The Facts Of Fatigue

By A B BRAITHWAITE*

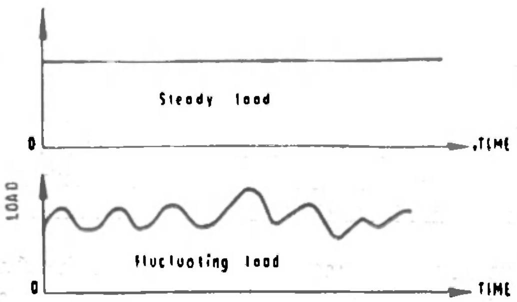
For some designers, the word 'fatigue' is associated with long haired scientists, Goodman diagrams and complicated expressions for cumulative damage. These are misconceptions, the basic facts are very simple, and knowledge of them can save time, material and money.

For other designers,fatigue does not exist, because their structures have been so over-designed that nothing, short of an aerial bombardment, will break them. This may be satisfying, but is also expensive.

It is uncompetitive today to over-design. There is enough information available to make a critical design possible and fatigue failure is likely only if the basic rules are disregarded. In this context it is unrealistic to call fatigue failures something else.

The Facts

Steel structures containing welds may be stressed to just below yield under static loading conditions without failure occurring.† When the load fluctuates, the maximum permissible stress may be as low as 2 tons/in^2. This characteristic of reduced strength under fluctuating loads applies to most metals and their welded, riveted or bolted connections.



When you design a structure, you must have a clear idea of the type of loading that it will be up against. Is it—

STEADY LOAD—due to dead load or self weight ;

FLUCTUATING LOAD from

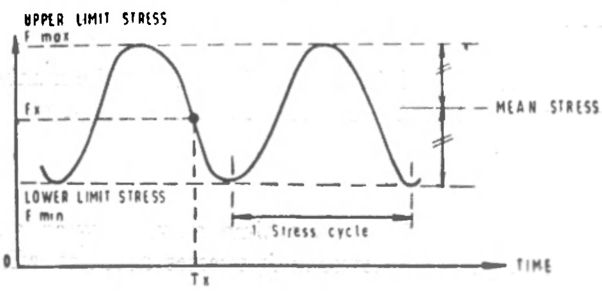
(1) live loads
(2) vibration
(3) temperature fluctuations

If it is any one of the last three types, then the possibility of failure by fatigue must first be considered, and then eliminated. Three factors govern the life of a structure :

(1) NUMBER OF STRESS CYCLES
(2) MAGNITUDE OF STRESS FLUCTUATION
(3) TYPE OF WELD

Stress Cycles

The first thing to do is to show that fatigue terminology is quite straightforward. This is best achieved by using a figure :



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† This statement disregards the possibility of brittle failure.

This curve shows the magnitude of the stress level n relation to time, *i.e.* at the moment in time T_x the tress is F_x.

This particular curve could be produced by a train gauge placed on a very slender bridge that is)eing crossed and recrossed by a fat man on a bicycle.

)bservations

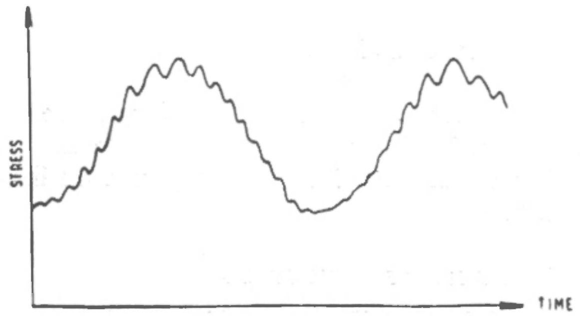
1. Crossing the bridge represents one cycle.

2. The upper limit is reached when he is at mid-span.

3. The lower limit is reached when he rides off the end, and is due to the dead weight of the bridge.

4. The reason for being personal about the man is that he produces an upper limit stress that is at least twice the lower limit stress. (*i.e.* he is of similar weight to the bridge).

5. If the man had walked across the bridge, each step would produce a small stress change, and the curve might look more like this :



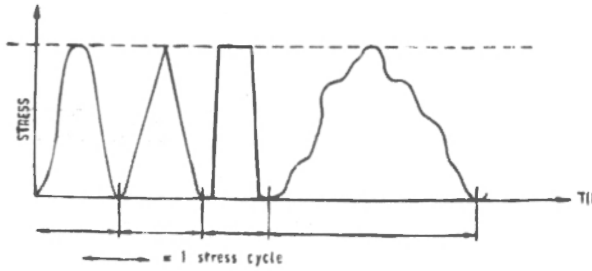
The following pages show the various types of tress fluctuations that occur in practice.

Remember, fatigue life in terms of days or years lepends on three things, STRESS RANGE, TYPE OF WELD, 1UMBER OF STRESS CYCLES. In a critical design, it is mportant to get all three facts right. If you get one vrong, figuring out the other two is largely a waste of ime.

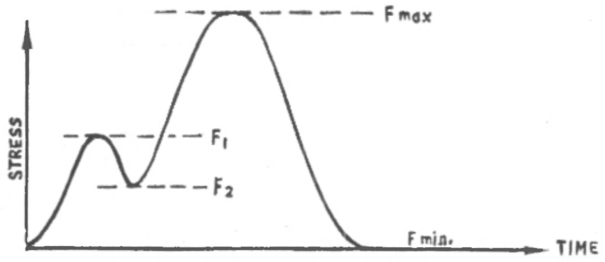
The hardest of the three is determining the number ınd type of stress cycles that will occur in service.

Curve Shape

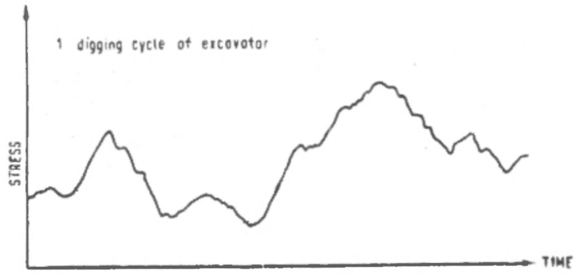
The shape of the stress/time curve between suc-:essive upper and lower limit stresses does not affect fatigue strength, provided that the slope of the curve does not change sign :



Each of the cycles shown above, or any other odd shape you care to draw, produces the same amount of fatigue damage. The one exception is shown below. This is not only one cycle of F_{max} to F_{min}, but also one cycle of F_1 to F_2 :



In fact, many structures and machines produce stress/time curves of an entirely random nature, of which a typical one is shown below. This is called random loading, a phrase that annoys scientists, because they are not sure that they have found a rule that it obeys entirely.



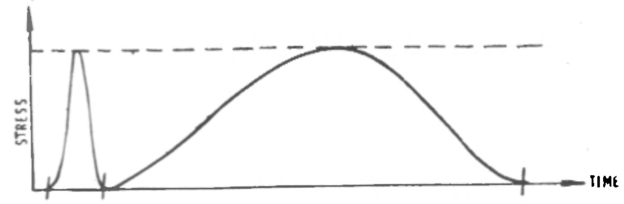
The only way of obtaining the type of curve shown above is by actual measurements with strain gauges during service. In critical design, this information is essential, and is far cheaper than trial and error.

Dynamic strain recordings show both the number of cycles and their magnitude. As the weld type adjacent to the gauge is presumably obvious, you have the three facts immediately available at your finger tips to make an extremely accurate assessment of fatigue life. What more could you want ? (BWRA operates such a service).

Loading Frequency

This has little effect on fatigue strength. For example, take a press operating once a minute, or a machine operating 5,000 times a minute ; if the stress in each on a similar weld detail is the same, they will each fail after the same number of loading cycles, assuming of course that the designer chose excessive working stresses. They will **not** fail after the same amount of **time** has elapsed.

Each cycle produces the same amount of fatigue damage.

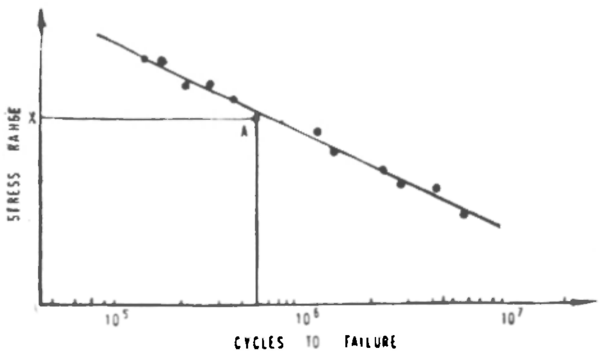


Effect of Stress Range

The stress range necessary to produce fatigue failure decreases with increasing numbers of stress cycles.

When specimens are tested in the laboratory, identical specimens are loaded at various stress ranges until failure occurs. A convenient method presenting the results is an S-N curve.

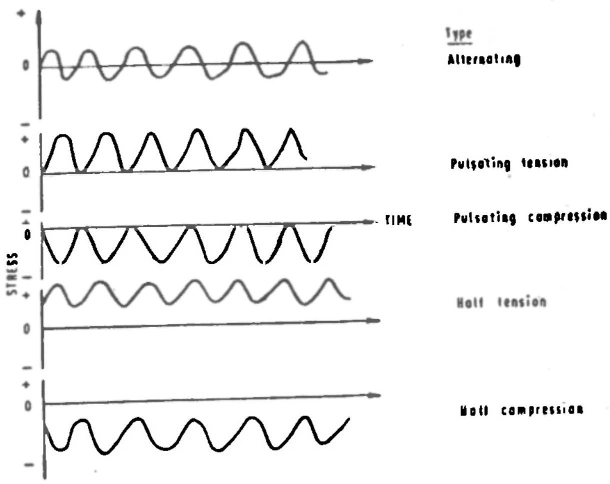
Remember this phrase, it is a handy one to drop when discussing fatigue with the experts. The result looks something like this :



If the horizontal scale is logarithmic, the curve becomes a straight line.

This is the usual form of an S - N curve. If we consider the specimen represented by point A, this was tested at a stress range of x tons/in^2 and failed after 5×10^5 cycles.

In establishing an S - N curve, F_{min} is the same for each specimen and the stress range is varied by changing F_{max}.



The relative position of the fluctuating stress to zero has a considerable effect on fatigue life.

The examples shown above all obey the same rule. For a given stress range, as the mean stress increases in magnitude, the fatigue life decreases.

Reminder : **Fatigue life** is the number of cycles that occur before failure.

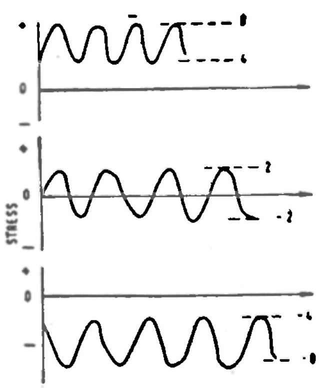
Mean stress : Mean of the upper and lower limit stresses.

Stress range : Difference between the maximum and minimum stresses.

To give some idea of the effect of mean stress, below are some figures that apply to a certain type of weld. The stress range in each case is 4 tons/in^2.

All the necessary information on allowable stresses for steel for all loading conditions is contained in Parts 3B and 4 of B.S. 153.

As there is nothing like a few worked examples, these are included at the end of this article. But before these are examined, please read the final section below.

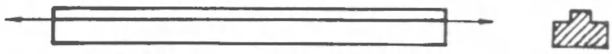


$\frac{F_{min}}{F_{max}}$	F_{max}	Fatigue life (cycles)
0·5	8	$0·8 \times 10^6$
-1	2	2×10^6
0 5	-8	100×10^7

Effect of Welding on Fatigue Strength

The preceding pages could equally well apply to any form of fatigue—plain plate, riveted, bolted or welded but this last section is exclusive to welding, and in many ways, appears to go against the grain of, so to speak, 'unwelded fatigue'.

Fatigue cracks are produced by stress concentrations. A stress concentration is formed at every change of section of the material. Every weld produces a change of section. But, the change of section must lie transversely to the direction of stress to have any effect :



No effect on fatigue strength

Considerable effect on fatigue strength

A weld does not have to be transmitting any load to produce a stress concentration.

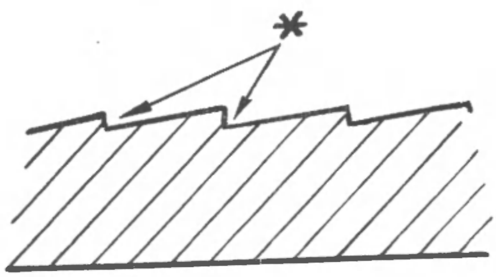
Small attachments such as clips, gussets, ribs, etc. all normally attached by fillet welds, and not in themselves carrying any load may result in a low allowable stress in the member to which they are attached.

Welds Lying in the Direction of Stress

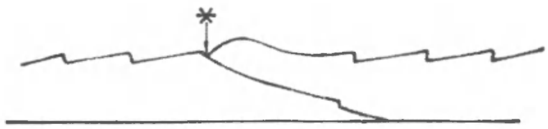
(Example : web/flange weld on a beam).

The stress concentration formed by these welds, whether fillet or butt welds, is due to the ripple on the weld surface.

It is important to realise that the weld metal is an extension of the parent metal, and not just something that is 'stuck on'. A magnified section of a longitudinal weld looks like this :

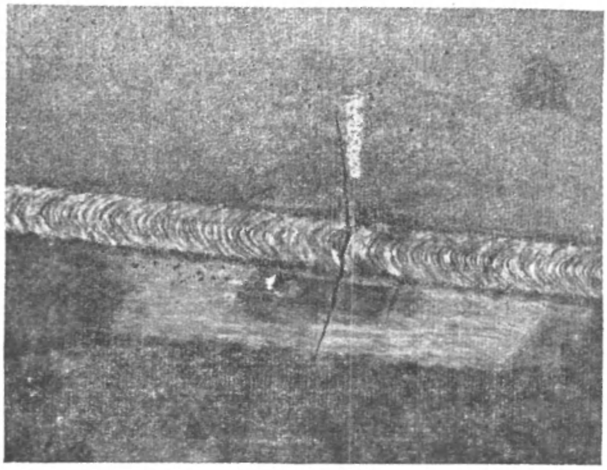


If it is a manual weld using stick electrodes, then a 'stop/start position' looks like this :



A fatigue crack produced by a stop/start

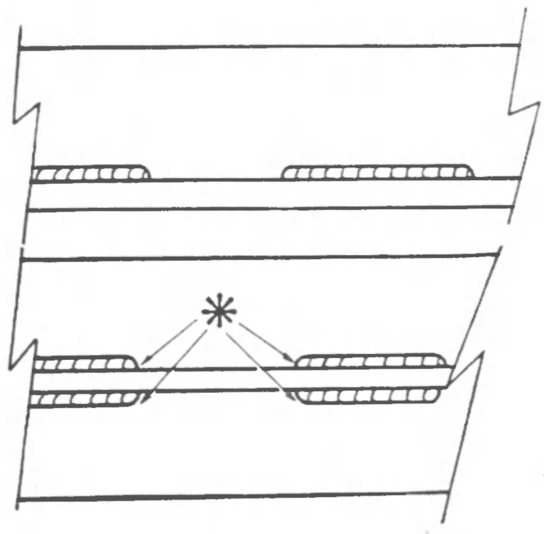
This obviously produces a more severe stress concentration than an automatic weld with no stop/start position and a fatigue crack may readily initiate from this point :



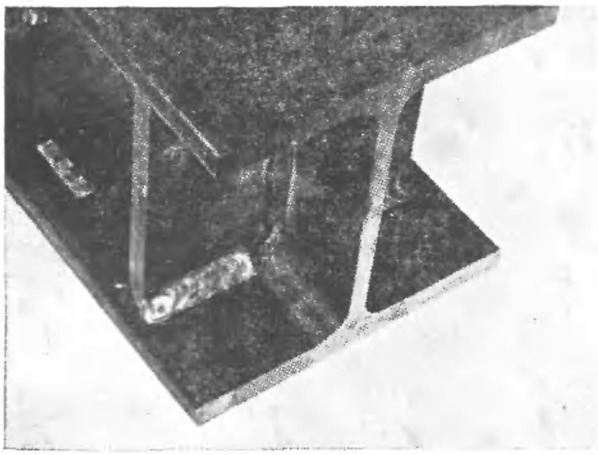
This is the reason why B.S. 153 gives an allowable stress range for automatic longitudinal fillet welds of 11 tons/in², with $\frac{f\ min}{f\ max} = 0$ for 2×10^6 cycles and for manual welds 8.5 tons/in².

These conditions of 2×10^6 cycles at $\frac{f\ min}{f\ max} = 0$ are commonly used when comparing the fatigue strength of welds. 2×10^6 is just a 'magic' figure, that was often used in the early days, and has no particular significance.

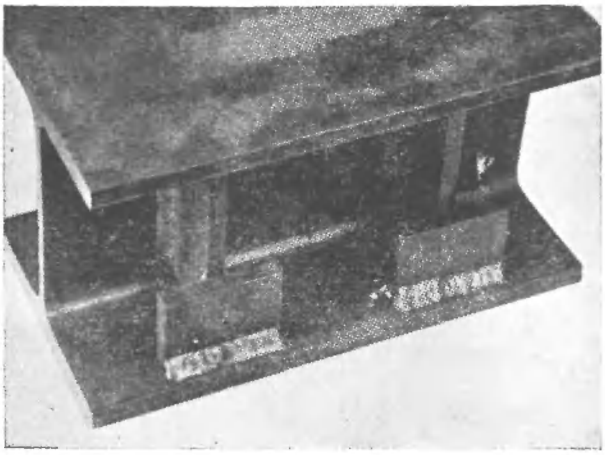
The type of longitudinal weld that causes the most trouble is the intermittent weld. A very severe stress concentration is formed by the ends of the weld :



This type of weld has the same fatigue strength as a transverse fillet weld :



Failure of transverse fillet weld.



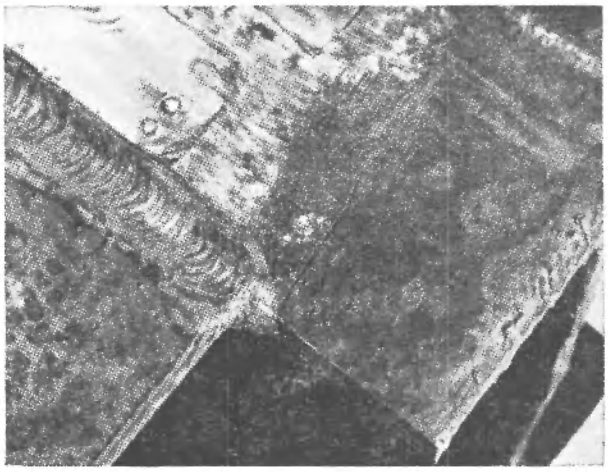
Failure of longitudinal intermittent weld.

A weld end on a plate edge is one degree worse, in fact it is the worst detail that can be produced. This should be avoided at all costs :

Longitudinal partial penetration welds are not to be recommended, as if there is any degree of transverse bending associated with the principal stress, failure may occur.

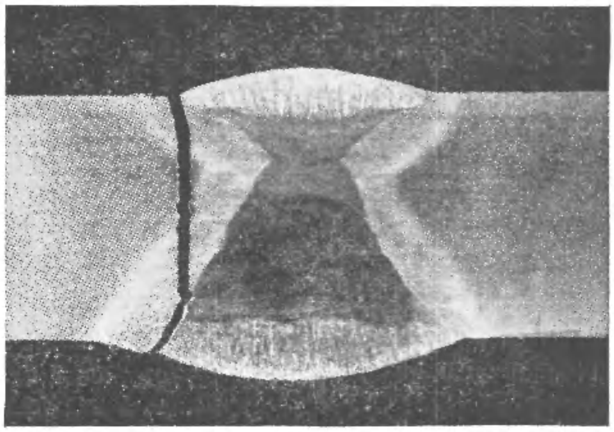
Welds Transverse to the Direction of Stress

In these cases, the stress concentration is formed by the shape of the overfill, together with any undercutting present. It follows then, that the more a



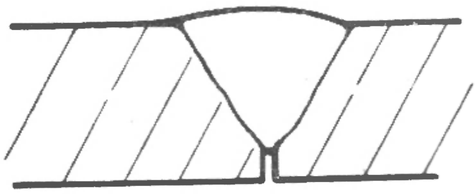
Failure at weld end.

weld is built up to 'strengthen' it, the lower its fatigue strength will be :

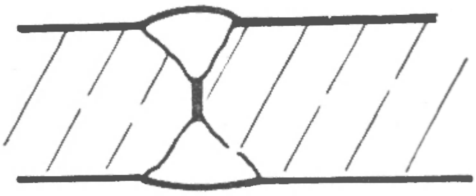


Failure from toe of weld.

Partial penetration welds should never be used :

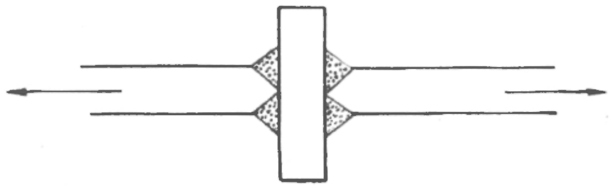


or even double sided welds with lack of penetration at the centre :

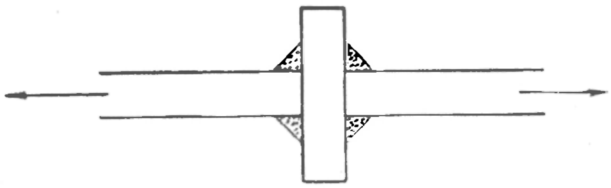


In each case a crack-like defect is sitting there just itching to get moving, and it does not take much in the way of stress fluctuation to do this.

Cruciform butt welds have a geometric stress concentration due to stresses in the components joined being coupled with those caused by the weld :

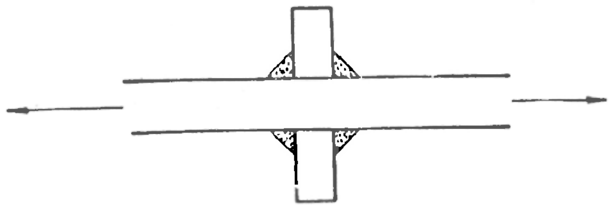


However, this type of joint is much stronger than fillet welds doing the same job :



A load carrying fillet weld has the lowest fatigue strength of all types of weld.

In between the last two cases is the transverse non-load carrying fillet weld :



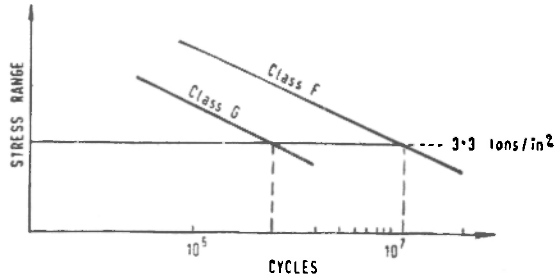
Note again that the weld is carrying no load, but that it produces a stress concentration on the load carrying plate.

When failure occurs from a tranverse butt weld, it will always originate from the weld toe and propagate through the parent plate, **not** in weld metal. The one exception is a butt weld with lack of penetration ; here the mode of failure is through weld metal.

Having covered most common weld configurations, it may now be useful to present them in order of merit. If you have much to do with the design of welded structures, the next page is worth tearing out and pinning to your drawing board as a quick reminder.

For most engineering structures, the weld that governs the allowable stresses is very rarely higher than E or possibly D. However, this does result in acceptable design stresses. The great thing is to get out of the Third Division stuff—classes F and G, for which allowable stresses are low. It should be borne in mind that a small increase in allowable stresses means a large increase in life.

If the maximum stress in a joint of class G is 3.3 tons/in^2, the life is 2×10^6 cycles. When the joint is modified to class F, the life is 12×10^6 cycles—an increase of SIX times.

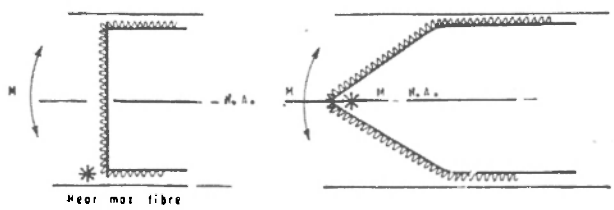


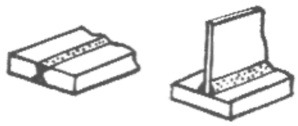
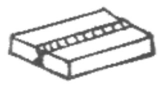
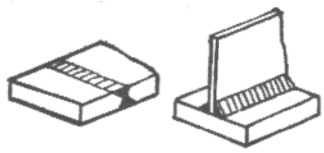
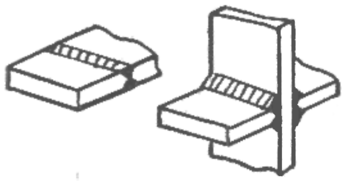
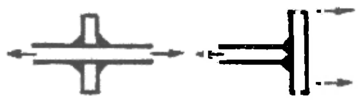
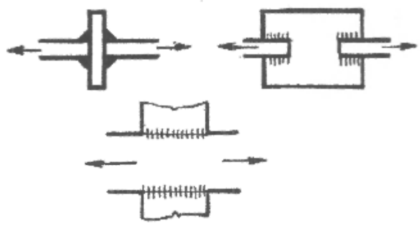
An important point to remember is that the allowable stresses refer to all types of steel. In other words, when welded all steels have the same fatigue strength. This is a very sad fact of life, and so far the scientists have not found the reason. The **only** time the use of high tensile steel is justified in a fabrication subjected to fatigue loading is when F_{max} is above the permissible stress for mild steel.

Finally, in a further attempt to lay the ghost of cover plate geometry, here are the bald facts :

Once you have decided to use a cover plate to locally thicken the flange of a beam, the shape of the cover plate end is immaterial. Whatever shape you choose, you cannot escape the dreaded class F detail —either a transverse weld or a weld end. Each has the same low fatigue strength.

The only time any advantage from shape can be obtained is when the weld end can be arranged at the neutral axis, as on a web.



Weld type	Class as in B.S. 153	Strength at 2×10^6 cycles, tons/in^2 $\frac{F\ min}{F\ max} = 0$	
Plain plate as rolled condition.	A	12.5	
Longitudinal fillet or butt welds made with automatic process (no stop/start positions).	B	11.0	
Longitudinal butt welds made manually.	C	9.5	
Longitudinal fillet welds made manually. Transverse butt welds dressed flush.	D	8.5	
Transverse butt welds. Cruciform butt welds.	E	6.5	
T butt welds. Transverse non-load carrying fillet or butt welds and weld ends.	F	5.0	
Transverse or longitudinal load carrying fillet welds. Welds on plate edges.	G	3.3	

Some Worked Examples Using B.S. 153

(I) A welded girder is required for a certain job in which it is known that a load will be applied once a minute for its total life, which is four years. What is the allowable stress in the girder if web stiffeners are to be welded to the tension flange ? The type of weld under consideration is class F (non-load carrying fillet weld).

(1) Assume that there is no stress arising from dead weight.

thus $\frac{F_{min}}{F_{max}} = 0$

$N = 1 \times 60 \times 24 \times 365 \times 4 \simeq 2.1 \times 10^6$

$\therefore$ F_{max} from B.S. 153 = 5 tons/in^2

(2) Assume that dead load to live load is 1 : 2

thus $\frac{F_{min}}{F_{max}} = +0.5$

with $N = 2.1 \times 10^6$ again, F_{max} from B.S. 153 = 8.4 tons/in^2

$\therefore$ The stress range from load is 4.2 tons/in^2

(II) In one year a hydraulic press has loads applied as follows to a particular member.

Load A
120,000 cycles resulting in 6.8 tons/in^2

Load B
40,000 cycles resulting in 5.0 tons/in^2

Load C
1,000,000 cycles resulting in 3.5 tons/in^2

The press was well designed and incorporated weld details of class D or better. However, a modification is required that involves a weld end on the member. How long will the press last ?

Weld type required is Class F.

$\frac{f_{min}}{f_{max}} = 0$ in all cases (no stress when press is unloaded).

Use Miner's rule : $\Sigma \frac{n}{N} = 1$ when failure will occur.

Look up the appropriate values of N in B.S. 153 for F_{max} stresses of 6.8, 5.0 and 3.5 tons/in^2.

We obtain 0.6×10^6, 2×10^6 and 10×10^6.

Thus in one year

$$\Sigma \frac{n}{N} \; \frac{120{,}000}{0.6 \times 10^6} + \frac{40{,}000}{2 \times 10^6} + \frac{1{,}000{,}000}{10 \times 10^6}$$

$$= 1/5 + 1/50 + 1/10$$

$$= 16/50$$

For failure to occur $\Sigma \frac{n}{N}$ must equal 1,

and in one year $\Sigma \frac{n}{N} = 16/50$.

$\therefore$ The expected life is $\frac{50}{16}$ years $\simeq$ 3 years.

Obviously one would have to think again about the modification.