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Classification of Welded Bridge Details for Fatigue Loading

An NCHRP staff digest of the essential findings from an interim report on NCHRP Project 12-15, "Detection and Repair of Fatigue Cracking in Highway Bridges," by John W. Fisher, Fritz Engineering Laboratory, Lehigh University.

THE PROBLEM AND ITS SOLUTION

The fatigue fractures observed in cover-plated steel-beam bridges during the AASHO Road Test, and more recently in a number of structures in the field, illustrate the influence of welding and welded details on the life expectancy of highway bridges. Also of great significance in these bridges are such factors as the loading history of the structure, the types of materials, the design details, and the quality of fabrication. Among the more important design details are cover plates, stiffeners, attachments, and splices. The study summarized herein classifies these and other details in terms of their effect on the fatigue strength of welded steel bridge members.

Because this Research Results Digest is also the full text of the agency interim report, the statement above concerning loans of the uncorrected draft does not apply.

Lehigh University started work on NCHRP Project 12-15 in October 1972. A final report is expected to be available early in 1975. The primary effort in this study is being directed at the evaluation of methods for improving fatigue life and arresting the progress of fatigue damage that occurs at severe notch-producing details. An additional objective was the production of two state-of-the-art reports. This Digest comprises the report on a review of typical welded bridge details and an evaluation of those most susceptible to fatigue crack growth. A Digest to be published in the near future will contain a state-of-the-art review of existing methods of nondestructive inspection and an evaluation of their reliability and adaptability for the detection of fatigue cracks in welded highway bridges.

Other NCHRP research in progress in the area of fatigue includes: Project 12-12, "Welded Steel Bridge Members Under Variable-Cycle Fatigue," and Project 12-14, "Subcritical Crack Growth in Steel Bridge Members," both at United States Steel Corporation. Project 12-15 was preceded at Lehigh by NCHRP Project 12-7, "Effect of Weldments on Fatigue Strength of Steel Beams." The objective of this earlier study was the development of statistically documented design relationships to define the fatigue strength of steel beams.

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These fatigue studies have revealed that the primary variables influencing fatigue strength are the type of detail and the stress range to which the detail is subjected. The findings from NCHRP Project 12-7 have lead to development of comprehensive changes to the fatigue provisions of the AASHTO specifications. These new provisions use the concept of stress range for each structural detail and loading condition. The use of stress range greatly simplifies design computations and at the same time reflects the available experimental and theoretical fatigue findings.

The revisions to Article 1.7.3 of the AASHTO specifications are summarized in Tables 1 and 2. Table 1 gives the allowable ranges of stress for a number of categories that are defined in Table 2. The results are comprehensive and cover both welded and mechanically fastened joints.

The objective of the research phase reported herein is to classify existing and currently designed welded bridge details in terms of the specification provisions. The categories that are defined in detail in Table 2 of the specification are illustrated by various types of joints that are in common use. Details used on bridges in various parts of the United States are examined and classified according to their susceptibility to fatigue in order to provide bridge engineers with a better understanding of design conditions. The purpose of this Research Results Digest is to call immediate attention to the findings and recommendations of this part of the study.

FINDINGS

Fatigue Strength and Design Variables

In the past, only approximate general design relationships have been possible for fatigue because of the limited experimental data available. Research undertaken in the first phase of NCHRP Project 12-7 has been reported in *NCHRP Report 102*, "Effect of Weldments on the Fatigue Strength of Steel Beams" (1). Findings from the second phase have been summarized in *NCHRP Research Results Digest 44*, "Fatigue Strength of Welded Steel Beams," and will be covered in depth in *NCHRP Report 147*, "Fatigue Strength of Steel Beams with Transverse Stiffeners and Attachments" (2), to be published in 1974. These studies on some 531 steel beams and girders having two or more details have shown that stress range is the most significant stress factor for designing a given detail against fatigue. Other stress variables and the type of steel do not significantly affect the fatigue strength as long as stresses are below the yield point. However, because design provisions require that the maximum stress not exceed $0.55\ \sigma_y$, there are obvious advantages to using high-strength steels under large dead loads. These findings were found to be applicable to every beam and detail examined. Included were rolled beams, welded beams, square-ended cover plates with and without transverse end welds, cover-plate width and thickness transitions, groove-welded splices with the reinforcement removed at transitions in width, multiple cover plates, and beams with stiffeners and attachments.

The cracks in the rolled beams were observed to originate from the rolled surface of the tension flange. Cracks generally initiated from small discontinuties in the flange surface. These discontinuties were all small; the result was a high fatigue strength. The lower bound to the results of the rolled-beam studies was used to develop the design relationship for stress Category A. This provides the highest stress range that the base metal or rolled element can be subjected to for a given number of stress cycles.

TABLE 1 [a]

Category [b]	Allowable Range of Stress, F_{sr} (ksi), for			
	100,000 Cycles	500,000 Cycles	2,000,000 Cycles	over 2,000,000 Cycles
A	60	36	24	24
B	45	27.5	18	16
C	32	19	13	10 [c]
D	27	16	10	7
E	21	12.5	8	5
F	15	12	9	8

[a] AASHTO Table 1.7.3B.
[b] See Table 2.
[c] Except for transverse stiffener welds on girder webs or flanges, where 12 ksi should be used.

TABLE 2 [a]

General Condition	Situation	Kind of Stress [b]	Stress Category [c]
Plain	Base metal with rolled or cleaned surfaces. Flame-cut edges with ASA smoothness of 1000 or less.	T or Rev.	A
Built-up	Base metal and weld metal in members without attachments, built up of plates or shapes connected by continuous full or partial-penetration groove welds or continuous fillet welds parallel to the direction of applied stress.	T or Rev.	B
	Calculated flexural stress at toe of transverse stiffener welds on girder webs or flanges.	T or Rev.	C
	Base metal at end of partial-length welded cover plates having square or tapered ends, with or without welds across the ends.	T or Rev.	E
Groove Welds	Base metal and weld metal at full-penetration groove-welded splices of rolled and welded sections having similar profiles when welds are ground flush and weld soundness established by non-destructive inspection.	T or Rev.	B
	Base metal and weld metal in or adjacent to full-penetration groove-welded splices at transitions in width or thickness, with welds ground to provide slopes no steeper than 1 to 2 1/2, with grinding in the direction of applied stress, and weld soundness established by non-destructive inspection.	T or Rev.	B
	Base metal and weld metal in or adjacent to full-penetration groove-welded splices, with or without transitions having slopes no greater than 1 to 2 1/2 when reinforcement is not removed and weld soundness is established by non-destructive inspection.	T or Rev.	C
	Base metal at details attached by groove welds subject to transverse and/or longitudinal loading when the detail length, L, parallel to the line of stress is between 2 in. and 12 times the plate thickness, but less than 4 in.	T or Rev.	D
	Base metal at details attached by groove welds subject to transverse and/or longitudinal loading when the detail length, L, is greater than 12 times the plate thickness or greater than 4 in. long.	T or Rev.	E
Fillet-Welded Connections	Base metal at intermittent fillet welds.	T or Rev.	E
	Base metal adjacent to fillet-welded attachments with length, L, in direction of stress less than 2 in. and stud-type shear connectors.	T or Rev.	C
	Base metal at details attached by fillet welds with detail length, L, in direction of stress between 2 in. and 12 times the plate thickness, but less than 4 in.	T or Rev.	D
	Base metal at attachment details with detail length, L, in direction of stress (length of fillet weld) greater than 12 times the plate thickness or greater than 4 in.	T or Rev.	E
Mechanically Fastened Connections	Base metal at gross section of high-strength bolted slip-resistant connections, except axially loaded joints which induce out-of-plane bending in connected material.	T or Rev.	B
	Base metal at net section of high-strength bolted bearing-type connections and other mechanically fastened joints.	T or Rev.	B
Fillet Welds	Shear stress on throat of fillet welds.	Shear	F

[a] AASHTO Table 1.7.3C.

[b] T=a range in tensile stress only; Rev. = a range of stress involving both tension and compression during a stress cycle.

[c] See Table 1.

In welded built-up beams the crack causing failure initiated at a discontinuity in the fillet weld at the flange-to-web junction. In nearly all situations the crack started at discontinuties such as gas pockets, blowholes, and other fusion-type flaws and took the shape of a disc perpendicular to the stress field. The fatigue strength of the welded beam was observed to be about 75 percent of the strength provided by the rolled beam. This relationship was used to define stress category B in Table 1.

In beams with groove-welded flange splices at transitions in width, fatigue crack propagation generally occurred either from a weld discontinuity in the longitudinal fillet weld at the flange-to-web junction in a manner similar to the built-up beams or from a discontinuity or mechanical notch that was caused by the grinding operation at the groove weld transition. A relatively high fatigue strength resulted and the test results for the flange transition at a groove weld with the reinforcement removed provided a fatigue strength that was identical to the welded beam (Category B).

Fatigue crack propagation at nearly all other structural details occurred as cracks initiating from the toes of fillet or groove welds. In general, the growth of fatigue cracks is most likely to occur at such locations because the area is a region of high stress concentration and residual tension stress and is also the location of the initial discontinuity. The initial micro-discontinuity condition is provided by slag inclusions, undercut, or other conditions that exist at the toes of both fillet and groove welds. These imperfections are common to all welding procedures. Such flaws cannot be avoided, although their sizes and frequency of occurrence may be controlled by various welding techniques. In general the discontinuity results in crack growth in the form of a semielliptical shape until the crack has penetrated the thickness of the load-carrying element. Thereafter very rapid growth occurs and relatively little life remains in the structural detail. The various details examined, such as cover-plated beams, stiffeners, and other types of attachments, only differ in their as-welded fatigue behavior, as the stress concentration condition changes due to the geometry of the detail and the state of residual stress.

Transverse stiffeners which provide a minimum length of detail in the direction of the primary bending stress provide the least decrease in fatigue strength. The reduction in fatigue strength at a transverse stiffener is approximately 50 to 55 percent of the strength for base metal or rolled beam and is defined by Category C. Category C is also applicable to short attachments up to 2 inches in length in the direction of the applied stress.

As the attachment length of either fillet- or groove-welded flange or web attachments is increased the forces developed in the attachment increase. This causes a higher stress concentration, which causes lower fatigue strength. For fillet- or groove-welded attachments up to 4 in. in length an additional 10 percent decrease in fatigue strength results. Design Category D was developed to provide for this type of detail.

A loss of 60 to 70 percent of the fatigue strength of the rolled beam is experienced at the end of cover plates (Category E). As the length of an attachment continued to increase, the fatigue strength was observed to further decrease. The longer attachments provided the same behavior as a cover-plated beam when the length in the direction of the applied stress was equal to two or three times the depth of the attachment. The increasing length of the attachment results in development of greater forces in the attachment, which in turn cause a more severe stress concentration condition at the termination of the weld. All experimental evidence on fillet- and groove-welded details verifies the reduction in fatigue strength with increasing attachment length (3). Studies show that a cover-plated section reaches conformance with the theory of flexure at a distance from the end equal to approximately twice the cover-plate width for beams with welds across the cover-plate end and a distance equal to approximately three times the cover-plate width for beams with no end welds (4). Hence, the limiting definition of longer attachments appears reasonable. Finite element studies of the stress field and stress concentration conditions confirmed the general trend of the experimental observations.

The studies have also indicated that details located in compression stress regions are not fatigue critical unless there is a possibility of some stress reversal. Although cracks may form at a detail in a residual tensile stress region under repeated cycles of compressive stress, these cracks will not propagate beyond that region and do not adversely affect the member's load-carrying capability. The crack provides a condition analogous to any compression splice that has been proportioned to carry only part of the member's strength.

A fracture mechanics analysis indicated that the behavior of structural details that experience crack growth from the weld toe termination is primarily dependent upon the stress concentration at that point. Therefore, analytical studies of the stress concentration condition at other structural details can be used to help provide an approximation of their fatigue behavior.

Classification Of Typical Bridge Details

Welded bridge details were examined and classified according to their severity on the basis of existing experimental data and analytical studies of the stress concentration effect and initial stress intensity factor. Details are grouped according to the six categories of fatigue stresses defined in Table 1. These categories (ranging from Category A, which permits the highest allowable ranges of fatigue stress, to Category E, which provides the lowest allowable ranges of stress) are described in general terms in Table 2. Category F applies to the shear stress on the throat of fillet welds: its allowable stresses are close to those of Category E.

A number of bridge details are shown in Figures 1-30. In each figure one or more classifications are indicated, depending on the location and direction of the applied stress. A small double-ended arrow is shown near or adjacent to the detail to indicate the direction of the stress field that is governed by the stress category shown. The arrow indicates the critically stressed point in the base metal adjacent to the weld.

Category A. - Structural components and joints that fall under Category A consist of plain material with rolled or cleaned surfaces. This "base metal" condition is for rolled shapes and plate without a welded detail. It provides the upper limit to the fatigue strength of any structural detail. Fatigue studies on rolled beams of A36, A441, and A514 steel have shown that the fatigue cracks originate from the surface of the tension flange. Studies on plate specimens have also shown that the fatigue cracks originate from the surface on the specimen. The point of crack initiation is a micro-discontinuity at the surface of the material. Generally these occur at locally adhered mill scale or other similar surface imperfections. If the surface discontinuity is at the edge of a flange or plate it is slightly more severe. This is due to the higher stress intensity factor at an edge. The wide scatter band observed in fatigue data for rolled beam specimens reflects the variability of the initial imperfection. The design provisions are based on the lower confidence limit, which corresponds to the worst initial condition.

The slight surface depressions from rolled-in mill scale found usually are not as detremental to fatigue strength as sharp surface indentations. None of the test beams in NCHRP Project 12-7 indicated the existence of sharp surface cracks at points of rolled-in mill scale or roll marks. The surface of rolled elements provides a notch condition that is not very severe, and this results in a relatively high fatigue strength.

Figures 1 and 2 show typical rolled beam and plate elements that are defined by Category A. The small arrow on the flange indicates the direction of the limiting stress. The category is shown by the circled letter.

Category B. - Stress Category B applies to a variety of welded beam details. Typical bridge details that fall into this category are shown in Figures 3 to 10. They include groove-welded joints with the reinforcement removed and the weld soundness established by nondestructive inspection. Flange and web butt welds are illustrated in Figs. 3 and 4. Straight tapered transition details with slopes not greater than 1 to 2 1/2 in either the thickness or width are shown in Figures 5, 6, and 7.

Groove welds at transitions in width sometimes use a curved radius transition. This transition is required for A514 steel. If the reinforcement has been removed and the weld soundness established by nondestructive inspection, Category B is also applicable. Typical examples of curved transitions at gusset plates and at flange thickness and width transitions are shown in Figures 8, 9, and 10.

Longitudinal welds in built-up plates or shapes that are continuous and parallel to the direction of the applied stress field also fall into stress Category B. This includes the groove and fillet web-to-flange welds in welded built-up girders shown in Figures 3 to 7. As long as the longitudinal weld is continuous, the primary factors influencing the fatigue strength are the size and location of the imperfections that exist in the weldment. If crack growth occurs it results in embedded disk-like cracks that originate in the weldment at these flaws. Because there is no significant stress concentration condition, a high fatigue strength results. The same fatigue strength relationship applies to both continuous groove welds and longitudinal fillet welds.

Stress Category B is also applicable to continuous longitudinal welds for attachments, gussets, and cover plates. Only the weld-toe termination at the end of the longitudinal weldment causes a substantial decrease in fatigue strength. Examples of the portions of the welds for which Category B is applicable are shown in Figures 21, 23, and 24.

Category C. - Stress Category C is primarily applicable to stiffeners and short attachments. These structural elements exhibit fatigue crack growth from their terminating weld toes. In addition, groove-welded connections perpendicular to the applied stress and having the reinforcement left in place and the weld soundness established by nondestructive inspection also fall into Category C. Examples of various groove-welded splices with the reinforcement in place are given in Figures 3 to 7. Groove welds that are parallel to the applied stresses are governed by Category B and are comparable to continuous fillet welds.

A number of stiffener details that fall into Category C are shown in Figures 12, 13, and 14. It is recommended that stiffeners of this type be cut short a distance of 4 to 6 times the web thickness in order to minimize the possibility of web cracking due to shipping or handling stresses. As shown in Figure 14, welds attaching transverse stiffeners to either the web or the flange are in the same stress category. Category C is also applicable to vertical gussets attached to the web, as indicated in Figure 17, and to short flange attachments less than 2 inches long. A stud shear connector (Fig. 16) in the negative moment region reduces the strength of the flange to Category C. In all of these cases the critical point is in the base metal adjacent to the weld.

If attachments are fillet or groove welded to the edge of the flange, as indicated in Figure 20, the stress category at the weld termination is dependent on the transition radius. If the transition radius is sharp ($R \sim 0$), a fillet or groove weld provides a right angle attachment similar to the flange attachment in Figure 19 and stress Category E is applicable. If the transition radius is less than 24 in. but greater than 6 in., Category C is applicable, as shown in Figures 9 and 20. The improvement in fatigue strength is caused by a decrease in the stress concentration condition with an increase in the transition radius R and the removal of the weld ends by grinding. The categories shown in Figure 20 also apply to web attachments. In most bracket attachments the transverse forces acting on the bracket nearly cancel each other and the weld attaching the bracket to the web or flange is primarily subjected to shear. This shear stress in the weld material is governed by Category F but is seldom large enough to be critical in design. Hence, such weldments can usually be treated as other longitudinal welds.

Category D. - Category D provides an intermediate level between short fillet- or groove-welded attachments and longer attachments (such as cover plates). If the attachment length in the direction of the applied stress is greater than 2 in. but less than 4 in., the controlling stress at the weld end is given by Category D (see Figs. 18 and 19).

Category D is also applicable to the cross beam connection shown in Figure 27. The secondary rolled beam has part of the web cut away. The change in geometry at the flange-to-web junction provides a stress concentration effect. Analytical studies indicate that the fatigue strength is reduced to stress Category D because of the resulting stress concentration. An increased fatigue strength can be developed by providing a curved corner at the rolled beam cut-out. A 1-in. radius at the web-flange juncture can increase the fatigue strength in a rolled beam to Category B.

When cross-girder connections are made by groove welding the beam flanges to the girder flange, a decreased fatigue strength can result, as shown in Figure 30. When the flanges are not of equal thickness the stress concentration condition reduces the fatigue strength of the secondary girder connection to Category D or E. If higher fatigue strength is desirable it is preferable to make the beam flange continuous by passing it over the top of the girder flange (see Fig. 28) or by passing it through the web.

Other possible applications of stress Category D would be short plate connections, or channel-type shear connectors that are between 2 and 4 in. long.

Category E. - A wide class of fillet- and groove-welded details are covered by stress Category E. It provides the lower-bound fatigue strength of welded details and has been defined by experimental work on cover-plated beams and other comparable details. Studies on attachments have shown that as the attachment length exceeds 4 in. the fatigue strength rapidly approaches the lower-bound cover-plated beam condition. The critical point is at the end of the longitudinal weld. Crack growth originates at micro-discontinuities at the weld toe and continues perpendicular to the stress field into the plate thickness.

A number of commonly used details have fatigue strengths near this lower-bound level. Included are the weld toe terminations of longitudinal stiffeners, as shown in Figure 15, and of gusset stiffeners, as shown in Figure 8. Although Category E applies at the end of a longitudinal stiffener, stress Category B is applicable at points away from the weld end. When attachments to the web or flange are greater than 4 in. in length in the direction of the applied stress (see Figs. 18 and 19), stress Category E is applicable. Category E is also applicable to gussets that are attached to flanges (see Fig. 21) or to other structural elements, as shown in Fig. 22.

A variety of cover-plated beam details with tapered or square ends are shown in Figures 23, 24, and 25. Stress Category E applies to the base metal at the ends of the cover plates. The continuous longitudinal fillet welds along the edges of the cover plate are covered by stress Category B.

When discontinuous or intermittent fillet welds are used (see Fig. 26), stress Category E is applicable at the end of each intermittent weld. This is a conservative treatment of intermittent welds because of the lack of test data. It is probable that higher fatigue strengths exist when the intermittent welds are continuing (i.e., web-to-flange connection) so that the connected plates are about equally strained. Further work is needed to clarify this condition.

Beam-girder intersections often result in low fatigue strength details. This is shown in Figures 27 to 30. Groove-welded flange-to-web or flange-to-flange joints can cause substantial reductions in the allowable bending stress range. Because the length of the weld connecting the secondary beam to the web or flange will always be greater than 4 in., Category E applies. If a continuous web-to-flange weld abruptly terminates, as shown in Figure 28, Category E is also applicable. The stress gradient through the main girder depth may result in stress ranges in the web that are low and not fatigue critical at the floor beam compression flange in Figures 27, 28, and 29. A more critical condition is provided by the flange welds in Figure 30. When higher fatigue strengths are needed in either the main girder or the cross girder, appropriate transitions can be used and the cross girder flange can be made continuous and passed over the main girder flange or through its web, as shown in the detail of Figure 28.

Category F. - Category F is applicable to the shear stress acting on the throat of fillet welds. It applies to continuous or intermittent longitudinal or transverse weldments. These stress conditions are obvious and are not shown in the figures. It is seldom that Category F controls a design. Under normal design conditions the shear stresses in the weld are low enough to prevent cracks from forming in the weld. Cracks form instead at the weld toe termination and propagate into the connected material. Category F was derived from tests of small plate specimens with specially designed welds[15] purposely subjected to high shear stresses.

Details Most Susceptible To Fatigue

Of all the details shown in Figures 1-30, those that fall into stress Category E are the most susceptible to fatigue crack growth in highway bridges. Existing studies of the stress history in bridges have indicated that the stress range seldom exceeds 6 to 8 ksi. Hence, most details are never subjected to fatigue crack growth because the stresses are below the crack growth threshold. Only details falling into stress Category E are likely to experience crack growth.

The designer has two major factors he can control. These are the choice of detail and the design stress range. If a low fatigue-strength detail is used, every effort should be made to avoid locating it in a region of significant cyclic stress. Otherwise, the stress range must be reduced by changing the section properties to accomodate the detail. When details are located in compression stress regions and no possibility of stress reversal exists, there is no fatigue problem. Under these conditions any crack growth will be limited to the residual tensile stress zone unless out-of-plane deformations occur. The crack will not affect the member's behavior.

Details designed in accordance with the provisions of the AASHTO Interim Specifications - 1974, will provide satisfactory performance and no appreciable amount of crack growth can be expected throughout their life.

Significance Of Manufacturing And Fabrication Discontinuities

Although only indirectly related to the design of connections, imperfections from the manufacturing or fabrication processes may affect fatigue life, depending on their location, size, and orientation with respect to the applied stresses. In general, a discontinuity in a plane parallel to the line of applies stress has little or no effect on the fatigue strength or performance of the member or detail. Crack growth results only when a substantial amount of cyclic tension from the applied loads crosses a planar region that contains a discontinuity.

This section provides guidance to the bridge engineer on the significance of conditions that frequently develop during manufacture and fabrication.

Rolled Plates and Shapes. - In rolled structural plates and shapes the discontinuities may be in the form of surface imperfections, irregularities in mill scale, laminations, seams, or inclusions. Generally, laminations, seams, and inclusions have a microscopic thickness with respect to the direction of rolling; hence, they have a negligible effect on a member's behavior when stresses are parallel to the direction of the discontinuity. Experimental fatigue studies have demonstrated that fabricated planes of discontinuity parallel to the applied stress have no detrimental influence on fatigue behavior and strength(1,2,3). Even small irregularly shaped pits in the flange or plate surface have little effect and do not preclude high fatigue strength; an example is the surface discontinuity shown in Figure 31a. This beam sustained 4,456,000 cycles at a 36-ksi stress range, which placed it near the upper confidence limit of Category A test results(1).

Most discontinuities in planes parallel to the applied stresses are not injurious and should be left alone. Attempts to remove them will usually result in a condition that is worse than the original discontinuity.

During fabrication, nicks or notches may occasionally result from handling devices. Smooth or flat discontinuities have little effect, as they do not result in a significant increase in stress concentration. However, if a sharp, severe notch condition results from either fabrication or manufacture (see Fig. 31b), it should be removed or repaired to prevent an undesirable condition from developing. The sharp gouge in the flange tip shown in Fig. 31b resulted in failure after 2,846,000 cycles at a 20.5-ksi stress range, which was below the threshold level for Category A. Frequently, such discontinuities can be removed by grinding out the notch to a smooth transition.

Sometimes surface imperfections from the manufacturing process are repaired by welding and then grinding the reinforcement off(6). Some surface and edge imperfections that are conditioned in this manner are mechanical gouges, scabs, slivers, and large seams. Criteria for conditioning plates and shapes are given in Ref. 6. These repairs are usually very shallow and only a visual inspection of the repaired surface is needed to ensure that no severe surface discontinuity exists transverse to the applied stresses. Any micro-discontinuities that may exist in the repaired region have no significant influence on the member's behavior because once the reinforcement is removed they are not at locations of stress concentration and geometric change.

Occasionally a severe notch condition may exist at the flame-cut edge of a plate, as shown in Figure 32. Fatigue tests of beams with flame-cut edges have shown that an ASA roughness* of 1000 or less will not result in crack growth from the flame-cut edge prior to failure from discontinuities in the flange-web fillet welds of built-up beams(1). However, poor-quality cutting can result in substantial reductions in strength and much earlier crack growth(3). If high fatigue or fracture strength is desired, severe flaws that result from flame irregularity or other causes should be removed by grinding.

Inclusions sometimes exist in fine-grained killed steels when a highly refractory aluminum oxide is entrapped during solidification. During slab rolling these nonmetallic inclusions are extended longitudinally in the direction of rolling. When the slab or bloom is rolled into a plate or a structural shape, further elongation and some lateral spreading of these inclusions occur, resulting in inclusion stringers or clusters of stringers oriented in elongated flat areas parallel to the rolled surfaces. These nonmetallic particles are very small, as shown in Figure 33. Generally they are only 0.001 in. thick and 0.1 in. or less wide. These types of discontinuities have no significant effect on the fatigue strength (Category A) and performance of the material when they are oriented parallel to the applied stress.

Figure 34 shows a fatigue fracture surface of a W36x300 rolled beam that experienced fatigue crack growth at the end of a welded cover plate(7). The fracture surface is in the beam section away from the cover plate. Fatigue crack growth occurred at the weld toe and penetrated into the flange perpendicular to the line of stress. An inclusion condition existed at mid-depth of the flange and was defined by ultrasonic inspection to be about 5 1/2 in. wide and running for some length centered on the web. It is apparent in Figure 34 that the inclusion intercepted the crack as it grew upward into the flange perpendicular to the inclusion. The crack was forced to grow around the inclusion, as evidenced by the change in the fatigue crack growth path. Figure 35 shows a ground and etched cross section about 1 in. from the fatigue crack surface. The etched cross section confirmed the presence of the inclusion condition. Because the dimension of the inclusion perpendicular to the line of stress was extremely small, the inclusion had no detrimental effect on the behavior of the member. In fact, the inclusion's being parallel to the line of stress was beneficial in this case, as it served to arrest the crack front.

An inclusion condition of this type would be of greater concern if the member were subjected to forces perpendicular to the flange. For example, if a structural element were attached perpendicular to the direction of rolling and cyclical forces were applied through the attachment so that stresses are applied perpendicular to the rolled surface, such an inclusion condition could be detrimental to the member's performance.

*ANSI E46.1 Surface Texture.

Seams or laminations may result from rolling thick plates or heavy shapes. Fortunately, they are usually in planes parallel to the line of stress and do not affect a member's fatigue performance.

Mechanically Fastened Joints and Members. - In mechanically fastened (riveted or bolted) members and joints the primary concern is with the drilled or punched holes needed for the fasteners. Other discontinuities exist, but they are not critical. For example, most mechancially fastened built-up members have multiple plies that result in planes of discontinuity between plates. These planes are all parallel to the applied stresses and have no effect on the member's strength or performance. Most laminations, seams, or inclusions behave alike when they have similar orientations. Tests on mechanically fastened built-up members have shown clearly that the fabricated planes of discontinuity are not a critical factor. Columns, beams, and tension members are not affected by their presence.

When drilled or subpunched and reamed holes are used, a very high fatigue strength generally results because the surfaces of the reamed or drilled holes are smooth, with very small initial discontinuities. These hole surfaces are similar to rolled surfaces of plates and shapes as far as fatigue life is concerned.

The bolt clamping force in a high-strength bolted joint assists with the load transfer, and often crack growth does not occur at the bolt hole[8,9]. Often a fretting condition occurs on the faying surface, which results in crack growth in the gross section, as shown in Figure 36. The resulting fatigue strength is almost as high as that of the plain material. This high strength is made possible by the high bolt clamping force, which reduces the stress magnitude at the very small-sized discontinuities at the bolt hole.

Punched holes can result in substantial reductions in fatigue strength because of the imperfections introduced during punching, as shown in Figure 37. If subjected to cyclic loading, a punched hole is more likely to experience crack growth than a drilled hole. A second factor of concern is the influence of the punching on the toughness of the material in the immediate area of the hole. Studies have indicated that substantial variation can be expected in notch toughness and in the initial discontinuity condition from misalignment of the punches or other fabrication factors [10]. These conditions may result in a brittle fracture from rapid crack propagation if cyclic loading results in an enlargement of the initial cracks from punching and a critical combination of crack size, stress magnitude, and notch toughness occurs. The situation is less severe for joints containing high-strength bolts with their high clamping force.

Misplaced drilled holes have little effect on fatigue strength. If they do not adversely influence static strength and maintenance they can be left open or filled with a bolt. If it is necessary for such holes to be welded shut, care must be taken to ensure that large welding discontinuities are not present (cracking in members has been traced to poor welding). The same inspection criteria applied to transverse groove welds should be used to establish weld soundness if such holes are welded shut.

Welded Details and Members. - Small, sharp discontinuities exist at the weld periphery or in the welds of both fillet- and groove-welded details in welded built-up structural members. In addition, many planes of discontinuity can be induced by fabrication.

Whether or not these discontinuities are critical, and constitute an initial crack condition that may grow, depends largely on their orientation with respect to the applied stress. Fatigue studies of welded members and details have provided insight into the crack growth behavior of welded details.

Signes, et al.[11] have shown that fatigue cracks initiating from fillet-weld toes start from small sharp intrusions of slag that emanated from the welding flux or the plate. These observations were confirmed by further studies by Watkinson et al.[12], who showed that these discontinuties exist in all conventionally made welds. These micro-flaws cannot be detected or characterized by currently used nondestructive inspection techniques.

All experimental evidence has confirmed that fatigue crack growth from fillet-welded details normally initiates at the weld toe of a weldment, starting from a micro-discontinuity when the applied stresses are perpendicular to the weld toe[1,2,3]. This is shown in Figures 38, 39, and 40, which show the cracks that formed in a beam flange and web at fillet weld toes[1,2]. The primary difference between the details shown in Figures 38, 39, and 40 is the geometrical stress concentration condition produced by the welded detail. This is reflected in the fatigue strength of details: the stiffener and the short attachment have a higher fatigue strength (Category C and D) than the cover-plated beam (Category E).

If tack welds are used to temporarily align or position plates and are not incorporated into the final weld they should be treated as any other welded detail. Tack welds parallel to the applied stresses are more severe than perpendicular ones because of the geometrical effect of length (they provide a Category C, D, or E design condition, depending on their length). If used, it is preferable to place them in low-stress regions or in the compression zone. Tack welds incorporated into fillet or groove welds do not adversely affect the joint.

Fatigue cracks that occur in multiple-cover-plated beams form at weld ends perpendicular to the direction of applied stress. As shown in Figure 41, the fatigue crack growth is initially through the primary cover plate at the terminating toe of the fillet weld. Crack growth is arrested when it intersects the fabricated plane of discontinuity between the primary plate and the beam flange. Continued growth of the crack can only occur if it is propagated into the beam flange via the continuous longitudinal fillet weld connecting the primary cover plate to the flange. The fabricated plane of discontinuitv had no detrimental influence on the fatigue behavior and strength of multiple-cover-plated beams(1). Their fatigue behavior is analogous to that of multiple-ply bolted or riveted members.

In some types of welded joints fatigue cracks may initiate at points other than the weld toe when the stress concentration effect is not great at the toe. For example, in joints involving transverse load-carrying fillet welds or transverse partial-penetration groove welds, cracking can initiate at the weld root with propagation through the weld as shown in Figure 42. If the welds are sufficiently large and have satisfactory geometry, with small initial cracks (lack of penetration) they will not experience crack growth at the weld root but at the weld toe (Category C). In these cases the condition at the weld toe is more severe than the condition resulting from the fabricated partial-penetration discontinuity.

Fillet welds connecting flange and web plates such as in the welded built-up girder, are also structural details that experience fatigue crack growth from an internal weld discontinuity. The flange-web fillet welds often result in internal discontinuities. Porosity (gas pockets, shown in Figure 43) represents a typical type of initial discontinuity. Lack of penetration in a web-flange joint constitutes a discontinuity the full length of the member. This discontinuity is parallel to the line of stress and has no influence on the fatigue crack growth. Other sources of crack growth are at stop-start positions and weld repairs where incomplete fusion or trapped slag exists(1,2). Cracks starting at porosity, stop-start, or weld repair locations were initially completely inside the weld and therefore not visible on the surface until substantial crack growth had occurred. These cracks took the shape of a disc and maintained this shape until the crack penetrated the flange and assumed a three-ended crack shape. Most of the fatigue life was spent propagating the crack inside the weld(1,13).

A directly comparable condition occurs in longitudinal groove welds. In either continuous longitudinal fillet or groove welds, the usual discontinuity (such as porosity, incomplete fusion, or trapped slag) results in a high fatigue strength (Category B). Unless these discontinuities exceed currently acceptable limits(14) they should not be removed as the resulting repair will often result in a worse condition(1,3).

The fatigue strength is governed by discontinuities that are perpendicular to the applied stresses, not by those that are parallel. Hence, the inspection procedure used for fillet welds is equally applicable to longitudinal groove welds. Generally this includes a visual inspection, with some magnetic particle examination to determine whether or not the welds contain cracks. Ultrasonic and radiographic inspection are not necessary for longitudinal welds. Large internal discontinuities perpendicular to the applied stresses are not possible, as would be the case with transverse groove welds in the web or flange.

Transverse groove welds with the reinforcement in place result in a stress concentration at the weld toe. This stress concentration is associated with small discontinuities at the weld toe and is usually more severe (Category C) than the condition caused by other minor internal flaws (Category B). This is particularly true if a severe geometrical stress concentration exists at the weld toe, as in a flange attachment.

It has been common practice in bridge construction to provide nondestructive inspection of groove welds transverse to the applied stresses so that the internal flaw can be minimized. This, coupled with the removal of the weld reinforcement, minimized the stress concentration and toe discontinuity. Crack growth generally initiates in these cases at a mechanical notch in the flange plate or in the longitudinal flange-web fillet weld. The fatigue strength thus cannot exceed that of the welded built-up girder.

If the internal groove-weld discontinuities or slag inclusions are comparatively large in size in a plane perpendicular to the stress field, crack growth is more critical at those locations (3,14). The orientation of the internal discontinuities is of primary importance. Only those discontinuities that are perpendicular to the applied stress are critical. Studies by Gurney and Harrison(3) have shown that when slag inclusions were parallel to the applied stress, they had little little if any effect, the fatigue strength was not impaired (Category B), and crack growth did not occur. For example, the discontinuities shown in Figure 44 are long alumina stringer inclusions. They are oriented parallel to the line of stress and have no appreciable influence on fatigue strength. If their width perpendicular to the line of stress is substantial they will have a deleterious effect.

APPLICATIONS

The findings from this study should be of value to structural engineers involved in the design, construction, and maintenance of welded steel bridges. Another Research Results Digest emanating from this study will be published in the near future and will review the methods of nondestructive inspection now available for detection of fatigue cracking in bridges.

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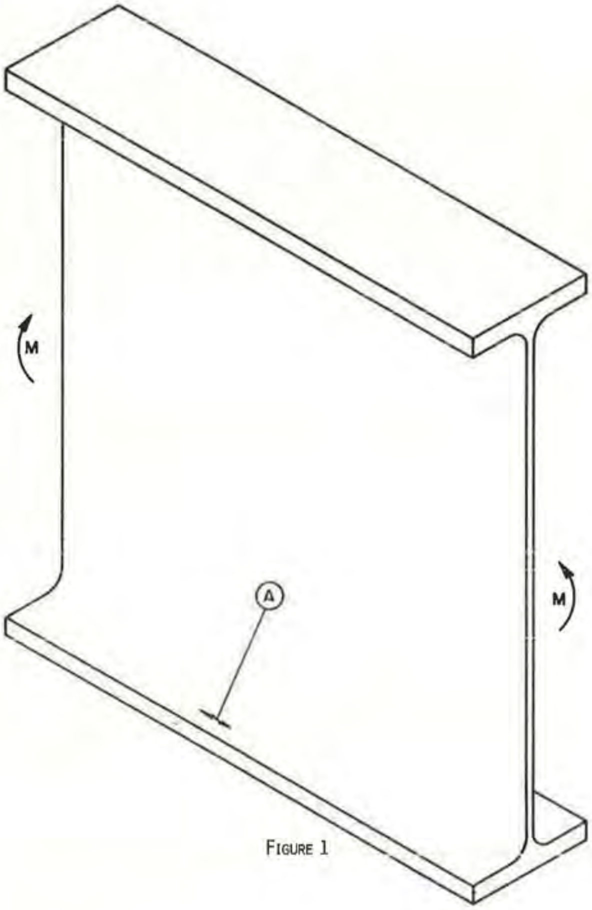


FIGURE 1

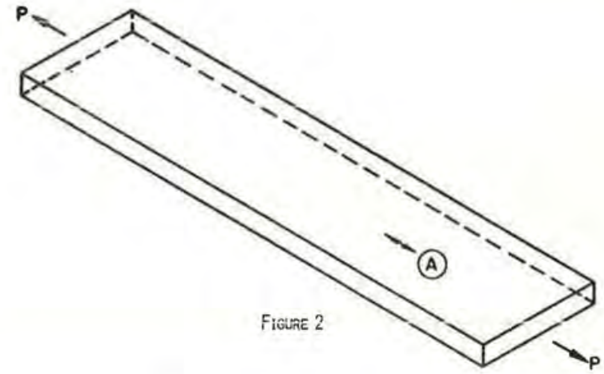
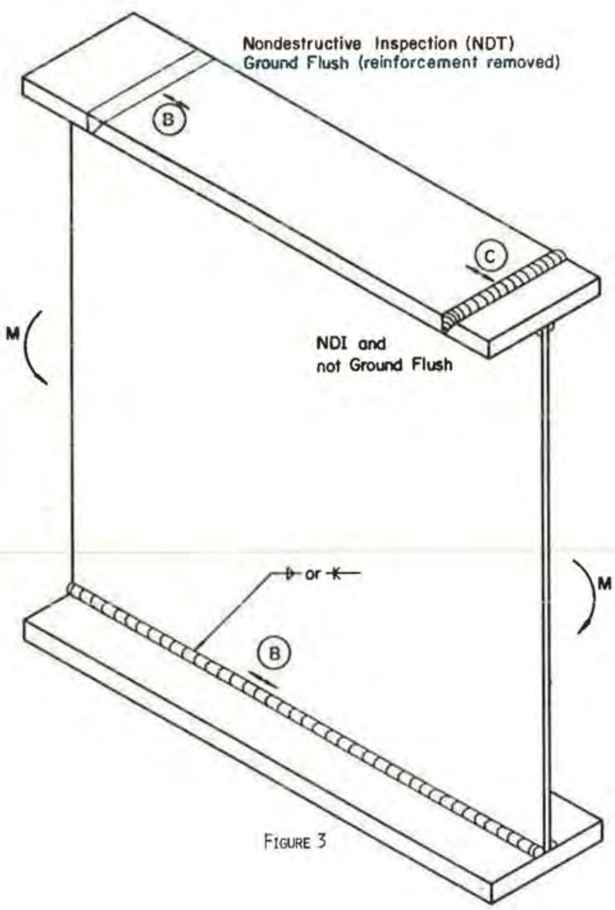


FIGURE 2



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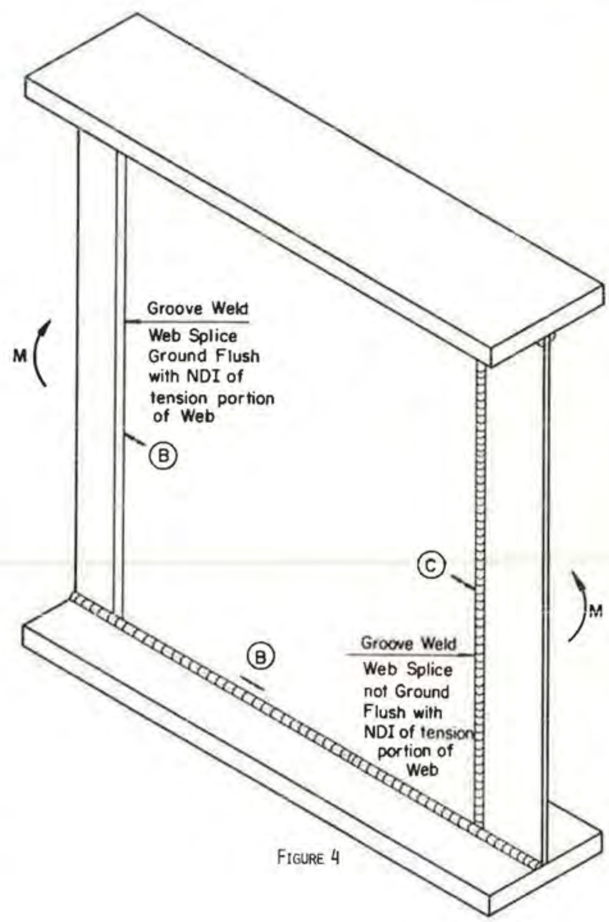

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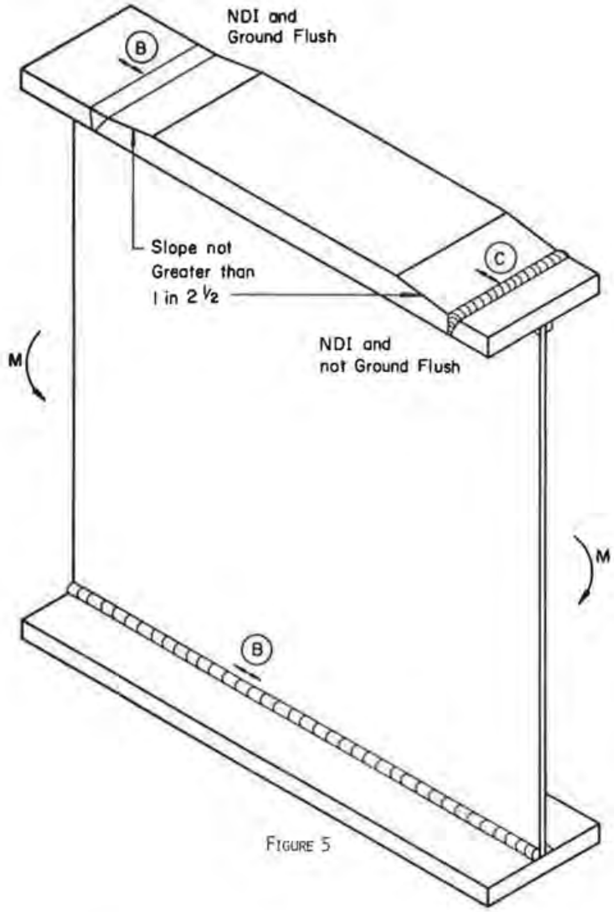

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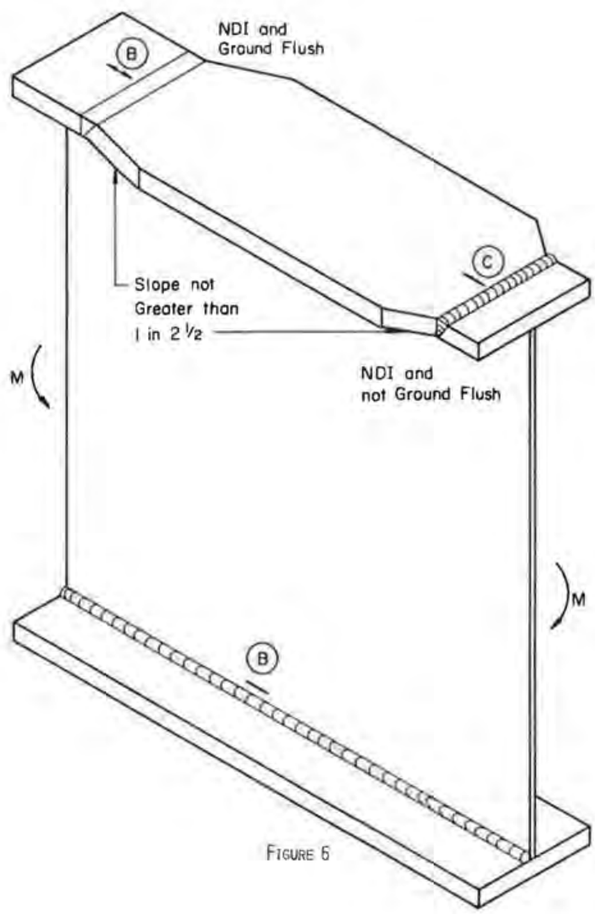

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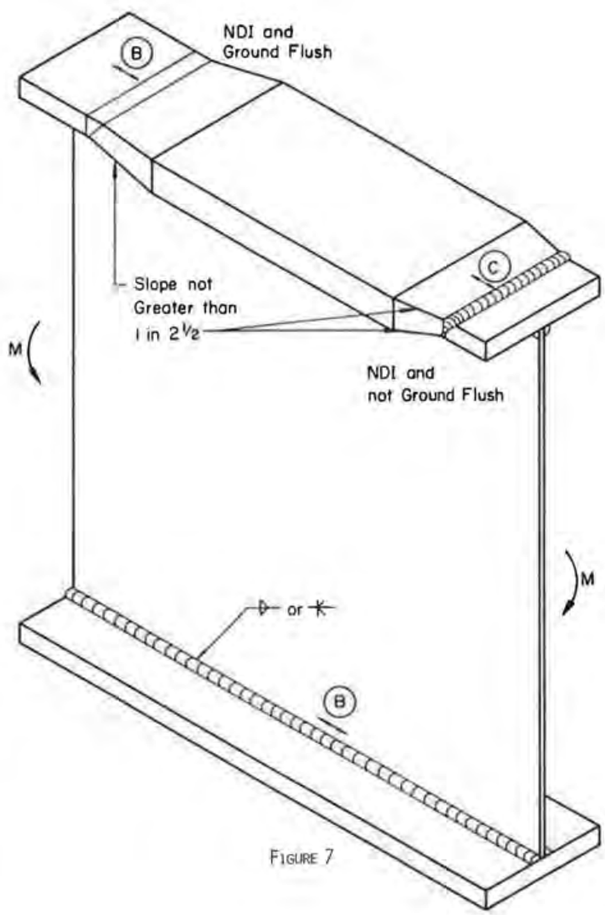

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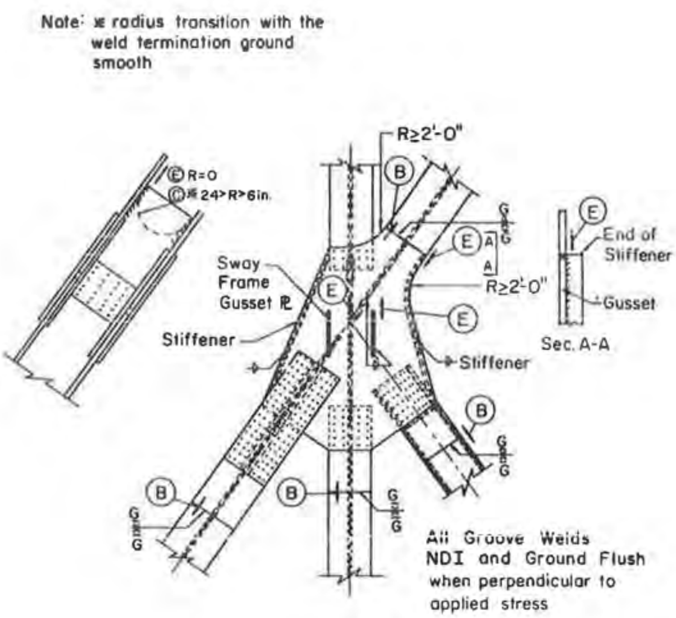

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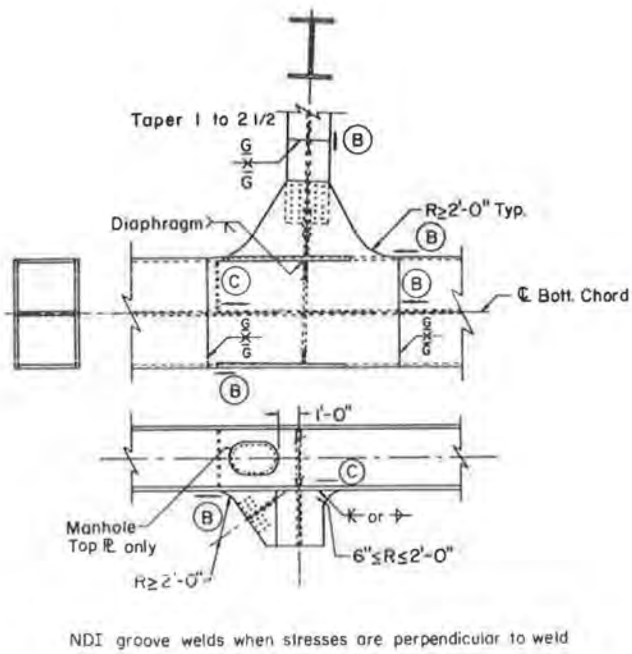

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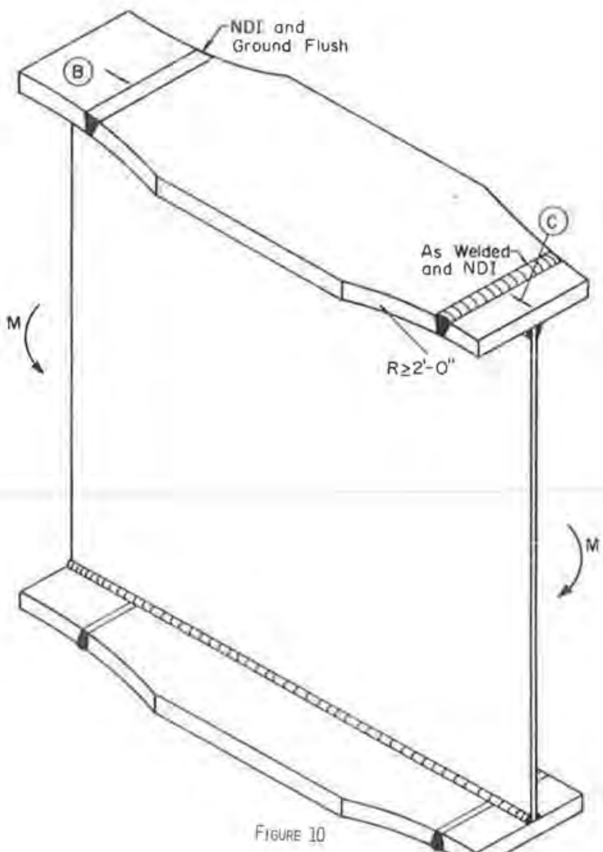
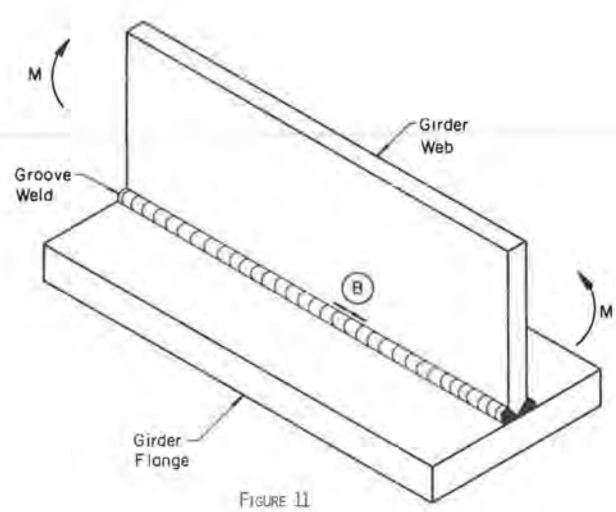


FIGURE 10



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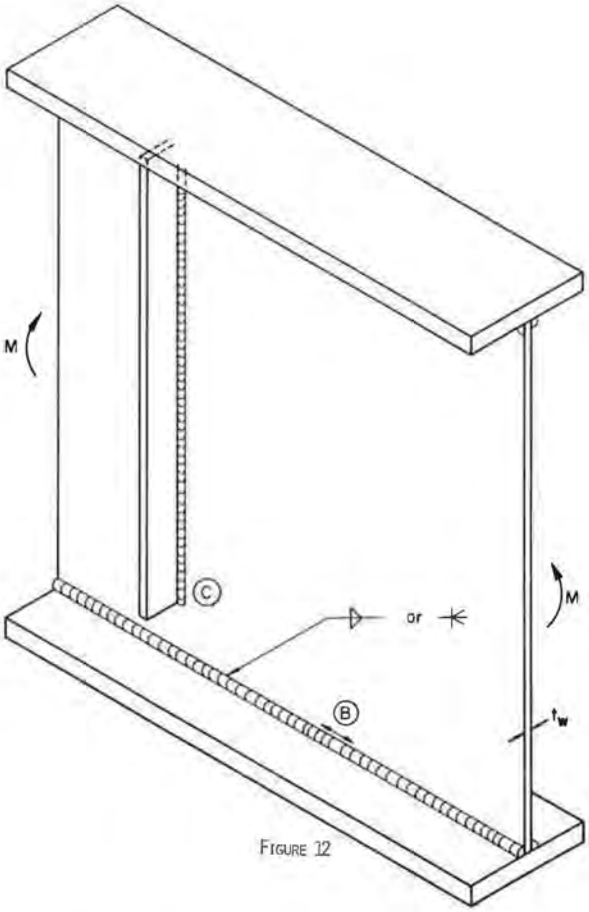

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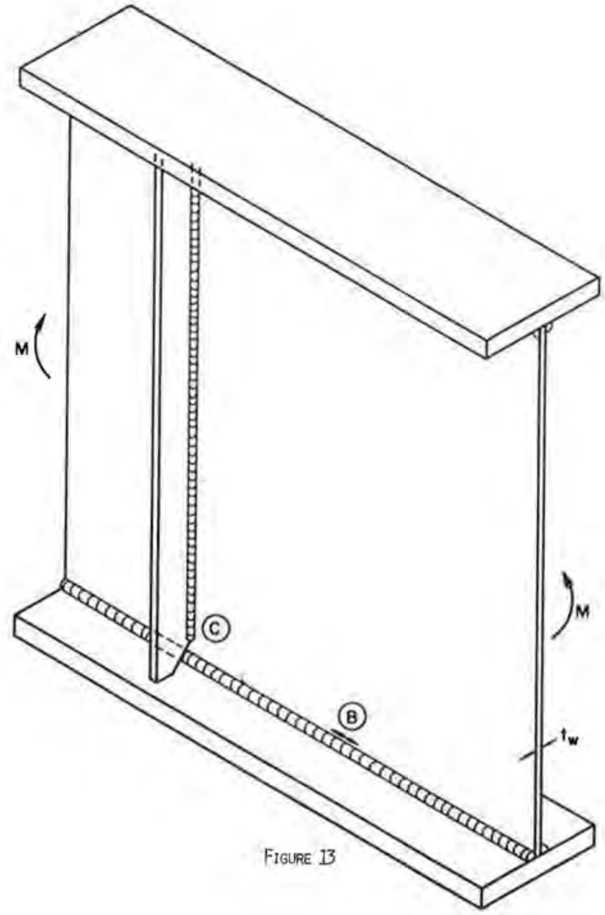
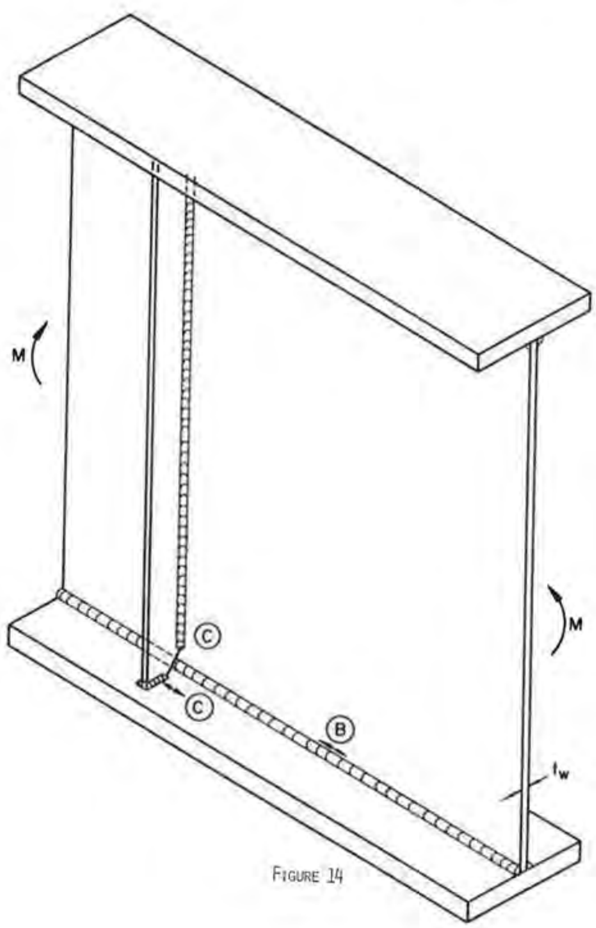


FIGURE 13



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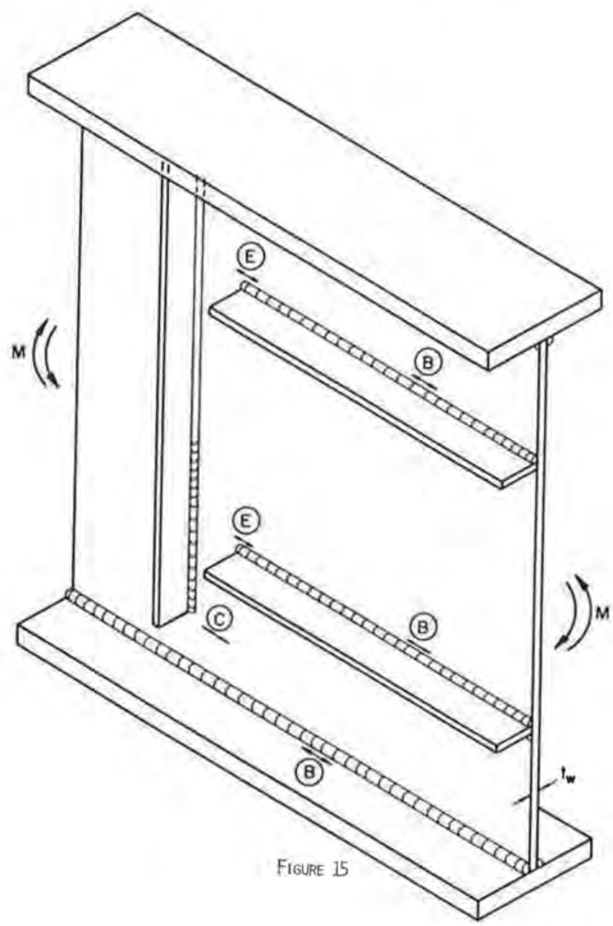

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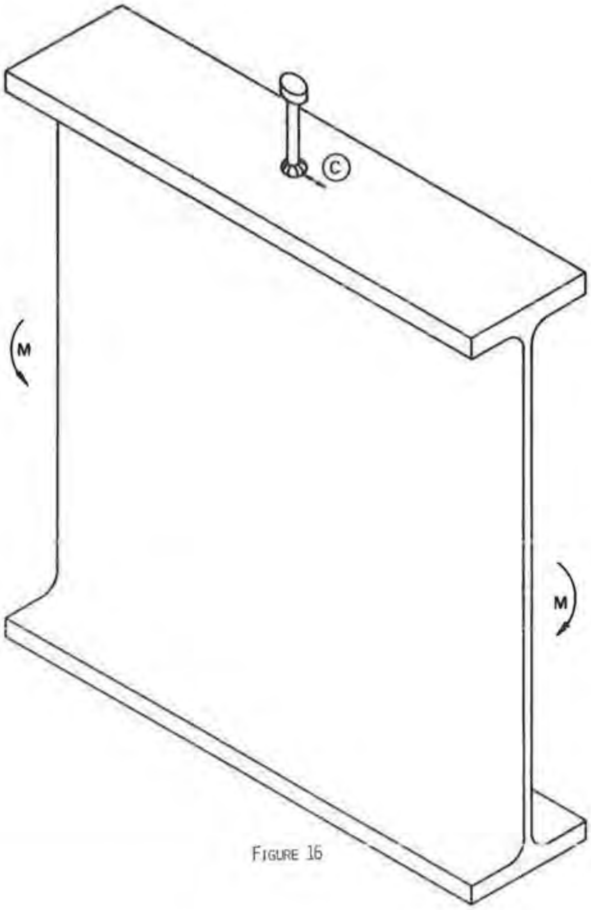
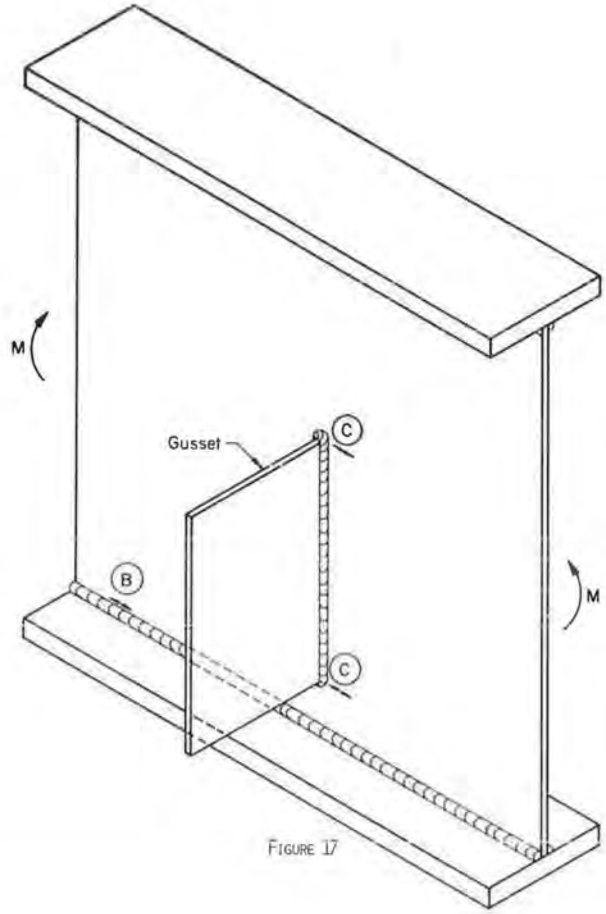


FIGURE 16



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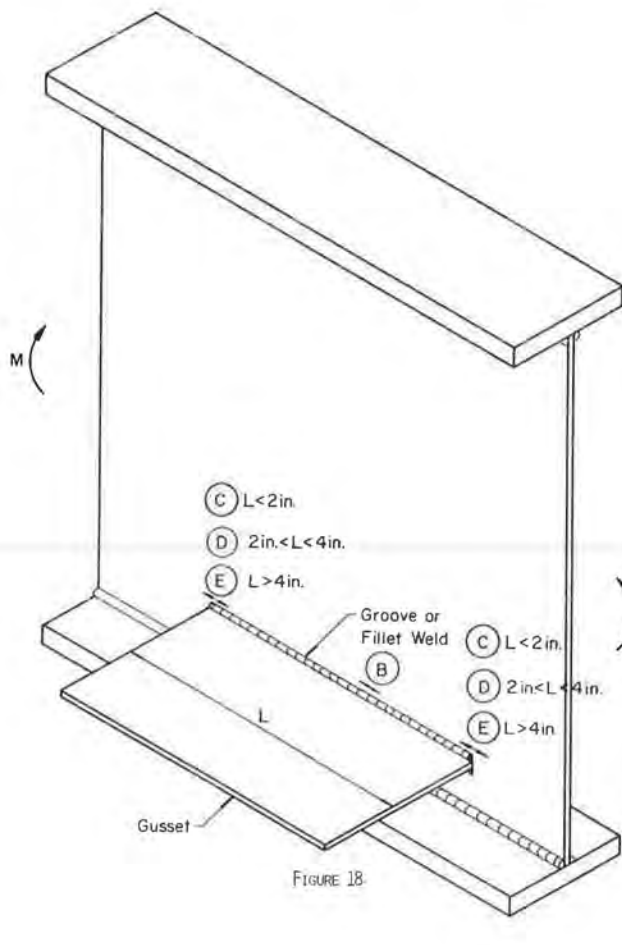

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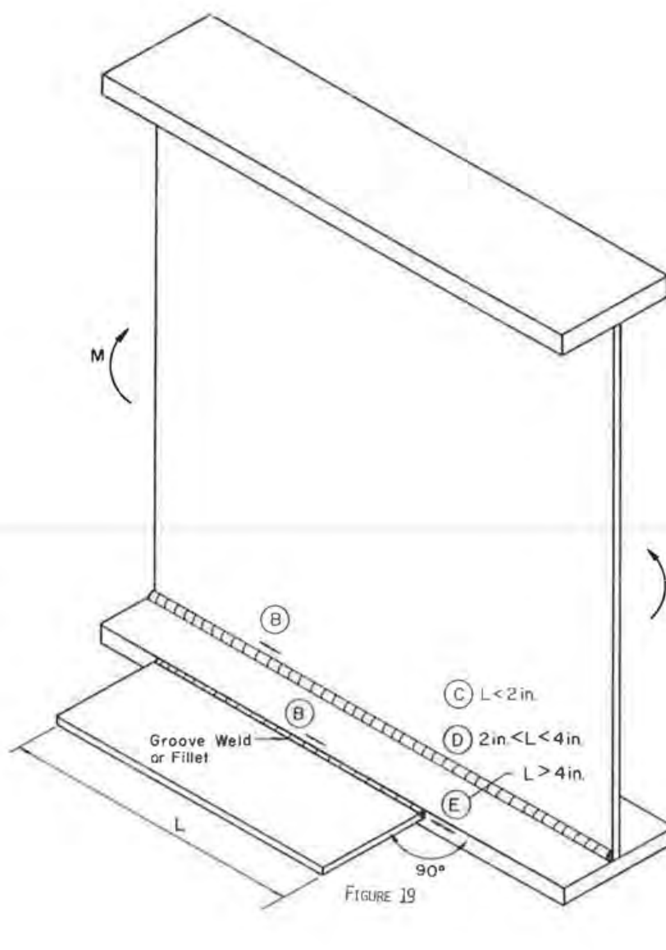
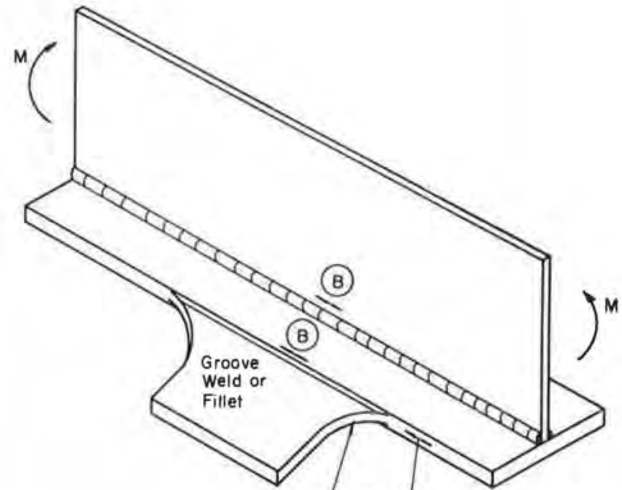


FIGURE 19



R	Category
R ≥ 24 in.	B
24 > R > 6 in.	C
0	E (See Fig. 19)

Note: The weld end must be ground smooth at the transition radius.

Figure 20

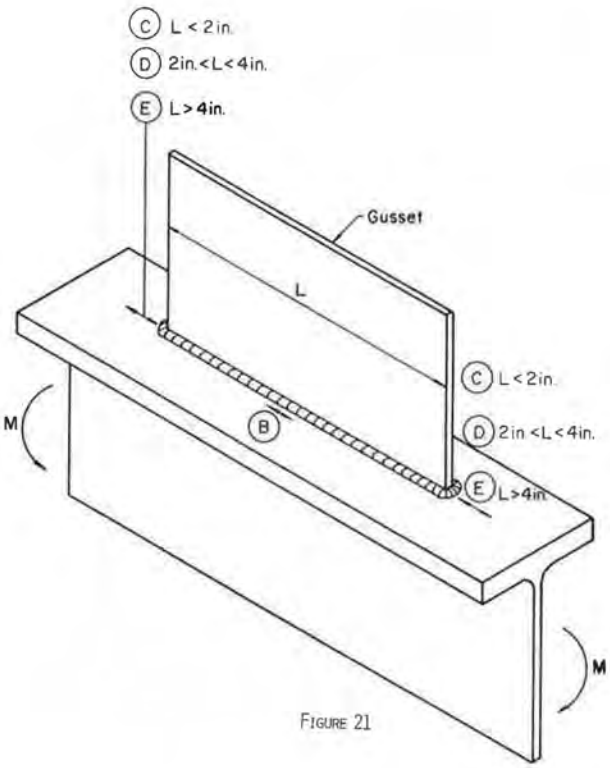


Figure 21

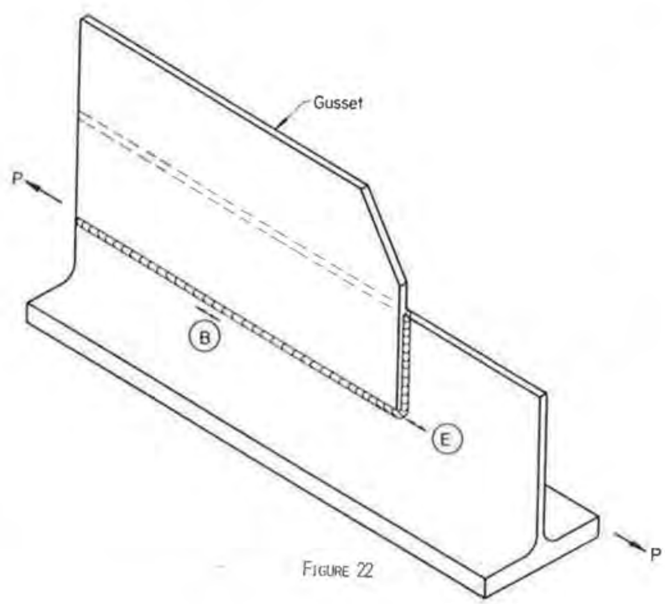


Figure 22

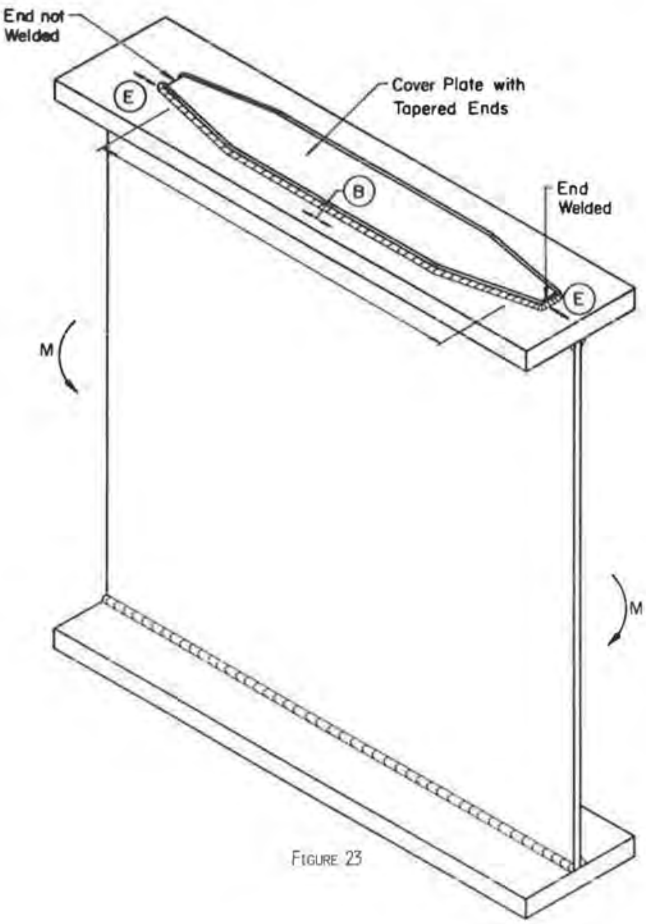
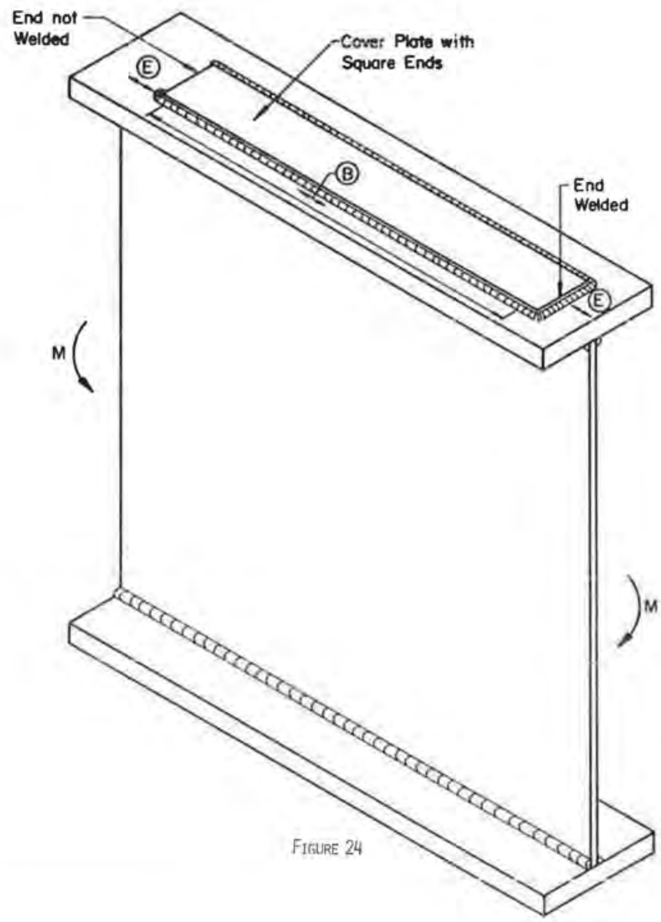


Figure 23



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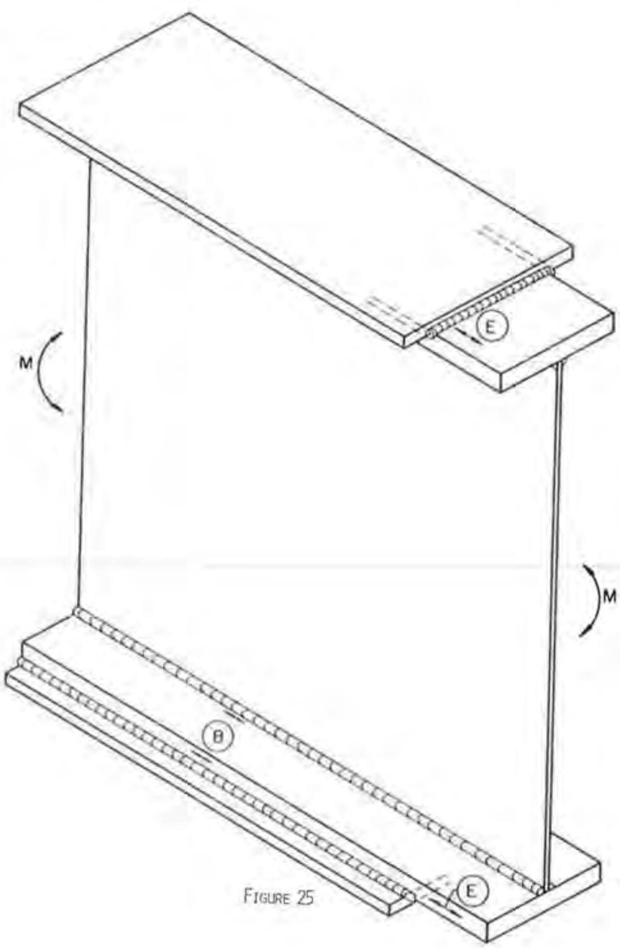

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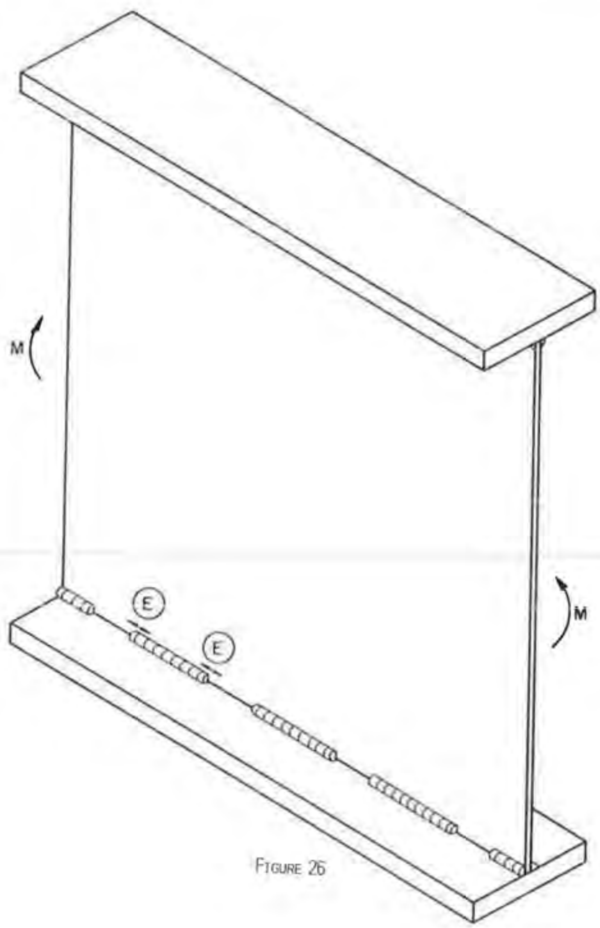

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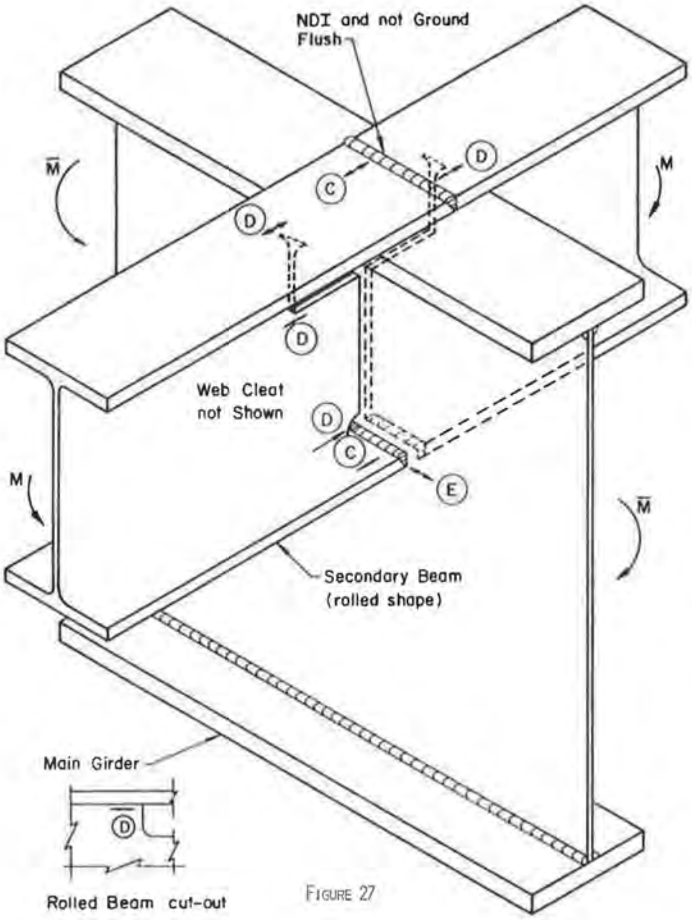
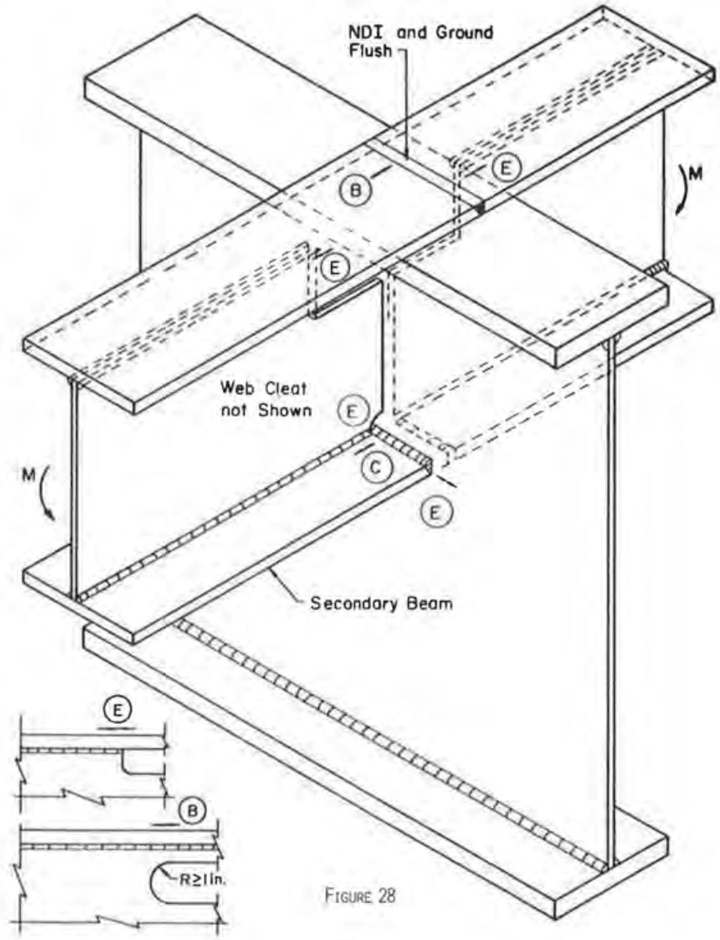


FIGURE 27



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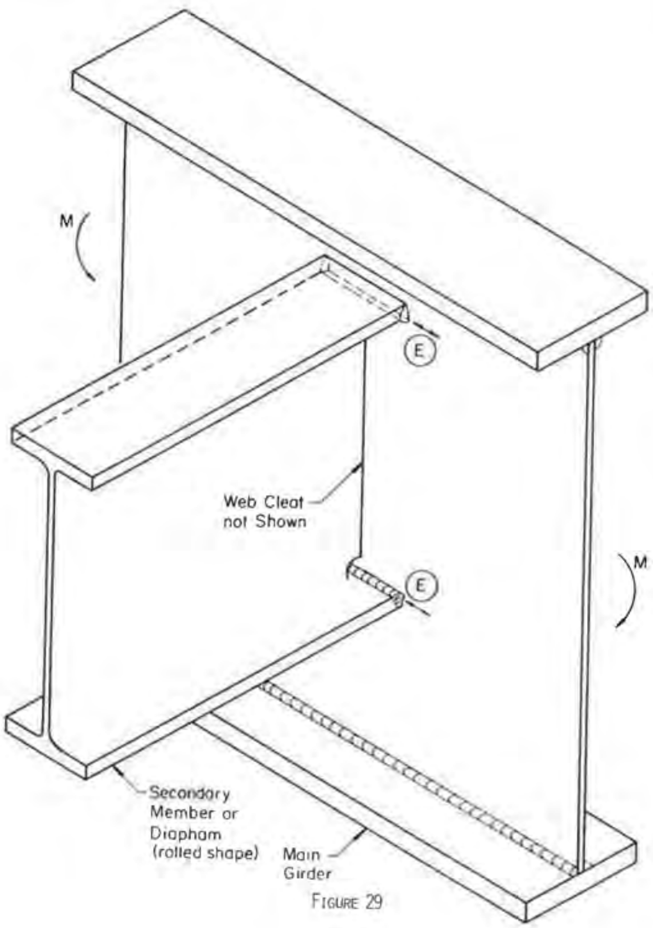

FIGURE 29

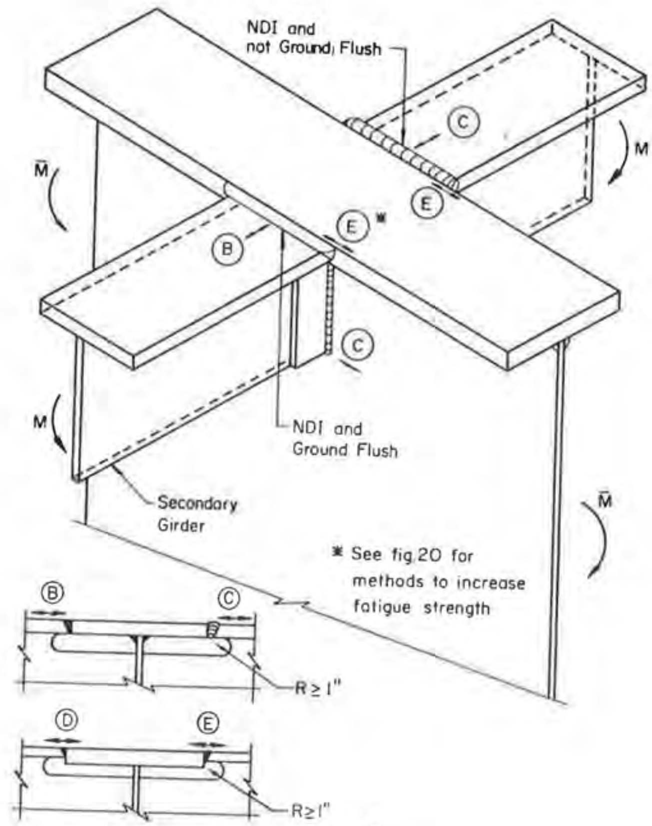

FIGURE 30

(a) From discontinuities in rolled surface,

(b) From sharp gouge in flange tip,

Fig. 31. Typical fatigue cracks initiating from surface flaws.

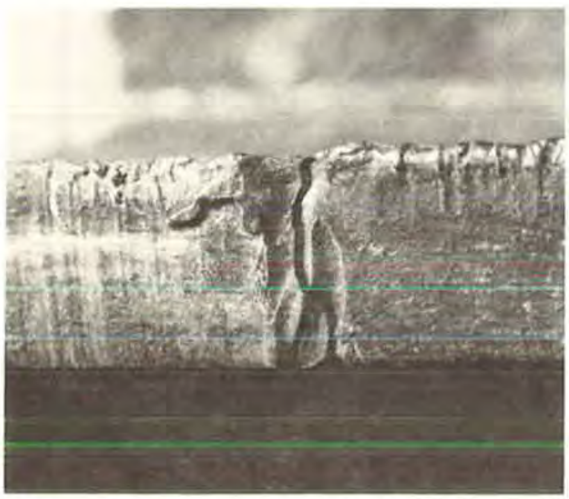

Fig. 32, Fatigue crack at flame-cut flange tip of beam.

Fig. 33. Etched surface of steel plate showing nonmetallic inclusion stringers.

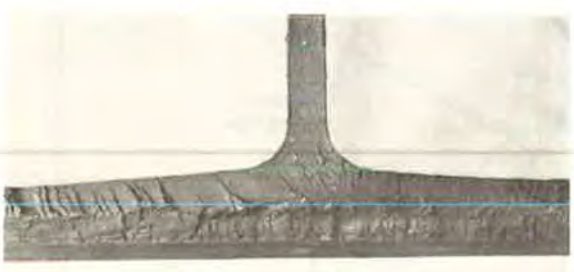

Fig. 34 Fatigue crack surface of rolled beam at end of welded cover plate; inclusion condition at mid-thickness of flange.

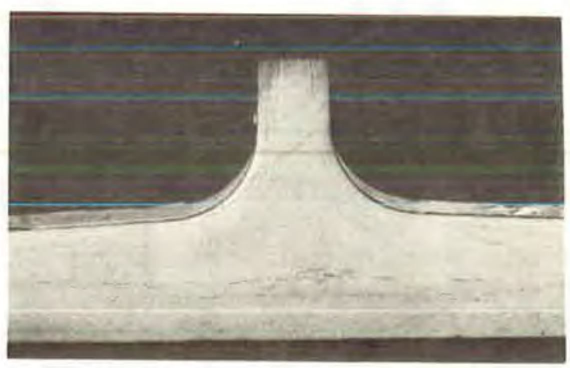

Fig. 35, Etched cross section showing inclusion condition at mid-thickness,

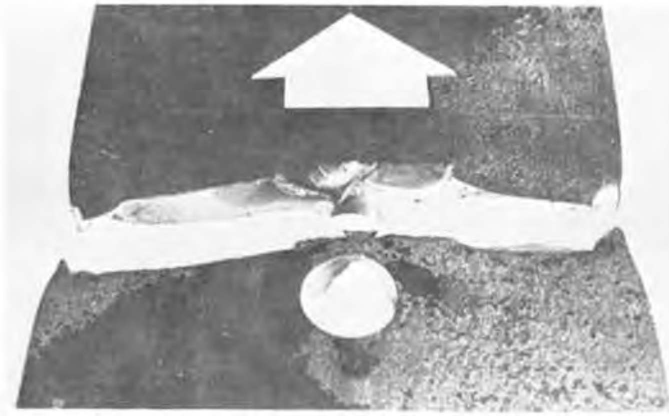

Fig. 36. Fatigue crack growth in gross section of bolted joint.

(a) Crack in surface of punched hole. (b) Shear tip from misaligned punch.

Fig. 37. Discontinuities in punched holes of bolted joint.

(a) At end of longitudinal weld

(b) At toe of transverse fillet weld

Fig. 38. Fatigue cracks at ends of cover plates.

Fig. 39. Fatigue cracking at weld termination of a 4-in. flange attachment.

Fig. 40. Fatigue crack at weld toe of a transverse stiffener.

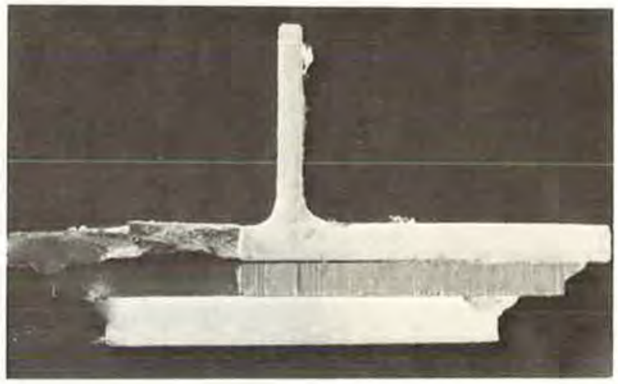

Fig. 41. Fatigue crack growth in multiple-cover-plated beam at unwelded end of secondary cover plate.

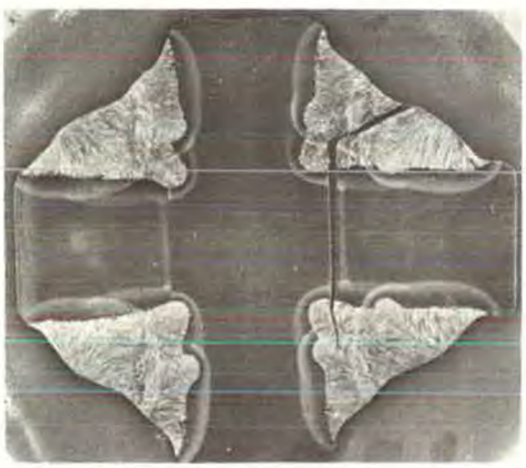

Fig. 42. Fatigue crack growth from root of partial-penetration load-carrying fillet welds.

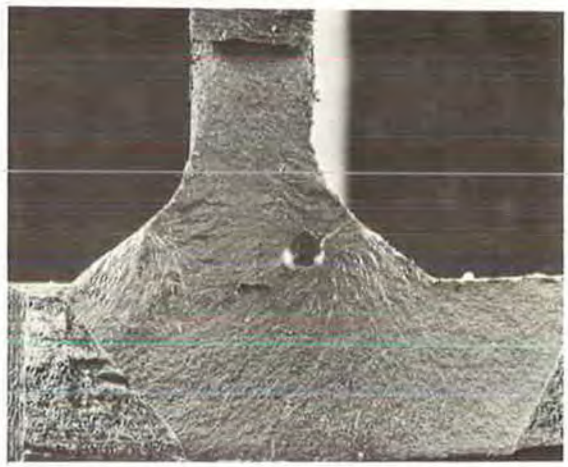

Fig. 43. Crack initiation from gas porosity in web-flange fillet welds.

Fig. 44. Alumina stringer inclusions in plate adjacent to groove weld.