If all values of S_{ri} are less than S_{oc} it may be assumed that fatigue failure will not occur. Experience (e.g. [8,9]) indicates that this can be assumed to be the case with a stationary narrow band variable amplitude loading spectrum, for which the histogram of stress cycles (including all increases due to misalignment, thickness correction etc.) follows a Rayleigh distribution, if the stress range corresponding to 9 times the root mean square of the stress amplitude for the stress-time history is no greater than the initial non-propagating stress range S_{oc}, (see **16.4**).

However, if any values of S_{ri} exceed S_{oc}, all the stress ranges, including those below S_{oc}, should be included in the summation. This is because the higher stresses in the spectrum are capable of propagating cracks which might then be propagated further by the lower stresses. Some of the lower stresses in the spectrum may be assumed to be less damaging than indicated by the basic *S-N* curve (see **16.4**).

In general, the required fatigue life is achieved if $D \leq 1.0$. Fatigue testing (e.g. [10, 11, 12]) has confirmed that this assumption is safe if the loading produces a spectrum with gradual variation in stress range, notably narrow-band random loading conforming to a Rayleigh distribution of peaks. However, under some stress spectra, including those involving fully-tensile stress cycling about a high tensile mean stress or where there is little variation in the maximum applied tensile stress, tests have shown that fatigue failure can occur when $D < 1$, typically when $D \sim 0.5$ but sometimes even lower [12]. Therefore, if there is any uncertainty about the nature of the service stress spectrum, or for particularly critical cases, it is advisable to limit D to 0.5. Alternatively, D can be established for the particular stress spectrum and welded joint type concerned by reference to relevant published data or by special testing (see Annex E).

If the damage sum D obtained from Equation 8 is greater than the limiting value selected for design (e.g. 0.5), measures that can be taken to improve the fatigue strength of the joint include strengthening the detail to reduce the applied stresses, re-design of the detail to a higher class or the application of a weld toe improvement technique (see Annex F).

Annex A (normative) Fatigue design

A.1 S-*N* relationships

The S_r-*N* relationships for the various structural detail classes have been based on statistical analyses of available experimental data obtained under tensile or shear loading. The analyses involved linear regression analyses of log S_r and log *N* with the slopes of the curves predetermined. In addition some minor empirical adjustments were made to ensure compatibility of results between the various classes [1-3].

The change of slope in the curves from *m* to (*m* + 2) (see Figure 14) is a mathematical device to avoid difficulties in cumulative damage calculations using Miner's rule. The bent *S-N* curve should not be assumed to represent the results that would be obtained in tests under constant amplitude loading.

As far as welded joints are concerned, it has been shown experimentally that, when high tensile residual stresses are present, fatigue strength is a function of stress range alone; mean stress and stress ratio have no significant effect. In general it is impossible to predict what residual stresses might be present in any particular structure and therefore the design rules are based upon the assumption that high tensile residual stresses are likely to be present. For simplicity the same assumption has been made with regard to non-welded details. This is a reasonable assumption to make for both welded (as-welded or stress relieved) and non-welded details if long range tensile residual stresses are introduced, for example as a result of imperfect fit-up during subsequent assembly involving the parts concerned.

Although the fatigue test data used to determine the design S_r-*N* relationships were obtained from arc welded joints it has been found that they are also suitable for similar joints made with either power beam (electron beam or laser) or friction welding [13].

A.2 Fatigue life for various failure probabilities

The standard basic S_r-*N* curves in Figure 10 are based on two standard deviations below the mean line assuming a log normal distribution, with a nominal probability of failure of 2.3%. In certain cases, a higher probability of failure could be acceptable, for example where fatigue cracking would not have serious consequences or where a crack could be easily located and repaired. In situations where, for example, there is no structural redundancy or where the joint is uninspectable it might be desirable to design against a lower probability of failure.

The nominal probabilities of failure for a known stress spectrum associated with various numbers of standard deviations below the mean curve are given in Table 19. The *Sr*-*N* curves appropriate to other numbers of standard deviations below the mean curve can be derived from Equation 2 (see **16.2**).

NOTE The overall probability of failure during the design life of a typical product is substantially lower than the values in Table 19 (which are only applicable to the fatigue strength distribution) when the upper bound values of loading are assumed (see Clause ***7****).*

A.3 Fatigue design philosophy

A.3.1 Safe life design

The procedures and design data provided in this British Standard are primarily intended for use in safe life design. The safe life design approach is based on the use of standard lower-bound fatigue endurance data and an upper bound estimate of the fatigue loading. It therefore provides a conservative estimate of fatigue strength and does not depend on in-service inspection for fatigue damage.

A.3.2 Damage-tolerant design

The damage-tolerant design method should only be used if the product, or the relevant part of it, can be safely and economically inspected by appropriate NDT, and any cracks detected and repaired before they reach a length that could cause failure under static loading. The following should be taken into account and evaluated at the design stage when deciding to take a damage-tolerant approach:

a) the strength of the structure;

b) the consequences of failure; and

c) the need for inspection and the feasibility of repair.

NOTE Damage-tolerant design might be suitable for application where a safe life assessment shows that fatigue has a significant effect on design economy or where a higher risk of fatigue cracking during the design life may be justified than is permitted using safe life design principles.

Damage-tolerant design should ensure that when fatigue cracking occurs in service the remaining intact material can sustain the maximum working load without failure until the damage is detected. Therefore, a prescribed inspection and maintenance programme for detecting and correcting any fatigue should be put in place and followed throughout the life

The following design features should be used to help achieve damage tolerance:

1) selection of materials and stress levels to provide low rates of crack propagation and long critical crack lengths;

2) provision of multiple load paths;

3) provision of crack-arresting details; and

4) provision of readily inspectable details.

Damage tolerance depends on the level of inspection to be applied to the product and is not automatically ensured by replaceable components. Inspection should be planned to ensure adequate detection and monitoring of damage and to allow repair or replacement of components. The following factors should be taken into account:

i) location and mode of failure;

ii) remaining structural strength;

iii) detectability and associated inspection technique, which should be based on the largest flaw not likely to be detected rather than the smallest it is possible to find;

iv) inspection frequency;

v) expected propagation rate allowing for stress redistribution; and

vi) critical crack length before repair or replacement is required.

The calculated fatigue lives enable critical parts to be ranked in terms of fatigue sensitivity. When in-service inspection is an option, this can be used, in conjunction with an assessment of the consequences of failure of specific members, to establish a priority basis for developing a selective inspection programme to be followed during the service life of the product. For non-structurally redundant parts where the consequence of failure is high, or for which in-service inspection would be difficult to achieve, it is often preferable to re-design critical parts to a higher fatigue classification to reduce the level of future inspection required.

Annex B (normative) Explanatory notes on detail classification

B.1 General

This annex gives background information on the detail classifications given in Table 1 to Table 10, including the potential modes of failure, important factors influencing the class of each detail type and some guidance on selection for design.

B.2 Non-welded details (see Table 1 and Table 2)

B.2.1 Potential modes of failure

In unwelded steel, fatigue cracks normally initiate at surface irregularities, corners of the cross sections or holes and re-entrant corners. In steel which is connected with rivets or bolts, failure generally initiates at the edge of the hole and propagates across the net section. However, in double covered joints made with high strength friction grip bolts this mode of failure is eliminated by the pre-tensioning, providing joint slip is avoided, and failure initiates on the surface near the boundary of the compression ring due to fretting under repeated strain.

B.2.2 General comments

B.2.2.1 Classes A to C

In welded construction, fatigue failure rarely initiates in regions of unwelded material as the fatigue strength of the welded joints is usually much lower.

Class A requires special manufacturing procedures which generally render it inappropriate for structural work. Hence assessment of fatigue strength for this class is not included in this British Standard.

Classes B and C should be applied with caution in cases where the high class is dependent on surface finish as this might degrade in service, for example from corrosion or abrasion. However, with due attention to the detrimental features mentioned, there might be scope for adopting a higher design curve than those specified. Such alternatives should be established in accordance with Annex E.

B.2.2.2 Fit-up and pre-tensioning of bolted connections

The specified fit-up of bolted connections should be achieved in practice. If not, the stress ranges applied to the bolts might be much higher than those assumed in design, which could lead to premature failure.

After a group of bolts has been tightened, the torque on all the bolts should be checked. This is because it is possible for some pre-tension to be lost as later ones are tightened, even if they were originally tightened using tension or torque control. If not, bending could be introduced with the result that stress ranges applied to the bolts would be higher than those assumed in design.

B.2.2.3 Fasteners

In threaded fasteners fatigue cracks normally initiate at the root of the thread, particularly at the first load-carrying thread in the joint. Alternatively, failure is sometimes located immediately under the head of the bolt, particularly in bolts with rolled threads and in joints subjected to bending loads.

B.3 Continuous butt welds and welded attachments essentially parallel to the direction of stress (see Table 3)

B.3.1 Dressing of butt welds (type 3.1)

Fatigue tests on butt welds with the weld overfill dressed flush have shown that class C is a realistic design classification provided that the weld is free of flaws. However, this classification is reliant on the detection of surface and embedded flaws that could reduce the fatigue strength below class C. This has been shown to be possible [14] but it does require the provision of NDT techniques and operators capable of both detecting and sizing flaws, a requirement that is generally beyond the scope of routine workmanship inspection. Guidance is provided in Clause **14** and BS 7910. Acceptance levels for welding flaws to meet class C are given in **14.3.4**, or they can be determined using fracture mechanics (see Annex D).

B.3.2 Potential modes of failure

With the reinforcement dressed flush (type 3.1), failure in longitudinal butt welds tends to be associated with embedded flaws. In continuous butt welds or in butt or fillet welded continuous attachments (types 3.2 and 3.3), away from weld ends, fatigue cracks normally initiate at ripples or lumps at stop/start positions on the weld surface. However, in the case of discontinuous welds (types 3.4 and 3.5) fatigue cracks occur in the parent metal at the weld ends.

B.3.3 General comments

B.3.3.1 Welds near plate edges (see Figure B.1)

Although welding attachments to plate edges can result in a very low classification (e.g. types 4.7 and 7.7) there is no downgrading for welds close to a plate edge or ones that accidentally overlap an edge. However, as with edge attachment welds, in such cases the possibility of local stress concentrations occurring at unwelded corners as a result of, for example, undercut, weld spatter and excessive leg length at stop-start positions or accidental overweave in manual welding should be limited. Similarly, the unwelded corners of, for example, cover plates or box members [see Figure B.1a) and Figure B.1b)] should not be undercut. If this does occur, it should subsequently be ground out to a smooth profile.

Figure B.1 **Welds at plate edges**

Key

1 Avoid or grind out to a smooth profile any undercut to these exposed corners

B.3.3.2 Attachment of permanent backing strips

If a permanent backing strip is used in making a longitudinal butt welded joint it should be continuous or made continuous by welding. Any welds in the backing strip, and those attaching it, should also conform to the relevant class requirements. The classification might reduce to class E or lower (type 5.3 or 5.4) at any transverse butt welds in the backing strip that have not been dressed flush or nominal stress class E at any permanent tack weld (see type 3.6).

B.3.3.3 Tack welds

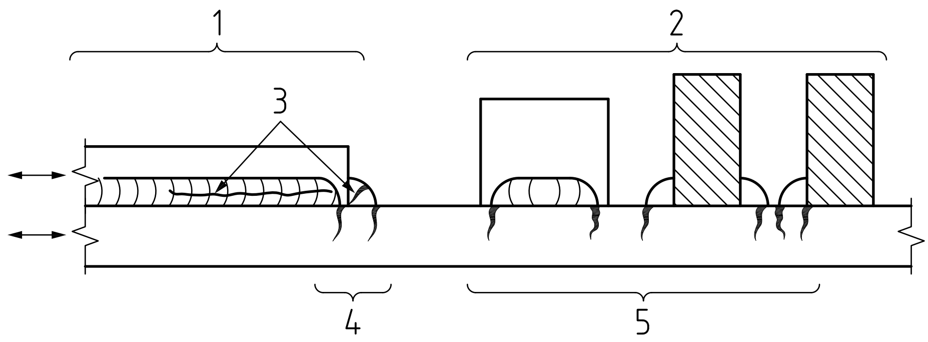
Tack welds, unless carefully ground out or buried in a subsequent run, provide potential crack locations similar to any other weld end. Their use in the fabrication process should be strictly controlled.

B.4 Welded attachments on the surface or edge of a stressed member (see Table 4)

B.4.1 Potential modes of failure (see Figure B.2)

When the weld is parallel to the direction of the applied stress fatigue cracks normally initiate at the weld ends, but when it is transverse to the direction of stressing they usually initiate at the weld toe; for attachments involving a single fillet weld, as opposed to a double, weld cracks might also initiate at the weld root. In each case the cracks then propagate into the stressed member.

Figure B.2 **Failure modes at weld ends and weld toes of welded attachments**



For classification purposes, an "attachment" should be taken as the adjacent structural element connected by welding to the stressed element under consideration. Apart from the particular dimensional requirements given for each type in Table 4 the relative size of the "stressed element" and the "attachment" influences the correction for thickness and bending (see **16.3.2**).

Key

1	Long attachment
2	Short attachments
3	Weld failure cracks (type, 7.8 and 7.10)
4	Joint types 4.2 to 4.6 (or 4.7 at edge)
5	Joint types 4.1 and 4.2 (or 4.7 at edge)

B.4.2 General comments

B.4.2.1 Stress concentrations

Stress concentrations are increased, and the fatigue strength or joint classification is therefore reduced, where the following apply:

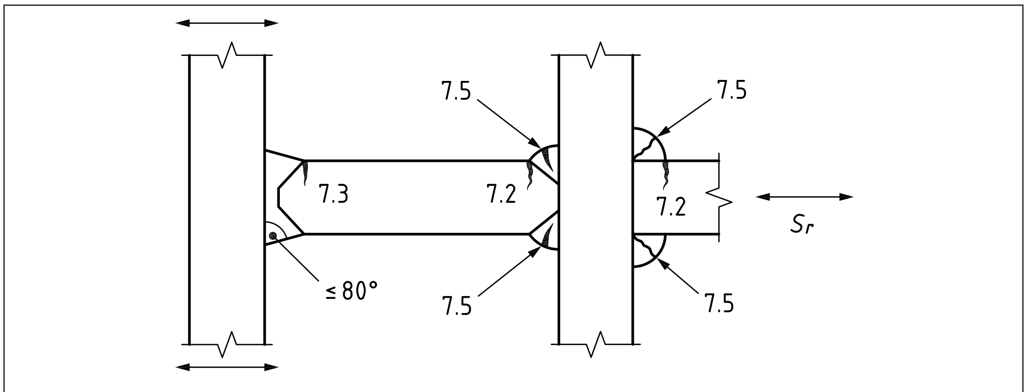
a) the weld ends or toes are on an unwelded corner of the element; and

b) the attachment is long in the direction of stressing and, as a result, transfer of a part of the load in the element to and from the attachment is likely to occur through welds adjacent to its ends. This effect is further intensified with thick attachments.

B.4.2.2 Weld forms

Full or partial penetration butt welded joints of T form, including cruciform joints, (e.g. those that would connect attachments to the surface of a stressed element) should be completed by fillet welds of sufficient leg length to produce nominal weld toe angles no greater than 80° (see Figure B.3). The fillets exclude the possibility of an increase in stress concentration arising at an acute re-entrant angle between the element surface and the toe of the weld, and it is therefore unimportant whether the attachment is fillet or butt welded to the surface when assessing the effects on the stressed element, as a similar toe profile results in both cases.

Figure B.3 **Failure modes in cruciform and T-joints for joint types indicated**



NOTE T-joint shown with minimum weld angle to be achieved when adding fillet weld to full or partial penetration butt welded joint.

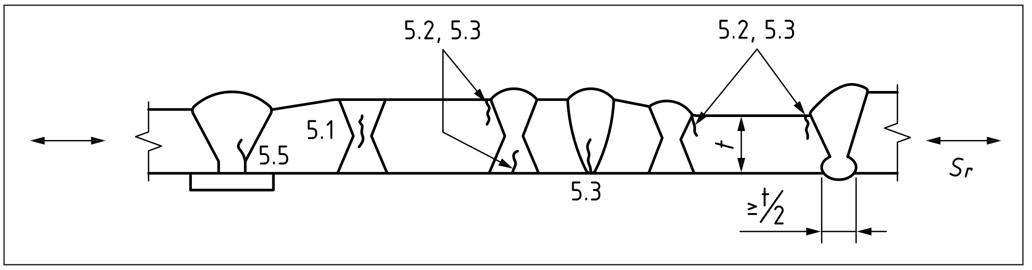
B.5 Transverse butt welds (see Table 5 and Table 6)

B.5.1 Potential modes of failure (see Figure B.4)

With the ends of butt welds machined flush with the plate edges, fatigue cracks normally initiate at the weld toe and propagate into the parent metal, so that the fatigue strength depends largely upon the toe profile of the weld. If the reinforcement of a butt weld is dressed flush (see type 5.1), failure is more likely to occur in the weld material from embedded flaws or from minor weld flaws which become exposed on the surface, e.g. surface porosity in the dressing area.

In the case of butt welds made on a permanent backing strip, fatigue cracks initiate at the weld metal backing strip junction and then propagate into the weld metal.

Figure B.4 **Failure modes in transverse butt welds for joint types indicated**



B.5.2 General

B.5.2.1 Misalignment

Butt welded joints between plates or tubes are susceptible to misalignment (see **C.6**) and therefore transverse joints might experience secondary bending under applied axial loading. No allowance is made for this in the classifications. For elements where out-of-plane bending is resisted by contiguous construction, e.g. beam flanges supported by webs, wide plates supported by effectively continuous stiffeners, eccentricities due to axial misalignments in the thickness direction may be neglected.

However, where such support is not provided, e.g. tension links, the design stress should include an allowance for the bending effects of any misalignment [1], i.e. the nominal distance between the centres of thickness of the two abutting components, *e*. For components tapered in thickness, the mid-plane of the untapered section should be used. The nominal stress should be multiplied by the following stress magnification factor:

$$k_m = 1 + 6\frac{e}{t_1} \times \frac{t_1^3}{t_1^3 + t_2^3} \qquad (B.1)$$

where

t_1	is the thickness of the thinner plate
t_2	is the thickness of the thicker plate

Thus, when $t_1 = t_2$, the stress concentration factor becomes $1+3\frac{e}{t}$.

For other cases, including angular misalignment, see BS 7910. For additional solutions specific to girth welded joints in pipes, reference should be made to DNV-RP-C203.

B.5.2.2 Element edges

Fatigue failures in butt welded plates tend to be associated with plate edges and undercut at the weld toes on the corners of the cross section of the stressed element (or on the edge at the toes of any return welds) should be avoided. If it does occur, any undercut should be ground out to a smooth profile.

B.5.2.3 Part width welds

Butt type welds might also occur within the length of a member or individual plate, e.g. in the case of:

a) a plug weld to fill a small hole;

b) a weld closing a temporary access hole with an infill plate.

Although such geometries have not been given specific categories, the relevant type in Table 5 or Table 6, may be deemed to cover plug and infill plate welds.

[1] This includes unintentional misalignment to the extent of the acceptance limit specified by the manufacturer or fabrication standard being used. Tightening that acceptance limit (see **14.3**) would be beneficial from the fatigue viewpoint.

B.5.2.4 Joints butt welded from one side only

Butt welds should be produced with full-penetration welds. The most reliable way to achieve this in joints welded from one side is by the use of permanent backing (types 5.5 and 6.8). However, the design class is relatively low (class F) and the alternative use of temporary non-fusible backing (types 5.3, 5.4, 6.6 and 6.7) allows some improvement [15]. In this case, inspection of the weld root to assess whether or not there is full penetration is feasible and should be carried out to justify class E. In the case of butt welds in pipes (types 6.6 and 6.7) the surfaces of the pipe and backing should be aligned to within ±1 mm to avoid the seepage of weld metal through the gap and the subsequent formation of a cold lap on the inside of the pipe [16]. In the absence of any backing (types 5.3, 5.4, 6.6 and 6.7) the main requirement is full penetration and to justify class E, this should be assessed by inspection. If this is only possible from one side of the joint, as in pipe girth welds, specialist NDT such as automated ultrasonic testing (AUT) should be carried out, further guidance is given in BS 7910. Experience indicates that the techniques used are capable of detecting root flaws due to incomplete penetration down to approximately 0.6 mm in depth [17].

B.5.2.5 Penetration of butt welds

Butt welds transmitting stress between plates, sections or built-up members connected end-to-end should be full penetration welds.

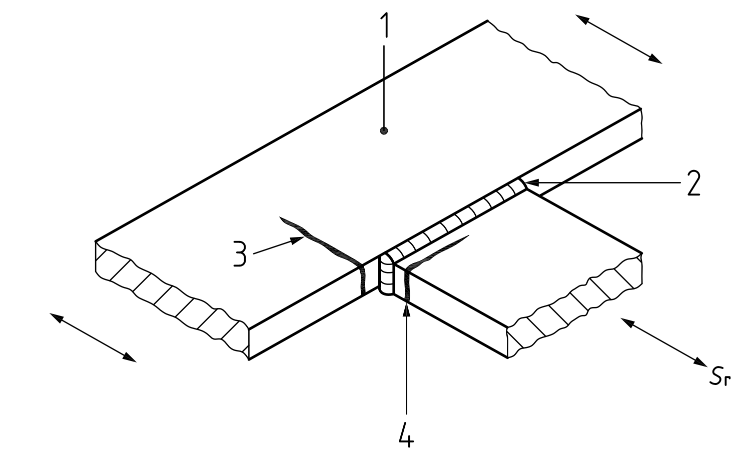
B.5.2.6 Dressing of butt welded types 5.1 and 6.4

The information given in **B.3.1** for longitudinal butt welds is equally applicable to transverse welds, with the additional recommendation that the dressing is sufficient to ensure that all the traces of the weld toe are removed.

B.5.3 Cruciform and T-joints between plates in the same plane (type 5.6)

Often, the load is transmitted from a member to a transverse member primarily via flange plates in the same plane (see Figure B.5). This can occur in the case of a junction between cross girders and main girders, diagonals and truss chords, or in Vierendeel frames.

Figure B.5 **T-junction of two flange plates**

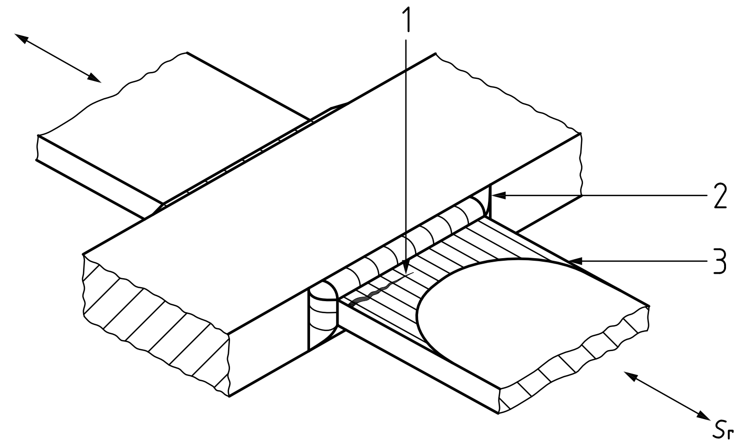


Key

1	Transverse member	3	Type 4.7
2	Full penetration butt weld	4	Type 5.6 (with stress concentration factor)

If a full penetration butt weld is used and the joint geometry is in accordance with the requirements of type 5.6, and if in addition the joint is either of the cruciform type (see Figure B.6) or if the transverse member is relatively stiff, i.e. its width is at least three times the width of the stressed member, the nominal stress-based classification should be as given for type 5.6 with a stress concentration factor of unity.

Figure B.6 **Cruciform junction between flange plates**



Key

1 Type 5.6 (with stress concentration factor)

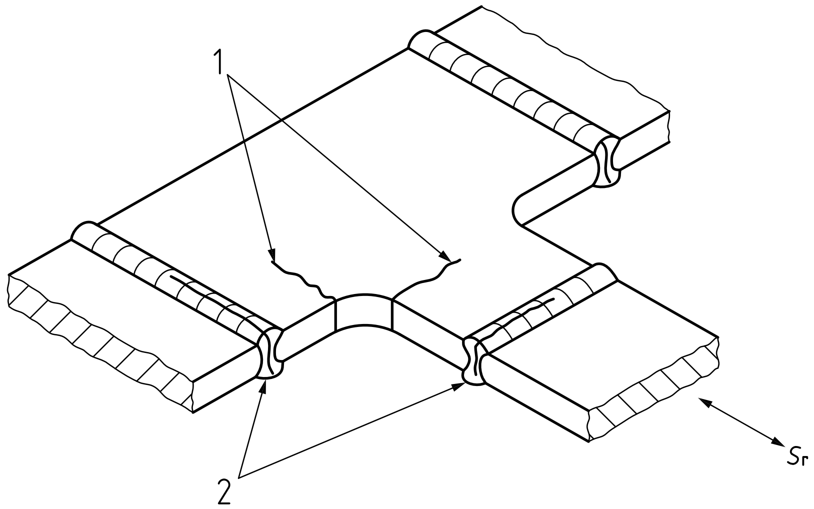
2 Full penetration butt weld

3 Typical stress pattern

Otherwise the classification should be assumed to be that of type 5.2 with the appropriate stress concentration factor.

In the case of trusses, secondary stresses due to joint fixity should be taken into account. The fatigue strength of both flange plates can be improved by the insertion of a smoothly radiused gusset plate in the transverse member so that all butt welds are further from re-entrant corners (see Figure B.7).

Figure B.7 **Alternative method for joining two flange plates**



Key

1 Types 1.3 or 1.4 (with stress concentration factor)

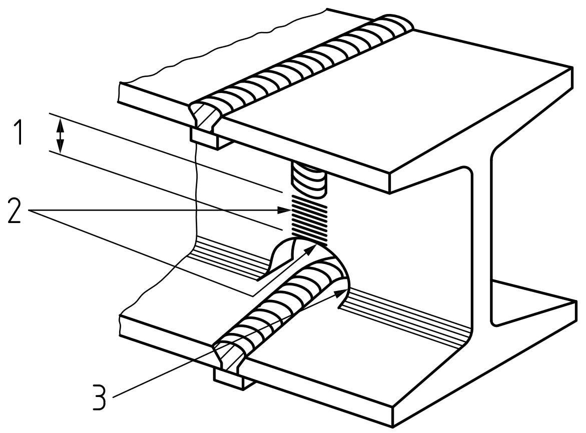
2 Types 5.2, 5.5 or 6.1

B.6 Transverse butt welds in sections (see Table 6)

Butt welds between rolled or built up sections (type 6.1) are prone to weld flaws in the region of the web/flange junction. The low classification reflects the fact that these are very difficult to detect. The normal classifications for transverse butt welds in Table 5 should only be adopted if special preparations, procedures and inspection have been undertaken that show the weld is free from significant flaws.

The same types of joints are frequently made using cope holes to provide access for making the weld in the flange. The end of the web butt weld at the cope hole (type 6.2) is equivalent to class D if the end of the butt weld, and the weld reinforcement within a distance equal to the radius of the cope hole, are ground flush (see Figure B.8). Otherwise, class E is applicable (type 6.3).The relevant stress should include allowance for the stress concentration effect of the of the cope hole (see DNV-RP-C203). Mitred cope holes of triangular shape should not be used.

Figure B.8 **Local grinding adjacent to cope hole in type 6.2 joint**



Key

1 Distance = *r*

2 Grind

3 Radius *r*

B.7 Load-carrying fillet and T-butt joints (see Table 7)

B.7.1 Potential modes of failure (see Figure B.3)

Failure in cruciform or T-joints with full penetration welds normally initiates at the weld toe, but in joints made with load-carrying fillet or partial penetration butt welds cracking might initiate either at the weld toe and propagate into the plate or at the weld root and propagate through the weld. In welds parallel to the direction of the applied stress, however, weld failure is uncommon; cracks normally initiate at the weld end and propagate into the plate perpendicular to the direction of applied stress. Nevertheless, provision is made for possible shear failure through the weld throat (see type 7.10).