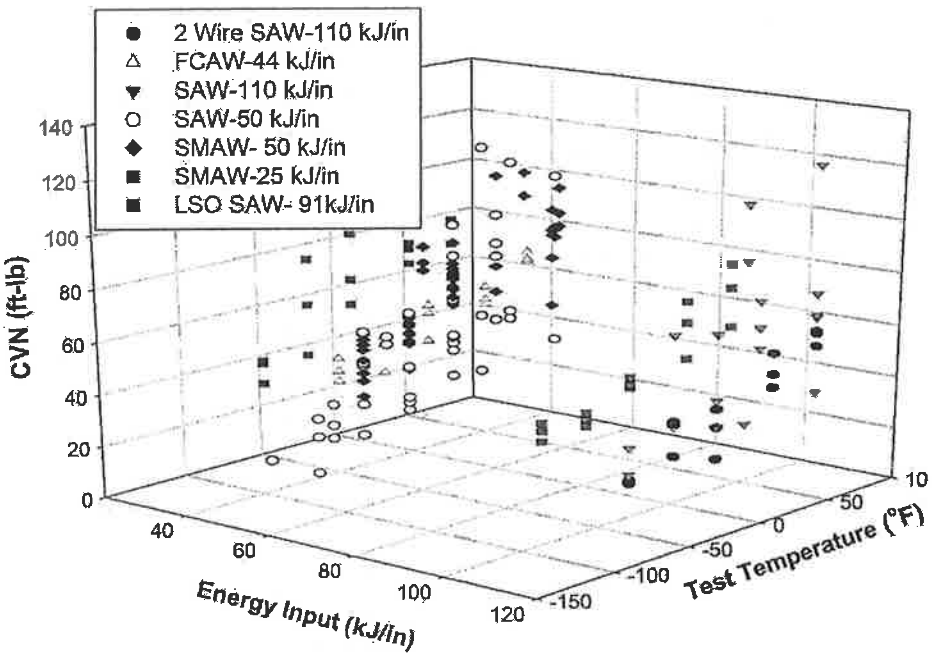


Figure A-5 HAZ (regions B) CVN values of A514 steels

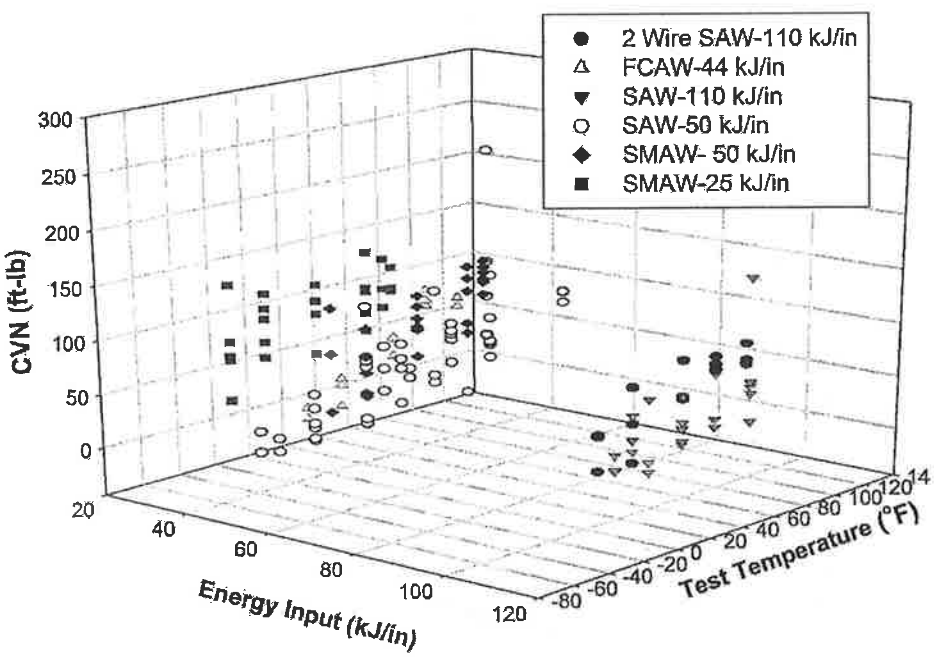


Figure A-6 HAZ (regions B, A) CVN values of A588 steels

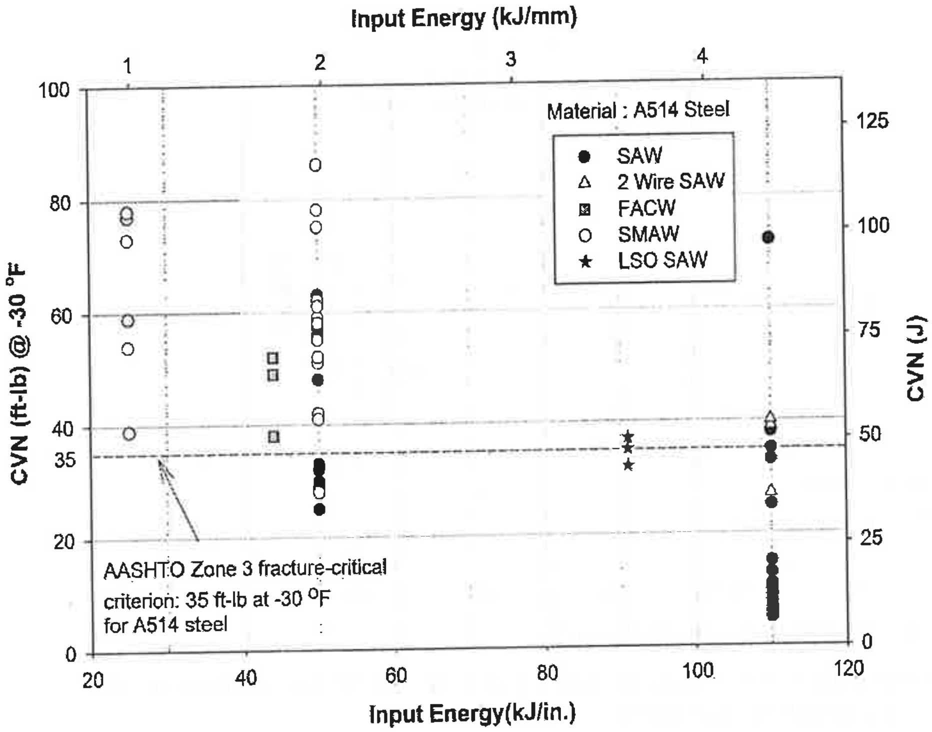


Figure A-7 HAZ (region B) CVN values of A514 steel for different welding procedures at -30 °F

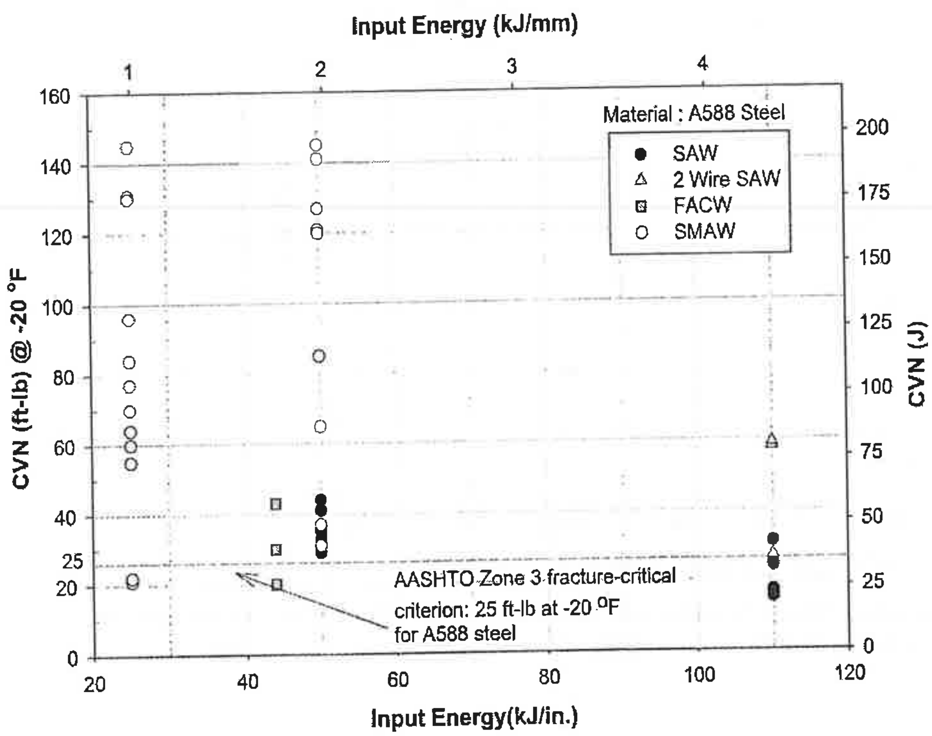


Figure A-8 HAZ (region B) CVN values of A588 steel for different welding procedures at -20 °F

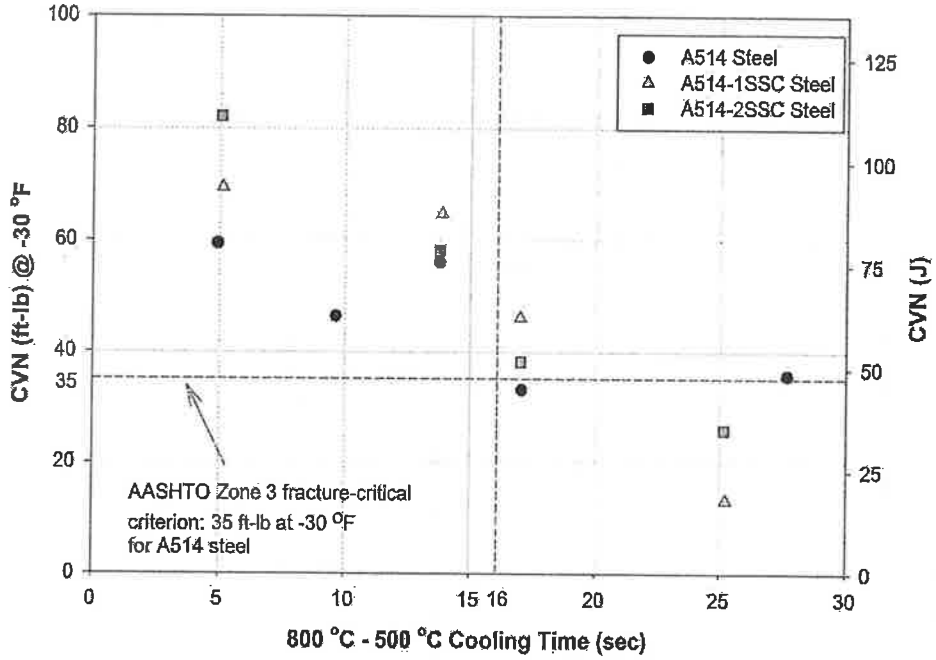


Figure A-9 HAZ (region B) CVN values of A514 steels @ -30 °F for weldments of different cooling times from 800 °C to 500 °C

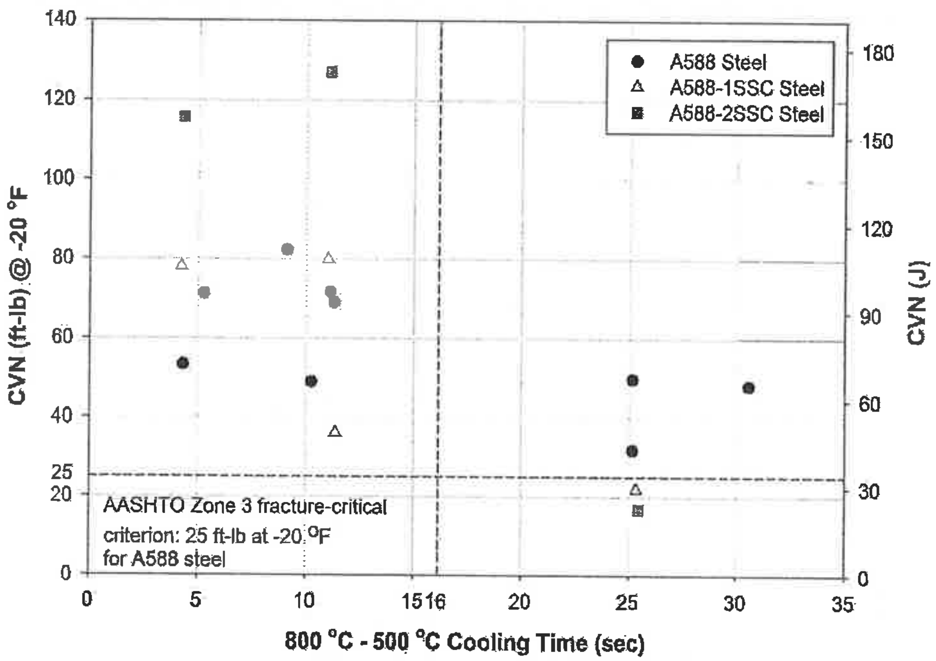


Figure A-10 HAZ (region B) CVN values of A588 steels @ -20 °F for weldments of different cooling times from 800 800 °C to 500 °C

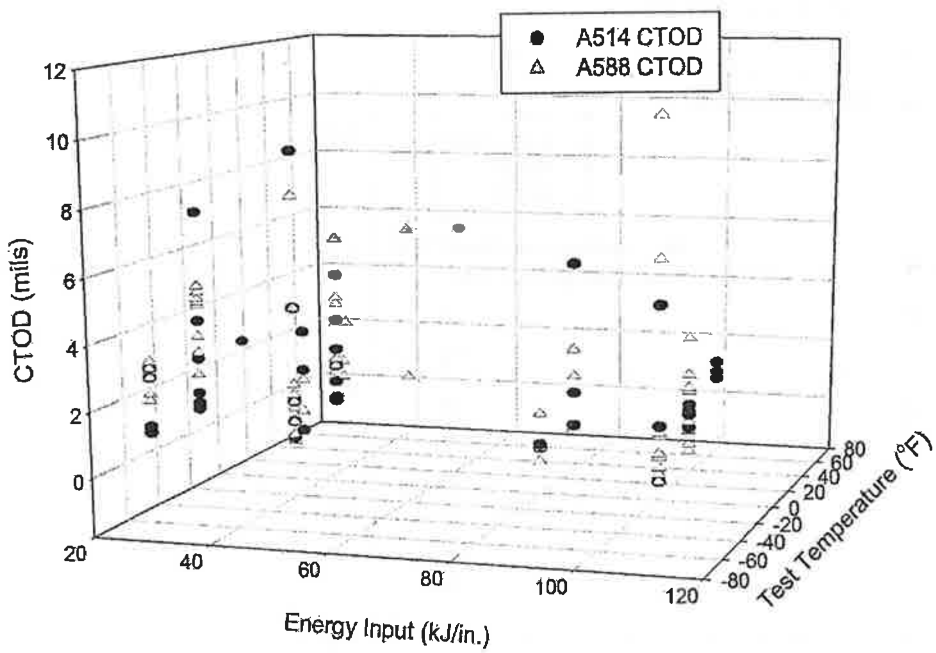


Figure A-11 Valid CTOD values at HAZ (region R) of A514 and A588 steels

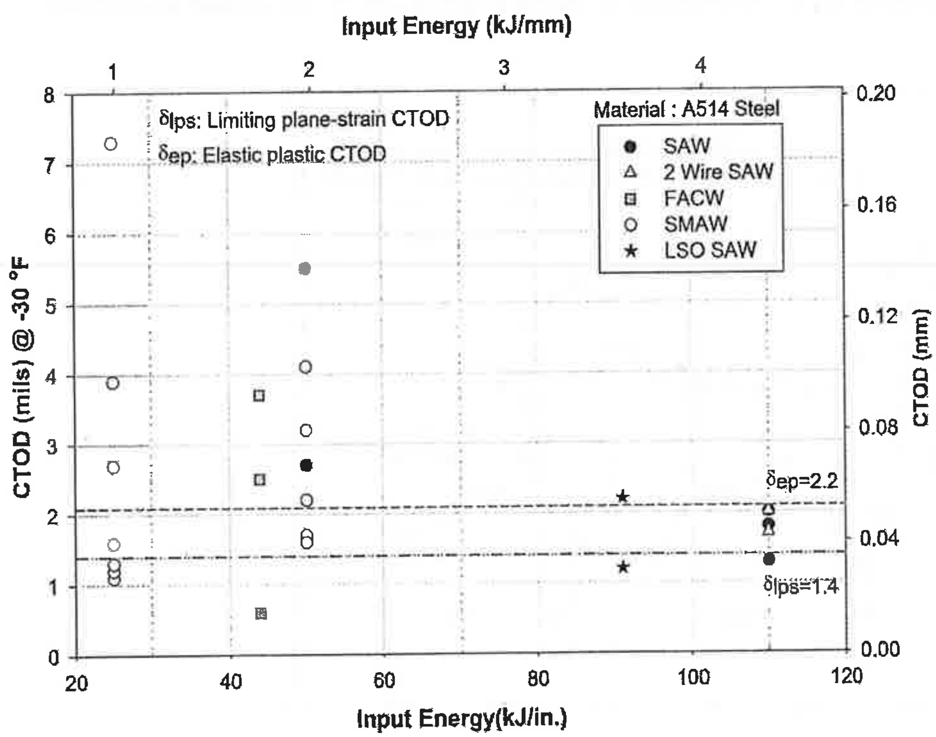


Figure A-12 HAZ (region B) CTOD values of A514 steel @ -30 °F for different welding procedures

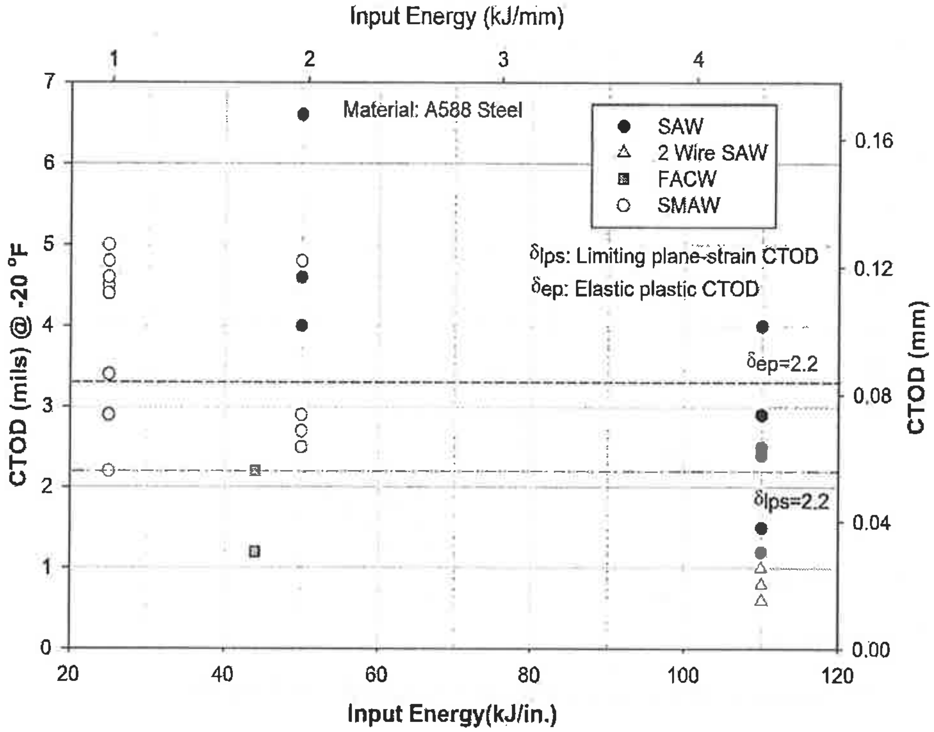


Figure A-13 HAZ (region B) CTOD values of A588 steel @ -20 °F for different welding procedures

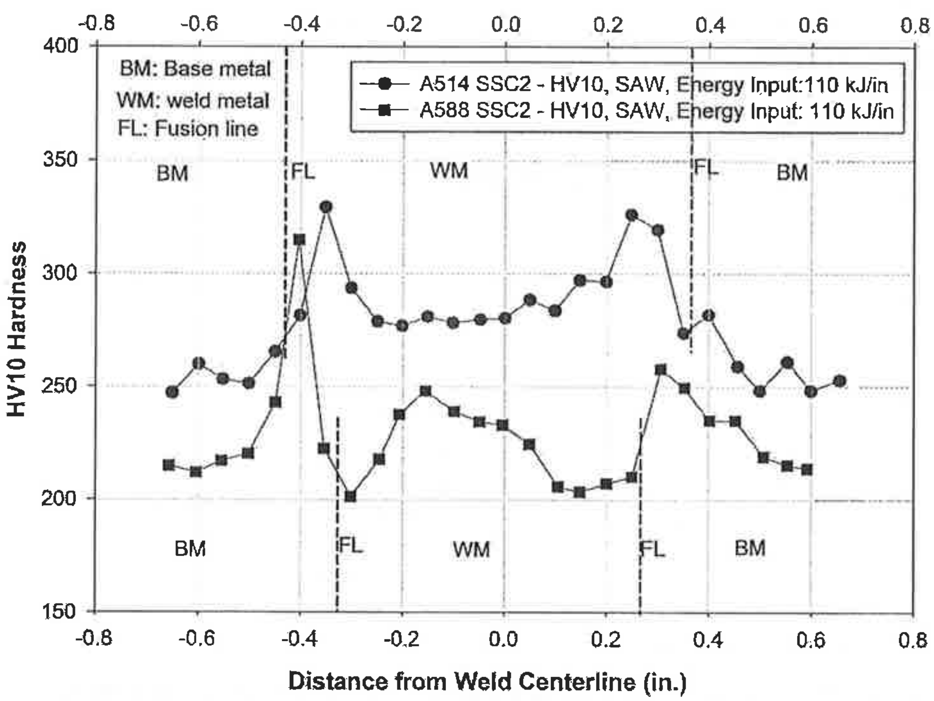


Figure A-14 HV 10 Hardness profile across weldment on a through thickness plane

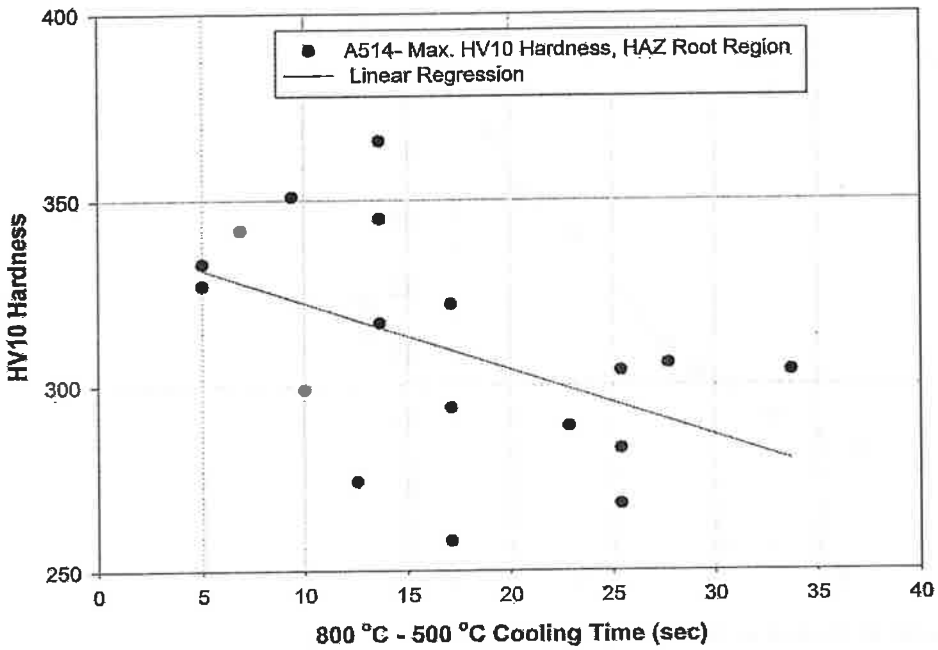


Figure A-15 **Maximum HV10 Hardness on at weld root HAZ (region R) Vs cooling time for A514 steel**

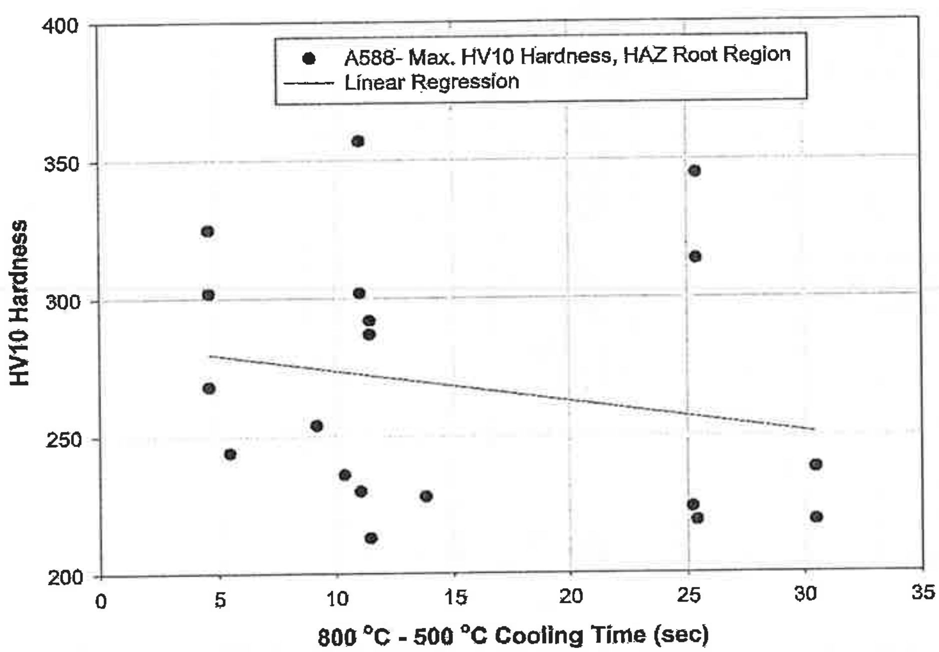


Figure A-16 **Maximum HV10 Hardness on at weld root HAZ (region R) Vs cooling time for A588 steel**

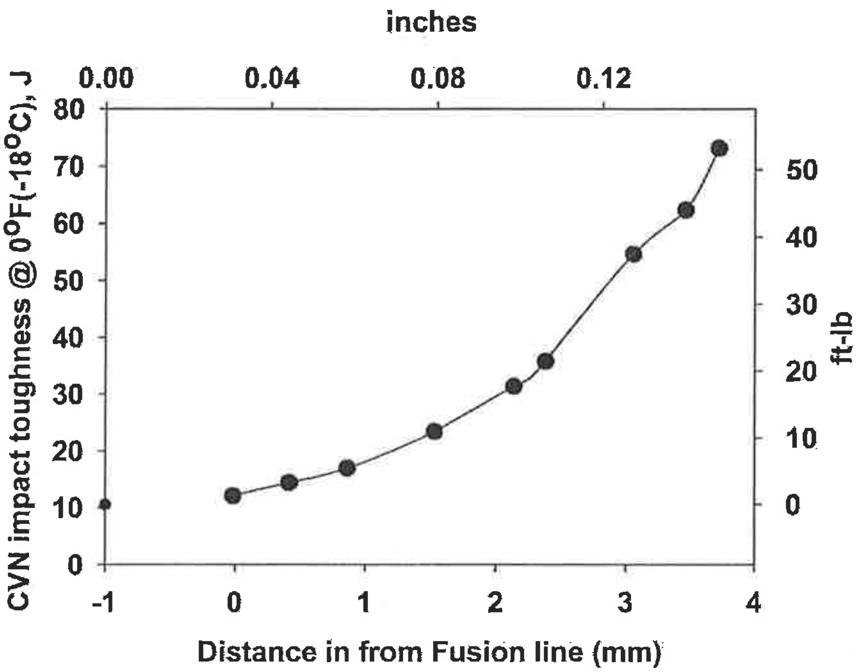


Figure A-17 CVN toughness as a function of distance from the fusion line (Wood et al, 1987)

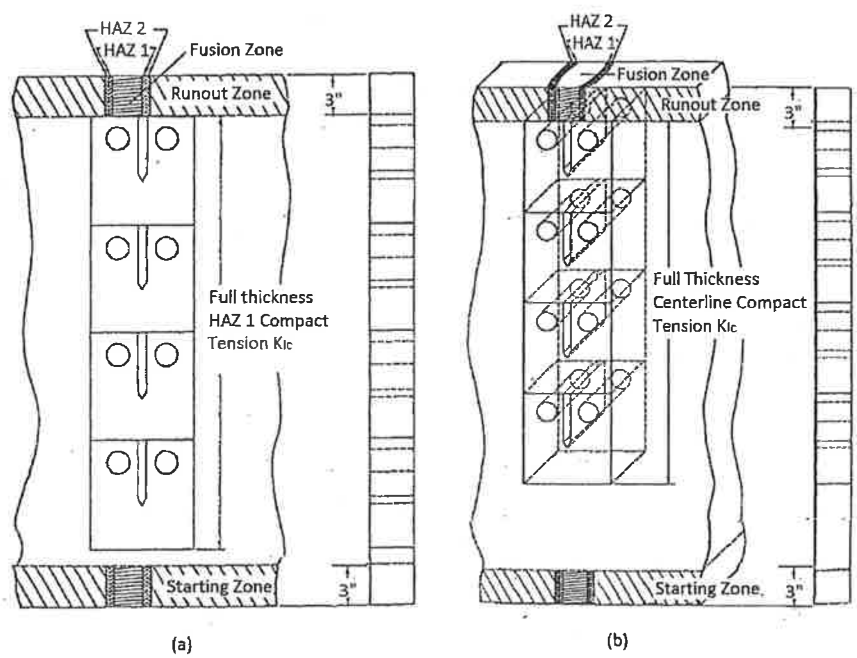


Figure A-18 Location K_{Ic} specimens: (*a*) with respect to HAZ; and (*b*) With respect to weld location (Wood et al, 1987)

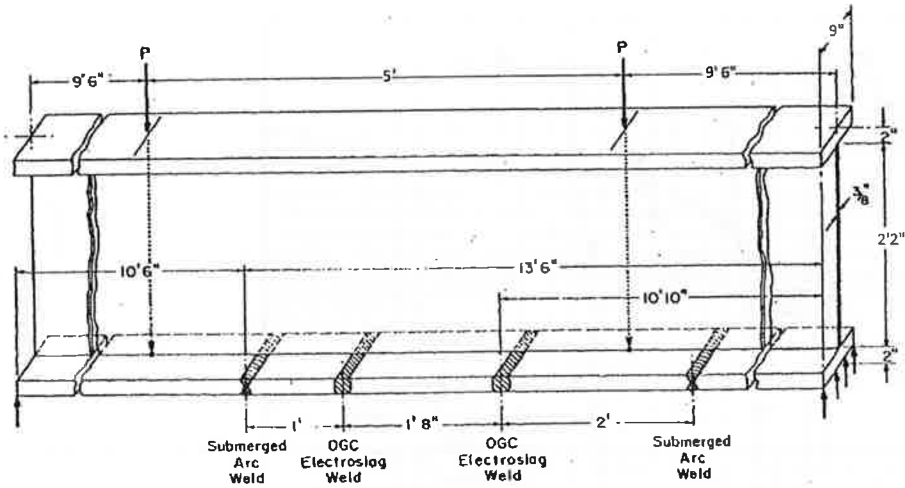


Figure A-19 Schematic illustration of the full-scale I-beam containing electroslag weldments for fatigue testing (Wood et al, 1987)

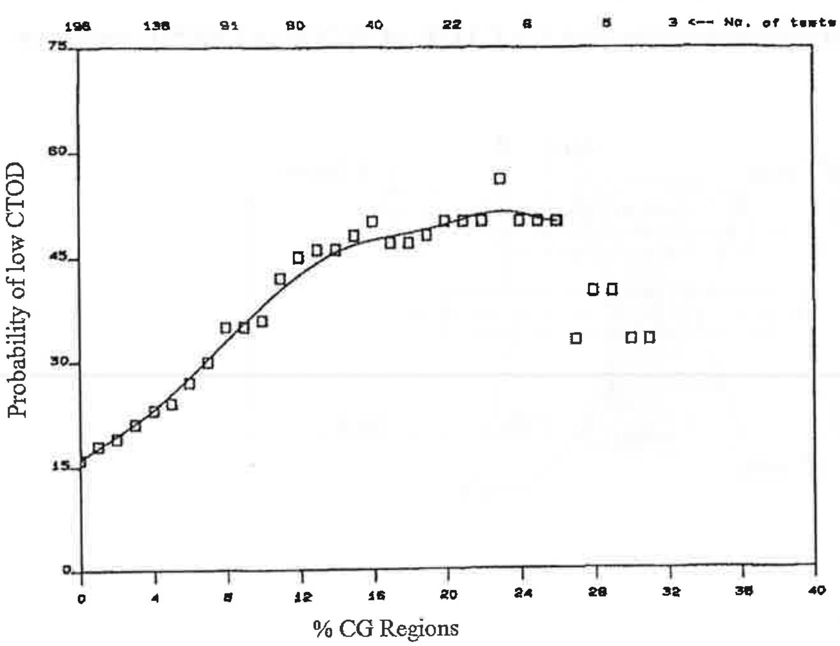


Figure A-20 Probability of low CTOD versus different ranges of % CG regions

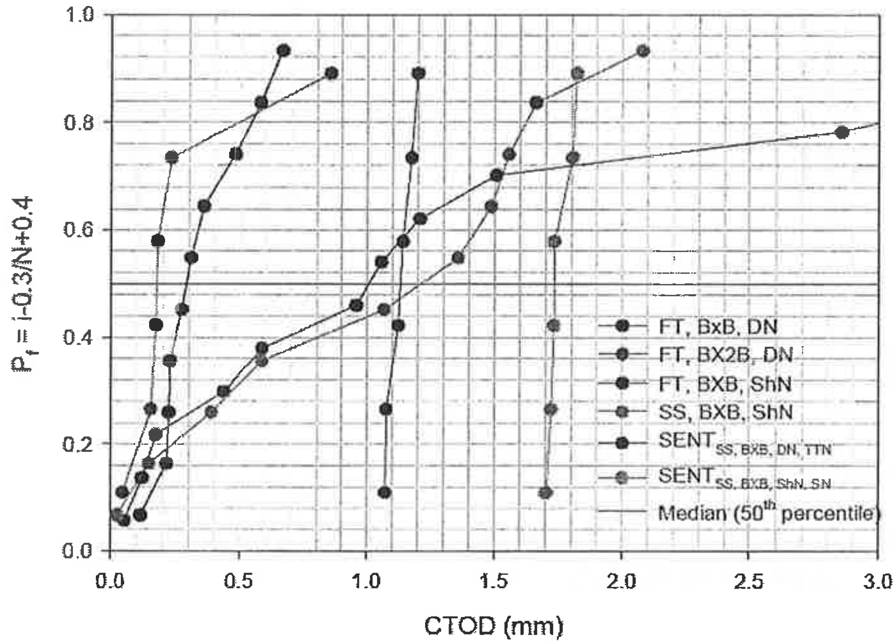


Figure A-21 Cummulative probability plot for CTOD of SENB and SENT specimen (*Amadioha et al, 2011*)

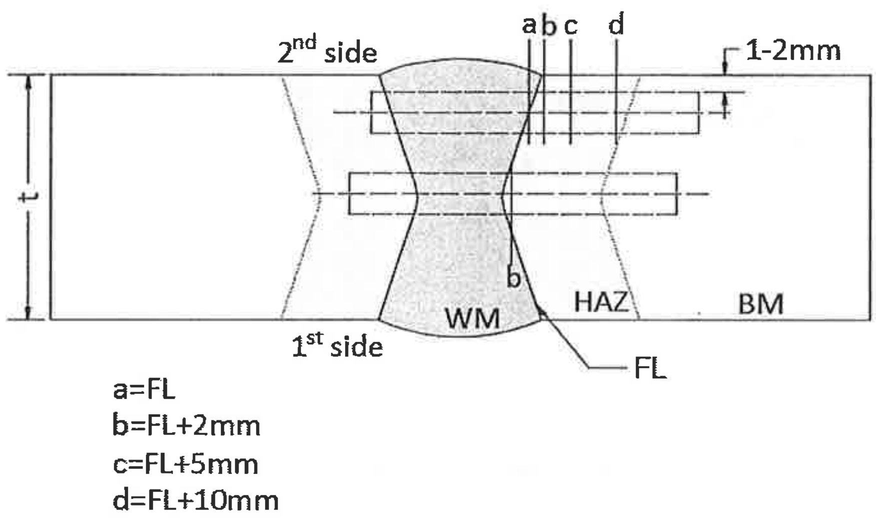


Figure A-22 CVN notch locations for butt welds

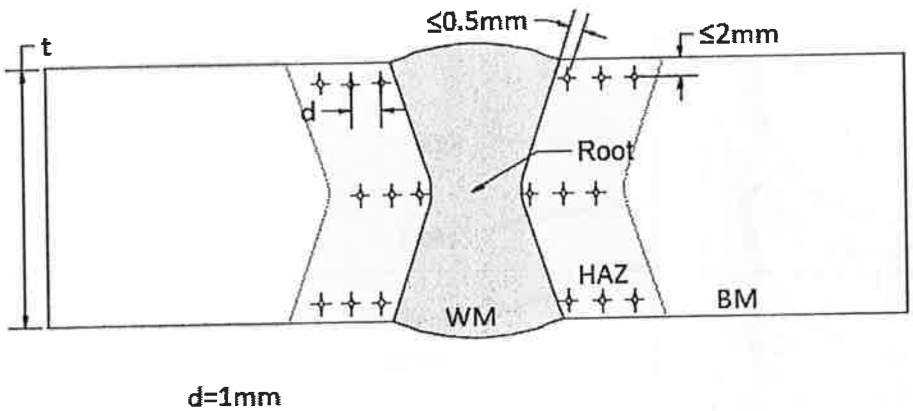


Figure A-23 Position of hardness test indentation rows for butt weld types

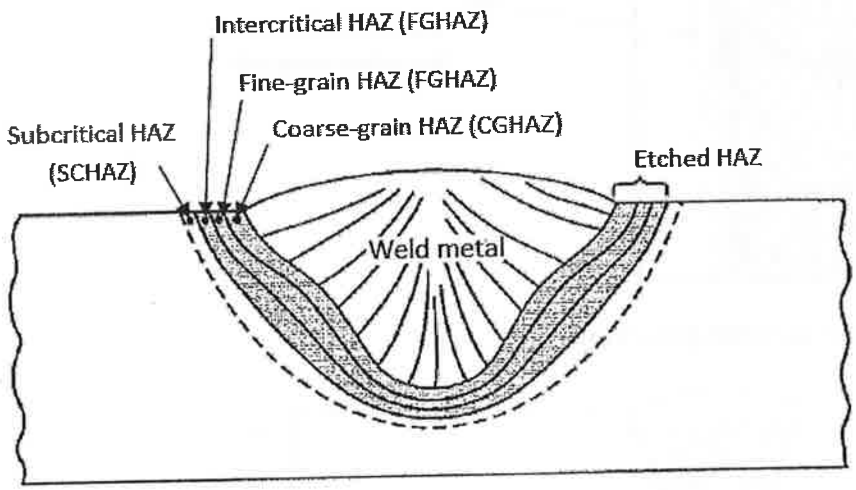


Figure A-24 Various regions of a Single-pass, bead-on-plate weld (*API RP-2Z*)

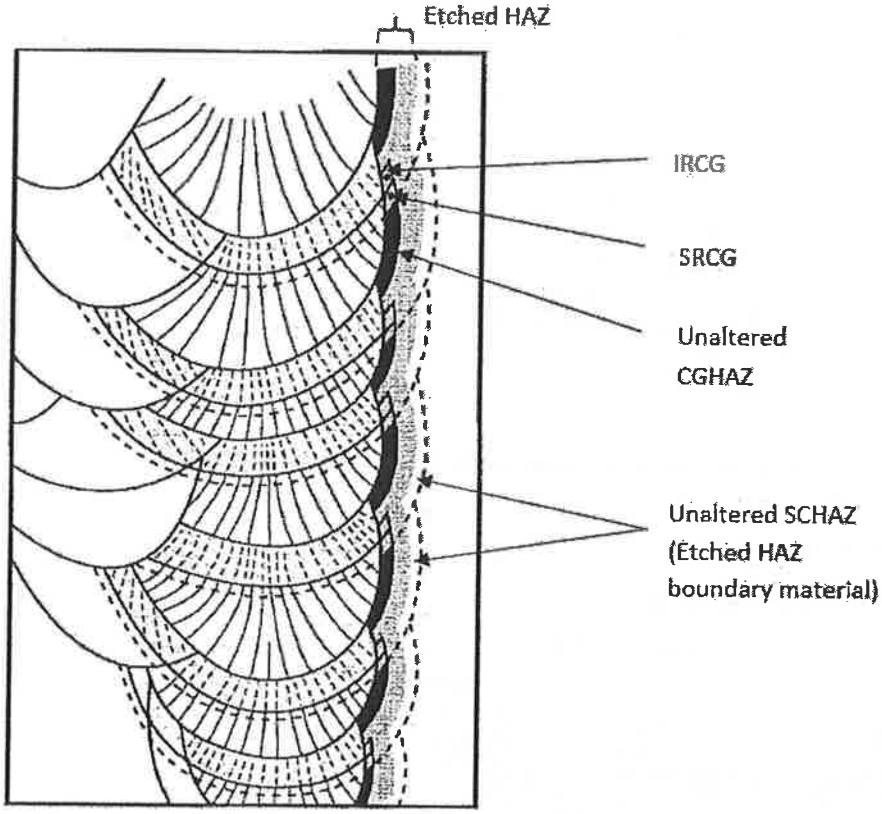


Figure A-25 HAZ regions in multi-pass weld

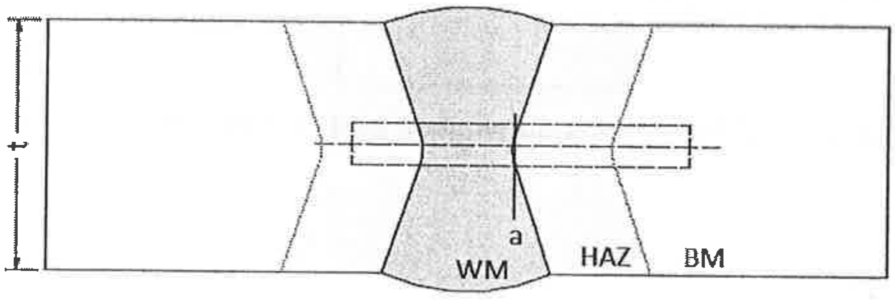


Figure A-26 CVN test location; a- notch close to fusion line, t- pipe wall thickness

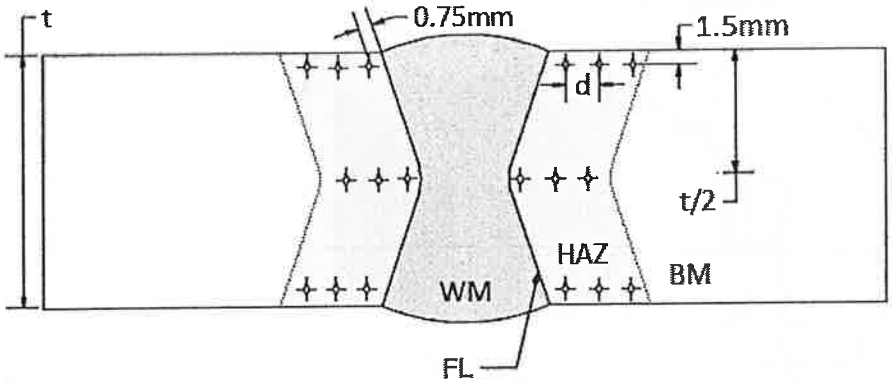


Figure A-27 Hardness test locations, d- 1mm, t- pipe wall thickness

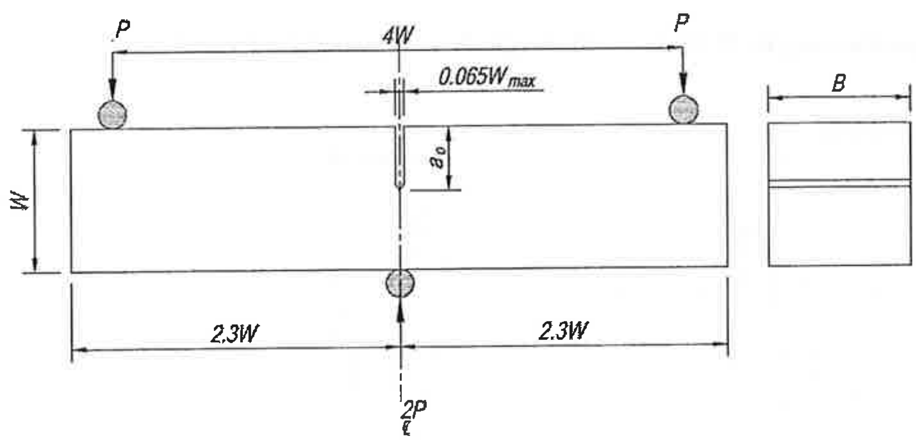


Figure A-28 Configuration of three point bending specimen [SE(B)]

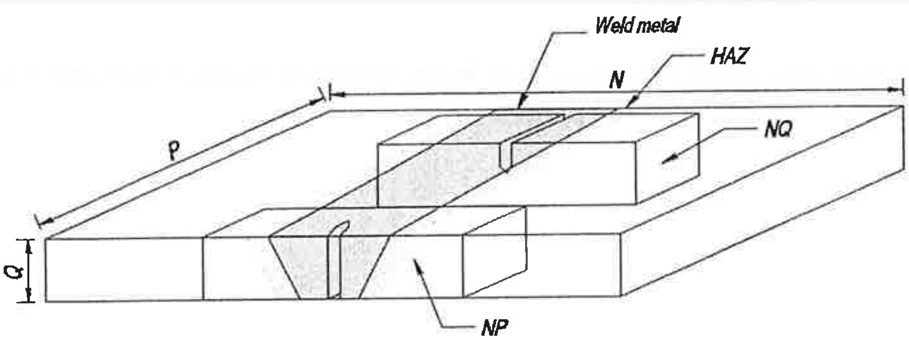


Figure A-29 Designation of orientations with respect to weld direction and plate thickness

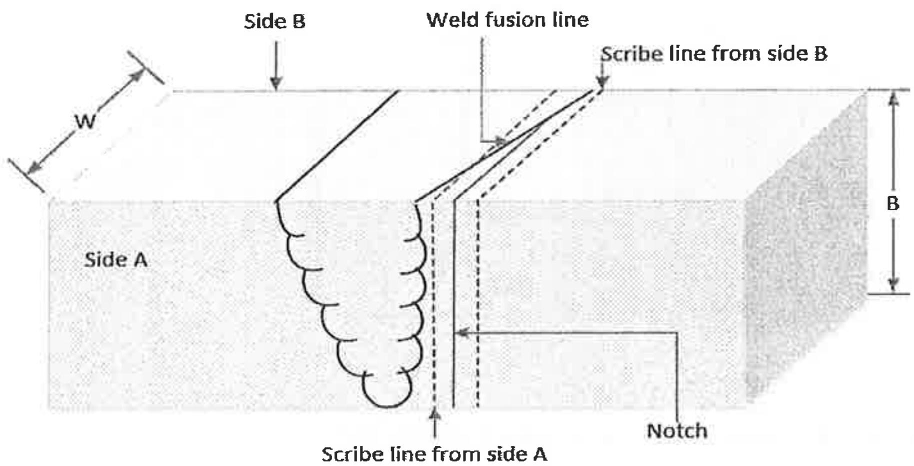


Figure A-30 Notch positioning in HAZ for a through thickness notched specimen

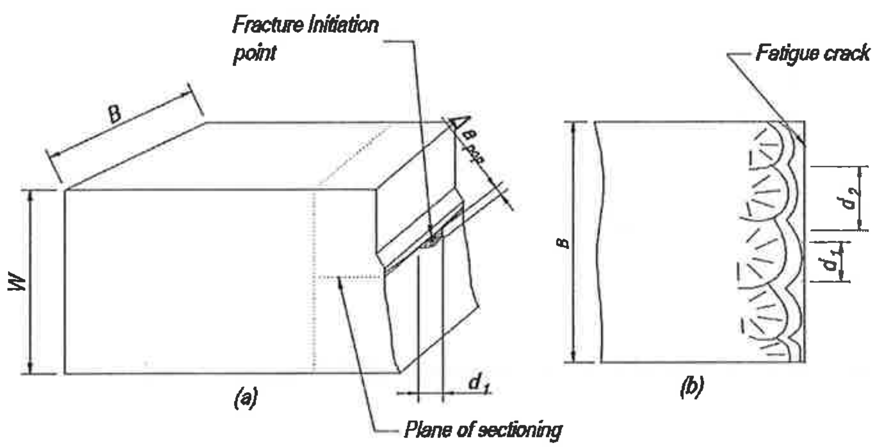


Figure A-31 Through thickness notched specimen in HAZ, (*a*) Measurement of d_1 and Δa $_{pop}$; (*b*) Measurement of d_1 and d_2 on sectioned plane

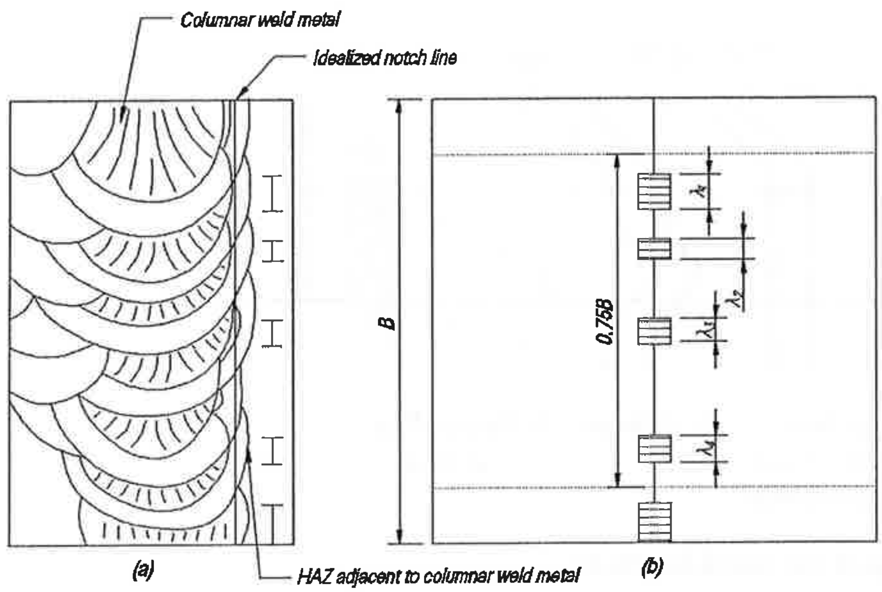


Figure A-32 Estimation of percentage microstructure, (*a*) HAZ adjacent to columnar weld metal for idealized notch line on macrosection; (*b*) Microstructural map of HAZ adjacent to columnar weld metal

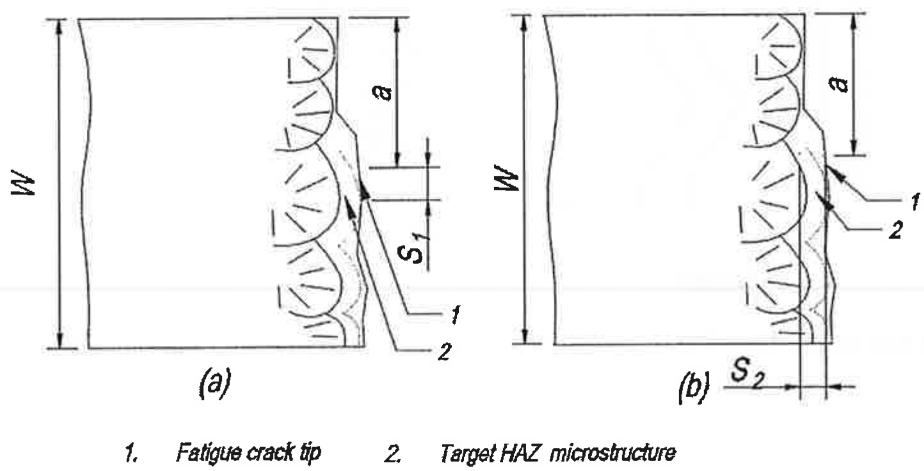


Figure A-33 Measurement of S1 and S2 in a surface notched SM specimen, (*a*) Target microstructure a head of fatigue crack tip, (*b*) Target microstructure on one side of fatigue crack tip

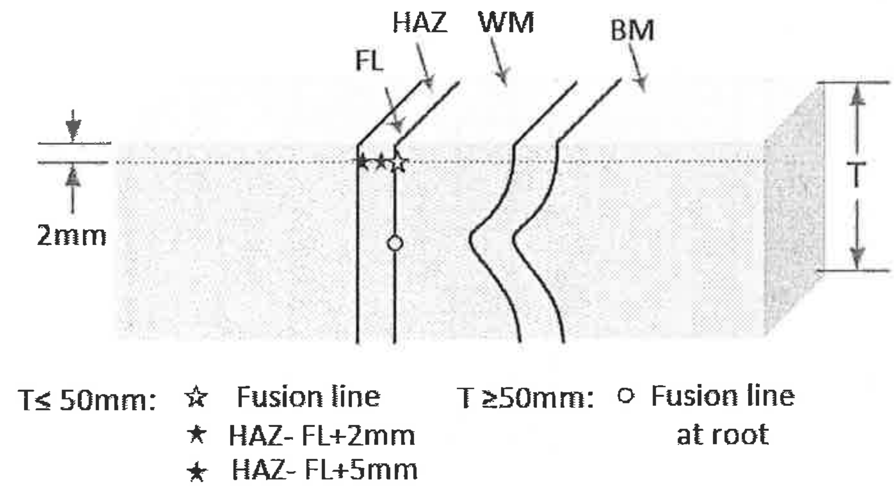


Figure A-34 CVN impact test notch locations

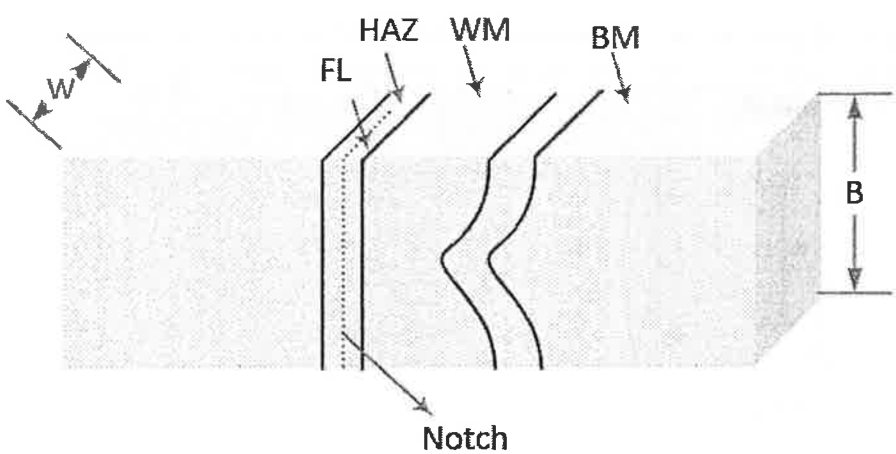


Figure A-35 CTOD test notch locations

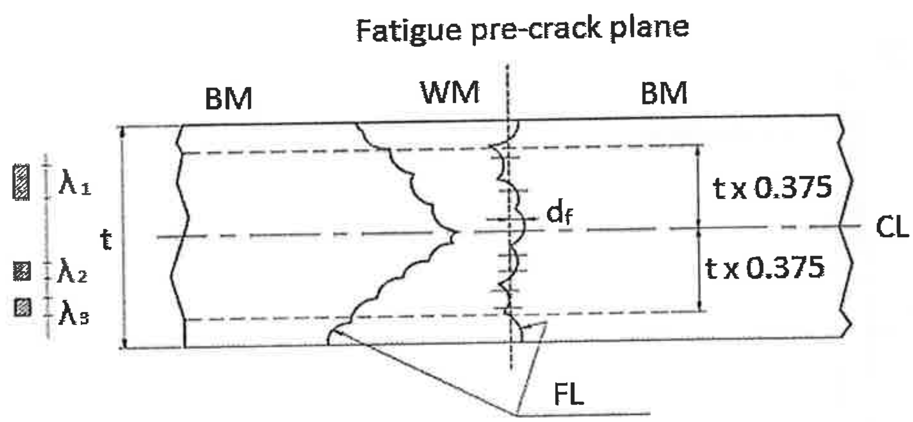


Figure A-36 Unfractured specimen- Cross-section through the weld

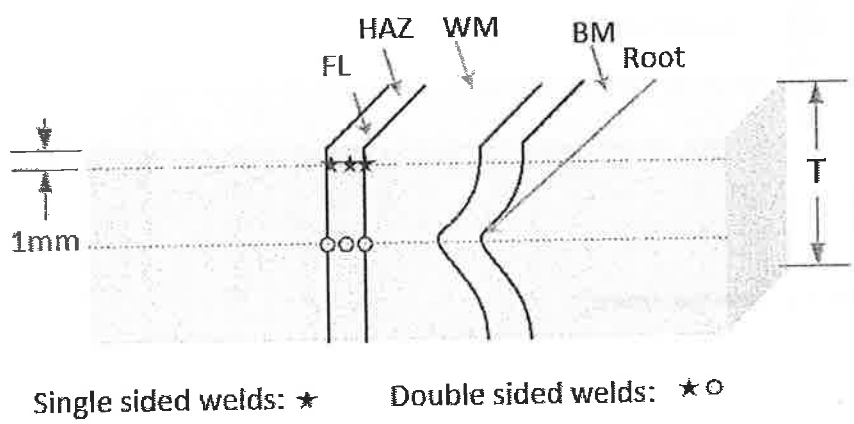


Figure A-37 Locations for hardness test in HAZ

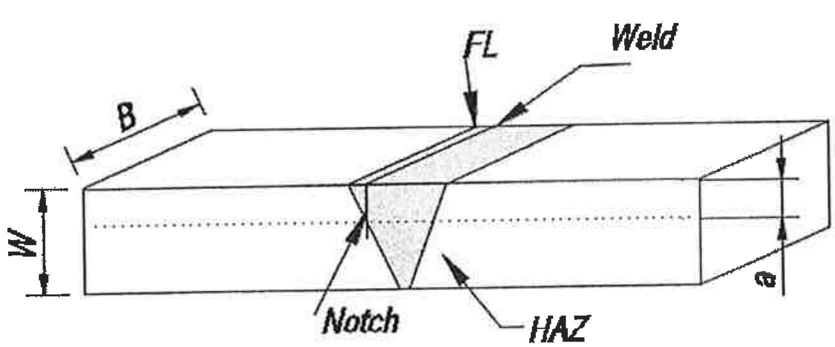


Figure A-38 Notch location in SENT specimen for testing HAZ

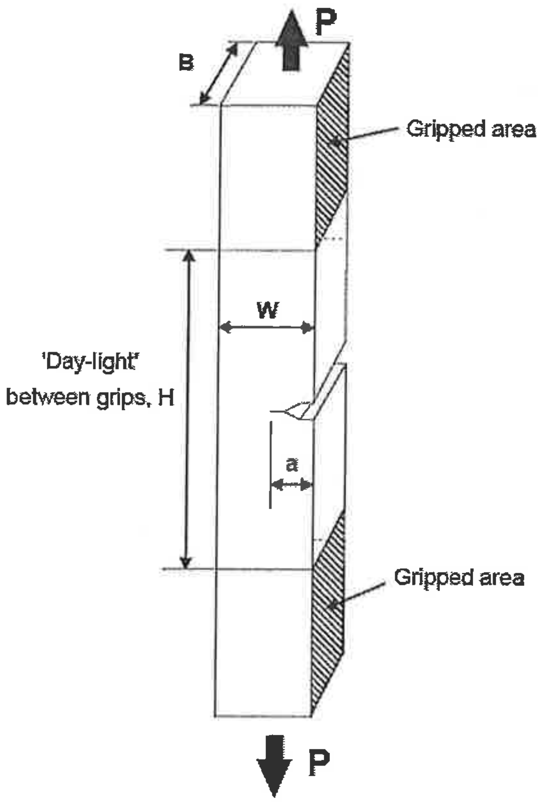


Figure A-39 Typical SENT test specimen

APPENDIX B

SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION

SURVEY QUESTIONNAIRE

Background.

AASHTO M270 (ASTM A709), Standard Specification for Structural Steel for Bridges, covers the chemical, mechanical, and toughness properties of structural steel intended for use in bridges. *AASHTO/AWS D1.5, Bridge Welding Code* covers the welding processes and requirements for welded highway bridges, but it does not address the toughness requirements for heat-affected zones (HAZs) of welded structural steel. Also, toughness requirements for HAZs of welded structural steel are not covered in *AASHTO LRFD Bridge Design Specifications*. There is a need to identify the factors affecting the toughness for HAZs of welded structural steels used in highway bridges and determine what toughness requirements are necessary for incorporation in the *AASHTO/AWS Bridge Welding Code* and the *AASHTO LRFD Bridge Design Specifications*. This information will ensure that the HAZs will exhibit the toughness properties that are necessary for the intended performance and service life.

The objective of this research is to develop proposed toughness requirements for the heat-affected zones of welded structural steels for highway bridges. The research will deal with steels intended for use in bridges as identified in AASHTO M270.

The purpose of this survey is to gather pertinent information from the owners on specific topics including: commonly used materials and welding processes for highway steel bridges; experiences with HAZ and its toughness on performance; special provisions for HAZ toughness; and common design practices.

General Information

Contact. Please provide the name and contact information of the person filling out this survey:

Organization	
Last Name	
First Name	
Position	
Street Address	

City

State

Zip Code

Telephone (xxx-xxxxxxx)

Fax (xxx-xxxxxxx)

Email

Material, Welding Processes and Specifications

Q1. Does your agency follow any special welding guidelines for steel bridge fabrication, in addition to *AASHTO/AWS D1.5: Bridge Welding Code*?

○ Yes (Please specify the guidelines.)

○ No

Q2. Does your agency use *AWS D1.1: Structural Welding Code* in addition to *AASHTO/AWS D1.5: Bridge Welding Code* for welding steel bridges?

○ Yes (Please note the *AWS D1.1* sections used.)

○ No

Q3. Which of the following welding parameters cited in *AWS D1.1* and *D1.5* are supplemented by additional specifications, requirements or special provisions for steel bridge welding by your agency? (Please provide details under each choice.)

- ☐ Weld Preheat Temperatures
- ☐ Weld Interpass Temperatures
- ☐ Welding Heat Input
- ☐ Weld Speed
- ☐ Weld Cooling Rate
- ☐ Post Weld Heat Treatment (PWHT)
- ☐ Others (Please Identify. Enter "N/A" or "None" if appropriate.)

Q4. Does your agency allow Narrow Gap Improved Electroslag Welding (ESW-NGI) for steel bridge welding?

- ○ Yes
- ○ No (Please explain why ESW-NGI is not permitted.)

Q5. Please provide the following information for each process used or specified by your agency for welding steel bridges(Please enter "N/A" or "None" if appropriate):

	Approximate % of total	**Maximum** plate thickness (in.)	**Minimum** plate thickness (in.)
Flux Cored Arc Welding (FCAW)			
Gas Metal Arc Welding (GMAW)			
Submerged Arc Welding (SAW)			
Shielded Metal Arc Welding (SMAW)			
Narrow Gap Improved Electroslag Welding (ESW-NGI)			

Q6. Which of the following AASHTO M270 structural steel grades are allowed by your agency for welding steel bridges using each of the processes listed below?

	Steel Grades				
	Grade 50	Grade 50W	Grade HPS 50W	Grade HPS 70W	Grade HPS 100W
FCAW	☐	☐	☐	☐	☐
GMAW	☐	☐	☐	☐	☐
SAW	☐	☐	☐	☐	☐
SMAW	☐	☐	☐	☐	☐
ESW-NGI	☐	☐	☐	☐	☐

Q7. Please provide the following information pertaining to steel bridges built by your agency since 2005. This information is to identify current trends in the usage of each steel grade. (Please enter "N/A" or "None" if appropriate):

	Approximate % of total	**Maximum** plate thickness (in.)	**Minimum** plate thickness (in.)
Grade 50			
Grade 50W			
Grade HPS 50W			
Grade HPS 70W			
Grade HPS 100W			
Others (Please specify)			

Q8. Which of the following typical plate thickness transitions are commonly specified by your agency?

- ☐ 1.0 in. to 1.5 in.
- ☐ 1.5 in. to 2.0 in.
- ☐ 2.0 in. to 2.5 in.
- ☐ 2.5 in. to 3.0 in.
- ☐ 3.0 in. to 3.5 in.
- ☐ 3.5 in. to 4.0 in.
- ☐ Others

(Please indicate. Enter "N/A" or "None" if appropriate.)

Q9. Please indicate any limitations of plate thickness specified by your agency for steel bridges (Please enter "N/A" or "None" if appropriate):

Heat-Affected Zone (HAZ) Topics

Q10. Has your agency developed any acceptance criteria that considers weldment toughness for steel bridge welding?

○ Yes (Please specify criteria.)

○ No

Q11. As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are specified by your agency?

☐ Charpy V-Notch (CVN) (Please indicate applicable specification.)

☐ Crack Tip Opening Displacement (CTOD) (Please indicate applicable specification.)

☐ Others (Please indicate tests and applicable specifications. Enter "N/A" or "None" if appropriate.)

Q12. As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are specified by your agency for each of the welding processes noted below?

	Welding Process				
	FCAW	GMAW	SAW	SMAW	ESW-NGI
Charpy V-Notch (CVN)	☐	☐	☐	☐	☐
Crack Tip Opening Displacement (CTOD)	☐	☐	☐	☐	☐
Others (As indicated in previous question.)	☐	☐	☐	☐	☐

Q13. Which of the following adverse effects in the HAZ of welded bridge steels have been experienced by your agency?

☐ Cracking

☐ Low Toughness

☐ Others (Please indicate. Enter "N/A" or "None" if appropriate.)

Q14. Please provide details related to your experiences with adverse effects in the HAZ of welded bridge steels, if any. (Please enter "N/A" or "None" if appropriate.)

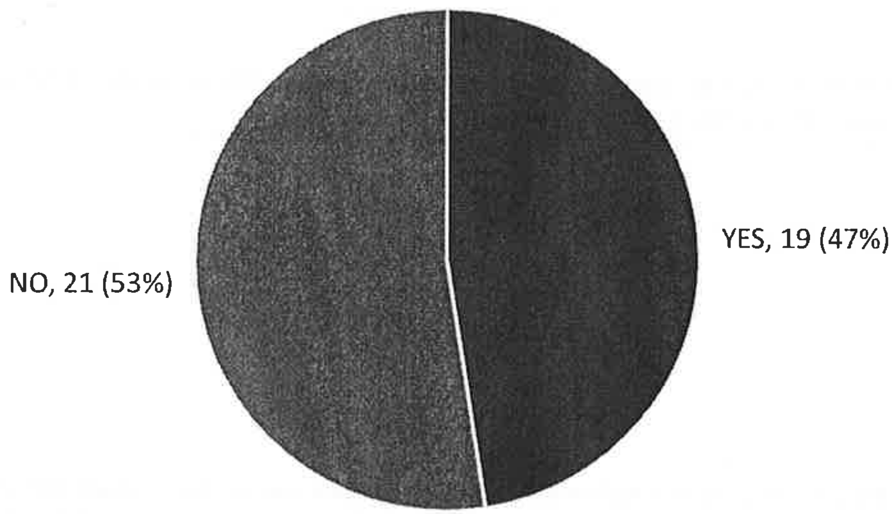
Miscellaneous

Q15. Please indicate what information related to the research subject can be made available for this project and how our research team can obtain them. These information must be available for sharing in the public domain.

SURVEY RESULTS

Followings are the results of the survey of the state department of transportations. Altogether 40 agencies responded to the survey. The responses were followed up by further email and/or telephone interview. Analysis of the survey results are presented as follows.

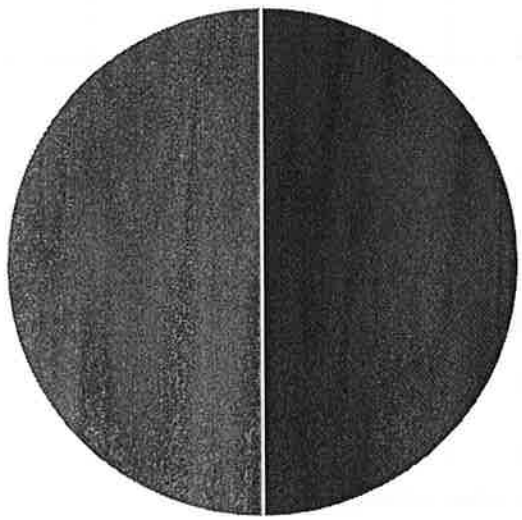
1) Does your agency follow any special welding guidelines for steel bridge fabrication, in addition to *AASHTO/AWS D1.5: Bridge Welding Code*?



Yes	CA, CO, GA, IA, ID, IL, ME, MI, NC, NE, NH, NY, OK, PA, TX, VA, WA, WI, WY
No	AK, AL, AR, AZ, FL, HI, LA, MA, MN, MO, NJ, NV, OH, OR, RI, SC, SD, TN, UT, VT, WV

Comments: Out of the 40 responding states, 19 states responded that they follow special welding guidelines in addition to *AASHTO/AWS D1.5: Bridge Welding Code*. These are mostly standard specifications, construction manual or special provisions of each state DOT. In addition, some DOT refer to AASHTO Guide Specification, NSBA special publications, and AREMA Chapter 15. The relevant special welding guidelines for presented along with the response of Q3.

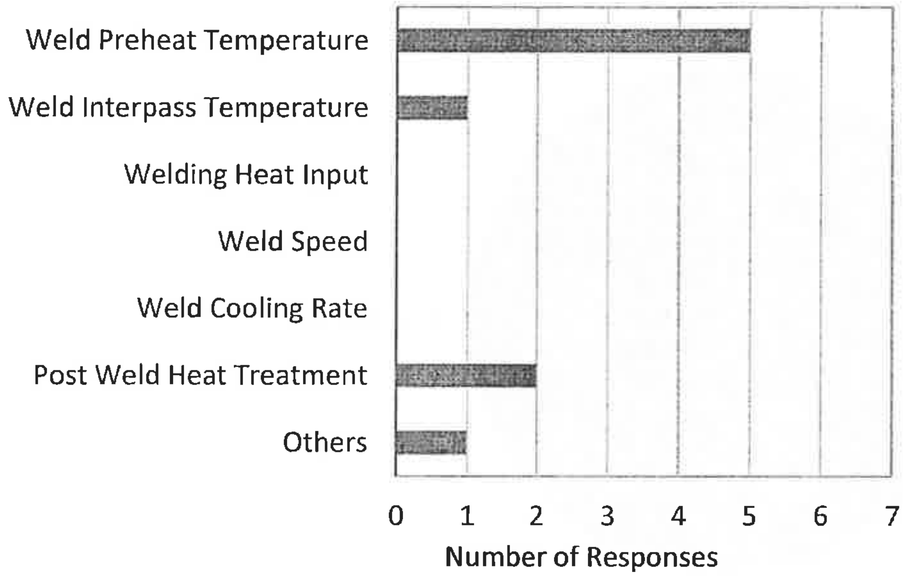
2) Does your agency use *AWS D1.1: Structural Welding Code* in addition to *AASHTO/AWS D1.5: Bridge Welding Code* for welding steel bridges?



Yes	AK, AR, FL, GA, IA, MA, MI, MS, NE, NH, NJ, NY, OK, OR, PA, TX, UT, VA, WA, WI
No	AL AZ, CA, CO, HI, ID, IL, LA, ME, MN, NC, NV, OH, RI, SC, SD,TN, VT, WV, WY

Comments: Twenty out of the 40 responding states use *AWS D1.1* in addition to *AWS D1.5*, mostly for welding tubular members, including sign, signal and luminaire support structures, pedestrian bridges, railings, pile splices and other ancillary items. None of the states follows *AWS D1.1* for primary load bearing members in bridges.

3) Which of the following welding parameters cited in *AWS D1.1* and *D1.5* are supplemented by additional specifications, requirements or special provisions for steel bridge welding by your agency?



Weld Preheat and Interpass Temperatures

States	Additional Requirements
IA	We require a higher preheat. Plates < 0.5 in. (13 mm) use 70°F (21°C) ; 0.5 in. (13 mm) to 1.5 in. (38 mm) use 150°F (66°C); above 1.5 in. (38 mm) follow *AWS 1.5*
ID	Pre-heat web and flange plates, bearing stiffeners, bearing plates, and heavy sections (restrained when welded) to at least 250°F (121°C).
NY	Higher values than *AWS D1.5* as per SCM Table 708:

Plate Thickness	ASTM A709 Grade 50	ASTM A709 Grade 50W, HPS 50W, HPS 70W
To 0.75 in, inclusive	50°F (10°C)	100°F (38°C)
Over 0.75 in. to 1.5 in., inclusive	70°F (21°C)	200°F (93°C)
Over 1.5 in. to 2.5 in., inclusive	150°F (66°C)	300°F (149°C)
Over 2.5 in.	225°F (107°C)	350°F (177°C)

States	Additional Requirements
WA	100°F (38°C) minimum for main members
WY	Perform welding on main load-carrying bridge members, including repairs, at a minimum preheat and interpass temperature of 150°F (66°C) for material thicknesses less than or equal to 2.5 in. (64 mm) and 225°F (107 °C) for thicker material.

Post Weld Heat Treatment (PWHT)

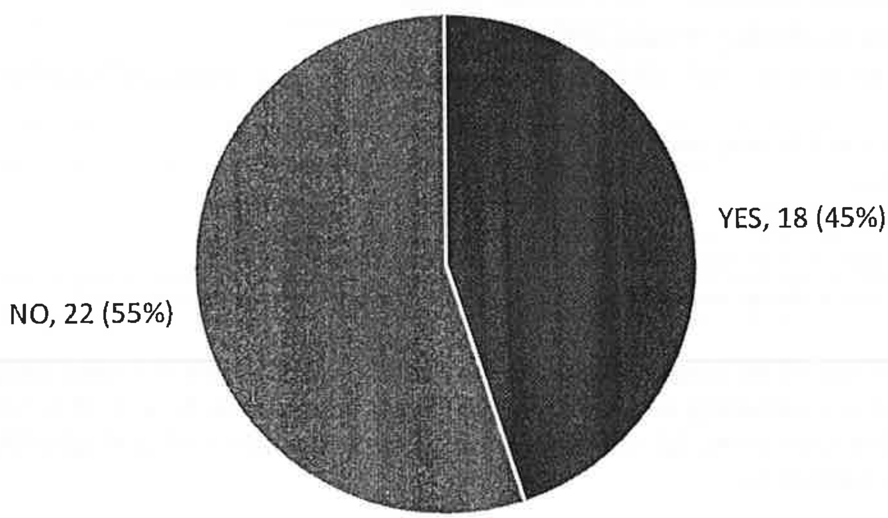
States	Additional Requirements
NY	More stringent than *AWS D1.5* for FCM repairs. See SCM section 9: Postheat shall be employed and shall continue without interruption from the completion of repair welding to the end of the minimum specified postheat period. Postheat of the repair area shall be

	between 400°F and 500°F for one hour minimum for each inch of weld thickness or for two hours, whichever is less.
WY	Stress-relieving stress in welded bearing assemblies by heat treating in accordance with section 4.4 of AASHTO/AWS D1.5. Perform finish machining after heat treating. Adequately support the weld assembly in the furnace. Ensure the provision of an accurate recording pyrometer with thermocouple junctions at the hottest and coolest points on the assembly but not in the direct path of heating flames. Ensure that the recording device provides a continuous permanent record of the temperatures. Give the department's inspector two copies of the records.

Others

States	Additional Requirements
NY	All WPSs are reviewed in Main Office. Various parameters (speed, cooling rate) specified as needed.

4) Does your agency allow Narrow Gap Improved Electroslag Welding (ESW-NGI) for steel bridge welding?



Yes	AL, CA, FL, LA, MA, ME, MS, NV, OH, OK, OR, RI, TN, TX, UT, VA, VT, WA
No	AK, AR, AZ, CO, GA, HI, IA, ID, IL, MI, MN, NC, NE, NH, NJ, NY, PA, SC, SD, WI, WV, WY

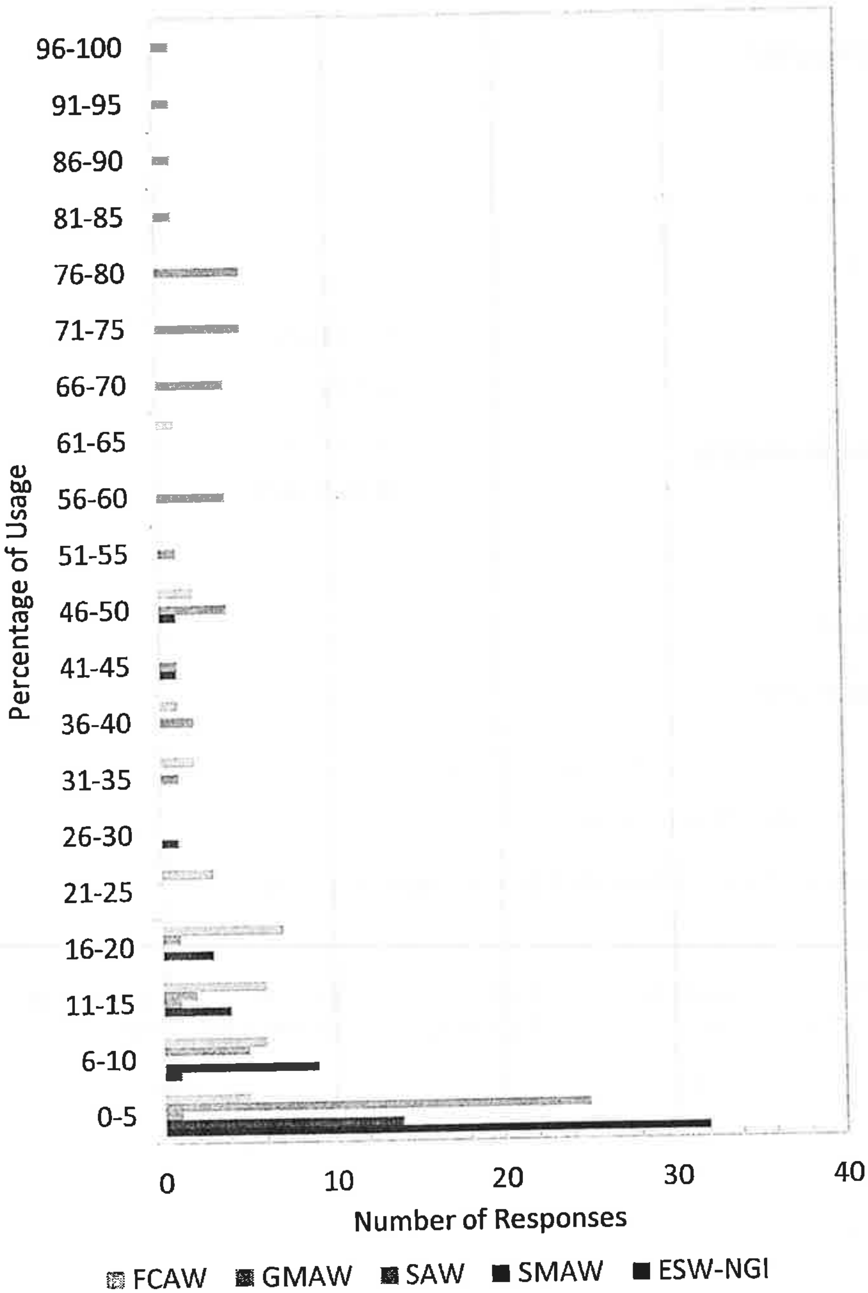
Justification for not allowing ESW-NGI

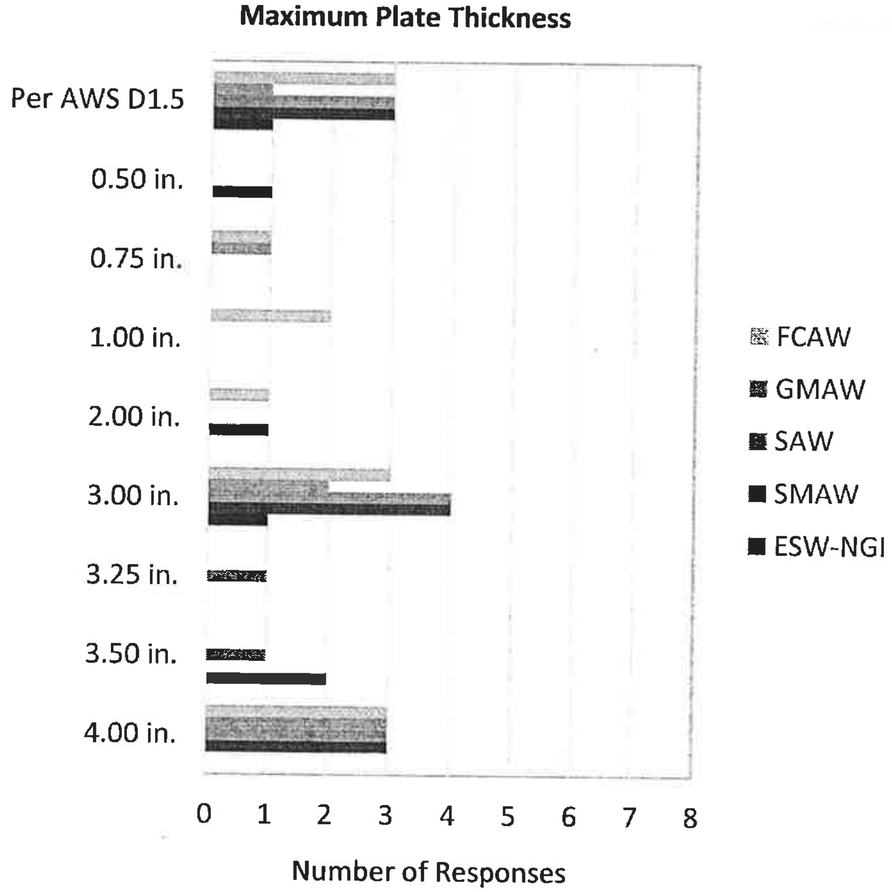
States	Comments
AK	We use temperature Zone 3 for the entire state. ESW-NGI is only permitted in Zones 1 and 2.
AR	Previous experiences with ESW-NGI were negative
AZ	ESW-NGI not permitted in agency's standard specification

States	Comments
CO	Current CDOT Standard Specifications specify SAW for butt welded splices, and web/flange welds. CDOT will consider allowing ESW-NGI when submitted with WPQR
GA	ESW-NGI has not been allowed by the Georgia DOT since 1976 due to bad experience with a railroad bridge. No failure has been occurred, but railroad did not accept the as fabricated girders. So they had to be spliced as a precaution and the bridge are still functioning without any trouble.
IA	Never had the need to use this process.
ID	Most of the state is AASHTO Temperature Zone 3
IL	Prior FHWA Ban on ESW-NGI leads to concerns about quality & durability. No experience with ESW-NGI.
MI	Past experience with ESW-NGI; Hasn't been proposed by fabricators.
MN	Minnesota uses Zone 3 criterial state wide and ESW-NGI is not approved for Zone 3
NC	Not allowed, because none of the fabricators currently doing bridge work in the state has demonstrated capability of using ESW-NGI for steel bridges. Demonstration by a fabricator was not successful.
NE	Most of our plate thicknesses do not exceed 1.0 in. (25 mm) (51 mm) and this would be in flanges.
NH	No reason to allow it. We don't use the thickness plates involved. It is still a relatively new process. No fabricator has asked to use it on a NH project.
NJ	NJDOT prohibits Electro Slag Welding (ESW-NGI)
NY	Inability by fabricators to meet HAZ toughness requirements on a consistent/repeatable basis.
PA	Not at this time, but it is being considered.
SC	No prior experience
WI	Its use has not been required
WY	Fatigue performance due to large grain formation resulting from ESW-NGI
SD	No requests or proposals for use of ESW-NGI from our fabricators have been received.

Comments: Twenty two out of 40 responding states do not allow ESW-NGI for steel bridge welding. The reasons for not permitting are: (*a*) ESW-NGI is not permitted in Zone 3; (*b*) ESW-NGI have not proposed by fabricators; (*c*) welding thicker plates was not needed; and (*d*) ESW-NGI provided negative experiences.

5) Please provide the following information for each process used or specified by your agency for welding steel bridges.

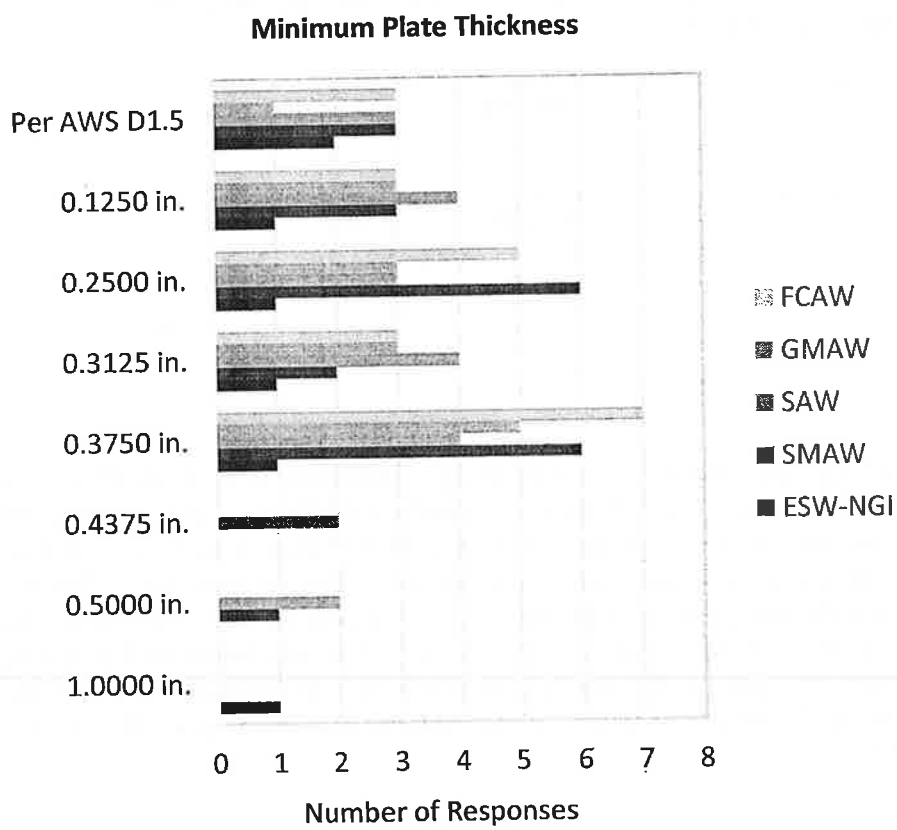




Maximum Plate Thicknesses Used or Specified for Welding Processes

Thickness \ Welding Process	FCAW	GMAW	SAW	SMAW	ESW-NGI
Per AWS D1.5	ID, MS, OH	OH	ID, MS, OH	ID, MS, OH	OH
0.50 in.				AR	
0.75 in.	CO	CO			
1.00 in.	AR, GA				
2.00 in.	IA			IA	
3.00 in.	NC, OR, TX	NC, TX	GA, IA, NC, OR	GA, NC, OR, TX	NC
3.25 in.			AR		

Thickness \ Welding Process	FCAW	GMAW	SAW	SMAW	ESW-NGI
3.50 in.			TX		LA, TX
4.00 in.	IL, MA, WI	IL, MA, WI	IL, MA, WI	IL, MA, WI	



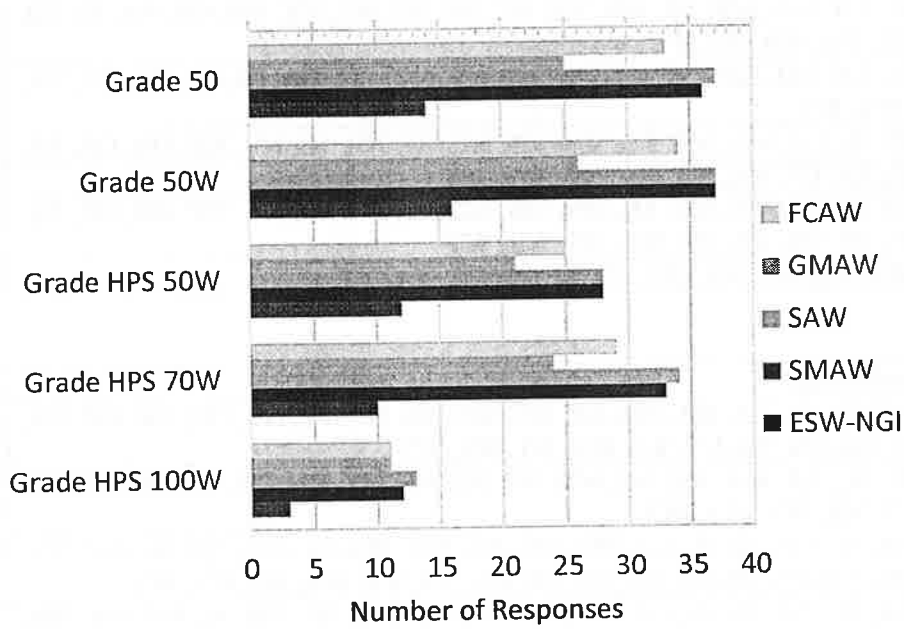
Minimum Plate Thicknesses Used or Specified for Welding Processes

Thickness \ Welding Process	FCAW	GMAW	SAW	SMAW	ESW-NGI
Per AWS D1.5	ID, MS, OH	OH	ID, MS, OH	ID, MS, OH	MS, OH
0.1250 in.	MA, SC, UT	MA, SC, UT	MA, SC, UT, VA	MA, SC, UT	UT

Thickness \ Welding Process	FCAW	GMAW	SAW	SMAW	ESW-NGI
0.2500 in.	CO, IA, ME, OR, RI	CO, ME, RI	ME, OR, RI	CO, IA, ME, NJ, OR, RI	RI
0.3125 in.	NJ, TN, TX	NJ, TN, TX	GA, NJ, TN, TX	GA, TN	TN
0.3750 in.	AR, GA, IL, NC, NE, NY, WI	IL, NC, NE, NY, WI	IL, NC, NY, WI	AR, IL, NC, NE, NY, WI	NC
0.4375 in.			AR, NE		
0.5000 in.			CO, IA	TX	
1.000 in.					TX

Comments: In the responding states, most of the steel bridge fabrication is performed by SAW process, although all processes (except ESW-NGI) are allowed for welding all plate thicknesses. The FCAW and SMAW are the next most commonly used process. GMAW and ESW-NGI are not used by most states. The maximum plate thickness for each welding process ranged between 3.0 in. (76 mm) and 4.0 in. (102 mm), and the minimum plate thickness for each welding process mostly ranged between $^1/_8$ in. (3.2 mm) and $^3/_8$ in. (9.5 mm). The maximum and minimum thickness as "per AWS D1.5" represent the restrictions noted in *AASHTO/AWS D1.5,* which includes a minimum plate thickness of $^1/_8$ in. (3.2 mm), and the maximum plate thickness as demonstrated by weld PQR.

6) **Which of the following AASHTO M270 structural steel grades are allowed by your agency for welding steel bridges using each of the processes listed below?**



Grade 50

Weld Processes	Allowed States
FCAW	AK, AL, AR, CO, FL, GA, IA, ID, IL, LA, MA, ME, MI, MN, MS, NE, NJ, NV, NY, OH, OR, PA, RI, SC, SD, TN, TX, UT, VA, WA, WI, WV, WY
GMAW	AK, CO, FL, IL, LA, MA, ME, MI, MN, NE, NJ, NV, NY, OH, OR, PA, RI, SC, TN, TX, UT, VA, WA, WV, WY
SAW	AK, AL, AR, CO, FL, GA, IA, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NH, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY
SMAW	AK, AL, AR, CO, FL, GA, IA, ID, IL, LA, MA, ME, MI, MN, MS, NE, NH, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY
ESW-NGI	FL, LA, MA, ME, MS, NV, OH, OR, RI, TN, TX, UT, VA, VT

Grade 50W

Weld Processes	Allowed States
FCAW	AK, AL, AR, CO, FL, IA, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, WA, WI, WV, WY
GMAW	AK, CO, FL, IL, LA, MA, ME, MI, MN, NE, NJ, NV, NY, OH, OK, OR, PA, RI, SC, TN, TX, UT, VA, WA, WV, WY
SAW	AK, AL, AR, CO, FL, GA, IA, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NH, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY
SMAW	AK, AL, AR, CO, FL, GA, IA, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NH, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY
ESW-NGI	FL, LA, MA, ME, MS, NV, OH, OK, OR, RI, TN, TX, UT, VA, VT, WA,

Grade HPS 50W

Weld Processes	Allowed States
FCAW	AK, IL, LA, MA, ME, MI, MN, MS, NC, NE, NJ, NV, NY, OH, OR, PA, RI, SD, TN, UT, VA, WA, WI, WV, WY
GMAW	AK, IL, LA, MA, ME, MI, MN, NE, NJ, NV, NY, OH, OR, PA, RI, TN, UT, VA, WA, WV, WY
SAW	AK, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NH, NJ, NV, NY, OH, OR, PA, RI, SD, TN, UT, VA, VT, WA, WI, WV, WY
SMAW	AK, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NH, NJ, NV, NY, OH, OR, PA, RI, SC, TN, UT, VA, VT, WA, WI, WY, WV
ESW-NGI	LA, MA, ME, MS, NV, OH, OR, RI, TN, UT, VA, VT,

Grade HPS 70W

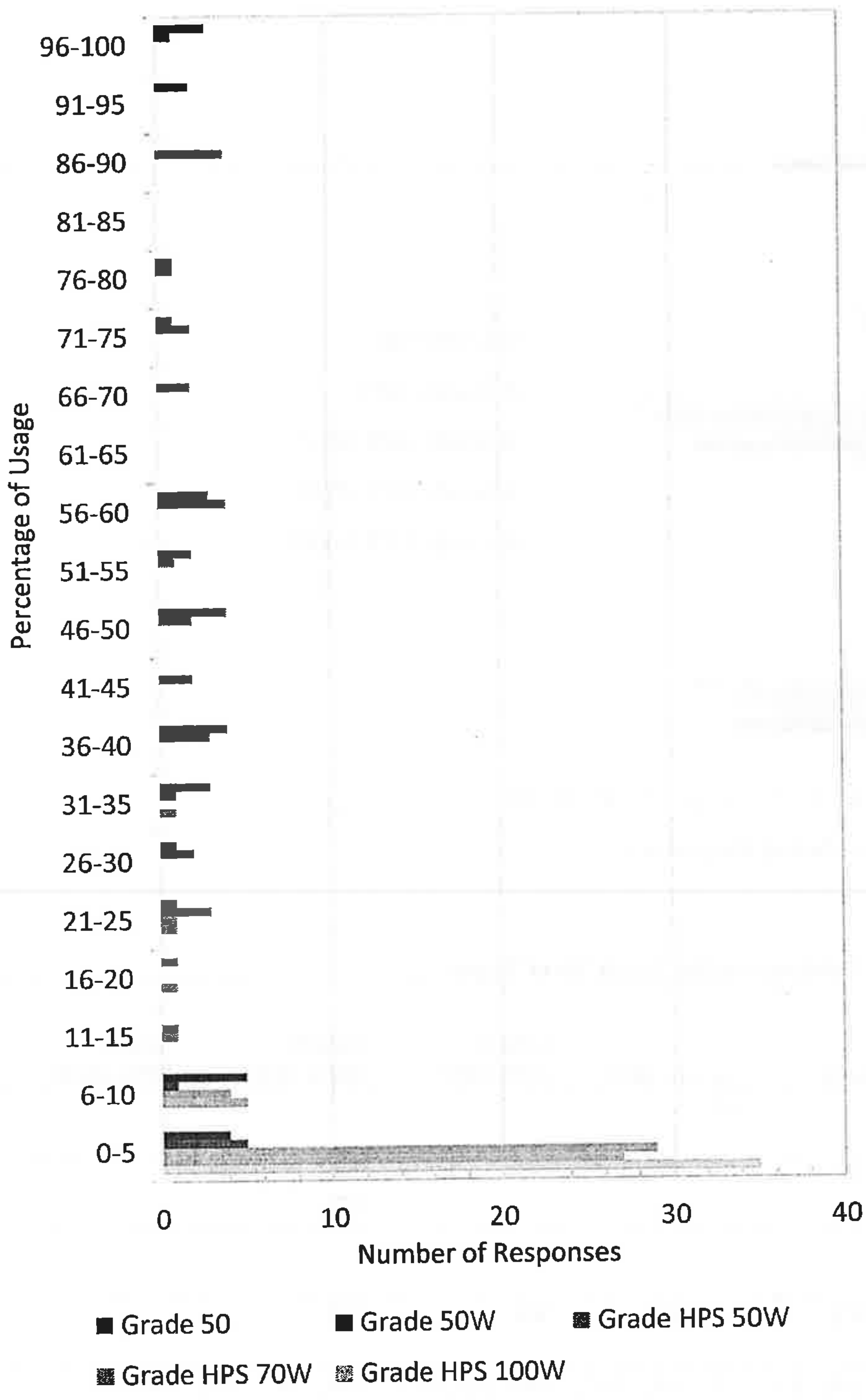
Weld Processes	Allowed States
FCAW	AK, AR, FL, IL, LA, MA, ME, MI, MN, MS, NE, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, WA, WI, WV, WY
GMAW	AK, FL, IL, LA, MA, ME, MI, MN, NE, NJ, NV, NY, OH, OK, OR, PA, RI, SC, TN, UT, VA, WA, WV, WY
SAW	AK, AR, FL, GA, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NH, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY
SMAW	AK, AR, FL, GA, ID, IL, LA, MA, ME, MI, MN, MS, NE, NH, NJ, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY
ESW-NGI	LA, MA, ME, NV, OK, OR, RI, TX, UT, VA,

Grade HPS 100W

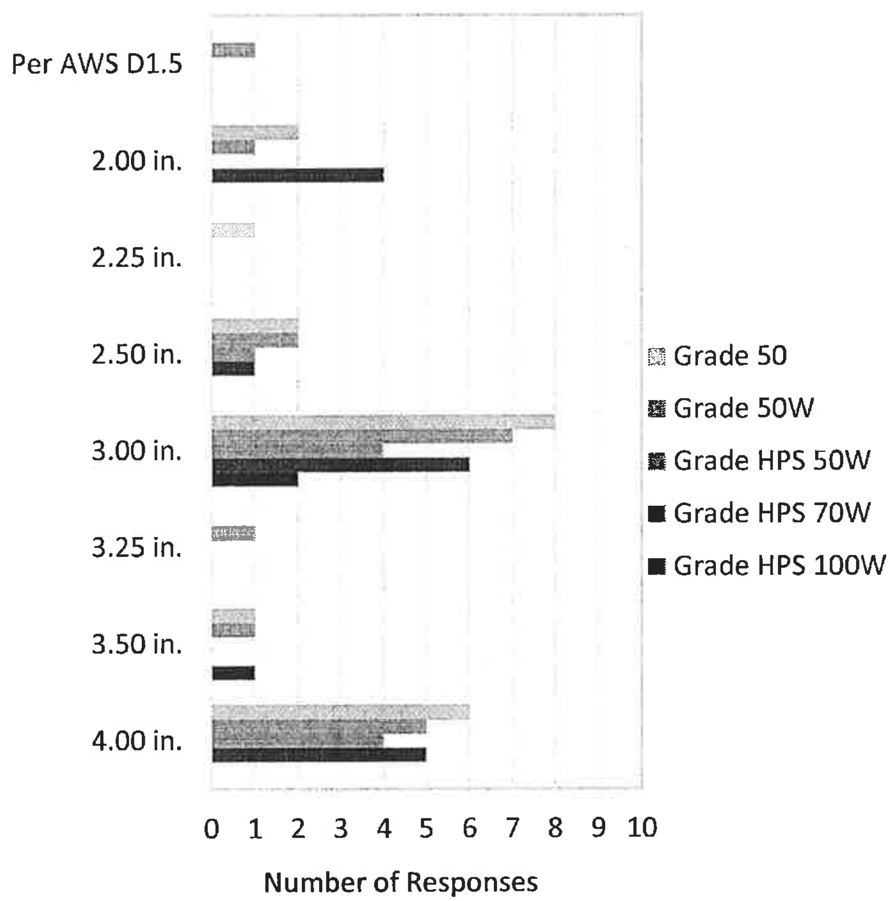
Weld Processes	Allowed States
FCAW	AK, IL, ME, MI, MN, NE, NV, TN, VA, WA, WV
GMAW	AK, IL, ME, MI, MN, MS, NE, NV, TN, VA, WV
SAW	AK, IL, ME, MI, MN, NC, NE, NV, TN, VA, WA, WI, WV
SMAW	AK, IL, ME, MI, MN, NE, NV, TN, VA, WA, WI, WV
ESW-NGI	ME, NV, VA,

Comments: Apparently, the responding states allow all welding processes for each steel grade, although use of SMAW, FCAW and SAW are preferred. From a lesser frequency of response it also appears that use of HPS 100W is limited. As it was presented in Q4, not many responding states permit ESW-NGI, which is also reflected in the response to the current question. One interesting observation is that some states allow use of ESW-NG for HPS grades 70W and 100W, even though not permitted by AASHTO/AWS D1.5.

7) Please provide the following information pertaining to steel bridges built by your agency since 2005. This information is to identify current trends in the usage of each steel grade.



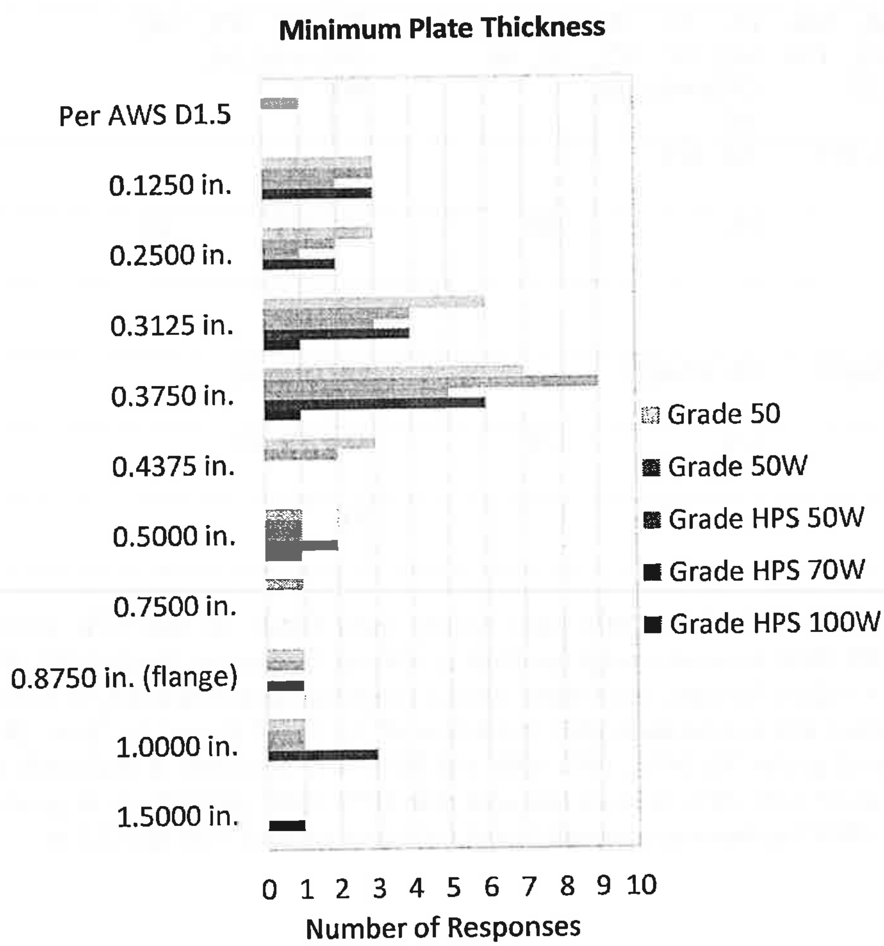
Maximum Plate Thickness



Maximum Used Plate Thicknesses for Each Steel Types

Thickness \ Steel Type	Grade 50	Grade 50W	Grade HPS 50W	Grade HPS 70W	Grade HPS 100W
Per AWS D1.5		ID			
2.00 in.	AZ, SD	SD		AR, OR, SD, UT	
2.25 in.	AR				
2.50 in.	VA, WY	VA, WY	VA	VA	
3.00 in.	AK, GA, IA, NC, NE, OR, UT, WA	FL, IA, NC, NE, OR, UT, WA	NC, NE, UT, WA	GA, NC, NE, TX, WA, WY	NC, NE

Thickness \ Steel Type	Grade 50	Grade 50W	Grade HPS 50W	Grade HPS 70W	Grade HPS 100W
3.25 in.		AR			
3.50 in.	TX	TX			WA
4.00 in.	FL, IL, MA, MS, TN, WI	IL, MA, MS, TN, WI	MA, MS, TN, WI	IL, MA, MS, TN, WI	



Minimum Used Plate Thicknesses for Each Steel Types

Thickness \ Steel Type	Grade 50	Grade 50W	Grade HPS 50W	Grade HPS 70W	Grade HPS 100W
Per AWS D1.5		ID			
0.1250 in.	MA, SC, VA	MA, SC, VA	MA, VA	MA, SC, VA	
0.2500 in.	AK, ME, OR	ME, OR	ME	ME, OR	
0.3125 in.	GA, NJ, TN, TX, WA, WI	NJ, TN, TX, WA	NJ, TN, WA	GA, NJ, TN, WA	WA
0.3750 in.	FL, IA, MS, NC, NY, OH (web), RI	FL, IA, IL, MS, NC, NY, OH (web), RI, WI	MS, NC, NY, RI, WI	IL, NC, NY, OH (web), RI, WI	NC
0.4375 in.	AR, IL, WY	AR, WY			
0.5000 in.	NE	NE	NE	NE, WY	NE
0.7500 in.	AZ				
0.8750 in.	OH (flange)	OH (flange)		OH (flange)	
1.0000 in.	UT	UT	UT	MS, TX, UT	
1.5000 in.				AR	

Comments: The steel bridges built since 2005 have mostly used Grade 50 and 50W steels. Grades HPS 50W and HPS 70W have also been used but at a lesser frequency. Grade HPS 100 W has been rarely used. For these bridges, most states used a maximum plate thickness of 3.0 in. (76 mm) to 4. in. (102 mm) and a minimum plate thickness of $^5/_{16}$ in. (7.9 mm) to $^3/_8$ in. (9.5 mm) for all steels. Usage of grades 50, 50W, HPS 50W and HPS 70W are noted at both ends of the spectrum, although use of HPS 70W is more frequent than HPS 50W, particularly at greater thicknesses. Grade HPS 100W has been occasionally used for plates as thick 3 in. and 3.5 in.

8) Which of the following typical plate thickness transitions are commonly specified by your agency?

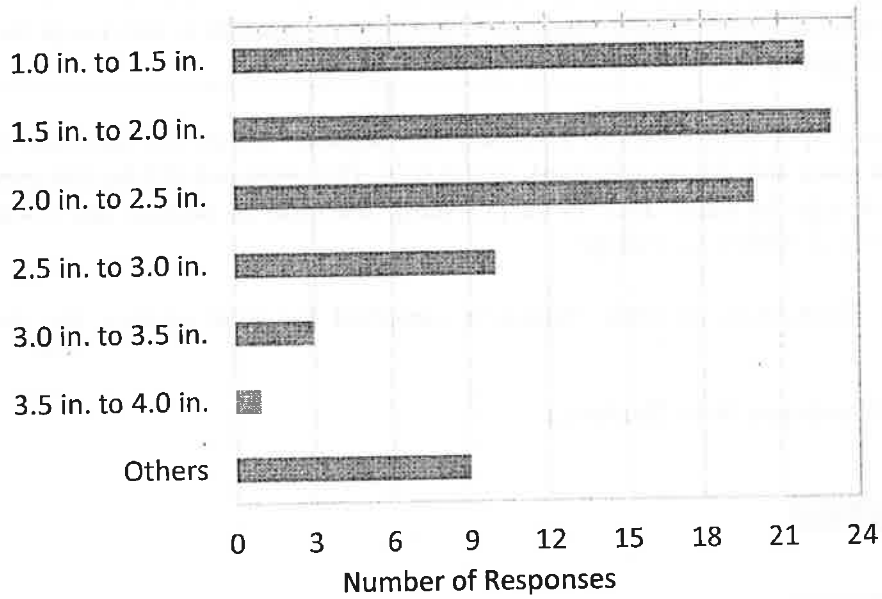


Plate Thickness Transitions	Responded States
1.0 in. to 1.5 in.	AL, AR, CO, GA, IA, IL, ME, MI, MS, NC, NH, NJ, OR, PA, RI, SD, TN, TX, VA, VT, WA, WV
1.5 in. to 2.0 in.	AL, AR, CO, GA, IA, MA, ME, MI, MS, NC, NE, NH, NJ, OR, PA, RI, SD, TN, TX, VA, VT, WA, WV
2.0 in. to 2.5 in.	AL, AR, CO, GA, IA, MA, ME, MI, MS, NC, NH, NJ, OR, PA, RI, TN, TX, VA, WA, WV
2.5 in. to 3.0 in.	AL, CO, GA, MI, NC, NJ, OR, TN, WA, WV
3.0 in. to 3.5 in.	NJ, TN, TX
3.5 in. to 4.0 in.	NJ
Others	AK, ID, IL, MN, NY, PA, SC, TN, UT

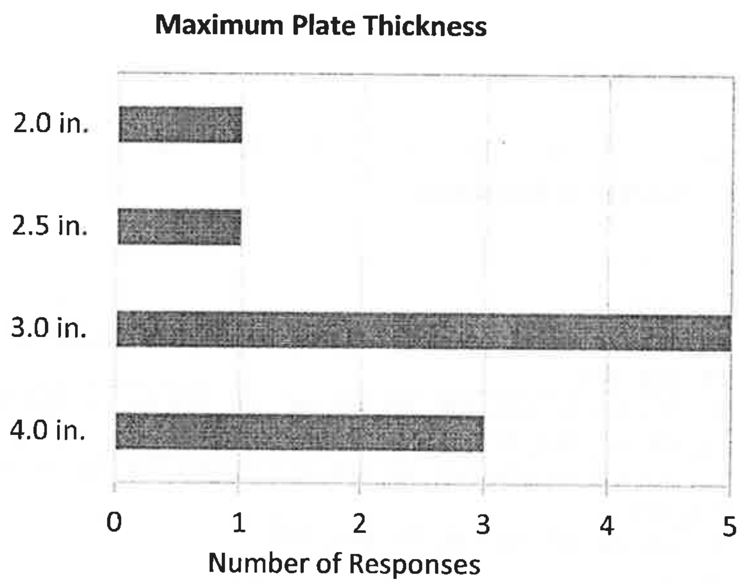
Responses for 'Others'

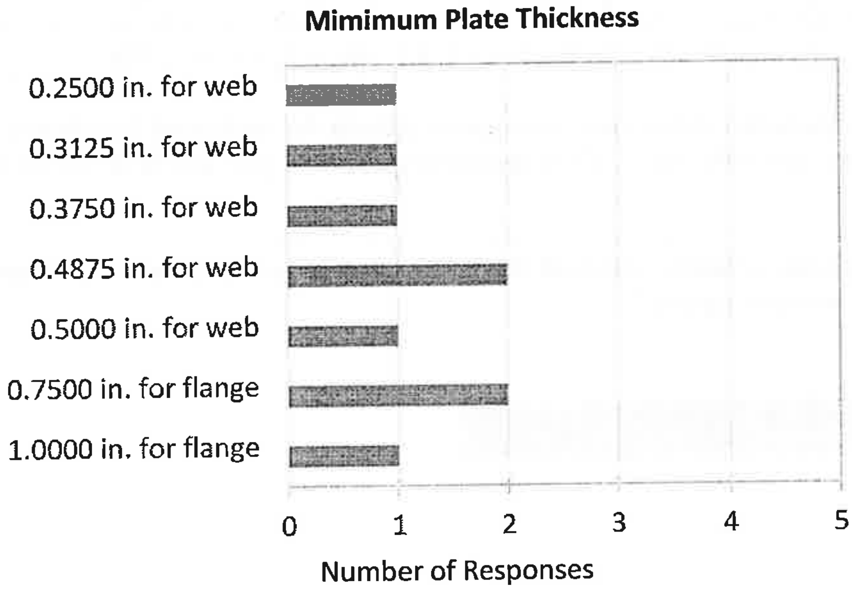
States	Comments
AK	No standard. Change section as design requires. Transition sections according to *AWS D1.5*
ID	Transitions are determined by design and follow Code requirements
IL	Thicker plate is limited to ~2x thinner plate thickness
MN	I would not say that we have "typical" plate thickness transitions. Thickness transitions range from $^1/_4$ in. (6.4 mm) increments up to 2× thickness change.
NY	We require the smaller plate to have at least half the area of the larger one.
PA	1 to 2.5 per the *AWS D1.5*
SC	2 to 1

States	Comments
TN	We allow thickness changes up to double thinner plate size. Typical thickness changes are less than 1" change, usually $^1/_2$ in. (13 mm) or $^3/_4$ in. (19 mm) change in thickness.
UT	We don't track specified plate thickness transitions. Design requirement is to not change the maximum plate thickness by more than a factor of 2.

Comments: The commonly specified thickness transitions are between 1.0 in. (25 mm) and 1.5 in. (38 mm), 1.5 in. (38 mm) and 2.0 in. (51 mm), and 2.0 in. (51 mm) and 2.5 in. (64 mm). Where the thicknesses change by more than $^1/_2$ in. (13 mm), the ratio of thinner and thicker plates is mostly limited to 1:2, with a 1:2.5 slope.

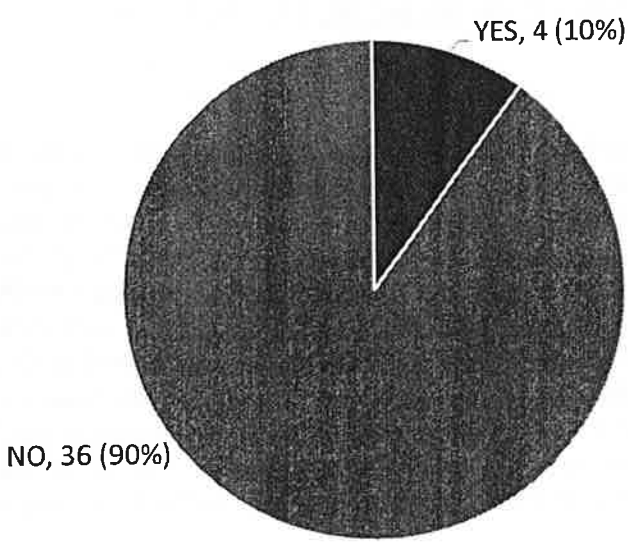
9) Please indicate any limitations of plate thickness specified by your agency for steel bridges





Comments: Fourteen states responded that they have thickness limitations in their standard specification or have unstated limitations for practical purpose. As it was shown from the responses of Q5 and Q7, maximum thickness limit is ranged from 3.0 in. (76 mm) to 4.0 in. (102 mm). The minimum thickness for web are thinner than the minimum thickness for flange and is ranged from $^1/_4$ in. (6.4 mm) to $^1/_2$ in. (13 mm). The minimum thickness for flange is ranged from $^3/_4$ in. (19 mm) to 1.0 in. (25 mm).

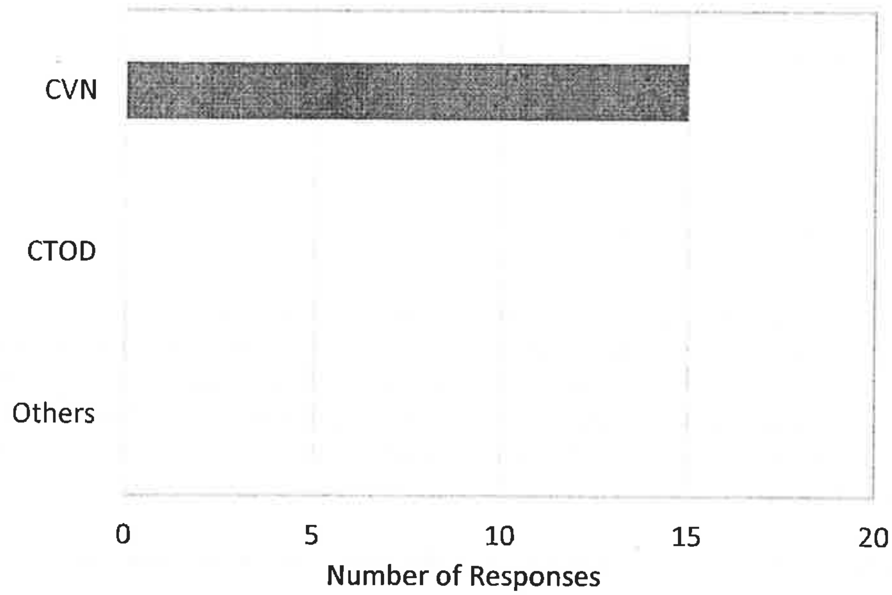
10) Has your agency developed any acceptance criteria that considers weldment toughness for steel bridge welding?



Yes	AK, NY, PA, WA
No	AL, AR, AZ, CA, CO, FL, GA, HI, IA, ID, IL, LA, MA, ME, MI, MN, MS, NC, NE, NH, NJ, NE, OH, OK, OR, RI, SC, SD, TN, TX, UT, VA, VT, WI, WV, WY

Comments: Only four responding states have acceptance criteria for weldment toughness. The acceptance criteria are set per *AWS D1.5*, CVN testing requirement per *ASTM A709*, or state construction manual.

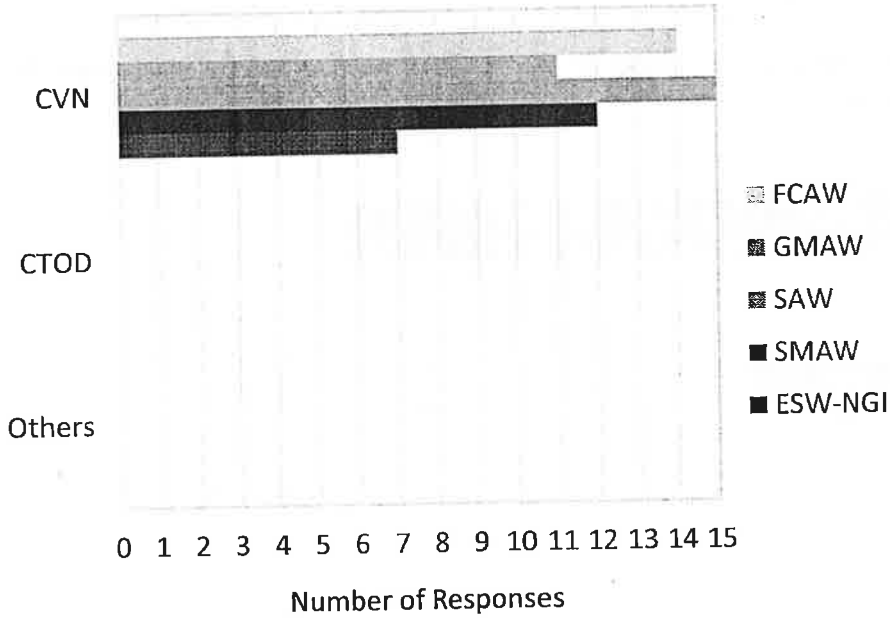
11) As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are specified by your agency?



Test Methods	Responded States
CVN	AK, AR, CA, ID, LA, MA, NC, NE, NJ, NY, SC, TX, VA, WA, WV
CTOD	
Others	

Comments: Although only four responding states developed acceptance criteria for weldment toughness, 15 responding states considers CVN test for HAZ fracture toughness as per standard specification, *AASHTO/AWS D1.5*, *AWS D1.1*, *ASTM A709*, or *AASHTO T243*. However, none of the specification except *AWS D1.1* provides CVN testing requirement for HAZ. As such, it was found that none of the responding state require any fracture toughness testing for HAZ. State of Washington required CVN testing in HAZ for HPS 70W steel in accordance with Annex III of *AWS D1.1* for one of their projects. The notch of the CVN specimen was located in CGHAZ as determined by microetching and the distance of the notch from the fusion line was $^{7}/_{32}$ in. (5.6 mm). Five CVN tests were conducted for each test location. The highest and lowest CVN test values were disregarded and remaining three test results were averaged. The minimum impact energy requirement was 30 ft-lb (41 J) at 0°F (–18°C). No other test method are considered for HAZ fracture toughness.

12) As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are specified by your agency for each of the welding processes noted below?

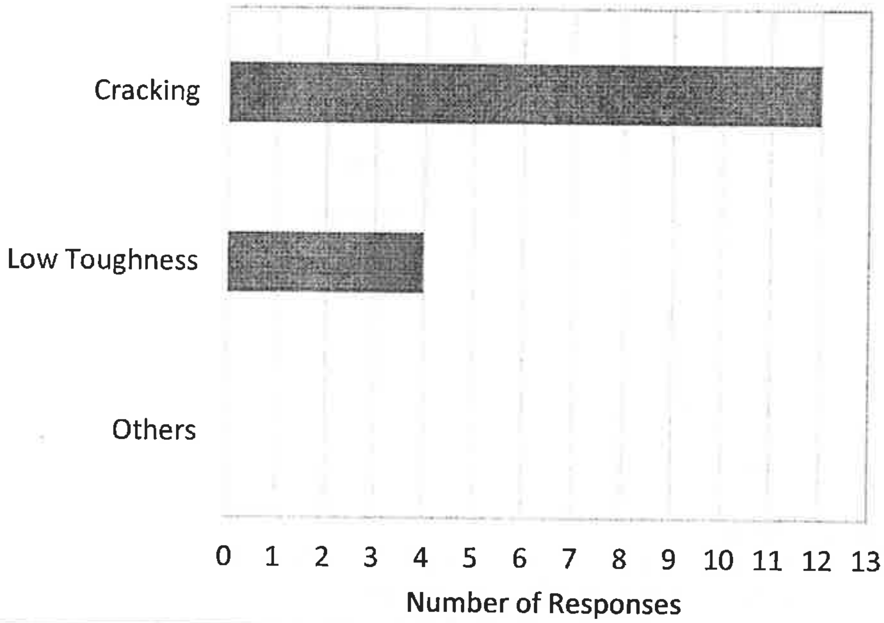


Welding Processes	Responded States
FCAW	AK, AR, CA, ID, LA, MA, NC, NE, NJ, RI, TX, VA, WA, WV
GMAW	AK, CA, LA, MA, NE, NJ, RI, TX, VA, WA, WV
SAW	AK, AR, CA, ID, LA, MA, NC, NE, NJ, NY, RI, TX, VA, WA, WV
SMAW	AK, CA, ID, LA, MA, NE, NJ, RI, TX, VA, WA, WV
ESW-NGI	CA, LA, MA, RI, TX, VA, WA

	Welding Procedures				
States	**FCAW**	**GMAW**	**SAW**	**SMAW**	**ESW-NGI**
Alaska	Yes	Yes	Yes	Yes	No
Arkansas	Yes	No	Yes	No	No
California	Yes	Yes	Yes	Yes	Yes
Idaho	Yes	No	Yes	Yes	No
Louisiana	Yes	Yes	Yes	Yes	Yes
Massachusetts	Yes	Yes	Yes	Yes	Yes
North Carolina	Yes	No	Yes	No	No
Nebraska	Yes	Yes	Yes	Yes	No
New Jersey	Yes	Yes	Yes	Yes	No
New York	No	No	Yes	No	No
Rhode Island	Yes	Yes	Yes	Yes	Yes
Texas	Yes	Yes	Yes	Yes	Yes
Virginia	Yes	Yes	Yes	Yes	Yes
Washington	Yes	Yes	Yes	Yes	Yes
West Virginia	Yes	Yes	Yes	Yes	No

Comments: All the responding states required HAZ CVN testing for SAW and most of the states required for FCAW. However, it is questionable because toughness testing for HAZ is not specified in each state specification.

13) Which of the following adverse effects in the HAZ of welded bridge steels have been experienced by your agency?



Adverse Effects	Responded States
Cracking	AL, CA, ID, MA, MI, NC, NE, NJ, NY, OH, PA, VA
Low Toughness	NJ, NY, OR, PA
Others	

Comments: Twelve responding states experienced cracking in HAZ and four responding states experienced low toughness in HAZ. Detail comments on these adverse effects are presented in the comments of the next question.

14) Please provide details related to your experiences with adverse effects in the HAZ of welded bridge steels, if any.

Comments: The reasons for experiencing cracking in HAZ were lack of preheat and ESW-NGI. As such, ESW-NGI was not allowed from many states and no states experienced cracking in HAZ after the prohibition. Low toughness problem was experienced from ESW-NGI and trial used of ASTM A1010 structural steel.

APPENDIX C

SURVEY OF STEEL BRIDGE FABRICATORS

SURVEY QUESTIONNAIRE

Background.

AASHTO M270 (ASTM A709), Standard Specification for Structural Steel for Bridges, covers the chemical, mechanical, and toughness properties of structural steel intended for use in bridges. *AASHTO/AWS D1.5, Bridge Welding Code* covers the welding processes and requirements for welded highway bridges, but it does not address the toughness requirements for heat-affected zones (HAZs) of welded structural steel. Also, toughness requirements for HAZs of welded structural steel are not covered in *AASHTO LRFD Bridge Design Specifications*. There is a need to identify the factors affecting the toughness for HAZs of welded structural steels used in highway bridges and determine what toughness requirements are necessary for incorporation in the *AASHTO/AWS Bridge Welding Code* and the *AASHTO LRFD Bridge Design Specifications*. This information will ensure that the HAZs will exhibit the toughness properties that are necessary for the intended performance and service life.

The objective of this research is to develop proposed toughness requirements for the heat-affected zones of welded structural steels for highway bridges. The research will deal with steels intended for use in bridges as identified in AASHTO M270.

The purpose of this online survey is to gather pertinent information from steel bridge fabricators on specific topics including: commonly used materials for highway steel bridges; experiences with HAZ and its toughness on performance; special provisions for HAZ toughness; preferred welding processes; and quality control procedures.

General Information

Contact. Please provide the name and contact information of the person filling out this survey:

Organization

Last Name

First Name

Position

Street Address

City

State

Zip Code

Telephone (xxx-xxxxxxx)

Fax (xxx-xxxxxxx)

Email

Material, Welding Processes and Specifications

Q1. Does your organization follow any special welding guidelines for steel bridge fabrication, in addition to *AASHTO/AWS D1.5: Bridge Welding Code*?

○ Yes (Please specify the guidelines.)

○ No

Q2. Does your organization use *AWS D1.1: Structural Welding Code* in addition to *AASHTO/AWS D1.5: Bridge Welding Code* for welding steel bridges?

○ Yes (Please note the *AWS D1.1* sections used.)

○ No

Q3. Does your organization follow any additional specifications, requirements or special provisions for any of the following that supplement *AWS D1.1* and *D1.5* for steel bridge welding? (Please provide details under each choice.)

- ☐ Weld Preheat Temperatures
- ☐ Weld Interpass Temperatures
- ☐ Welding Heat Input
- ☐ Weld Speed
- ☐ Weld Cooling Rate
- ☐ Post Weld Heat Treatment (PWHT)
- ☐ Others (Please Identify. Enter "N/A" or "None" if appropriate.)

Q4. Does your organization use Narrow Gap Improved Electroslag Welding (ESW-NGI) for steel bridge welding?

- ○ Yes
- ○ No (Please explain why ESW-NGI is not permitted.)

Q5. Please provide the following information for each process used by your organization for welding steel bridges (Please enter "N/A" or "None" if appropriate):

	Approximate % of total	**Maximum** plate thickness (in.)	**Minimum** plate thickness (in.)
Flux Cored Arc Welding (FCAW)	☐	☐	☐
Gas Metal Arc Welding (GMAW)	☐	☐	☐
Submerged Arc Welding (SAW)	☐	☐	☐
Shielded Metal Arc Welding (SMAW)	☐	☐	☐
Narrow Gap Improved Electroslag Welding (ESW-NGI)	☐	☐	☐

Q6. Which of the following AASHTO M270 structural steel grades are used by your organization for welding steel bridges using each of the processes listed below?

	Steel Grades				
	Grade 50	Grade 50W	Grade HPS 50W	Grade HPS 70W	Grade HPS 100W
FCAW	☐	☐	☐	☐	☐
GMAW	☐	☐	☐	☐	☐
SAW	☐	☐	☐	☐	☐
SMAW	☐	☐	☐	☐	☐
ESW-NGI	☐	☐	☐	☐	☐

Q7. Please provide the following information pertaining to steel bridges welded by your organization since 2005. This information is to identify current trends in the usage of each steel grade. (Please enter "N/A" or "None" if appropriate):

	Approximate % of total	**Maximum** plate thickness (in.)	**Minimum** plate thickness (in.)
Grade 50			
Grade 50W			
Grade HPS 50W			
Grade HPS 70W			
Grade HPS 100W			
Others (Please specify)			

Q8. Which of the following plate thickness transitions are commonly fabricated by your organization?

- ▢ 1.0 in. to 1.5 in.
- ▢ 1.5 in. to 2.0 in.
- ▢ 2.0 in. to 2.5 in.
- ▢ 2.5 in. to 3.0 in.
- ▢ 3.0 in. to 3.5 in.
- ▢ 3.5 in. to 4.0 in.
- ▢ Others

(Please indicate. Enter "N/A" or "None" if appropriate.)

Heat-Affected Zone (HAZ) Topics

Q9. Does your organization follow any acceptance criteria that considers weldment toughness for steel bridge welding?

- ○ Yes (Please specify criteria.)
- ○ No

Q10. As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are followed by your organization?

☐ Charpy V-Notch (CVN) (Please indicate applicable specification.)

☐ Crack Tip Opening Displacement (CTOD) (Please indicate applicable specification.)

☐ Others (Please indicate tests and applicable specifications. Enter "N/A" or "None" if appropriate.)

Q11. As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are followed by your organization for each of the welding processes noted below?

	Welding Process				
	FCAW	GMAW	SAW	SMAW	ESW-NGI
Charpy V-Notch (CVN)	☐	☐	☐	☐	☐
Crack Tip Opening Displacement (CTOD)	☐	☐	☐	☐	☐
Others (As indicated in previous question.)	☐	☐	☐	☐	☐

Q12. Which of the following adverse effects in the HAZ of welded bridge steels have been experienced by your organization?

☐ Cracking

☐ Low Toughness

☐ Others (Please indicate. Enter "N/A" or "None" if appropriate.)

Q13. Please provide details related to your experiences with adverse effects in the HAZ of welded bridge steels, if any. (Please enter "N/A" or "None" if appropriate.)

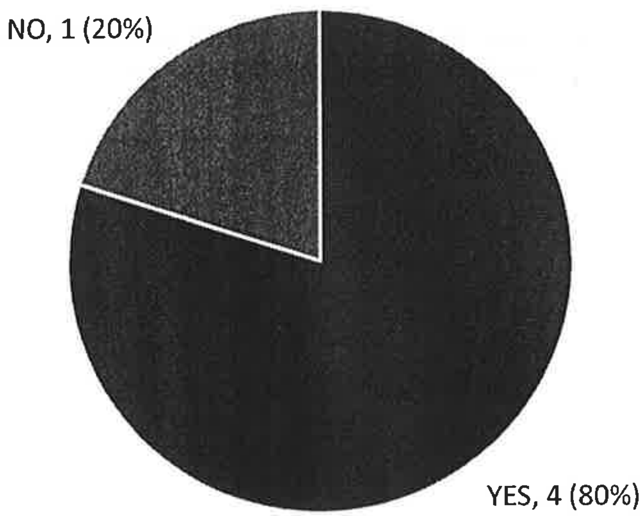
Miscellaneous

Q14. Please indicate what information related to the research subject can be made available for this project and how our research team can obtain them. These information must be available for sharing in the public domain.

SURVEY RESULTS

Followings are the results of the survey of the steel bridge fabricators. Altogether five organization responded to the survey. The responses were followed up by further email interview. Analysis of the survey results are presented as follows.

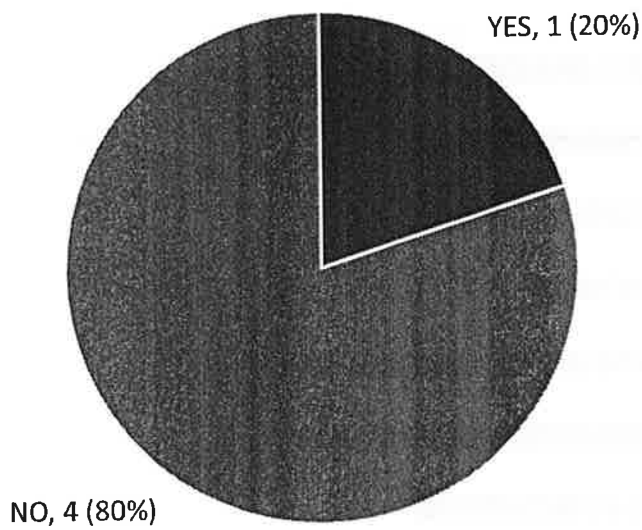
1) Does your organization follow any special welding guidelines for steel bridge fabrication, in addition to *AASHTO/AWS D1.5: Bridge Welding Code*?



Yes	AFCO, Cianbro, High, Tampa
No	Hirschfeld

Comments: Out of five responding fabricators, four fabricator follow special welding guidelines in addition to *AASHTO/AWS D1.5: Bridge Welding Code*. Those are state DOT standard specifications or internal guidelines.

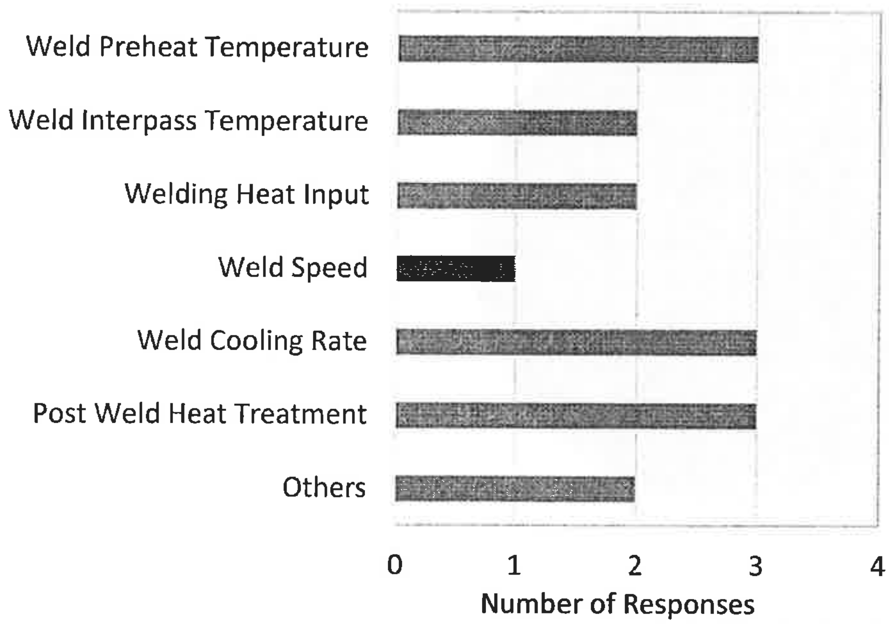
2) Does your organization use *AWS D1.1: Structural Welding Code* in addition to *AASHTO/AWS D1.5: Bridge Welding Code* for welding steel bridges?



Yes	Tampa
No	AFCO, Cianbro, High, Hirschfeld

Comments: Only one fabricators uses *AWS D1.1: Structural Welding Code* in addition to *AWS D1.5*, for welding tubular or ancillary/miscellaneous products.

3) Does your organization follow any additional specifications, requirements or special provisions for any of the following that supplement *AWS D1.1* and *D1.5* for steel bridge welding? (Please provide details under each choice.)



Weld Preheat/Interpass Temperatures

Organizations	Additional Requirements
Cianbro Fabrication and Coating	As required by the DOT or specific project specifications.
Tampa Tank/Florida Structural Steel	MnDOT has higher preheats for repair welding.

Welding Heat Input

Organizations	Additional Requirements
Cianbro Fabrication and Coating	As required by the DOT or specific project specifications.

Weld Speed

Organizations	Additional Requirements
Cianbro Fabrication and Coating	As required by the DOT or specific project specifications.

Welding Cooling Rate

Organizations	Additional Requirements
Cianbro Fabrication and Coating	As required by the DOT or specific project specifications.
AFCO Steel	Only for projects specific requirements which may be associated with heavily restrained weldments

Post Weld Heat Treatment (PWHT)

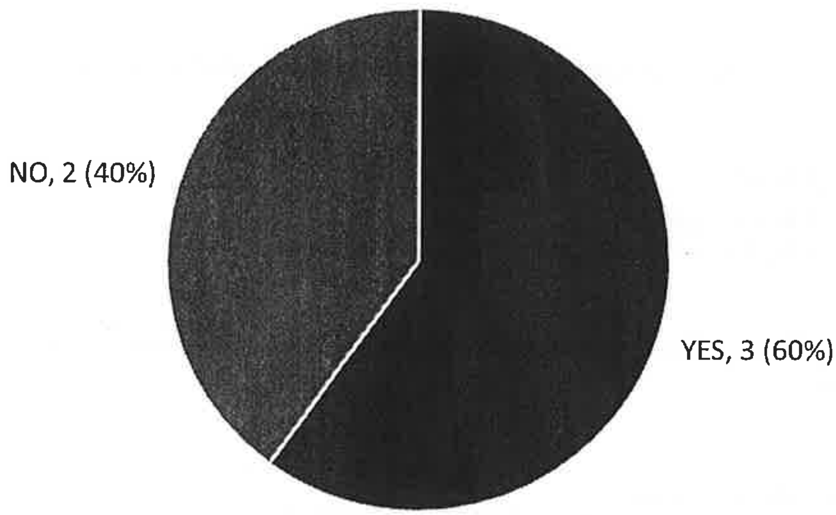
Organizations	Additional Requirements
Cianbro Fabrication and Coating	As required by the DOT or specific project specifications.
AFCO Steel	Only for projects specific requirements which may be associated with heavily restrained weldments.

Others

Organizations	Additional Requirements
Hirchfeld Steel Group	Post weld heating of ESW-NGI
High Steel Structures	FCM guidelines

Comments: Many fabricators follow additional welding guidelines in addition to *AWS D1.1* and *D1.5* for the listed items. The additional guidelines are state standard specifications or specific project requirements.

4) Does your organization use Narrow Gap Improved Electroslag Welding (ESW-NGI) for steel bridge welding?



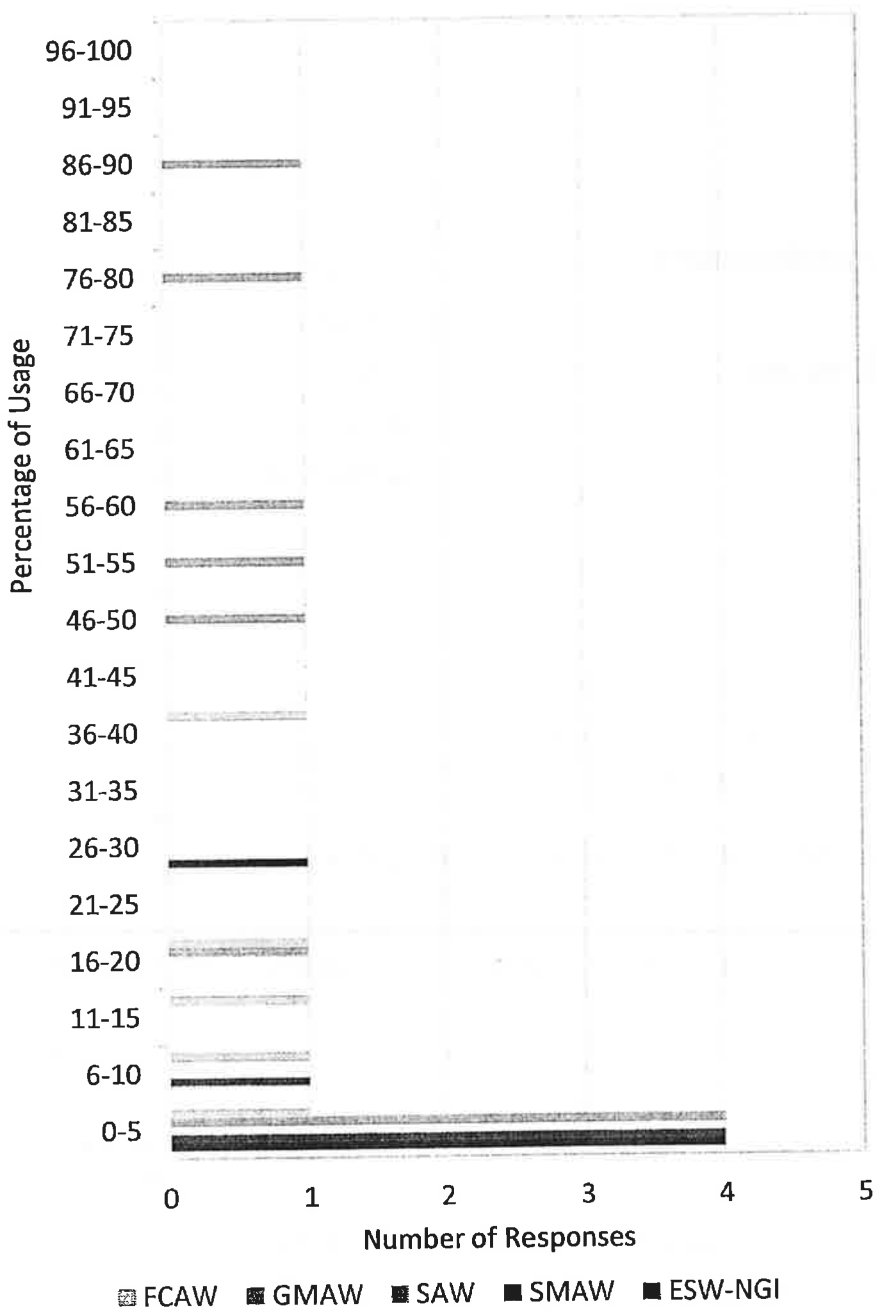
Yes	AFCO, Hirschfeld, High
No	Cianbro, Tampa

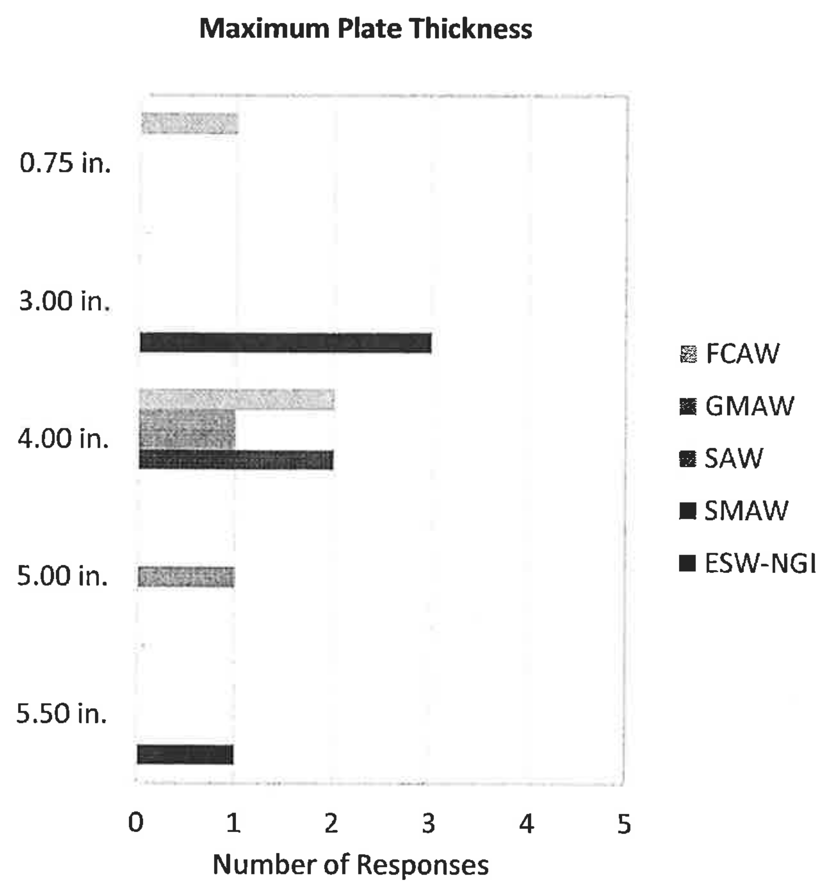
Justification for not allowing ESW-NGI

Organizations	Comments
Cianbro Fabrication and Coating	Not an approved welding process for the DOT's we work for.
Tampa Tank/Florida Structural Steel	Have used in past and will use again but not using right now; waiting for optimal projects configuration

Comments: The reasons for not permitting ESW-NGI are: (*a*) it was not approved by state DOT; and (*b*) it was not a suitable welding process for the projects.

5) Please provide the following information for each process used by your organization for welding steel bridges.

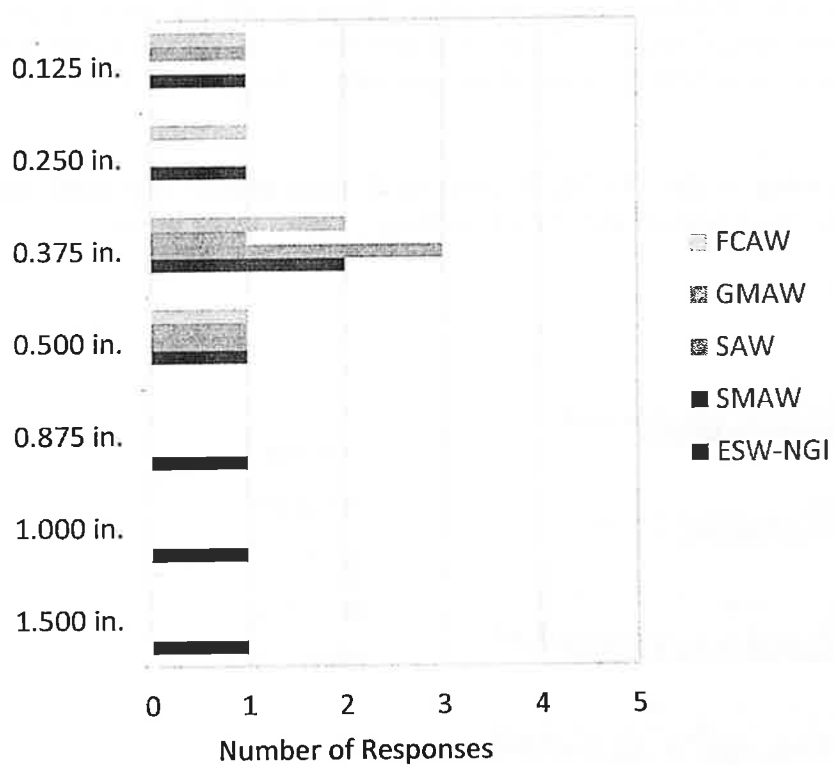




Maximum Plate Thicknesses Used or Specified for Welding Processes

Thickness \ Welding Process	FCAW	GMAW	SAW	SMAW	ESW-NGI
Per AWS D1.5					
0.75 in.	Cianbro				
3.00 in.					AFCO, Hirschfeld, Tampa
4.00 in.	AFCO, Tampa	Tampa	AFCO	AFCO, Tampa	
5.00 in			Tampa		
5.50 in.					High

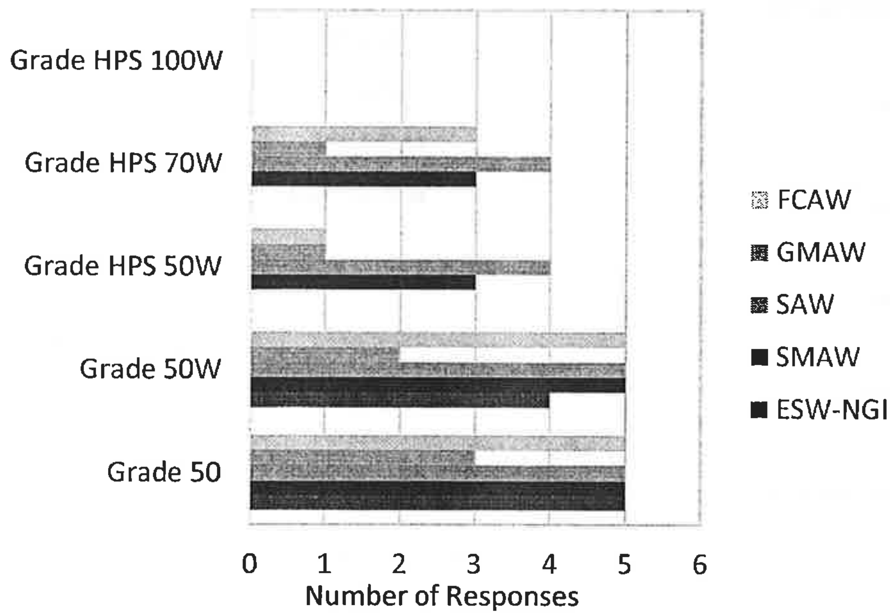
Minimum Plate Thickness



Thickness \ Welding Process	FCAW	GMAW	SAW	SMAW	ESW-NGI
Per AWS D1.5					
0.125 in.	High	High		High	
0.250 in.	Cianbro			Cianbro	
0.375 in.	AFCO, Tampa	Tampa	AFCO, High, Tampa	AFCO, Tampa	
0.500 in	Hirschfeld	Hirschfeld	Cianbro	Hirshfeld	
0.875 in.					AFCO
1.000 in.					Hirshfeld, Tampa
1.500 in.					High

Comments: Most of the steel bridge fabrication is performed by SAW and FCAW is the next. SMAW, GMAW, and ESW-NGI are not commonly used by the fabricators. The maximum thickness fabricated is about 4.0 in for SMAW, SAW, FCAW and GMAW processes, and 5.5 in. for ESW-NGI process. The minimum fabricated plate thickness for the welding processes (except ESW-NGI) mostly ranged betweem $^1/_8$ in. (3.2 mm) and $^1/_2$ in. (13 mm). The minimum fabricated thickness using ESW-NGI process ranged between $^7/_8$ in. (22 mm) and 1.5 in. (38 mm).

6) Which of the following AASHTO M270 structural steel grades are used by your organization for welding steel bridges using each of the processes listed below?



Grade 50

Weld Processes	Allowed Organizations
FCAW	AFCO, Cianbro, Hirschfeld, High, Tampa
GMAW	Cianbro, High, Tampa
SAW	AFCO, Cianbro, Hirschfeld, High, Tampa
SMAW	AFCO, Cianbro, Hirschfeld, High, Tampa
ESW-NGI	AFCO, Cianbro, Hirschfeld, High, Tampa

Grade 50W

Weld Processes	Allowed Organizations
FCAW	AFCO, Cianbro, Hirschfeld, High, Tampa
GMAW	High, Tampa
SAW	AFCO, Cianbro, Hirschfeld, High, Tampa
SMAW	AFCO, Cianbro, Hirschfeld, High, Tampa
ESW-NGI	AFCO, Hirschfeld, High, Tampa

Grade HPS 50W

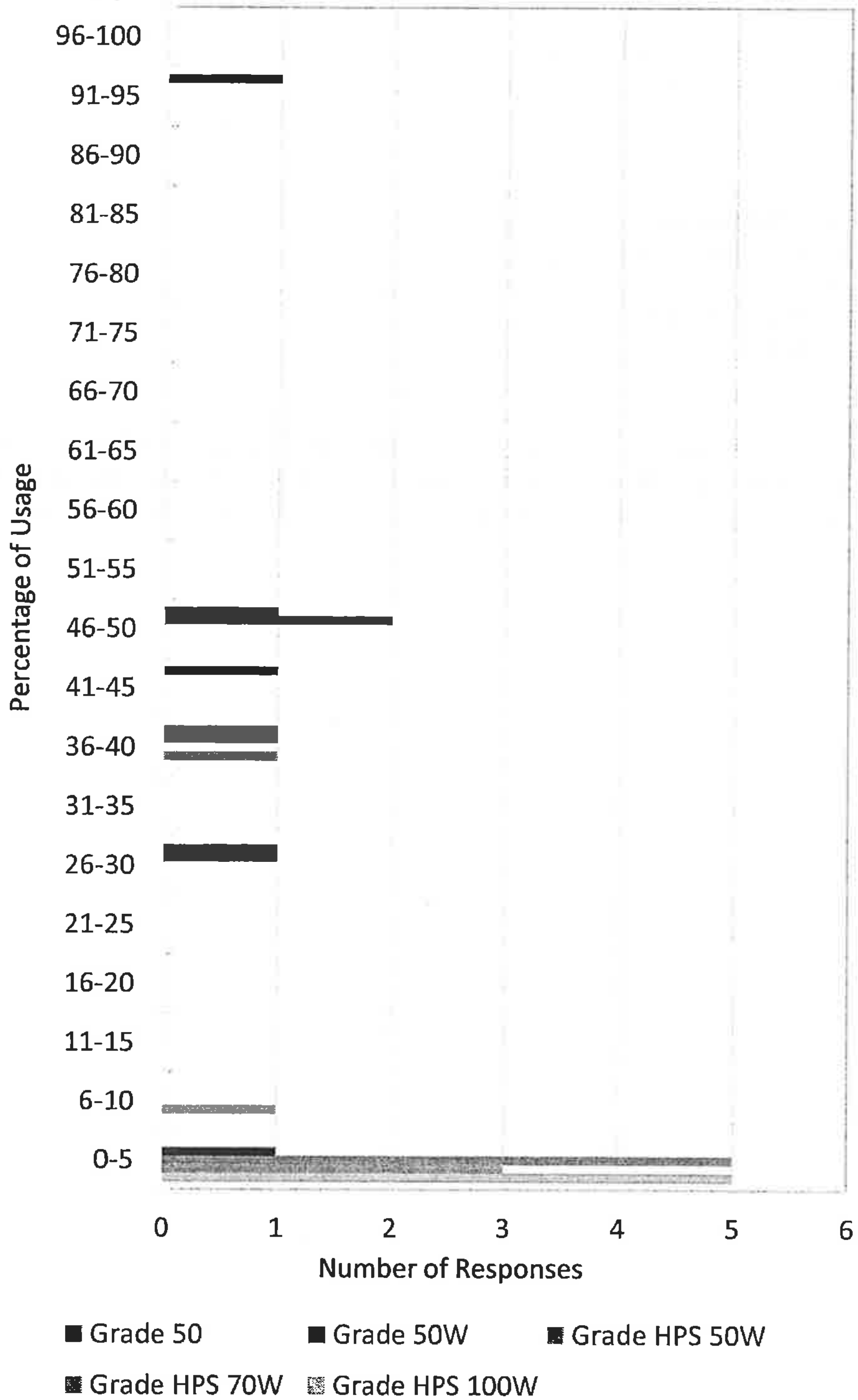
Weld Processes	Allowed Organizations
FCAW	AFCO
GMAW	High
SAW	AFCO, Cianbro, Hirschfeld, High
SMAW	AFCO, Cianbro, High
ESW-NGI	

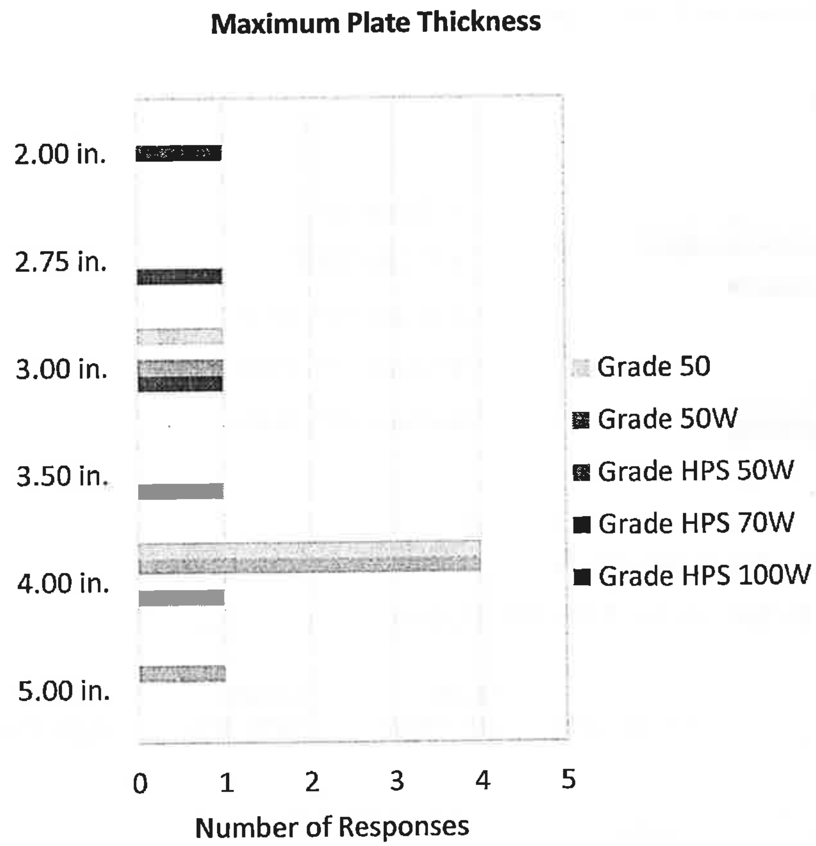
Grade HPS 70W

Weld Processes	Allowed Organizations
FCAW	AFCO, Hirschfeld, Tampa
GMAW	Tampa
SAW	AFCO, Hirschfeld, High, Tampa
SMAW	AFCO, High, Tampa
ESW-NGI	

Comments: All fabricators use Grade 50 and 50W for welding steel bridges, and most of the fabricators use Grade HPS 50W and 70W. However, Grade HPS 100W steel is not used at all by responding fabricators. The usage of ESW-NGI is limited to Grade 50 and 50W steel and not used for HPS steels.

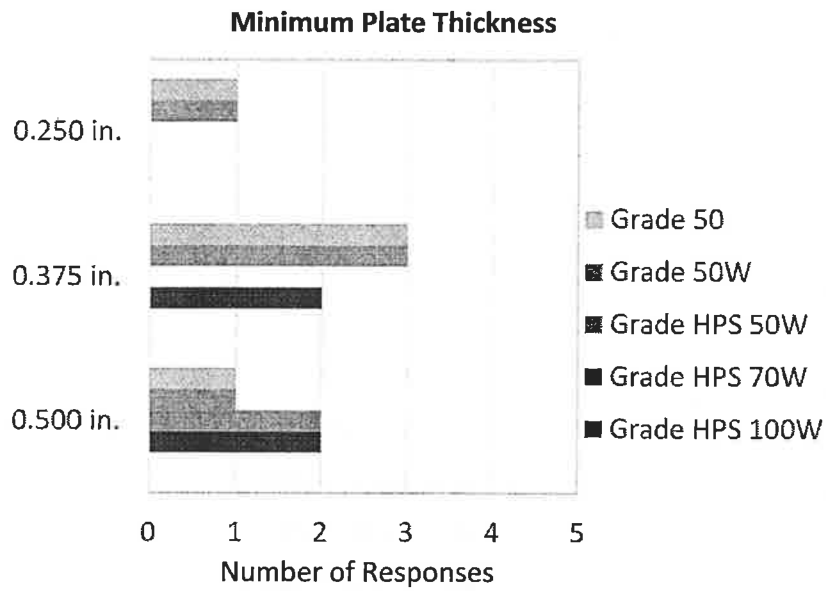
7) Please provide the following information pertaining to steel bridges welded by your organization since 2005. This information is to identify current trends in the usage of each steel grade.





Maximum Used Plate Thicknesses for Each Steel Types

Thickness \ Steel Type	Grade 50	Grade 50W	Grade HPS 50W	Grade HPS 70W	Grade HPS 100W
Per AWS D1.5					
2.00 in.			Cianbro		
2.75 in.				AFCO	
3.00 in.	High		AFCO	Hirschfeld	
3.50 in.				High	
4.00 in.	AFCO, Cianbro, Hirschfeld, Tampa	AFCO, Cianbro, Hirschfeld, Tampa		Tampa	
5.00 in.		High			



Minimum Used Plate Thicknesses for Each Steel Types

Thickness \ Steel Type	Grade 50	Grade 50W	Grade HPS 50W	Grade HPS 70W	Grade HPS 100W
Per AWS D1.5					
0.2500 in.	Cianbro	Cianbro			
0.3750 in.	AFCO, High, Tampa	AFCO, High, Tampa		High, Tampa	
0.5000 in.	Hirschfeld	Hirschfeld	AFCO, Cianbro	AFCO, Hirschfeld	

Comments: The responding fabricators have mostly used Grade 50 and Grade 50W steels for fabricating steel bridges since 2005. Use of HPS grades has been much less. For the bridges using Grade 50 and Grade 50W steels, the maximum thickness 4.0 in. (102 mm) have been used by most of the fabricators. The maximum thickness of Grade HPS 70W steel is prevalent from $2^3/_4$ in. (70 mm) to 4.0 in. (102 mm). The range of the minimum thickness for Grade 50 and Grade 50W is from $^1/_4$ in. (6.4 mm) to $^1/_2$ in. (13 mm) and that of Grade HPS 70W is from $^3/_8$ in. (9.5 mm) to $^1/_2$ in. (13 mm).

8) Which of the following plate thickness transitions are commonly fabricated by your organization?

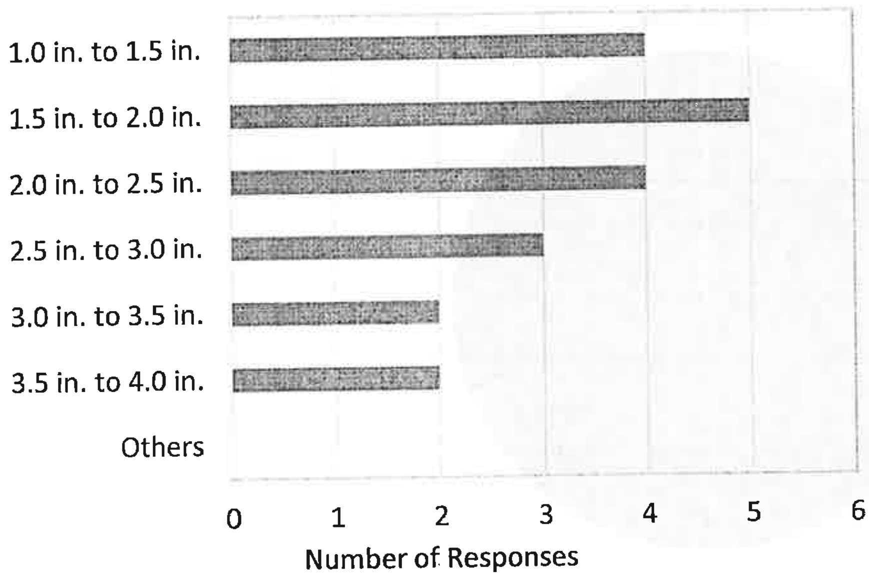
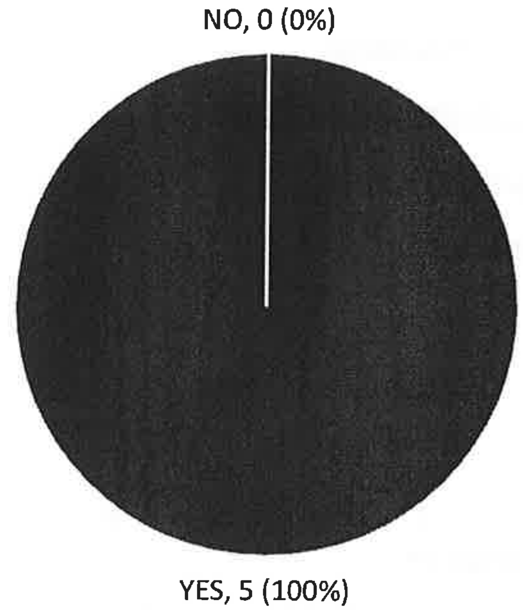


Plate Thickness Transitions	Responded Organizations
1.0 in. to 1.5 in.	AFCO, Hirschfeld, High, Tampa
1.5 in. to 2.0 in.	AFCO, Cianbro, Hirschfeld, High, Tampa
2.0 in. to 2.5 in.	AFCO, Hirschfeld, High, Tampa
2.5 in. to 3.0 in.	AFCO, Hirschfeld, Tampa
3.0 in. to 3.5 in.	Hirschfeld, Tampa
3.5 in. to 4.0 in.	Hirschfeld, Tampa
Others	

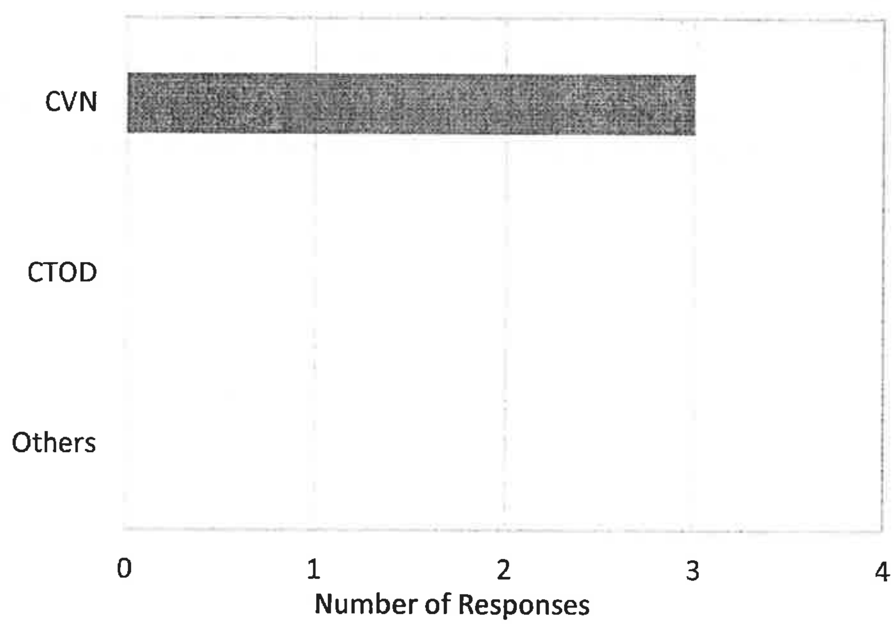
Comments: The commonly specified thickness transitions are between 1.0 in. (25 mm) and 1.5 in. (38 mm), 1.5 in. (38 mm) and 2.0 in. (51 mm), and 2.0 in. (51 mm) and 2.5 in. (64 mm).

9) Does your organization follow any acceptance criteria that considers weldment toughness for steel bridge welding?



Comment: All fabricators follows acceptance criteria of *ASTM A709* or *AWS D1.5* for weldment toughness.

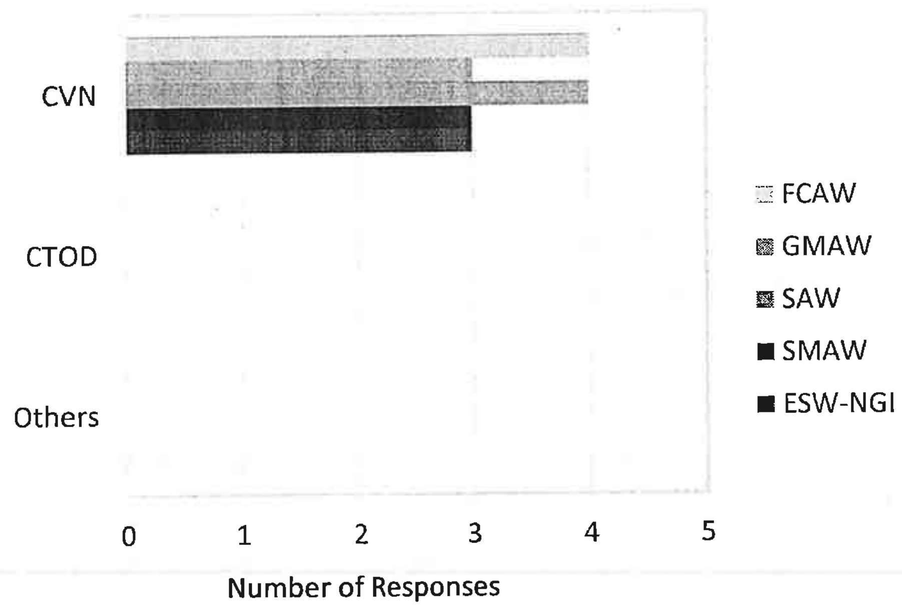
10) As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are followed by your organization?



Test Methods	Responded Organizations
CVN	AFCO, Cianbro, High
CTOD	
Others	

Comments: Three fabricators responded that they conduct CVN testing for HAZ as per *ASTM A709* and *AWS D1.5*. However, these specifications do not provide CVN testing requirement for HAZ.

11) As part of the acceptance criteria, which of the following test methods for HAZ fracture toughness are followed by your organization for each of the welding processes noted below?

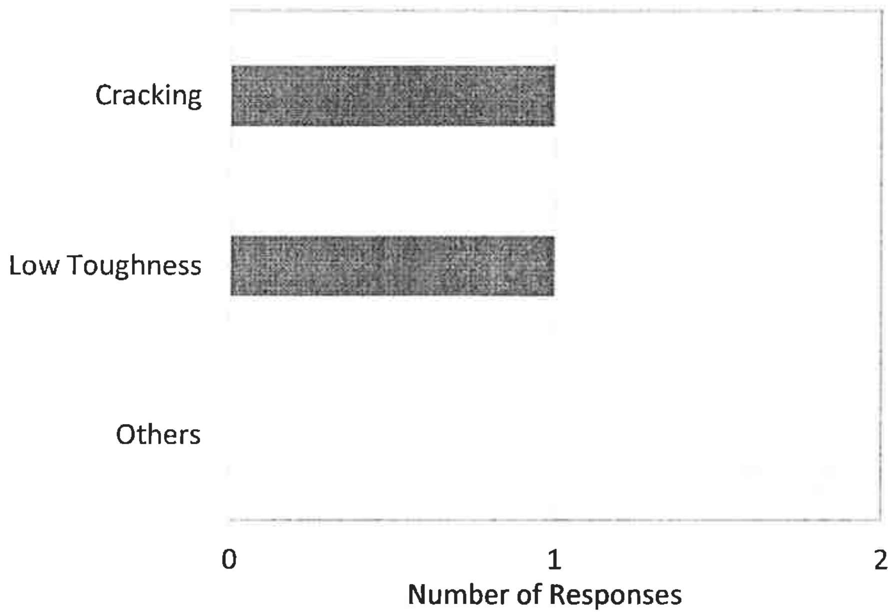


Welding Processes	Responded Organizations
FCAW	AFCO, Cianbro, High, Tampa
GMAW	Cianbro, High, Tampa
SAW	AFCO, Cianbro, High, Tampa
SMAW	AFCO, Cianbro, High
ESW-NGI	AFCO, Cianbro, High

	Welding Procedures				
Organizations	FCAW	GMAW	SAW	SMAW	ESW-NGI
AFCO	Yes	No	Yes	Yes	Yes
Cianbro	Yes	Yes	Yes	Yes	Yes
Hirschfeld	No	No	No	No	No
High	Yes	Yes	Yes	Yes	Yes
Tampa	Yes	Yes	Yes	No	No

Comments: CVN test for all welding processes is followed by most of the fabricators which conduct CVN testing for HAZ

12) Which of the following adverse effects in the HAZ of welded bridge steels have been experienced by your organization?



Adverse Effects	Responded Organizations
Cracking	Cianbro
Low Toughness	High
Others	

Comment: Cracking and low toughness problem were experienced by some fabricators. Detail discussion on these adverse effects is presented in next question.

13) Please provide details related to your experiences with adverse effects in the HAZ of welded bridge steels, if any.

Comments: The cracking in HAZ was experienced when proper preheat was not followed. The low toughness problem found from ESW-NGI and in tandem SAW on HPS steel.