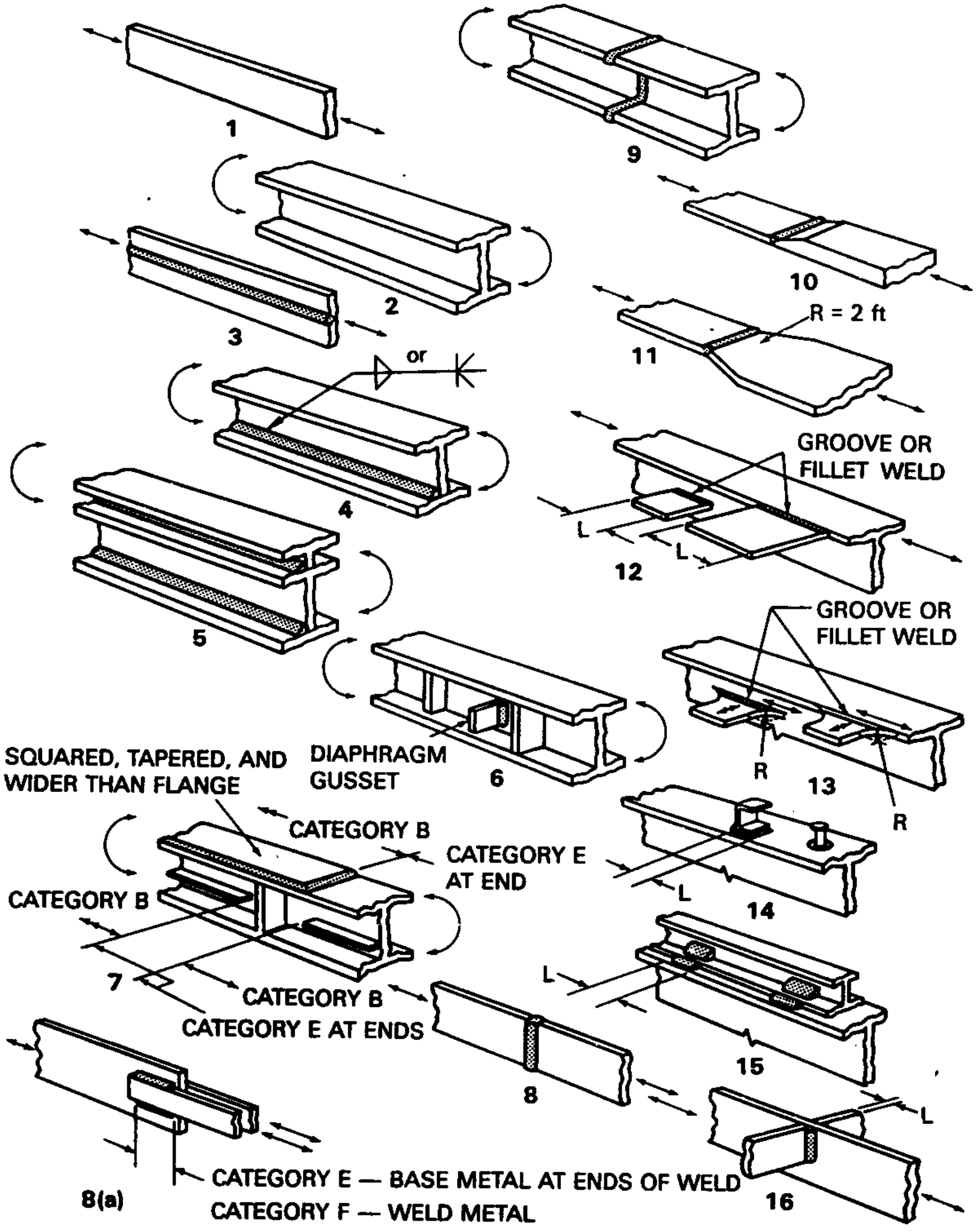
Lecture 18



Note: The numbers below each example are referenced in Table 5.11

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Figure 5.34—Examples of Various Fatigue Categories

Table 5.10
Fatigue Stress Provisions—Tension or Reversal Stresses*

General Condition Situation		Stress Category (See Fig. 5.34)	Example (See Fig. 5.34)
Plain material	Base metal with rolled or cleaned surfaces. Oxygen-cut edges with ANSI smoothness of 1000 μin. (25 μm)or less	A	1.2
Built-up members	Base metal and weld metal in members without attachments, built up of plates or shapes connected by continuous complete or partial joint penetration groove welds or by continuous fillet welds parallel to the direction of applied stress	B	3, 4, 5, 7
	Calculated flexural stress at toe of transverse stiffener welds on girder webs or flanges	C	6
	Base metal at end of partial length welded cover plates having square or tapered ends, with or without welds across the ends	E	7
Groove welds	Base metal and weld metal at complete joint penetration groove welded splices of rolled and welded sections having similar profiles when welds are ground[1] and weld soundness established by RT or UT Inspection	B	8, 9
	Base metal and weld metal in or adjacent to complete joint penetration groove welded splices at transitions in width or thickness, with welds ground[1] to provide slopes no steeper than 1:2-1/2 and weld soundness established by RT or UT Inspection	B	10.11

		Longitudinal loading	Transverse loading[2]			Example (See Fig. 5.33A)
			Materials having equal or unequal thickness, sloped,[1] welds ground,[1] (web connections excluded)	Materials having equal thickness, not ground: (web connections excluded)	Materials having unequal thickness, not sloped or ground, including web connections	
Groove welded connections	Base metal at details of any length attached by groove welds subjected to transverse or longitudinal loading, or both, when weld soundness transverse to the direction of stress is established by RT or UT Inspection and the detail embodies a transition radius, R, with the weld termination ground[1] when					
	(a) R ≥ 24 in.	B	B	C	E	13
	(b) 24 in. > R ≥ 6 in.	C	C	C	E	13
	(c) 6 in. > R ≥ 2 in.	D	D	D	E	13
	(d) 2 in. > R ≥ 0[3]	E	E	E	E	12, 13

Table 5.10 (Continued)

General Condition	Situation	Stress Category (See Fig. 5.34)	Example (See Fig. 5.34)
Groove welds	Base metal and weld metal or in adjacent to complete joint penetration groove welded splices either not requiring transition or when required with transsitions having slopes no greater than 1:2.5 and when in either case reinforcement is not removed and weld soundness is established by RT or UT inspection	C	8, 9, 10, 11
Groove or fillet welded connections[3]	Base metal at details attached by groove or fillet welds subject to longitudinal loading where the details embodies a transition radius, R, less than 2 in., and when the detail length, L, parallel to the line of stress is		
	(a) L < 2 in.	C	12, 14, 15, 16
	(b) 2 in. ≤ L < 4 in.	D	12
	(c) L ≥ 4 in.	E	12
Fillet welded connections	Base metal at details attached by fillet welds parallel to the direction of stress regardless of length when the detail embodies a transition radius. R, 2 in. or greater and with the weld termination ground[1]		
	(a) When R ≥ 24 in.	B[4]	13
	(b) When 24 in. > R ≥ 6 in.	C[4]	13
	(c) When 6 in. > R ≥ 2 in.	D[4]	13
Fillet welds	Shear stress on throat of fillet welds	F	8a
	Base metal at intermittent welds attaching transverse stiffeners and stud-type shear connectors	C	7, 14
	Base metal at intermittent fillet welds attaching longitudinal stiffeners	E	–
Stud welds	Shear stress on nominal shear area of Type B shear connectors	F	14
Plug and slot welds	Base metal adjacent to or connected by plug or slot welds	E	–

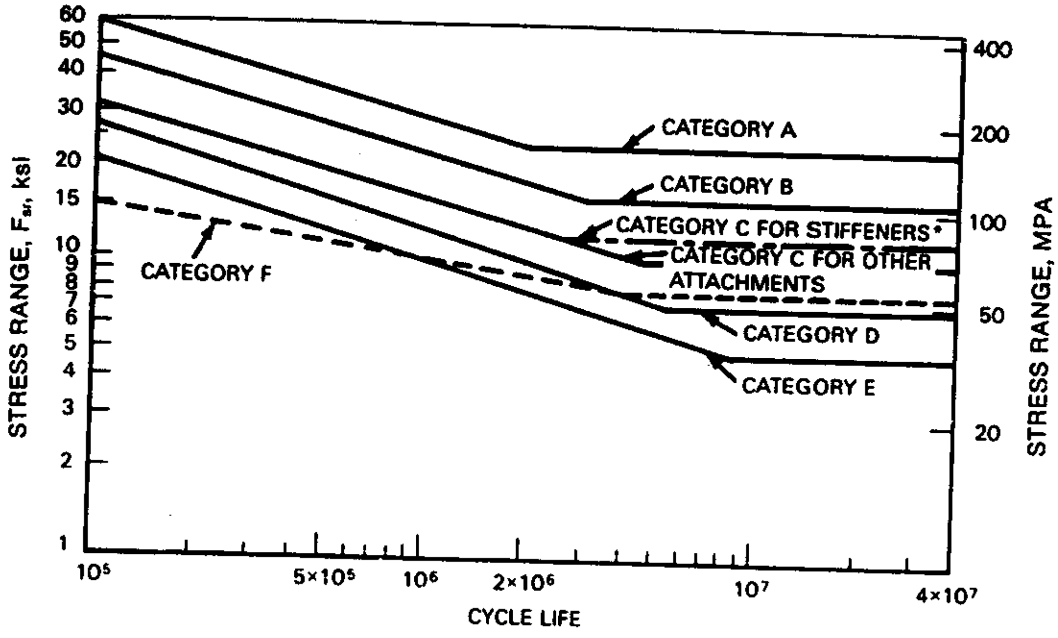
*Except as noted for fillet and stud welds.

[1] See AWS D1.1, Structural Welding Code—Steel.

[2] Applicable only to complete joint penetration groove welds.

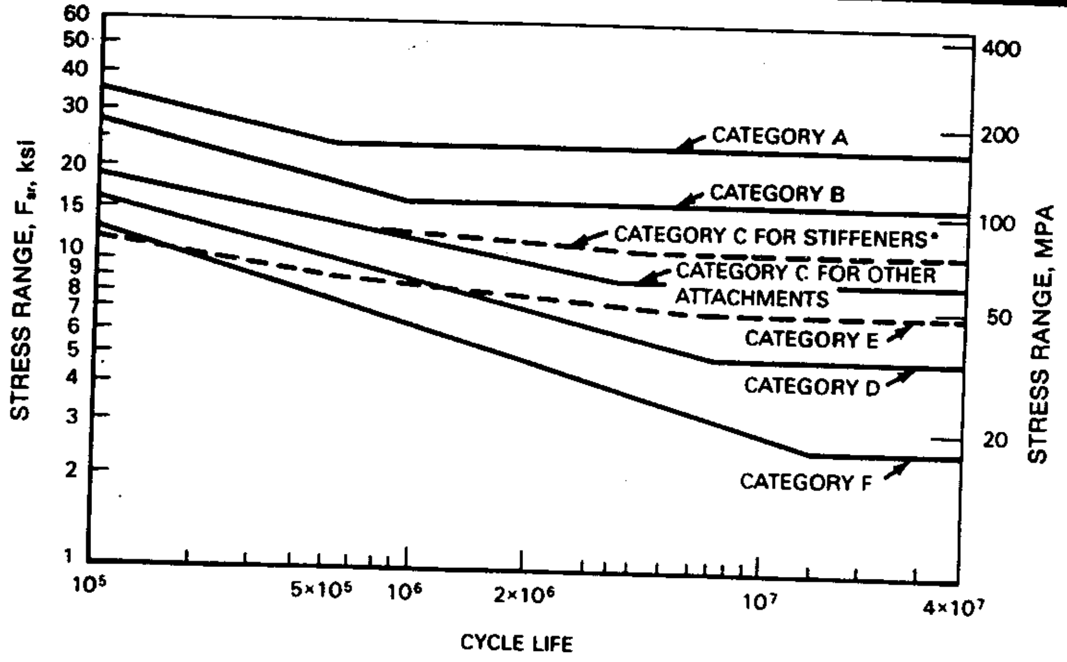
[3] Radii less than 2 in. need not be ground.

[4] Shear stress on throat of weld (loading through the weld in any direction) is governed by Category F.



*Transverse Stiffener Welds on Girder Webs or Flanges

Figure 5.35A—Design Stress Range Curves for Categories A to F—Nonredundant Structures



*Transverse Stiffener Welds on Girder Webs or Flanges

Figure 5.35B—Design Stress Range Curves for Categories A to F—Nonredundant Structures

Lecture 18

Designing Weldments for Fatigue Loading

This introduction to fatigue loading of welded connections can help structural designers understand the basics of this important facet of welding

BY OMER W. BLODGETT

Most engineers do not encounter fatigue failures. When they do, they might refer to a strength of materials text, and listed under "properties of materials" find the term "endurance limit." This sounds as if it could mean the same thing as fatigue, so an engineer might be tempted to use that number and apply a factor of safety to it. Such a conclusion can be very dangerous. First, the stated number is probably very old data. Secondly, it may come from data for polished specimens tested in a rotating beam. In this case, the only difference between the specimens would be the strength, or perhaps the metallurgy. These factors have little to do with typical weldments.

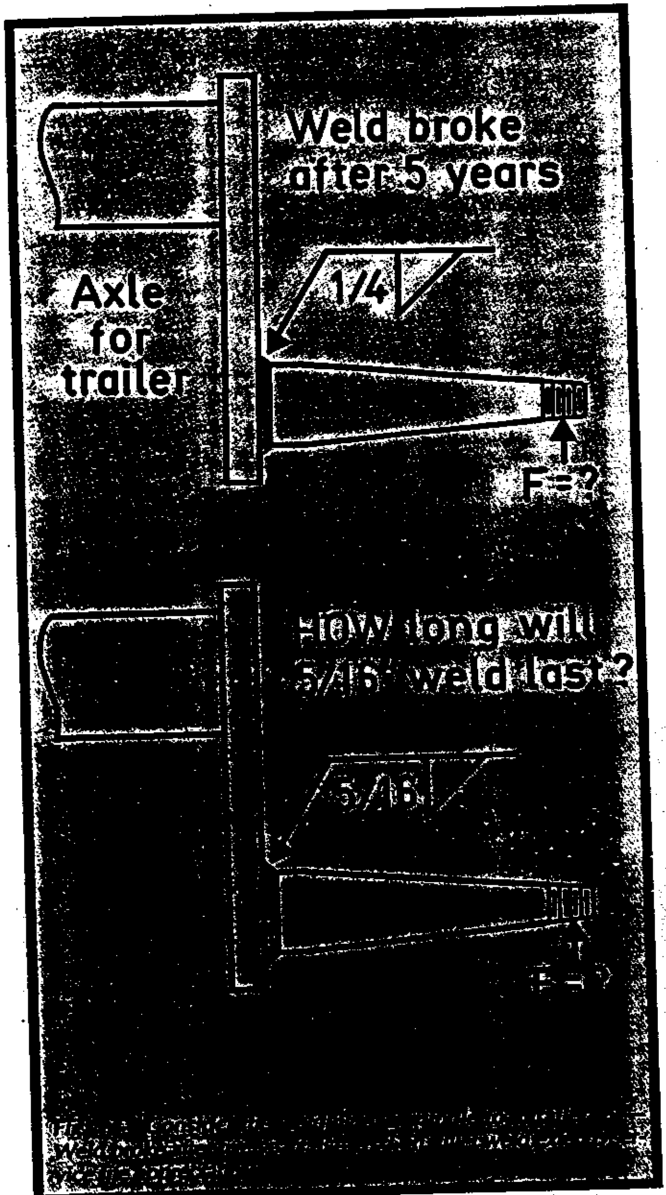
Fatigue failure is caused by repeated plastic yielding. For example, consider a situation in which the applied stress causing failure is 25 ksi (172 MPa), and the yield strength is 40 ksi (275 MPa). How can fatigue failure result when the applied stress is below the yield strength? This failure is due to an abrupt change in section, causing a stress riser. In this case, a 2 to 1 stress riser has caused a stress of 50 ksi (344 MPa) at the root of the notch. After a few thousand cycles, there will be a fatigue crack. The best way to avoid this failure is to provide a smooth transition.

Weld metal is good in fatigue. However, problems can be caused when there is an abrupt change in section caused by excess weld reinforcement, undercut transverse to the stress, the inclusion of slag, or lack of penetration or fusion. Porosity does not seem to be a problem unless it lies near the surface. The worst reduction in fatigue strength will be caused by a weld that already has a crack in it. Fillet welds would not be bad, except that the only way to use them is in a lap or T-joint. These two joints cause an abrupt change in section, even if the configurations are made out of solid metal, without any weld.

A Spindle to a Trailer

Generally, fatigue strength is inversely proportional to the ratio of life raised to a small exponent. Consider the welding of a spindle to a trailer — Fig. 1A. Although the weight of the trailer may be known, the actual force on this spindle is unknown because of the shock loading caused by potholes and other road conditions. We will let (?) stand for the stress on the ¼-in. (6.3-mm) fillet weld. This is a pretty good guess. The trailer is put into service and, after five years, the weld breaks. The trailer is brought into the repair shop. The broken weld is gouged out and replaced with a 5/16-in. (7.9-mm) fillet weld — Fig. 1B. What life can be expected from the new 5/16-in. weld, assuming the same road conditions? The stress can be tensile (σ) sigma, or shear (τ) tau, it doesn't really matter which, because it is the ratio of the stresses that is important.

With a 5/16-in. weld, the stress will be 80% that of the ¼-in. weld. When (?) and (0.8?) are plugged into the formula, the ratio becomes 1.25. Instead of raising the ratio of life



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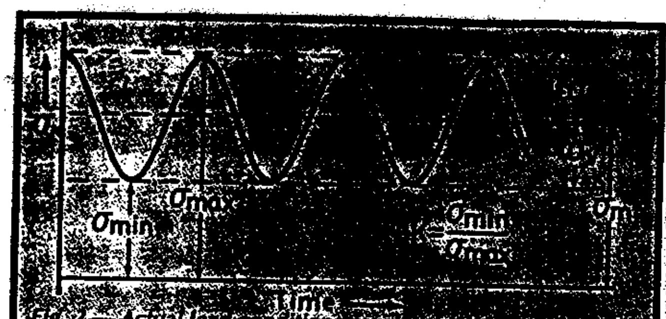

Fig. 2 — Actual load conditions usually result in a spectrum of stress, rather than a nice sine curve.

to the 0.13 power, we use the reciprocal or 7.69 to the ratio of stress. 1.25 raised to the 7.69 power becomes 5.56, meaning that the fatigue life has been increased more than five times, to about 28 years.

In fatigue testing, it is difficult to accurately predict fatigue life. There is a considerable amount of "scatter" in the data. Actual load conditions usually result in a spectrum of stress, rather than in the nice sine curve as shown in Fig. 2. In the past, mechanical engineers have considered a mean stress (σ_m) with a superimposed variable stress (σ_v), shown on the right-hand side of the drawing. Structural engineers have considered a maximum stress (σ_{max}) and a minimum stress (σ_{min}) using (K) as a ratio of the minimum to the maximum. The use of (K) allows its insertion into fatigue formula, permitting the calculation of an allowable fatigue strength.

The top of Fig. 3 illustrates a rather steady stress in which the minimum stress is about equal to the maximum stress, or K = +1. Just below is the load condition K = +½. Below this, the minimum stress reaches zero or K = 0. This fatigue condition would represent presses, brakes and rolling mills in which the stress in the frame is about zero when not used, then jumps to a high value during each operation. At the bottom is a complete reversal in which K = –1. This is typical of all rotating parts and represents the most severe type of fatigue cycle.

Concept of Stress Range

John W. Fisher of Lehigh University introduced the concept of stress range (σ_{sr}) shown in Fig. 4. This drawing shows several stress levels, but all have the same stress range. The stress range is caused by the application of a live load. In a steel weldment, the residual stresses are of the order of the yield point. In general, any application of load would place some portion of the weldment at yield stress. I recommend using the AISC fatigue data for the design of any weldment or structure for fatigue loading. Most of it is derived from the work of Fisher. The AISC program is an ongoing program of fatigue testing, with new data being added periodically (Ref. 1).

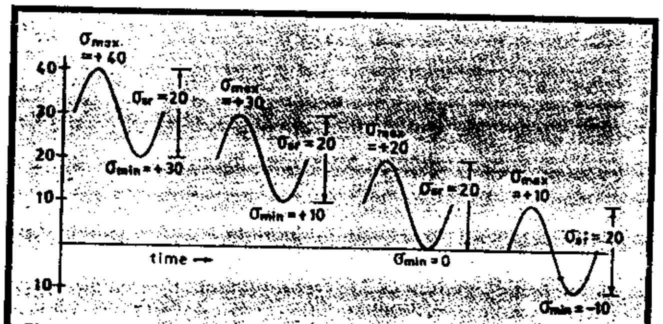

Fig. 4 — Fisher of Lehigh University introduced the concept of stress range to structural design.

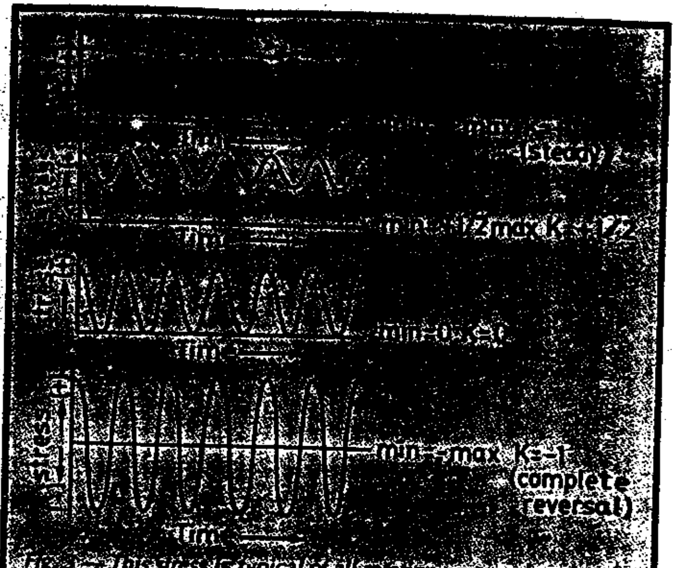

Fig. 3 — This stress is typical of all rotating parts and represents the most severe type of fatigue cycle.

Work done at the University of Florida in Gainesville is shown in Fig. 5. Using strain gauges at the termination of cover plates, it was found that a certain distance, called "terminal distance," is required before the attachment completely loads up. This distance is shorter if there is a transverse fillet weld. In addition, a transverse fillet weld results in a more even distribution of stress in the flange, as well as in the cover plate region.

The residual stresses are of the order of the yield point.

Figure 6 shows work done at the University of Illinois, indicating a slight decrease in fatigue strength when a transverse fillet weld was used. This continued as the weld size was increased. The AISC fatigue values provide the same value whether a transverse weld is used or not. This value is applied at the end of the weld.

One Way to Increase Fatigue Strength

Grinding along the toe of a transverse fillet weld will increase its fatigue strength and provide a much longer life.

Usually, there is a concern about having a smooth surface along the edges of a member. I believe that the central portion of a plate is a little more critical with regard to fatigue loading — Fig. 7. It has been shown that the standard tensile specimen starts to fail within the section. When the stress associated with yield strength is reached, the interior material cannot "neck down" because it is restrained by the surrounding material. It simply goes up to the ultimate tensile strength and fails first.

The central portion of the plate cannot exhibit its ductility when loading above its yield strength. This is the region where fatigue failure can originate.

Figure 8 shows a test of attachments welded with either transverse or parallel fillet welds. In each case, we will see what we have done in this critical central section. The top specimen shows an abrupt change in section in this central region due to the transverse welds. It has the lower fa-

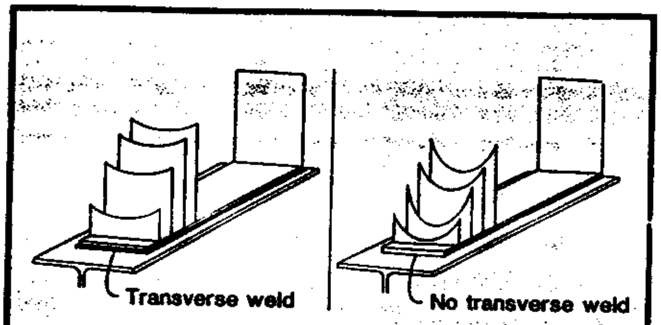

Fig. 5 — Using strain gauges at the termination of cover plates, it was found that a certain distance, called "terminal distance," is required before the attachment

tigue strength. The lower specimen exhibits a smooth transition in this critical region and hence, higher fatigue strength.

Is Money a Factor?

If money were no object, the termination of the cover plate would be tapered as shown on the left-hand side of Fig. 9. In the critical central region, there is an abrupt change in section at the end of the weld. This occurs in a highly stressed region, yet this is a standard practice on highway girders. The right-hand side of Fig. 9 shows an inverted tapered section. There is the same abrupt change in section at the end of the weld in the critical central section, but it is in a lower stressed region. Tests at the University of Illinois indicated a higher fatigue strength with this inverted tapered detail, when made in the form of an inverted semicircle.

Figure 10 illustrates a new addition to fatigue values, namely, the T-joint, using fillet or partial penetration welds (Ref. 2).

> *There are two types of cracking in a welded T-joint.*

There are two types of cracking in a welded T-joint, root cracking (Fig. 10A) and toe cracking (Fig. 10B). Root cracking can be analyzed by fracture mechanics using the unwelded portion (2a) as the size of the initial notch. In either case, increasing the relative size of the fillet weld (W) will increase the fatigue strength of the joint. As the amount of penetration is increased by increasing the depth of preparation of the partial penetration groove, hence decreasing the size of the notch (2a), the fatigue strength will increase until the form of failure shifts to the toe of the weld (b).

Decreasing Stress Concentration

When the unwelded portion (2A) is small enough so that failure is at the toe of the weld (2B), then increasing the size of the weld relative to plate thickness (w/t) will decrease the stress concentration at the toe of the weld, and will increase the fatigue strength of the joint.

The fatigue stress range for a T-joint loaded transverse is as follows:

$$\sigma_{sr} = \sigma_{sr}^{c} \frac{0.71 - \frac{2a}{t_p} + 0.79\frac{\omega}{t_p}}{1.10 t_p^{\frac{1}{6}}}.$$

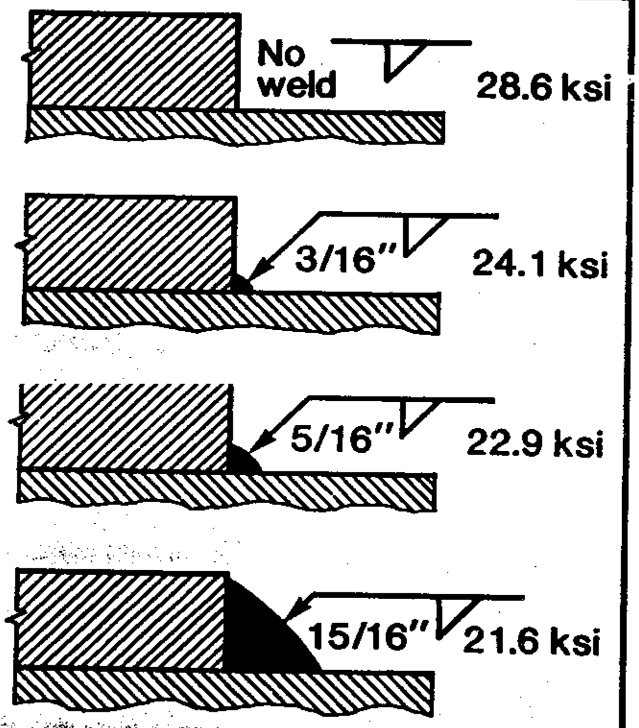

Fig. 6 — A slight decrease in fatigue strength occurs when a transverse fillet weld is used.

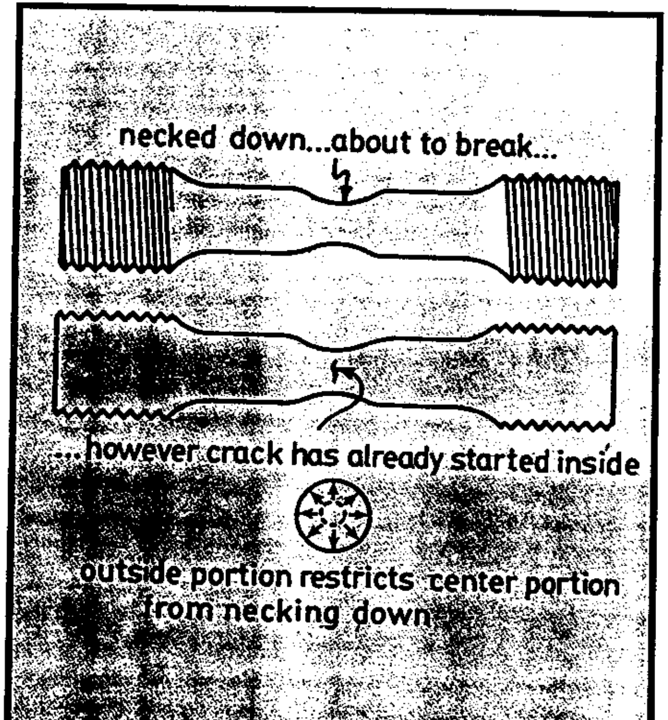

Fig. 7 — The central portion of a plate seems to be slightly more critical with regard to fatigue loading.

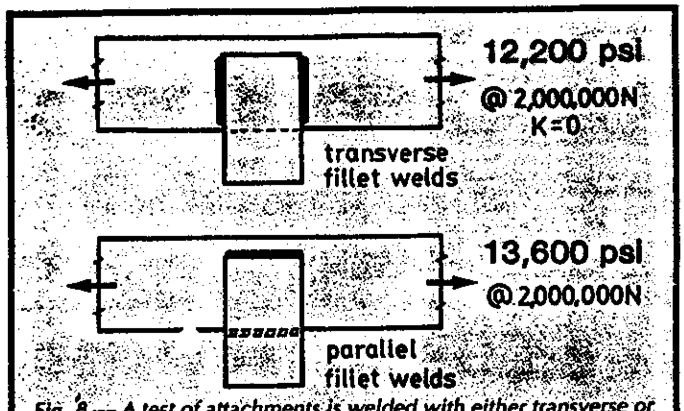

Fig. 8 — A test of attachments is welded with either transverse or parallel fillet welds.

For a fillet welded T-joint, in which $(\frac{2a}{t_p}=0)$ this formula becomes:

$$\sigma_{sr} = \sigma^{c}_{sr} \frac{0.06 + 0.79\frac{\omega}{t_p}}{1.10 t_p^{\frac{1}{6}}}$$

In Fig. 11, two cover plated rolled beams are tested to failure in fatigue. One has a 4 X 9/16-in. (10.1-cm X 14.2-mm) cover plate, and the other has a 6 X 3/8-in. (15.2-cm X 9.5-mm) cover plate. The narrow, thick cover plate assembly has the higher fatigue strength. Upon examination, Fig. 12 shows that the width to thickness ratio of the plate has little to do with the results. The 6 X 3/8-in. plate extends beyond the width of the 5-in. (12.7-cm) flange, presenting a problem where the two welds intersect. Because the 4 X 9/16-in. plate is within the flange of the beam, this problem is avoided. Although this is shown here as a structural problem, it occurs many times in other weldments, where welds on opposite sides of a plate are tied together.

Sometimes a large single-pass weld made in the flat position is selected because it facilitates a slightly higher welding speed. But when the weldment is completed, there are many weld intersections, any one of which would be a good candidate for fatigue failure. In this case, it would be better to choose a multiple-pass weld made in the horizontal position, even though the deposition rate might be a little less and the joint speed might be a little lower. All of these passes may be made continuously around the corner, thus producing a smooth uniform corner condition which is advantageous for fatigue loading.

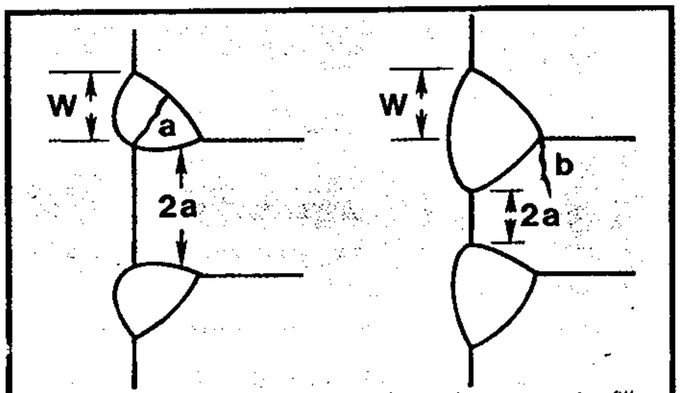

Fig. 10 — A new addition to fatigue values is the T-joint, using fillet or partial penetration welds. There are two types of cracking in a welded T-joint: A — root cracking; B — toe cracking.

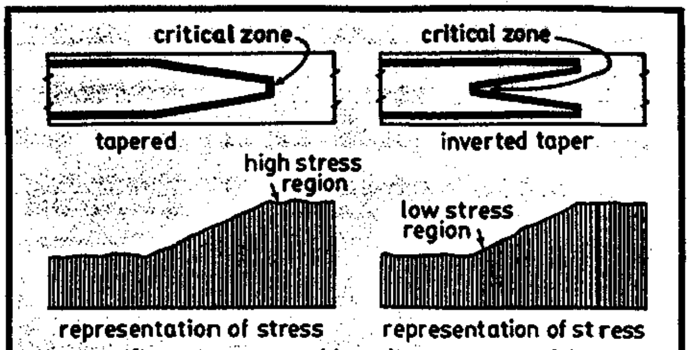

Fig. 9 — If money were no object, the termination of the cover plate would be tapered as shown on the left-hand side.

A Floor Beam to a Plate Girder

In the detail of the attachment of a floor beam into a plate girder shown in Fig. 13, the weld to the flange plate was purposely omitted. The designer was concerned about welding transverse to a flange. Rather quickly, a fatigue crack occurred in the web, adjacent to the end of the weld connecting it to a transverse stiffener. In this case, if the weld had been repaired, it soon would have cracked again because the basic design problem had not been solved. The tensile force in the upper flange of the floor beam from the bending moment must enter the upper flange (the portion lying parallel to the force) of the girder. There is no weld at this point to transfer this force to the girder flange, yet the force must get there. The force travels by deflecting or "diaphragming" the web, placing the web in bending through its thickness with very high stresses. The problem will not be corrected until a weld is placed between the top of the stiffener, and the girder flange.

Figure 14 shows the example of a circular housing of a gyratory crusher. Although several holes were drilled into this housing, a fatigue failure never occurred there. Apparently, the smoothly drilled holes did not produce a stress riser. However, in a similar location, four holes had been drilled and a rectangular section of the housing removed. In a short time, a fatigue failure resulted, even though the cut surfaces were smooth. Apparently, the larger opening caused movement of the housing around this opening, and this movement ultimately resulted in a fatigue crack.

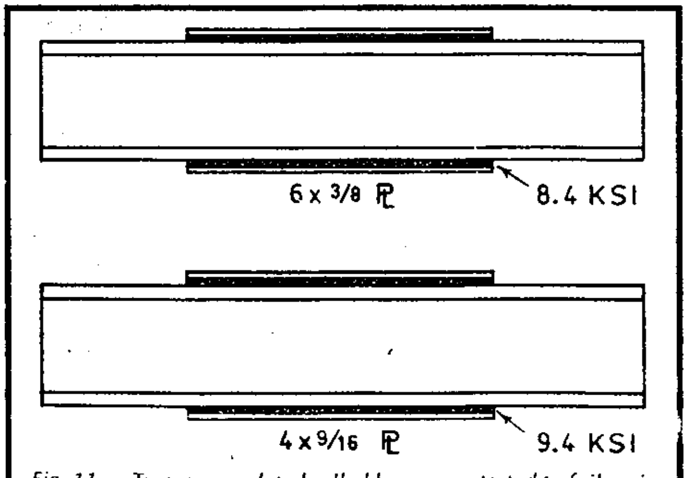

Fig. 11 — Two cover plated rolled beams are tested to failure in fatigue.

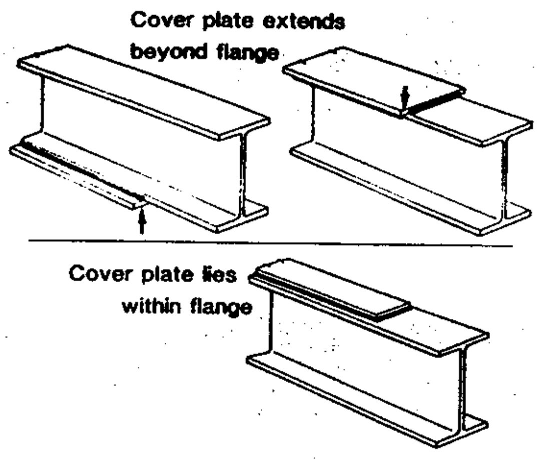

Fig. 12 — The width to thickness ratio of the plate has little to do with the results.

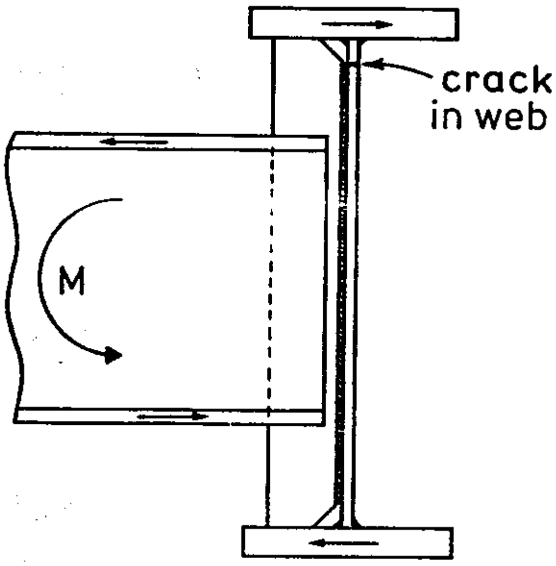

Fig. 13 — In the detail of the attachment of a floor beam into a plate girder, the weld to the flange plate was purposely omitted.

Rationale for Allowables

The relatively new AISC Fatigue Allowables (1989) are most useful to structural designers (Ref. 1). When the AISC first presented the fatigue values, it included values for compression loads (C). The compression values soon were removed. All weldments contain residual tensile and compressive stresses (see the central portion of Fig. 15). If a range of tensile stress is applied in the laboratory, eventually a transverse fatigue crack will occur across the weld (see the lower portion of Fig. 15). If this continues long enough, the crack will progress across the member. This is why AISC provides us with fatigue allowables, so there will be no failure. On the other hand, if a repeated compressive force is applied, see the upper portion of Fig. 15, the weld zone will again exhibit a range of tensile stress, and eventually a transverse crack may occur across the weld. However, in this case, this crack will relieve the initial residual tensile stress in the weld area and continued fatigue loading will not propagate the crack further. If the member is subjected to repeated compressive loading (not a reversal) then it would be designed as though it were subjected to a steady load.

All weldments contain residual tensile and compressive stresses.

A walking beam used in pumping oil, as, shown in Fig. 16, has experienced a fatigue failure. Figure 17 shows that the force (F_t) transverse to the flange of the beam is rather uniform. This is because the pull on the pump rod is uniform. The pull on the crank arm does vary to some extent. However, the parallel component (F_p) which enters the lower flange goes through a complete reversal.

If there is no transverse stiffener, as in Fig. 16, this transverse force (F_t) will not be uniformly distributed across the weld and flange. Since this force is not uniform, its component (F_c), and therefore the parallel force (F_p) will not be uniform, but will be concentrated in the midsection in

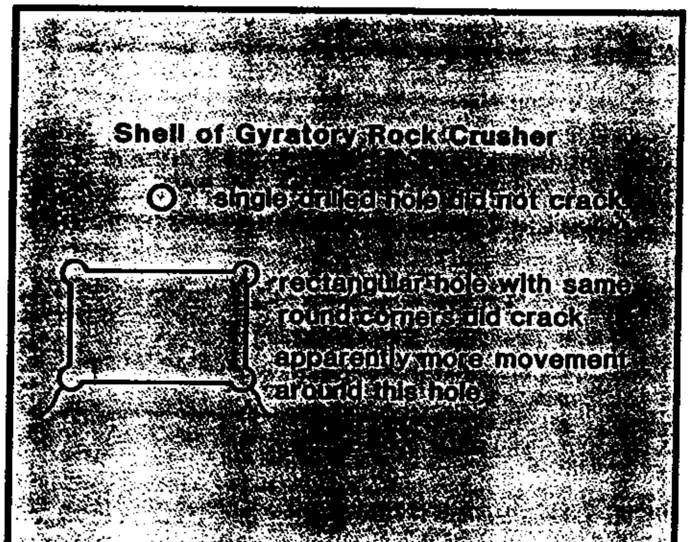

Fig. 14 — A circular housing of a gyratory crusher.

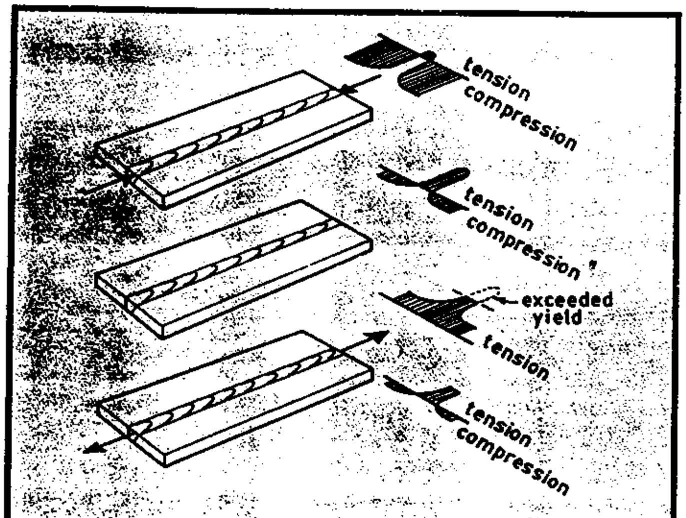

Fig. 15 — All weldments contain residual tensile and compressive stresses.

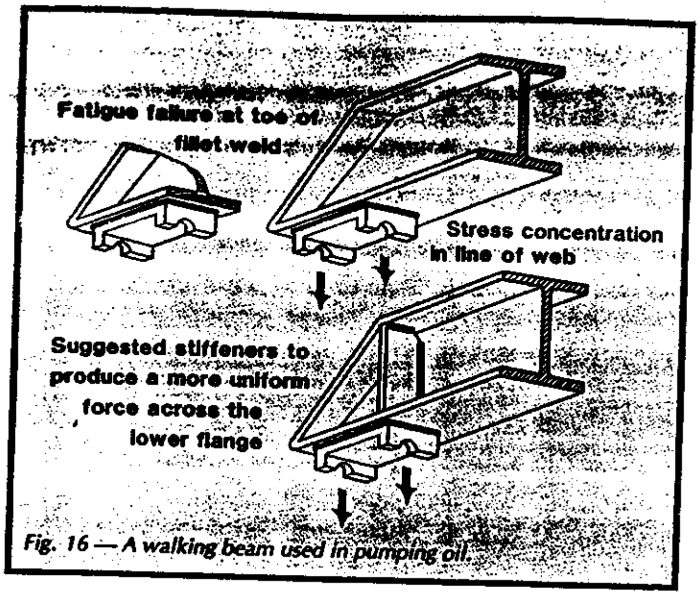

Fig. 16 — A walking beam used in pumping oil.

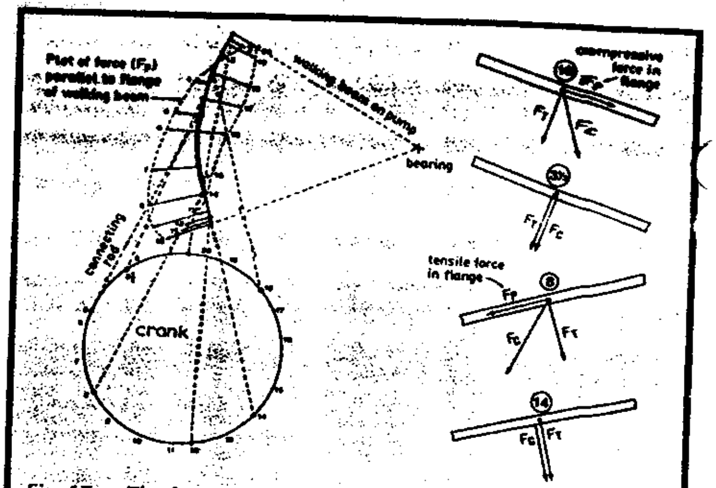

Fig. 17 — The force transverse to the flange of the beam is rather uniform.

line with the web of the beam. The fact that this parallel force is concentrated and goes through a complete reversal makes it a good candidate for fatigue failure. There is little that can be done about the reversal, but transverse stiffeners can be added as shown in Figure 16, lower portion.

This will make the transverse force (F_t), applied force from the crank (F_c) and the parallel force in the flange (F_p) uniform, which should help to solve the fatigue problem. In addition, it would help if the toe of the fillet weld which lies transverse to the flange was ground. This would reduce the stress raiser in the surface of the flange at the toe of the fillet weld. ◆

References

1. AISC. *Manual of Steel Construction - Allowable Stress Design.* 1989. Appendix K, p. 5-106 to p. 5-116.

2. Fisher, J. W., and Frank, K. H. 1979. Fatigue strength of fillet welded cruciform joints. ASCE Structural Division, September 1979, p. 1727.