PHASE II WORK PLAN

to the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

on Project 10-95: Toughness Requirements for Heat-Affected Zones of Welded Structural Steels for Highway Bridges

from

Center for Advanced Technology for Large Structural Systems
Lehigh University
Bethlehem, PA

July, 2015

CONTENTS

TABLES

FIGURES

ABBREVIATIONS

BM	Base Metal
CGHAZ	Coarse Grain Heat-Affected Zone
CTOD	Crack Tip Opening Displacement
CVN	Charpy V-Notch
ECA	Engineering Critical Assessment
ESW-NG	Electroslag Welding-Narrow Gap
FAD	Failure Analysis Diagram
FCAW	Flux-Cored Arc Welding
FL	Fusion Line
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
HPS	High Performance Steel
LBZ	Local Brittle Zones
MT	Mid-Thickness
PAUT	Phased Array Ultrasonic Testing
PQR	Procedure Qualification Record
PWHT	Post-Weld-Heat Treatment
QT	Quarter-Thickness
Q&T	Quenched and Tempered
SAW	Submerged Arc Welding
SENB	Single Edge Notched Bend
SMAW	Shielded Metal Arc Welding
SN	Shallow Notched
SS	Sub-Surface
TMCP	Thermo-Mechanically Controlled Process
WM	Weld Metal
WPS	Welding Procedure Specification

1. INTRODUCTION

A detailed work plan for Phase II, as developed in Task 4 of Phase I and reported in the Interim Report dated March 2015 (Roy et al. 2015), is presented in the following. This work plan incorporates the comments received on the Interim Report including those received at the Panel Meeting of May 22, 2015. The Phase II will consist of two tasks, *Task 6: Execute Approved Work Plan* and *Task 7: Prepare Final Report*. The work plan for Task 6 depicts the experimental investigations for developing heat affected zone (HAZ) toughness requirements of welded steel highway bridges. The work plan for Task 7 addresses preparation of final report including development of specification recommendations.

2. WORK PLAN FOR TASK 6: EXECUTE APPROVED WORK PLAN

In Task 6, the fracture toughness requirements will be experimentally determined for the weld HAZ in various grades of *AASHTO M270/ASTM A709* steel plates, where the weldments 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 shielded metal arc welding (SMAW), submerged arc welding (SAW), gas metal arc welding (GMAW), flux cored arc welding (FCAW), and electroslag welding-narrow gap (ESW-NG) processes. All processes, except ESW-NG, are allowed for all grades of *M 270/A 709* steels and for all applications. The use of ESW-NG is restricted to AASHTO temperature Zones 1 and 2, non-fracture critical members and member components, and for non-HPS grades. The steel grade (chemical composition), the welding process (cooling rate), and the component thickness are the primary factors affecting the weldment heat affected zone (HAZ) fracture toughness in bridge steels (Roy et al. 2015). The experiments for Task 6 are designed using these variables, based on the *rationale* discussed in the following. The work plan for Task 6 is distributed into five subtasks as described later.

Rationale for Experiment Design

The survey of the state departments of transportation and the steel bridge fabricators conducted in Task 1 of this project (Roy et al. 2015) revealed that *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 and toughness. Grade HPS 70W is more frequently used compared to HPS 50W, as thicker flange plates for hybrid girders, which can provide an optimum cost-effective solution. It should be noted that the specified chemical composition range 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, and HPS 70W. Since the specified range of 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.

As was noted in Tasks 2 and 3 of the Interim Report (Roy et al. 2015), for a grade of steel (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 specifications of *AWS D1.5*, the process that can most efficiently weld a particular thickness is selected for bridge fabrication. The AWS D.15 does not provide any limitation on heat input; rather the maximum heat input or the maximum-minimum heat input envelope is qualified through testing while developing the weld procedures. 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 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-automatic 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-NG 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 single pass. Both SAW and ESW-NG 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 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 the maximum possible preheat/interpass temperature will slow down the cooling rate, and can produce a coarser HAZ adjacent to the fusion line (FL). The high heat input associated with ESW-NG 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-NG 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 therefore 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. Accordingly, two cooling rates or combination of heat input and preheat/interpass temperature, as allowed by *AWS D1.5,* will be investigated for each welding process, and each steel grade and plate thickness with the objective of producing HAZ of lowest toughness.

The survey of state departments of transportation and steel bridge fabricators performed in Task 1 (Roy et al. 2015) revealed that the SAW process is mostly used for steel bridge fabrication, although all processes, except GMAW and ESW-NG, 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, and HPS 70W for SMAW, GMAW, FCAW, SAW, and ESW-NG 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. If 4.0 in. (102 mm) thick 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. Due to rare use in prevalent steel bridge fabrication, steel grades 36 and HPS 100W are not considered for this study.

Noting that currently the ESW-NG 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 it uses larger heat input for larger thicknesses (which would produce a slower cooling rate). 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. If adequate HAZ toughness can be demonstrated by this pilot study, follow on studies may be performed to address the current *AWS D1.5* limitations against using ESW-NG on HPS grades.

For welding processes other than ESW-NG, the cooling rate in a 4.0 in. (102 mm) thick plate is expected to be faster than that in a 3.0 in. (76 mm) thick plate, when welded with an identical combination of heat input and preheat/interpass temperature. With ESW-NG process, the heat input for the thicker plate will be larger, producing a slower cooling rate. Thus, the HAZ fracture toughness of 4.0 in. (102 mm) thick plate would be more critical than the 3.0 in. (76 mm) thick plate for all welding processes producing either faster or slower cooling rates. It may also be noted that for multipass welds the most critical coarse grained HAZ (CGHAZ) is produced by the capping pass. A suitable weld procedure with appropriate heat input and preheat/interpass temperature can be developed to reproduce similar critical HAZ condition of the multipass weld in a 3.0 in. (76 mm) thick plate as in a 4.0 in. (102 mm) thick plate.

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 steel. 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 steel, and on 2.0 in. (51 mm) thick plate of Grade 50 steel. Although GMAW process is typically not efficient for a thickness beyond $^5/_8$ in. (16 mm), it is proposed to be evaluated on 1.0 in. (25 mm) thick plates for all considered steel grades as an extreme condition.

For steel bridge fabrication, stress relieving post weld heat treatment (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 surveys of state departments of transportation and the steel bridge fabricators revealed that such treatments are rare and only used for highly restrained joints (Roy et al. 2015). 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 quenched and tempered (Q&T) steels can also degrade their toughness and strength. Accordingly, the effect of PWHT on HAZ fracture toughness has been excluded from the current study.

The influence of plate thickness transition is proposed to be evaluated by full scale tests using ESW-NG process. The surveys of state departments of transportation, and the steel bridge fabricators (Roy et al. 2015) 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 steel has been proposed.

For each combination of investigated steel grade, welding procedure, and thickness, the HAZ toughness will be measured by Charpy V-Notch (CVN) tests and will be verified by limited crack tip opening displacement (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 1 to 24 and are further discussed later in the text.

As noted earlier, the chemical composition of the base metal (BM) is one of the two primary variables affecting HAZ fracture toughness. Within the limits of the specifications, significant variability in chemical composition exists among the steels of same grade and thickness but from different heats. Accordingly, it is proposed to test specimens from randomly selected plates that are produced from different heats. Effective accomplishment of this goal may require procuring cut-pieces of steel plates of a specific grade and thickness but different heats from steel plate resellers. Other possibility might be procuring plate droppings from steel bridge fabricators. To avoid confounding the test results, effect of multiple heats will be considered selectively, where sufficient replicates are available to produce a statistically significant conclusion. Without knowing the availability of plates from different heat, this variable has not been explicitly identified in the test matrix at this time.

For an assessment of BM and WM contributions to the HAZ toughness, it is also proposed to determine BM and WM fracture toughness by CVN testing for each welding condition.

In addition, it is proposed to evaluate HAZ fracture toughness for all welding processes in Grade 50W steel by full scale tests, under the most severe service temperature. The purpose of these tests is to determine the significance of the weld HAZ fracture toughness as determined from the small scale tests on the integrity of full size structures. The literature review performed under Task 1 of this project (Roy et al. 2015) revealed that fractures of full size structures in service, such as bridges (Konkol et al. 1987), offshore structures (Webster and Bateson 1990), and others have never been reported, although low fracture toughness of HAZ was obtained from small scale specimens due to the presence of local brittle zone (LBZ). The different fracture behavior of full size structures from small scale specimens is possible due to the difference in actual strain field around the LBZ, and therefore the full scale fracture tests are necessary to assess this size effect and accurate interpretation of the small scale test results. The proposed full scale tests are discussed in detail under Subtask 6.4, including the relationship of the proposed tests to actual bridge construction. The test matrix is presented in Table 25.

Vickers hardness (HV10) of the BM, HAZ and the WM of each CVN and CTOD specimen will be measured at locations schematically identified in Figure 1. 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, where the weld axis is normal to the plate rolling direction. 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, as shown in Figure 2, will be used for the groove welded plate to obtain a vertical HAZ at the vertical edge of the joint preparation. The CVN and CTOD test specimens for HAZ will be prepared from this vertical side. As reported under literature review in Task 1 (Roy et al. 2015), 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. With a single-vee (such as prequalified *AWS D1.5* joint designation B-U2a-GF or B-U2-S) or a double-vee joint configuration for thinner or thicker plates respectively, which are more commonly used for groove welded splices, the fracture initiating in the HAZ tends to deviate into the BM, confounding the true fracture toughness of the HAZ (Bateson and Webster, 1990). 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. The welding will be performed in 1G position. For the largest possible arc angle with the vertical face of the joint for producing the maximum HAZ, the plates will be tilted 45 degrees with respect to the horizontal as shown in Figure 2. A flat position variant of prequalified *AWS D1.5* joint BU-4b or B-U4b-GF was considered with a small root gap and without a backing bar, however it limits the number of specimens that can be procured at the critical subsurface region.

For ESW-NG, 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 (normal to the plate rolling direction, commonly designated as L-S, where L is the length or the rolling direction, and S is the short transverse or the thickness direction.) For the CVN specimens in the WM and the BM, the notch will be oriented in the plane of the plate normal to the rolling direction (commonly designated as L-T direction, where T is the long transverse or width direction) to determine the lower bound fracture toughness. It is well known that the grains in the plate BM tend to elongate in the rolling direction, proviBding the largest toughness in the L-S direction, the least toughness in the S-L direction, and an intermediate toughness in the L-T direction. The fracture toughness in the S-L direction is of little concern unless the plate is extremely thick, where banding or segregation can lead to lower toughness and lamellar tearing, or under weld-bead cracking. In the CGHAZ, however, the grains become equiaxed due to recrystallization and growth, eliminating the effect of rolling direction. For HAZ, the natural direction of fracture propagation is normal to the plate surface initiating at the HAZ of the capping pass, and the notch orientation is selected accordingly.

For each weld process, the CVN and CTOD test specimens for the HAZ and the CVN test specimens for the WM and the BM will be produced from the same groove welded plate. The HAZ and the WM 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 Metallic Materials - Methods of Test for the Determination of Quasistatic Fracture Toughness of Welds.*

Plan for CVN Testing

The CVN tests for HAZ will be conducted at subsurface (SS), and at mid-thickness (MT) of the plates (Figure 3). The SS tests will be performed both at top and bottom surfaces and these locations are identified as SS-1 and SS-2 respectively. 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 be 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+0.5 mm are devised to capture the effect of LBZ in the CGHAZ adjacent to the FL, which is the most severe within the HAZ of the capping pass for a multipass weld. The tests with notch at the FL+5 mm are proposed to capture any possible embrittlement in the SCHAZ that has been reported in the literature. This test position may be adjusted commensurate with the actual SCHAZ. Since ESW-NG 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).

The CVN tests for BM will be conducted at P-frequency according to *ASTM 673-07: Standard Specification for Sampling Procedure for Impact Testing of Structural Steel.* The specimens will be sampled at quarter thickness (QT) of the plates (Figure 4).

For WM, the CVN test specimens will also be sampled at QT position of the plates (Figure 4). This will result in sampling at the mid-thickness of a bevel for the proposed K-joint configuration.

In all cases, three replicates will be tested at each location for each test temperature, except for WM during the pilot study (see discussion later), where five replicates are considered as recommended by the *AASHTO/AWS D1.5* specifications for WPS qualification tests. Most specifications require three replicates for CVN testing at each sampling location (Figure 3). Since all thicknesses are being sampled at two thickness positions for HAZ tests, three replicates at each position would provide a statistically significant data set for fracture toughness evaluation. This approach is also consistent with other previous research. In addition to providing replicates, the CVN tests of HAZ 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 for HAZ will be performed at three temperatures to capture the lower shelf fracture toughness. For grades 50 and 50W steels, the tests will be conducted at 10°F (-12°C), 40°F (4°C), and 70°F (21°C) respectively, in line with the *AASHTO LRFD Bridge Design Specifications* (BDS) for BM in fracture critical members with these steel grades. For Grade HPS 70W, the HAZ will be tested at –10°F (–23°C), 10°F (–12°C), and 40°F (4°C). Note that *AASHTO LRFD BDS* specifies only one test temperature of –10°F (–23°C) for BM for this steel. Based on preliminary test results the test temperatures may have to be adjusted for capturing the lower shelf impact toughness.

The CVN tests for BM will be performed at the largest and the smallest temperatures for the different steel grades noted in the previous paragraph.

The CVN tests for WM will be performed at only one temperature corresponding to AASHTO temperature zone III (same as zone 3 in BDS) as specified in the *AASHTO/AWS D1.5* for different grades of steel and welding processes.

The test matrices for CVN testing are shown in Tables 1 to 18 for each steel grade and each test temperature. Each cell of the matrix shows the replicates to be tested for the particular condition at the test temperature. The values in the parentheses represent the tests to be conducted in the pilot study under Subtask 6.1 (see discussion later.)

The CVN testing will be performed according to *ASTM E23-12c: Standard Test Methods for Notched Bar Impact Testing of Metallic Materials*. In addition, the HAZ microstructure at the notch location and on the fracture surface will be evaluated by post-test metallography and fractography.

Plan for CTOD Testing

The CTOD tests will be conducted only for HAZ using a single edge notch bend specimen (SENB) with a shallow surface notch ($a/W{\sim}0.15$) 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 notch (SN) is proposed as it more realistically represents the constraint condition of a likely flaw in the HAZ that may remain undetected by radiographic or ultrasonic testing during fabrication. In line with the rationale provided for the CVN testing in the previous section, the notch of the CTOD test specimens will be located in the CGHAZ within 0.02 in. (0.5 mm) from the FL for SMAW, GMAW, FCAW and SAW processes; for ESW-NG process, the notch will be located at 0.08 in. (2 mm) from the FL.

The test matrices for CTOD testing for different steel grades and test temperatures are shown in Tables 19 to 24. Each cell of the test matrices 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. Only a limited number of CTOD tests will be performed at the bridge loading rate (rise time to maximum load of approximately 1.0 sec.) and dynamic loading rate (rise time to maximum load of approximately 0.001 sec.), and each at two temperatures depending on the grade of steel and loading rate. Two replicates of CTOD tests will be performed for each combination. All CTOD tests will be performed for the most critical weld procedure determined from CVN testing.

The purpose of the CTOD testing is to capture any low fracture toughness exhibited by the LBZs at the lower shelf, and to determine the loading rate effects on the HAZ fracture toughness. For BM, several correlations between the plane strain fracture toughness at the slow loading rate and the CVN impact toughness under dynamic loading are available in the literature (Bannister 1998). This limited exercise is to verify if similar relationship can be established for HAZ. Distribution of CTOD and CVN testing for all weld processes, steel grades and plate thickness are compared in Table 26, demonstrating that the planned CTOD testing would be adequate for the purpose.

Grades 50 and 50W steels will be tested at –60°F (–51°C) and 0°F (–18°C), and 10°F (–12°C) and 70°F (21°C) respectively under the bridge and dynamic loading rates. Similarly, grade HPS 70W steel will be tested at –60°F (–51°C) and 0°F (–18°C), and –10°F (–23°C) and 40°F (4°C). The test temperatures may have to be adjusted based on preliminary test results to capture the lower shelf fracture toughness.

The tests will be performed according to *BS EN ISO 15653:2010* and *ASTM E1820-13: Standard Test Method for Measurement of Fracture Toughness*. 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.

Subtask 6.1: Pilot CVN and CTOD Testing of HAZ, WM and BM

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. The ESW-NG process will not be considered in this subtask, since well-developed procedures for this process with square joints exist with fabricators owning this technology.

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 Figure 5. 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 CVN tests on BM will be conducted from the PQR plates corresponding to the most critical of high and low heat inputs as determined from the HAZ testing.

Two procedures for each of the above weld processes will be qualified as per *AWS D1.5*, considering the combination of maximum and the minimum possible heat input and preheat/interpass temperature for a particular steel grade and plate thickness that would produce the slowest and the fastest cooling rate in the WM and the HAZ, and an acceptable weld quality. These procedures are expected to produce the least WM and HAZ fracture toughness within the stipulations of current *AWS D1.5*.

The *AWS D1.5* does not provide any limitation on heat input; rather the maximum heat input or the maximum-minimum heat input envelope is qualified through testing while developing the weld procedures. The maximum-minimum heat input method will be followed for this study.

The *AWS D1.5* provides requirements for minimum preheat/interpass temperatures to prevent weld cracking. The generic recommendations in Table 4.3 of the 2010 specifications are adequate in most cases. Depending on steel composition, thickness and restraint, Annex G of the specification provides alternative methods for determining preheat/interpass temperatures, either by controlling HAZ hardness through cooling rate, or by controlling diffusible hydrogen in the weld through adequate preheat/interpass temperature and/or use of suitable filler metals (of desired hydrogen content). The specifications also include provisions of lower preheat/interpass temperatures for HPS 70W, when used in non-fracture critical members welded with specific low hydrogen electrodes. Additional limits on the maximum and the minimum preheat/interpass temperatures are specified as part of WPS qualifications. In most cases, the generic recommendations of Table 4.3 provides a lower preheat/interpass temperature that would provide the faster cooling rate when used with the minimum possible heat input. The hardness control methodology in Annex G gives the allowable maximum cooling rate and corresponding minimum heat input for a given plate thickness to produce critical hardness for a steel composition. The nomographs included in the specifications are developed for single SAW fillet welds without any preheat, and using filler metals that are appropriate for plain C- and C-Mn steels (i.e., not very high strength filler metal) with low diffusible hydrogen content. Direct applicability of this information for the current study is limited.

Thus, the qualified weld procedures those incorporating combinations of heat input and preheat/interpass temperature for a particular steel grade and plate thickness that would produce the slowest and the fastest cooling rate in the WM and the HAZ will be developed experimentally as part of this subtask. Several trials will be performed in collaboration with specimen fabricators to develop these limiting weld procedures. Although the cooling rate controls the HAZ toughness for a given steel composition, it may be noted that the actual cooling rates will not to be considered explicitly in this study. Rather, they will be considered implicitly within the WPS in terms of heat input and preheat/interpass temperature. This approach is consistent with the current *AWS D1.5* specifications. Any relevant specification recommendation out of the current research is expected to be developed similarly in terms of limitations on heat input and/or preheat/interpass temperatures.

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 1 to 18), taking advantage of the PQR tests plates. The subset is identified by the number of replicates shown in parentheses in the test matrices. The thickness of the PQR test plates has been proposed 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 and CTOD testing will be performed as discussed earlier. In this subtask, 756 CVN and 32 CTOD specimens will be tested for HAZ. In addition, for BM and WM respectively 72 and 120 CVN 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 procedure will be identified for each process, steel grade and plate thickness, for consideration in the subsequent subtasks.

Subtask 6.2: CVN Testing of HAZ, WM and BM

In this subtask, CVN testing of HAZ, WM and BM will be performed based on the protocols established in Subtask 6.1. Only the critical weld procedure developed in Subtask 6.1 for each weld process, steel grade and plate thickness will be considered in this subtask. Refer

Tables 1 to 18 for the CVN test matrices. Altogether 684 CVN tests will be performed in this subtask.

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. Only the critical weld procedure developed in Subtask 6.1 for each weld process, steel grade and plate thickness will be considered in this subtask. Refer Tables 19 to 24 for the CTOD test matrices.

Subtask 6.4: Testing Full Scale Specimens

The significance of HAZ fracture toughness (determined in the previous subtasks) on full size structures will be assessed by testing full scale plate specimens under axial loading. The rationale for these tests is presented under *Rationale for Experiment Design*. These specimens will have a T-section, comprising a part web and a part flange of a full size I-girder as shown in (Figure 6). The flange of the T-specimens will include two groove welded splices. A full size girder, sans the T-section specimen, will be fabricated as a fixture (Figure 7). The T-specimens will be attached to the fixture girder using bolted splices, and the built-up girder will be tested under flexure as shown in Figure 8, 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-NG 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-NG process will be tested. Thus, six replicates of each weld process/configuration will be tested, which would enable statistically significant conclusions. 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-NG, 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 25.

The proposed specimen is representative of the tension flange and flange splice of a typical I-girder that is the most common structural form used in highway bridges. The specimen also simulates the details of a box girder web and flange in tension, noting that a box girder can be idealized by two I-girders with the bottom flanges connected by a plate. For steel-concrete composite construction the top flange of the box girder is similar to an I-section. As is well understood, the HAZ of the groove-welded tension flange splice is the most critical detail for fracture assessment. The proposed plate thicknesses are also representative of steel bridges in service, as was revealed by the surveys performed in Task 1 (Roy et al. 2015).

The specimens will be tested under cyclic loading to promote fatigue crack growth into the CGHAZ from the toe of the weld reinforcements. Irrespective of the width of the HAZ, a fatigue crack initiating at the weld toe will propagate into the CGHAZ adjacent to the FL, as has been demonstrated by numerous full scale fatigue test results available in the literature. 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) and promotes fatigue cracking at the weld toe. Similar to commonly performed fatigue pre-cracking of smalls scale specimens, the purpose of the fatigue cycling is to introduce sharp crack tip condition at LBZ within the CGHAZ. The splice details will be cooled down to –60°F (–51°C), the service temperature for

AASHTO Zone 3, at regular intervals, and the cyclic 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 crack growth 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 lead to unstable fracture under the cyclic loading, efforts will be made to promote unstable crack growth under a higher static loading not exceeding the nominal yield stress (50 ksi or 350 MPa) of the material in the flange. The testing will be continued until brittle fracture could be developed in the specimen or until the specimen develops large fatigue cracking 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.

It may be noted that similar testing methodology (but with a full girder specimen, which is different from the current proposed specimen) was adopted by Roberts et al. (1977) for determining tolerable flaw sizes in full size welded bridge details. The proposed tests, however, are different than the fatigue testing of full size girders having flange splices produced by standard gap and narrow gap ESW process (Wood and Devletian 1987), which was conducted to assess the fatigue performance of the improved ESW-NG process.

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 and WM 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 size structures may be assessed by Engineering Critical Assessment (ECA) calculations utilizing the Failure Assessment Diagram (FAD) in accordance with *BS7910:2005* Level 2. This assessment is a failure analysis technique considering both the possibilities of brittle fracture, and plastic collapse by net section yielding. The FAD is an interaction diagram of ratios of toughness demand to material fracture toughness (as ordinate), and net section stress to flow stress (as abscissa). The region of the diagram towards the origin is the safe side. *BS7910* provides guidance for establishing this diagram for different levels of refinement. For a given condition of flaw geometry, loading, and material if the point obtained from plotting the two parameters lies within the safe region, failure would be unlikely. The FAD graphically represents the degree to which both the failure modes contribute to the risk of structural failure. It is envisaged to analyze the full scale test results with respect to the material fracture toughness obtained from the small scale tests, and the material stress-strain data to assess the significance of the HAZ fracture toughness on steel highway bridges.

It is anticipated that the fracture toughness requirements will be defined in terms of impact energy absorbed per CVN testing, consistent with the AASHTO specifications for BM and WM. In addition, any limitations on cooling rate in the HAZ as determined from the current research are expected to be implemented in terms of limitations on heat input and preheat/interpass temperature, consistent with the current specifications.

It is estimated that 1632 CVN specimens, 120 CTOD specimens and 18 full scale specimens will be tested.

3. WORK PLAN FOR TASK 7: PREPARE FINAL REPORT

In this task, a final report will be prepared for the entire research project, along with a draft of the proposed specifications for HAZ toughness. The specifications and the 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*.

A tentative outline of the project's final report based on the research team's current thinking of the content and the structure is presented in Figure 9. It is envisaged that the report will contain five chapters and 11 appendices.

Chapter 1 will introduce the problem statement, the research objective, and the scope of study.

Chapter 2 will present the current state of the art as determined from the literature review and surveys of the steel bridge owners and fabricators, discuss the research approach, and provide the details of the experimental studies containing experiment design, test matrices, specimen preparation, and test methodology.

Chapter 3 will contain the summary of research findings including the results of CVN, CTOD and full scale testing.

Chapter 4 will provide interpretation and appraisal of results and will assess the significance of HAZ fracture toughness on integrity of steel bridges. This chapter will also include application examples as appropriate.

Chapter 5 will summarize the research conclusions and recommend any future research.

Relevant details of the study and the proposed specifications will be provided in the appendices. The details proposed to be included are the surveys, the details of specimen preparation, material properties, weld procedure specification, welder certification, individual test results, and any other relevant information produced during the study.

A draft copy of the report and the specifications will be submitted three months before the project end date to enable review by the NCHRP. It is anticipated that the NCHRP will take two months to review the report. The revision of the report incorporating all comments from NCHRP will be completed within one month of receiving the comments.

TABLES

Table 1 HAZ CVN Test Matrix for Grade 50 Steel at 10°F (−12°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes: GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
50	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	3
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		SS-2	FL+0.5mm		—		3		3		3	3
	4.0	SS-1	FL+0.5mm		—		—		—	(3)	(3)	3
			FL+5mm		—		—		—	(3)	(3)	3
		MT	FL+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 150; CVN specimens for Subtask 6.1 = 84
5. Legend:
   - SS-x = sub-surface at surface x
   - MT = mid-thickness
   - LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   - HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 2 HAZ CVN Test Matrix for Grade 50 Steel at 40°F (4°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
				Welding Processes								
50	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	3
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		SS-2	FL+0.5mm		—		3		3		3	3
	4.0	SS-1	FL+0.5mm		—		—		—	(3)	(3)	3
			FL+5mm		—		—		—	(3)	(3)	3
		MT	FL+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 150; CVN specimens for Subtask 6.1 = 84
5. Legend:
   SS-x = sub-surface at surface x
   MT = mid-thickness
   LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 3 HAZ CVN Test Matrix for Grade 50 Steel at 70°F (21°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes: GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
50	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	3
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		SS-2	FL+0.5mm		—		3		3		3	3
	4.0	SS-1	FL+0.5mm		—		—		—	(3)	(3)	3
			FL+5mm		—		—		—	(3)	(3)	3
		MT	FL+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 150; CVN specimens for Subtask 6.1 = 84
5. Legend:
    SS-x = sub-surface at surface x
    MT = mid-thickness
    LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
    HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 4 HAZ CVN Test Matrix for Grade 50W Steel at 10°F (–12°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes								
				GMAW		FCAW		SMAW		SAW		ESW-NG
				LH	HH	LH	HH	LH	HH	LH	HH	
50W	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	3
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		SS-2	FL+0.5mm		—		3		3		3	3
	4.0	SS-1	FL+0.5mm		—		—		—	(3)	(3)	3
			FL+5mm		—		—		—	(3)	(3)	3
		MT	FL+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 150; CVN specimens for Subtask 6.1 = 84
5. Legend:
   - SS-x = sub-surface at surface x
   - MT = mid-thickness
   - LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   - HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 5 HAZ CVN Test Matrix for Grade 50W Steel at 40°F (4°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes								
				GMAW		FCAW		SMAW		SAW		ESW-NG
				LH	HH	LH	HH	LH	HH	LH	HH	
50W	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	3
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		SS-2	FL+0.5mm		—		3		3		3	3
	4.0	SS-1	FL+0.5mm		—		—		—	(3)	(3)	3
			FL+5mm		—		—		—	(3)	(3)	3
		MT	FL+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 150; CVN specimens for Subtask 6.1 = 84
5. Legend:
   SS-x = sub-surface at surface x
   MT = mid-thickness
   LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 6 HAZ CVN Test Matrix for Grade 50W Steel at 70°F (21°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes: GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
50W	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	3
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	3
		SS-2	FL+0.5mm		—		3		3		3	3
	4.0	SS-1	FL+0.5mm		—		—		—	(3)	(3)	3
			FL+5mm		—		—		—	(3)	(3)	3
		MT	FL+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 150; CVN specimens for Subtask 6.1 = 84
5. Legend:
   SS-x = sub-surface at surface x
   MT = mid-thickness
   LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 7 HAZ CVN Test Matrix for Grade HPS 70W Steel at –10°F (–23°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes: GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
HPS 70W	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	—
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(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+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 138; CVN specimens for Subtask 6.1 = 84
5. Legend:
   - SS-x = sub-surface at surface x
   - MT = mid-thickness
   - LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   - HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 8 HAZ CVN Test Matrix for Grade HPS 70W Steel at 10°F (−12°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes: GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
HPS 70W	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3^6		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	—
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(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+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 138; CVN specimens for Subtask 6.1 = 84
5. Legend:
   SS-x = sub-surface at surface x
   MT = mid-thickness
   LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 9 HAZ CVN Test Matrix for Grade HPS 70W Steel at 40°F (4°C)

Grade of Steels	Thickness, in.	Specimen Locations in Plate Thickness	Notch Locations	Welding Processes								
				GMAW		FCAW		SMAW		SAW		ESW-NG
				LH	HH	LH	HH	LH	HH	LH	HH	
HPS 70W	1.0	SS-1	FL+0.5mm	(3)	(3)		3		—		3	—
			FL+5mm	(3)	(3)		3		—		3	—
		SS-2	FL+0.5mm		3[6]		3		—		3	—
	2.0	SS-1	FL+0.5mm		—	(3)	(3)	(3)	(3)		3	—
			FL+5mm		—	(3)	(3)	(3)	(3)		3	—
		MT	FL+0.5mm		—	(3)	(3)	(3)	(3)		—	—
			FL+5mm		—	(3)	(3)	(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+0.5mm		—		—		—	(3)	(3)	—
			FL+5mm		—		—		—	(3)	(3)	3
		SS-2	FL+0.5mm		—		—		—		3	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 138; CVN specimens for Subtask 6.1 = 84
5. Legend:
   - SS-x = sub-surface at surface x
   - MT = mid-thickness
   - LH = lowest possible combination of heat input and preheat/interpass temperature producing the fastest cooling rate - to be decided
   - HH = highest possible combination of heat input and preheat/interpass temperature producing the slowest cooling rate - to be decided
6. For Subtask 6.2 consider the most critical of LH and HH

Table 10 Weld Metal CVN Test Matrix for Grade 50 Steel at –20°F (–29°C)

Grade of Steels	Thickness, in.	Welding Processes: GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
50	1.0	(5)	(5)		3[7]		—		3	—
	2.0		—	(5)	(5)	(5)	(5)		3	3
	4.0		—		—		—	(5)	(5)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 55; CVN specimens in Subtask 6.1 = 40
5. All specimens to be sampled at quarter-thickness of the plate
6. Legend:
   LH = lowest possible combination of heat input and preheat/interpass temperature producing fastest cooling rate - to be decided
   HH = highest possible combination of heat input and preheat/interpass temperature producing slowest cooling rate - to be decided
7. For Subtask 6.2 consider the most critical of LH and HH

Table 11 Weld Metal CVN Test Matrix for Grade 50W at Steel –20°F (–29°C)

Grade of Steels	Thickness, in.	Welding Processes: GMAW LH	GMAW HH	FCAW LH	FCAW HH	SMAW LH	SMAW HH	SAW LH	SAW HH	ESW-NG
50W	1.0	(5)	(5)		3[7]		—		3	—
	2.0		—	(5)	(5)	(5)	(5)		3	3
	4.0		—		—		—	(5)	(5)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 55; CVN specimens in Subtask 6.1 = 40
5. All specimens to be sampled at quarter-thickness of the plate
6. Legend:
   LH = lowest possible combination of heat input and preheat/interpass temperature producing the fastest cooling rate - to be decided
   HH = highest possible combination of heat input and preheat/interpass temperature producing the slowest cooling rate - to be decided
7. For Subtask 6.2 consider the most critical of LH and HH

Table 12 Weld Metal CVN Test Matrix for Grade HPS 70W Steel at –25°F (–32°C)

Grade of Steels	Thickness, in.	Welding Processes								
		GMAW		FCAW		SMAW		SAW		
		LH	HH	LH	HH	LH	HH	LH	HH	ESW-NG
HPS 70W	1.0	(5)	(5)		3[7]		—		3	—
	2.0		—	(5)	(5)	(5)	(5)		3	—
	4.0		—		—		—	(5)	(5)	3

Notes:

1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 52; CVN specimens in Subtask 6.1 = 40
5. All specimens to be sampled at quarter-thickness of the plate
6. Legend:
   LH = lowest possible combination of heat input and preheat/interpass temperature producing the fastest cooling rate - to be decided
   HH = highest possible combination of heat input and preheat/interpass temperature producing the slowest cooling rate - to be decided
7. For Subtask 6.2 consider the most critical of LH and HH

Table 13 Base Metal CVN Test Matrix for Grade 50 Steel at 10°F (–12°C)

Grade of Steels	Thickness, in.	Welding Processes				
		GMAW	FCAW	SMAW	SAW	ESW-NG
50	1.0	(3)	3	—	3	—
	2.0	—	(3)	(3)	3	3
	4.0	—	—	—	(3)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 27; CVN specimens in Subtask 6.1 = 12
5. All specimens to be sampled at quarter-thickness of the plate

Table 14 Base Metal CVN Test Matrix for Grade 50 Steel at 70°F (21°C)

Grade of Steels	Thickness, in.	Welding Processes				
		GMAW	FCAW	SMAW	SAW	ESW-NG
50	1.0	(3)	3	—	3	—
	2.0	—	(3)	(3)	3	3
	4.0	—	—	—	(3)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 27; CVN specimens in Subtask 6.1 = 12
5. All specimens to be sampled at quarter-thickness of the plate

Table 15 Base Metal CVN Test Matrix for Grade 50W Steel at 10°F (–12°C)

Grade of Steels	Thickness, in.	Welding Processes				
		GMAW	FCAW	SMAW	SAW	ESW-NG
50W	1.0	(3)	3	—	3	—
	2.0	—	(3)	(3)	3	3
	4.0	—	—	—	(3)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 27; CVN specimens in Subtask 6.1 = 12
5. All specimens to be sampled at quarter-thickness of the plate

Table 16 Base Metal CVN Test Matrix for Grade 50W Steel at 70°F (21°C)

Grade of Steels	Thickness, in.	Welding Processes				
		GMAW	FCAW	SMAW	SAW	ESW-NG
50W	1.0	(3)	3	—	3	—
	2.0	—	(3)	(3)	3	3
	4.0	—	—	—	(3)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 27; CVN specimens in Subtask 6.1 = 12
5. All specimens to be sampled at quarter-thickness of the plate

Table 17 Base Metal CVN Test Matrix for Grade HPS 70W Steel at –10°F (–23°C)

Grade of Steels	Thickness, in.	Welding Processes				
		GMAW	FCAW	SMAW	SAW	ESW-NG
HPS 70W	1.0	(3)	3	—	3	—
	2.0	—	(3)	(3)	3	—
	4.0	—	—	—	(3)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 24; CVN specimens in Subtask 6.1 = 12
5. All specimens to be sampled at quarter-thickness of the plate

Table 18 Base Metal CVN Test Matrix for Grade HPS 70W Steel at 40°F (4°C)

Grade of Steels	Thickness, in.	Welding Processes				
		GMAW	FCAW	SMAW	SAW	ESW-NG
HPS 70W	1.0	(3)	3	—	3	—
	2.0	—	(3)	(3)	3	—
	4.0	—	—	—	(3)	3

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at the test temperature
3. Cases within parentheses are to be tested in Subtask 6.1, pilot study
4. Total number of CVN specimens = 24; CVN specimens in Subtask 6.1 = 12
5. All specimens to be sampled at quarter-thickness of the plate

Table 19 HAZ CTOD Test Matrix for Grade 50 Steel at Lower Temperatures

Grade of Steels	Thickness, in.	Welding Processes and Loading Rate									
		GMAW		FCAW		SMAW		SAW		ESW-NG	
		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

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at a test temperature
3. Total number of CTOD specimens = 12
4. Test loading rates
   a. Bridge loading rate: ~1.0 sec. to maximum load
   b. Dynamic loading rate: ~0.001 sec. to maximum load
5. Test temperatures
   a. For bridge loading rate: –60°F (–51°C)
   b. For dynamic loading rate: 10°F (–12°C)
6. All tests to be performed in Subtask 6.3 for the most critical weld procedure determined in Subtask 6.1 from CVN testing

Table 20 HAZ CTOD Test Matrix for Grade 50 Steel at Higher Temperatures

Grade of Steels	Thickness, in.	Welding Processes and Loading Rate									
		GMAW		FCAW		SMAW		SAW		ESW-NG	
		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

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at a test temperature
3. Total number of CTOD specimens = 12
4. Test loading rates
   a. Bridge loading rate: ~1.0 sec. to maximum load
   b. Dynamic loading rate: ~0.001 sec. to maximum load
5. Test temperatures
   a. For Bridge loading rate: 0°F (–18°C)
   b. For Dynamic loading rate: 70°F (21°C)
6. All tests to be performed in Subtask 6.3 for the most critical weld procedure determined in Subtask 6.1 from CVN testing

Table 21 HAZ CTOD Test Matrix for Grade 50W Steel at Lower Temperatures

Grade of Steels	Thickness, in.	Welding Processes and Loading Rate									
		GMAW		FCAW		SMAW		SAW		ESW-NG	
		Loading Rate		Loading Rate		Loading Rate		Loading Rate		Loading Rate	
		Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic
50W	1.0	(2)	—	—	—	—	—	2	2	—	—
	2.0	—	—	2	—	(2)	(2)	2	2	2	2
	4.0	—	—	—	—	—	—	(2)	2	2	2

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at a test temperature
3. Total number of CTOD specimens = 28; CTOD specimens in Subtask 6.1 = 8
4. Test loading rates
   a. Bridge loading rate: ~1.0 sec. to maximum load
   b. Dynamic loading rate: ~0.001 sec. to maximum load
5. Test temperatures
   a. For bridge loading rate: –60°F (–51°C)
   b. For dynamic loading rate: 10°F (–12°C)
6. Cases within parentheses are to be tested in Subtask 6.1, pilot study
7. All tests to be performed for the most critical weld procedure determined in Subtask 6.1 from CVN testing

Table 22 HAZ CTOD Test Matrix for Grade 50W Steel at Higher Temperatures

Grade of Steels	Thickness, in.	Welding Processes and Loading Rate									
		GMAW		FCAW		SMAW		SAW		ESW-NG	
		Loading Rate		Loading Rate		Loading Rate		Loading Rate		Loading Rate	
		Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic
50W	1.0	(2)	—	—	—	—	—	2	2	—	—
	2.0	—	—	2	—	(2)	(2)	2	2	2	2
	4.0	—	—	—	—	—	—	(2)	2	2	2

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at a test temperature
3. Total number of CTOD specimens = 28; CTOD specimens in Subtask 6.1 = 8
4. Test loading rates
   a. Bridge loading rate: ~1.0 sec. to maximum load
   b. Dynamic loading rate: ~0.001 sec. to maximum load
5. Test temperatures
   a. For Bridge loading rate: 0°F (–18°C)
   b. For Dynamic loading rate: 70°F (21°C)
6. Cases within parentheses are to be tested in Subtask 6.1, pilot study
7. All tests to be performed for the most critical weld procedure determined in Subtask 6.1 from CVN testing

Table 23 HAZ CTOD Test Matrix for Grade HPS 70W Steel at Lower Temperatures

Grade of Steels	Thickness, in.	Welding Processes and Loading Rate									
		GMAW		FCAW		SMAW		SAW		ESW-NG	
		Loading Rate		Loading Rate		Loading Rate		Loading Rate		Loading Rate	
		Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic
HPS 70W	1.0	(2)	(2)	—	—	—	—	—	—	—	—
	2.0	—	—	(2)	(2)	2	—	2	—	—	—
	4.0	—	—	—	—	—	—	2	2	2	2

Notes:

1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at a test temperature
3. Total number of CTOD specimens = 20; CTOD specimens in Subtask 6.1 = 8
4. Test loading rates
   a. Bridge loading rate: ~1.0 sec. to maximum load
   b. Dynamic loading rate: ~0.001 sec. to maximum load
5. Test temperatures
   a. For Bridge loading rate: –60°F (–51°C)
   b. For Dynamic loading rate: –10°F (–23°C)
6. Cases within parentheses are to be tested in Subtask 6.1, pilot study
7. All tests to be performed for the most critical weld procedure determined in Subtask 6.1 from CVN testing

Table 24 HAZ CTOD Test Matrix for Grade HPS 70W Steel at Higher Temperatures

Grade of Steels	Thickness, in.	Welding Processes and Loading Rate									
		GMAW		FCAW		SMAW		SAW		ESW-NG	
		Loading Rate		Loading Rate		Loading Rate		Loading Rate		Loading Rate	
		Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic	Bridge	Dynamic
HPS 70W	1.0	(2)	(2)	—	—	—	—	—	—	—	—
	2.0	—	—	(2)	(2)	2	—	2	—	—	—
	4.0	—	—	—	—	—	—	2	2	2	2

Notes:
1. 1.0 in. = 25.4 mm
2. Each cell in the test matrix indicates number of replicates at a test temperature
3. Total number of CTOD specimens = 20; CTOD specimens in Subtask 6.1 = 8
4. Test loading rates
   a. Bridge loading rate: ~1.0 sec. to maximum load
   b. Dynamic loading rate: ~0.001 sec. to maximum load
5. Test temperatures
   a. For Bridge loading rate: 0°F (–18°C)
   b. For Dynamic loading rate: 40°F (4°C)
6. Cases within parentheses are to be tested in Subtask 6.1, pilot study
7. All tests to be performed for the most critical weld procedure determined in Subtask 6.1 from CVN testing

Table 25 Matrix for Full Scale Testing

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

Notes:
1. 1.0 in. = 25.4 mm
2. Test temperature: –60°F (–51°C)
3. Total number of tests = 18

Table 26 Distribution of CVN and CTOD Testing of HAZ

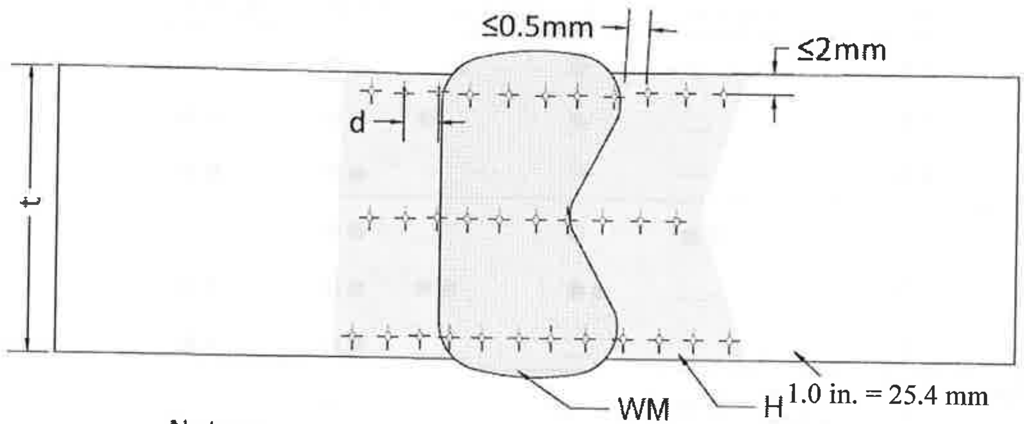
Steel Grades	Thickness, in.	Welding Processes				
		GMAW	FCAW	SMAW	SAW	ESW-NG
50	1.0	●	●	—	●●	—
	2.0	—	●	●	●●	●●
	4.0	—	—	—	●●	●●
50W	1.0	●●	●	—	●●	—
	2.0	—	●●	●●	●●	●●
	4.0	—	—	—	●●	●●
HPS 70W	1.0	●●	●	—	●	—
	2.0	—	●●	●●	●●	—
	4.0	—	—	—	●●	●●

Notes:
1. 1.0 in. = 25.4 mm
2. Legend:

●: CVN

●: CTOD

FIGURES



Notes:
1 in. = 25.4 mm
Legend: BM = Base metal
d = Distance between adjacent indentations
HAZ = Heat-affected zone
t = Plate thickness
WM = Weld metal

Figure 1 Locations for hardness measurements

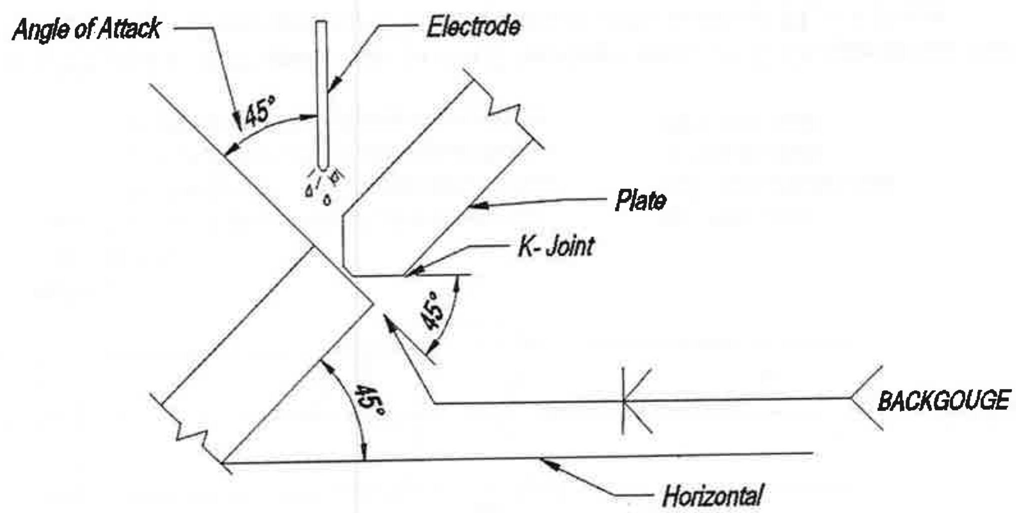


Figure 2 **Schematic of K-joint welding**

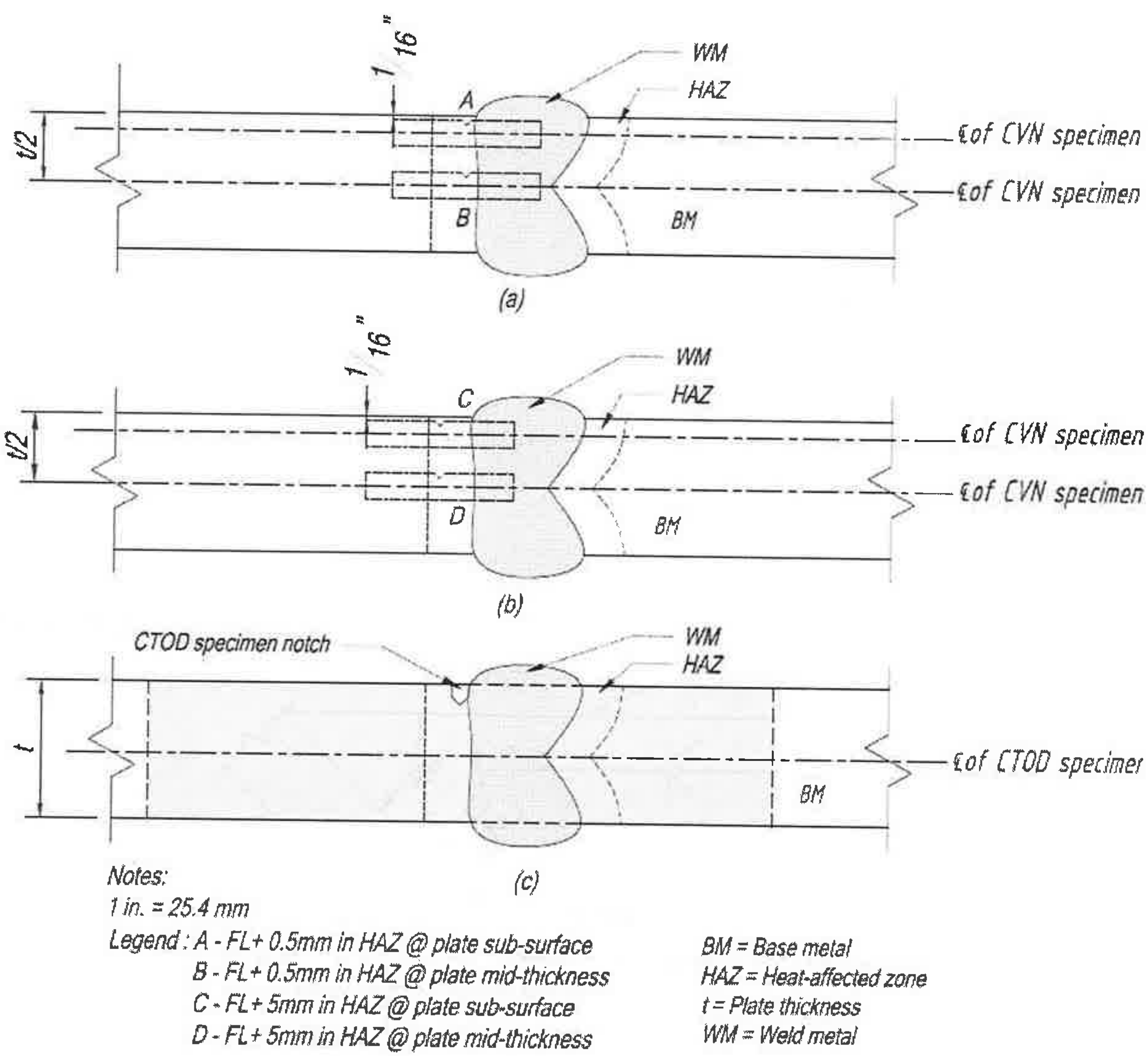
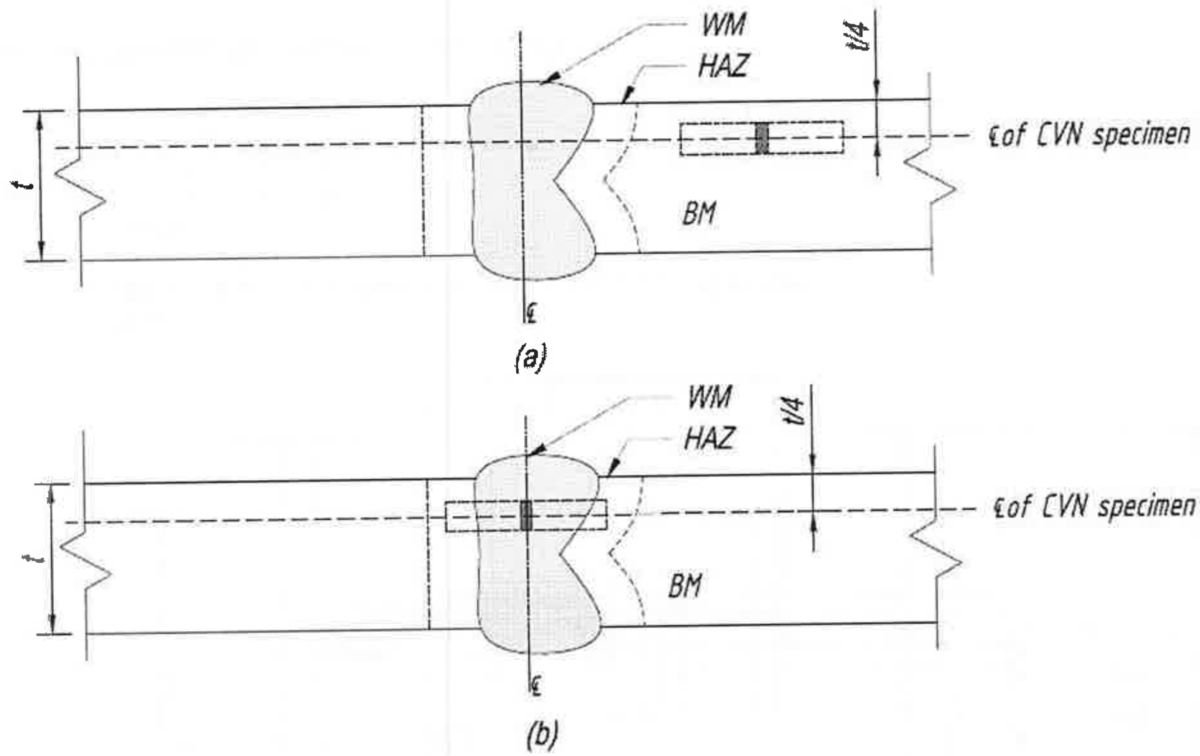
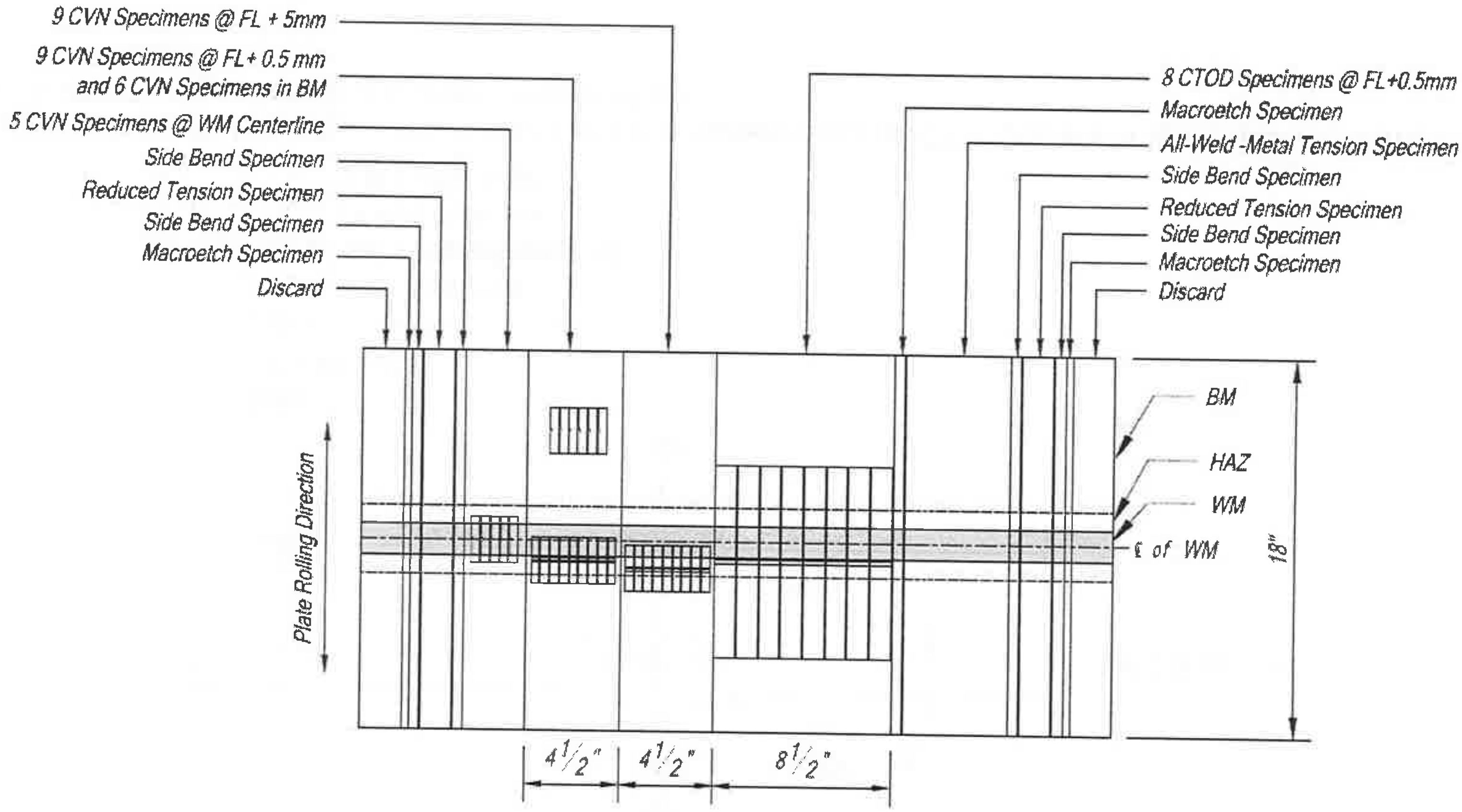


Figure 3 **Locations of CVN and CTOD specimens in HAZ (section view):** ***(a)*** **CVN specimens with notch at FL + 0.5 mm;** ***(b)*** **CVN specimens with notch at FL + 5 mm and** ***(c)*** **CTOD specimen with notch at FL + 0.5 mm**



Notes:
1 in. = 25.4 mm
Legend:
BM = Base metal
HAZ = Heat-affected zone
t = Plate thickness
WM = Weld metal

Figure 4 Locations of CVN specimens in BM and WM (section view): (a) CVN specimen in BM at quarter- thickness of plate; (b) CVN specimen in WM at quarter-thickness of plate



Notes:
Specimen dimensions not shown in the figure are according to AWS D1.5:2010
1 in. = 25.4 mm
Legend:
- *BM = Base metal*
- *FL = Fusion line*
- *HAZ = Heat-affected zone*
- *WM = Weld metal*

Figure 5 Details of WPS qualification plates (plan view)

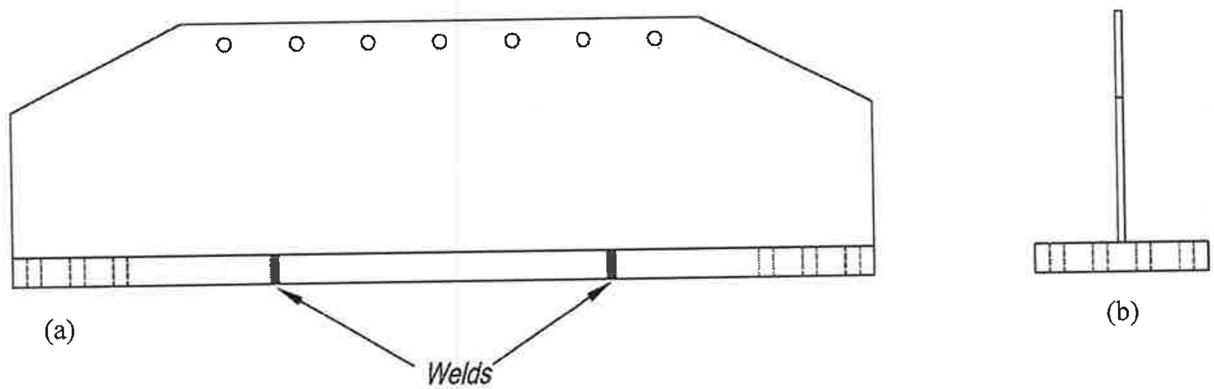


Figure 6 T-specimen: ***(a)*** **Elevation;** ***(b)*** **Side view**

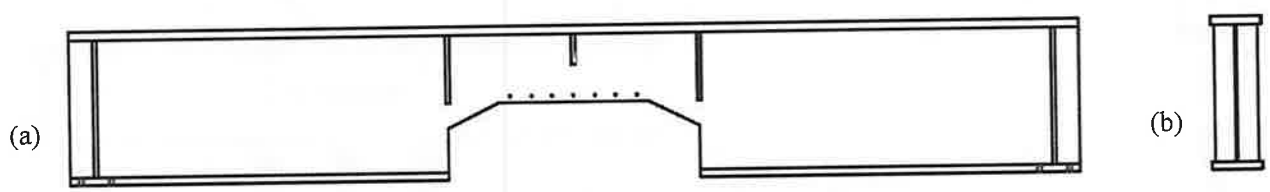


Figure 7 Fixture girder: ***(a)*** **Elevation;** ***(b)*** **Side view**

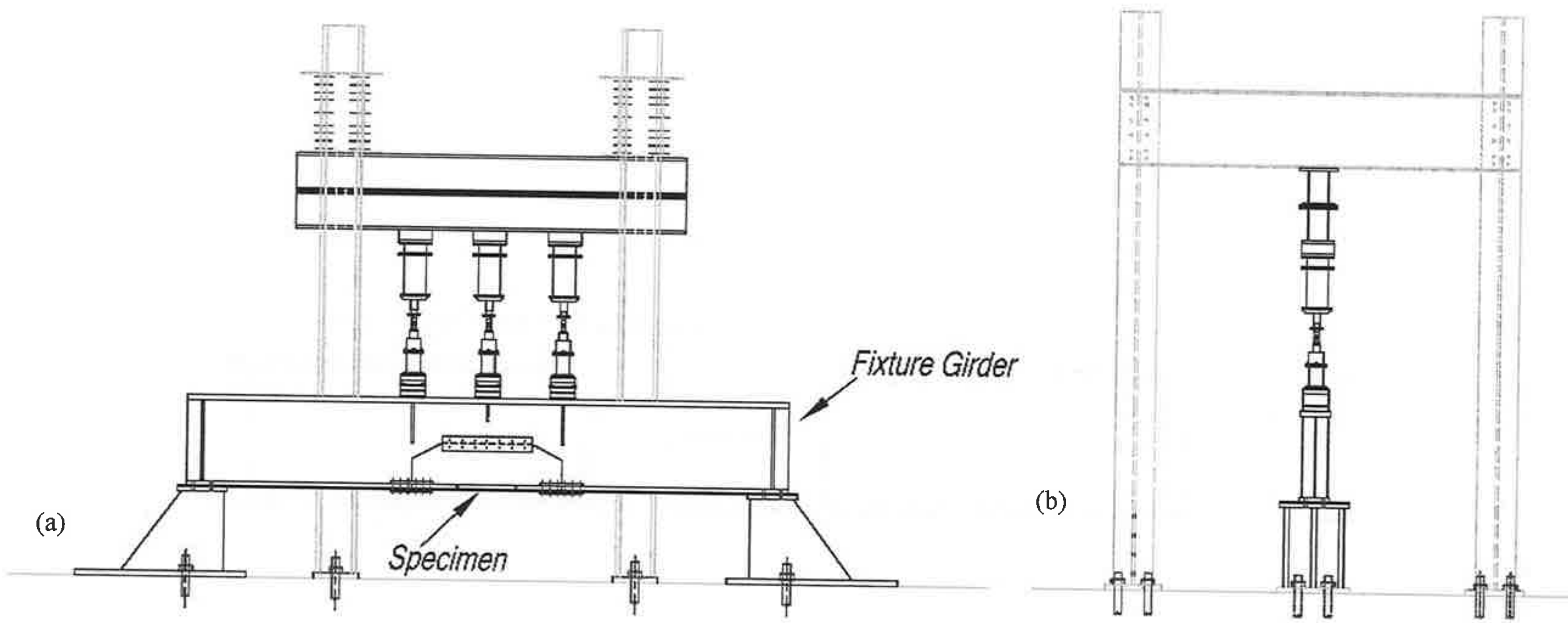


Figure 8 **Overview of girder testing setup:** ***(a)*** **Elevation;** ***(b)*** **Side view**

CONTENTS

v

Figure 9 Proposed Table of Content for the Final Report (contd. to next page)

vi

Figure 9 Proposed Table of Content for the Final Report (contd. from previous page)

REFERENCES

1. Bannister, A.C. 1998. *Toughness Characterisation of Modern Structural Steels with Relevance to European Design Codes.* Office for Official Publications of the European Communities, London, UK.
2. Bateson, P.H., and S.E. Webster. 1990. "The Significance of Local Brittle Zones to the Integrity of Large Welded Structures." *Journal of Offshore Mechanics and Arctic Engineering,* Vol. 112, No. 3, pp. 199-205.
3. Konkol, P.J., A.K. Shoemaker, S.T. Rolfe, E.J. Imhof, and D.E. Sonon. 1987. *Fracture Toughness and Weldability Tests for Submerged-Arc-Welded Joints.* Federal Highway Administration, Washington D.C.
4. Malik, L., L.N. Pussegoda, B.A. Graville, and W.R. Tyson. 1996. "Crack Arrest Toughness of a Heat-Affected Zone Containing Local Brittle Zones." *Journal of Offshore Mechanics and Arctic Engineering,* Vol. 118, No. 4, pp. 292-299.
5. Roberts, R., J.W. Fisher, G.R. Irwin, K.D. Boyer, H. Hausammann, G.V. Krishna, V. Morf, and R.E. Slockbower. 1977. *Determination of Tolerable Flaw Sizes in Full Size Welded Bridge Details.* Federal Highway Administration, Washington, D.C.
6. Roy, S., Y.C. Park, and B. Valeti. 2015. "Toughness Requirements for Heat-Affected Zones of Welded Structural Steels for Highway Bridges," *Interim Report NCHRP Project 10-95.* Transportation Research Board, Washington, D.C.
7. Wood, W.E. and J.H. Devletian. 1987. *Improved Fracture Toughness and Fatigue Characteristics of Electroslag Welds.* Federal Highway Administration, Washington D.C.