Chapter 4
DESIGN CALCULATION OF STRUCTURES AND FATIGUE BEHAVIOUR

4. DESIGN CALCULATION OF STRUCTURES

ALUMINIUM alloy structures are designed using the rules for calculating the strength of materials.

Compared with steels, the specific properties of aluminium such as Young's modulus of elasticity, which is one third that of steel, must be calculated relative to the criterion of strain. To make up for the low Young's modulus of aluminium, inertias must be optimised to achieve a modulus of inertia I/v that is as high as possible.

Unlike steels, in aluminium alloys the heat affected zone either side of a weld is softened. The mechanical properties to be taken into consideration are the annealed condition (O) for strain hardened alloys, and the T4 condition (naturally aged at ambient temperature) for age hardened alloys.

Because of the softening process, the residual stresses from welding are lower in aluminium alloy welds than steel welds.

The fatigue behaviour of aluminium alloys depends essentially on the design of the weldments and the quality of workmanship with which they are made.

Given aluminium's specific attributes in terms of its mechanical properties and fatigue strength, experience shows that it is possible for an aluminium alloy structure to achieve a saving in weight of some 50 % compared with its equivalent structure in steel.

The stress calculations of the structures of ships are based on the rules of classification societies which we shall not go into here (1). Suffice to say that these rules are based on the principles of the strength of materials, weighted by factors acquired from experience.

(1) The reader is invited to consult the relevant sources.

THE PRINCESS

AND FATIGUE BEHAVIOUR

1. PROPERTIES OF ALUMINIUM

For all aluminium alloys that are used in shipbuilding, according to Eurocode 9 (2), structures must be calculated with the following values for the basic properties (table 34):

It will be noted that whatever the alloy, Young's modulus is 70 000 MPa or one third that of steel, and that the coefficient of expansion, $23.10^{-6}.°C^{-1}$, is double that of steel. In no way is the low Young's modulus of aluminium an obstacle to designing structures normally resistant to buckling. To achieve this we just need to take advantage of the relative ease with which aluminium can be shaped and formed, especially by extrusion, and to optimise the distribution of masses as illustrated by the examples discussed in Section 3.2.

(2) Eurocode 9: Design of Aluminium Structures – Part 1-1 General rules and rules for buildings. Standard EN, ENV 1999-1-1.

PHYSICAL PROPERTIES OF ALUMINIUM

Property	Unit	Value
Young's modulus: E	$N.mm^{-2}$	70 000
Shear modulus: G	$N.mm^{-2}$	27 000
Poisson's ratio: ν		0,3
Coefficient of thermal expansion: α	$10^{-6}.°C^{-1}$	23
Density: ρ	$Kg.m^{-3}$	2 700

Table 34

2. DETERMINING THE MAXIMUM STATIC STRESS

The criteria used by most classification societies are usually based on a comparison of the calculated stress with the maximum admissible strain which is obtained from the calculation done according to the theory of the elastic deflection of structures [1].

The minimum test piece sampling of a structure is determined from:

- the load to which the structure is subjected (which depends on the characteristics of the ship),
- the mechanical properties of the material,
- the design rules; these may be weighted by correction factors drawn from experience.

THE PRINCESS

2.1 The case of a plane section reinforced with stiffeners

The criteria used by most classification societies are usually based on a comparison of the calculated stress with the maximum admissible strain which is obtained from the calculation done according to the theory of the elastic deflection of structures [2].

$$\sigma_{max} = pk\left|\frac{b}{t}\right|^2 \qquad [1]$$

where:
- σ_{max} = maximum admissible stress,
- p = hydrostatic pressure,
- k a correction coefficient,
- b = width of the panel,
- t = thickness.

In equation [1], thickness t of the sheet of the section is written:

$$t = b\sqrt{\frac{pk}{\sigma_{max}}} \qquad [2]$$

Compared with the yield strength $Rp_{0,2}$ of the metal, the above expression is expressed simply:

$$t = \sqrt{\frac{A}{Rp_{0.2}}} \qquad [3]$$

According to the DNV rules (3), thickness t can be calculated with the following equation:

$$t = s\sqrt{\frac{Cp}{\sigma}} \qquad [4]$$

where:
- σ = maximum admissible specific stress due to lateral pressure
- p = hydrostatic pressure,
- C = correction coefficient dependent on the geometry,
- s = space between stiffeners,
- t = thickness.

2.2 The case of a beam in bending subject to uniform hydrostatic pressure

The maximum stress is obtained from the formula (figure 29) [3] :

$$\sigma_{max} = \frac{Mv}{I} = \frac{M}{S} \qquad [5]$$

where:
- σ_{max} = maximum admissible bending stress,
- M = bending moment,
- v = distance from the neutral axis,
- I = moment of inertia,
- S = I/v = modulus of inertia.

Knowing the maximum admissible bending stress and the bending moment due to the load between two supports, there is:

$$S = \frac{M}{\sigma_{max}} \qquad [6]$$

As with the thickness, S depends on the yield strength of the metal:

$$S = \frac{k}{R_{p0.2}} \qquad [7]$$

According to the DNV rules (4), the equation [6] is written:

$$Z = \frac{ml^2\, s\, p}{\sigma} \qquad [6]$$

where:
- Z = section of the stiffener,
- m = correction factor for the bending moment,
- l = span,
- s = space between two longitudinal stiffeners,
- p = hydrostatic pressure,
- σ = admissible bending stress

(3) DNV Rules, Part. 3, Chap. 3, Sec. 5, B201.

(4) DNV Rules, Part. 3, Chap. 3, Sec. 5, C100.

PLATE IN BENDING

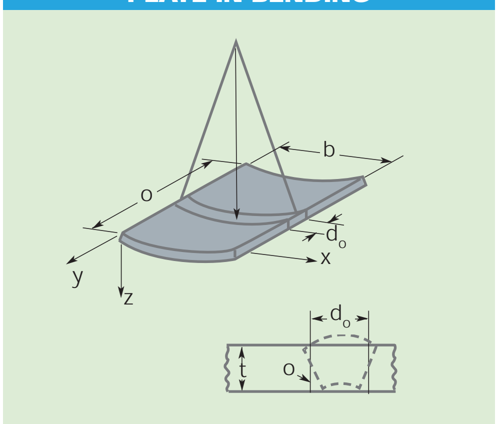


Figure 28

BEAM IN BENDING

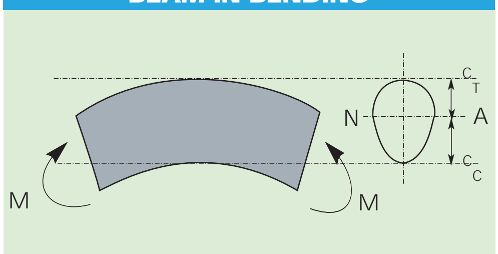
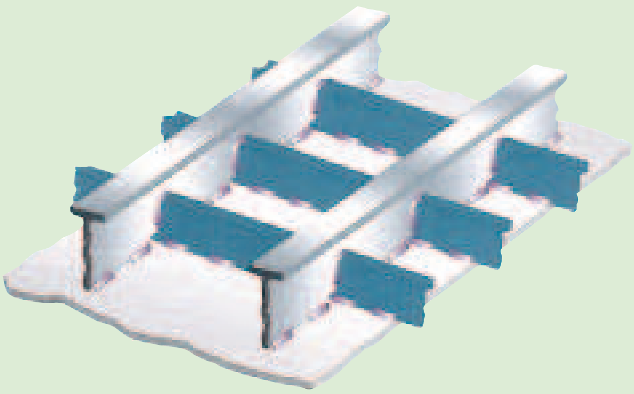


Figure 29

DESIGN OF A PLATE WITH STIFFENERS



Case (table 38)	Plate	Extruded shape
a	5083 H116	6082 T6
b	*Sealium*®	*Sealium*®
c	steel A275	steel A275

Figure 30

PRINCIPAL CHARACTERISTICS OF THE YACHT

Dimension	Value
Length OA	50,0 m
Rule Length	40,0 m
Beam	10,3 m
Draft	2,09 m
Space between frames	0,9 m
Displacement	450 tonnes
Speed	56 knots

Table 35

STRESS LEVELS

Parameters	Value
Vertical acceleration	1,5 g
Distance between stiffeners	213,0 mm
Distance between frames	900 mm
Stress on the panel	257,7 kN.m^{-2}
Stress on the stiffener	257,7 kN.m^{-2}
Stress on the frame	160,9 kN.m^{-2}

Table 36

3. TRANSPOSING FROM STEEL TO ALUMINIUM

Two cases must be considered :
- a plane section with stiffeners,
- a beam in bending.

3.1 The case of a plane section

The example chosen is that of a representative section of a conventional structure with sheet and stiffeners (figure 30) from the hull of a 50 metres yacht whose characteristics are shown in table 35:

The comparison relates to three cases:
- sheet and stiffeners in A27S steel,
- sheet in 5083 H116 and stiffeners in 6082 T6 shapes,
- sheet in *Sealium*® and stiffeners in *Sealium*® extrusions,

The stresses considered are the hydrostatic pressure and the pressure due to "slamming". They are evaluated according to the DNV rules referred to in (4). Their levels are given in table 36:

The mechanical properties used are those accepted by the DNV (table 37):

The DNV design rules (5) applied to this structural element result in the test pieces shown in table 38.

Structures made from aluminium can save between 48 and 51 % weight compared with steel, the combination of *Sealium*® sheet + shapes in *Sealium*® being a prime example (table 39).

(5) DNV Rules for Ships/High speed, Light Craft and Naval Surface Craft, January 2001.

MECHANICAL PROPERTIES OF MATERIALS							
Semi Product	Alloy	Non Welded Metal		Welded Metal		
		$Rp_{0,2}$ (MPa)	Rm (MPa)	$Rp_{0,2}$ (MPa)	Rm (MPa)	Coefficient f_1
Sheet	5083 H116	215	305	125	275	0,60
	Sealium®	220	305	145	290	0,64
	Steel A27S	265	400	Unchanged		1,08
Shapes	6082 T6	260	310	115	205	0,48
	Sealium®	190	310	145	290	0,64 (*)
	Steel A27S	265	400	Unchanged		1,08

(*) The DNV rules puts the 5383 H112 in the same category as Sealium® (5383 H116).

Table 37

TEST PIECES OF STRUCTURES			
Attachment	Sheet Thickness (mm)	Size of Stiffeners	Size of Longitudinals (T-shaped)
5083 H116/6082 T6	7	120 x 6 bulb flats @ 213 mm spacing	500 x 8 + 60 x 8 mm
Sealium®/*Sealium*®	7	105 x 6 bulb flats @ 220 mm spacing	460 x 8 + 65 x 8 mm
Steel A27S/Steel A27S	5	100 x 6 bulb flats @ 240 mm spacing	460 x 4 + 50 x 6 mm

Table 38

SAVING IN WEIGHT COMPARED WITH STEEL			
Structural Elements ($kg.m^{-2}$)	Steel	5083 Sheet + 6082 Shape	*Sealium*® Sheet + *Sealium*® Shape
Sheet	39,2	18,9	18,9
Stiffener	36,3	11,9	9,9
Longitudinal	18,7	13,3	12,6
Total	84,40	44,1	41,4
Saving in %		47,8	51,0

Table 39

STEEL AND ALUMINIUM SHAPES

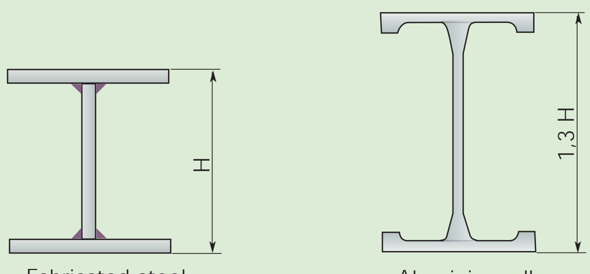


Figure 31

3.2 The case of a beam in bending

At equal strain, the following statement must be verified

$$\sigma_{e\,steel} \cdot I/v_{steel} = \sigma_{e\,alu} \cdot I/v_{alu}$$

hence:

$$I/v_{alu} = \frac{\sigma_{e\,steel}}{\sigma_{e\,alu}} \cdot I/v_{steel}$$

At equal inertia, the transposition will be made using extruded aluminium shapes whose height is some 30 % greater than the height of steel shapes (fabricated) (figure 31) or fabricated shapes.

As we have already asserted (6), aluminium's excellent extrudability makes it possible to achieve shapes that are optimised for marine applications: figure 32 and tables 41 and 42, pp. 61-62.

"TEE" SHAPE AND BULB FLAT IN *SEALIUM*®

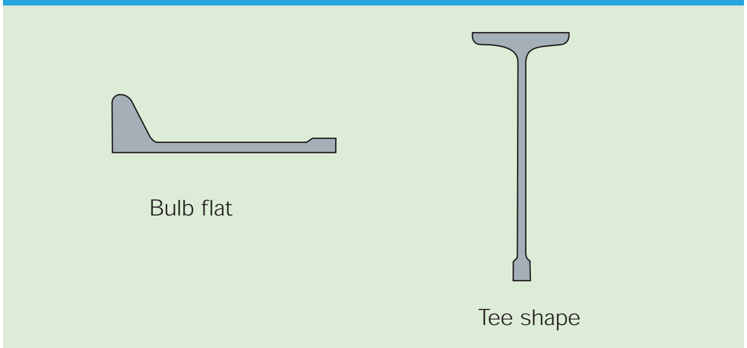


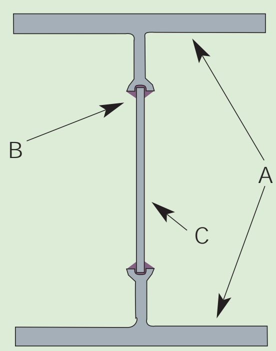
Figure 32

Calculations show that at equal inertia, the weight per linear metre of a Tee shape made from 5383 H112 is half that of its hot-rolled steel equivalent with simple geometric forms (table 40).

Aluminium can be used to fabricate large shapes by the automatic welding of flanges of shapes and sheet (figure 33). This very elegant solution offers a number of advantages: it places the weld seams in the least stressed zones and allows customising.

(6) *Cf. Chapter 2.*

SHAPES FABRICATED BY WELDING



A : Shapes
B : Fillet weld in lap joint
C : Extruded plate or sheet

Figure 33

4. FATIGUE BEHAVIOUR OF ALUMINIUM ALLOY STRUCTURES

Until relatively recently (the end of the Eighties), problems of fatigue in aluminium ships were virtually non-existent as they were never over 50 metres long. Structures were generously designed to take local loads with no great risk of crack propagation.

Since then, aluminium ships have increased in length to 80 metres and more, and with tougher conditions of service in heavy seas combined with the frequent transport of vehicles (cars and especially coaches and trucks), fatigue behaviour has become one of the major preoccupations of naval architects and shipowners [4].

Experience shows that after more or less long periods of service these large ships can display fatigue cracks in the most stressed zones, and these cracks must be repaired.

Given the implications of fatigue behaviour for the longevity of a structure and for the cost of maintaining vessels made of aluminium

COMPARISON OF "TEE" IN *SEALIUM*® AND IN STEEL

Dimensions	Steel "Tee" P 80X5	*Sealium*® "Tee" T100 X50	5383 relative to Steel
Mass ($kg.m^{-1}$)	4,25	2,20	– 48 %
Height (mm)	80	100	+ 25 %
Lateral area (mm^2)	541	830	+ 53 %
Moment of inertia (mm^4)	338 700	927 952	+ 274 %
Moment of elastic deflection relative to axis x – x (mm^3)	6 910	14 193	+ 205 %
Product E x I (*)	71 127	64 957	– 9 %

*(*) To compensate the differences (from 1 to 3) in elastic moduli at equal strain, the inertia of an aluminium beam must be 3 times greater than that of a steel beam. For the same load, the same length of beam and identical limit conditions, the strain is proportional to 1/E*I.*

Table 40

(or steel), this issue must be taken into account when a ship is designed and built [5].

The problem of sensitivity to fatigue is not one specific to aluminium, but affects steels just as much, especially those with a high limit of elasticity.

5. SERVICE CONDITIONS OF HIGH SPEED SHIPS

High speed ships (HSS) are subjected to cyclical stresses which are due mainly to three types of load:

- low level loads but with a large number of cycles. These are caused by vibrations from engines, shaft lines and waterjets,
- high level loads but with few cycles. These loads are generated during vehicle loading and unloading (coaches, trucks, cars),
- medium level loads of medium frequency due to the effect of waves [6, 7].

In high speed ships, the loads due to engines, shafts and waterjets are considered to be the dominating loads in regard to the bending moment of the beam which the ship represents [8].

This means that these ships have some very highly stressed zones, as shown in figure 34.

Experience shows that the problems of fatigue are generally localised in the zones where there is a change of direction and also in doors, windows etc.

LOAD ZONES ON HIGH SPEED SHIPS

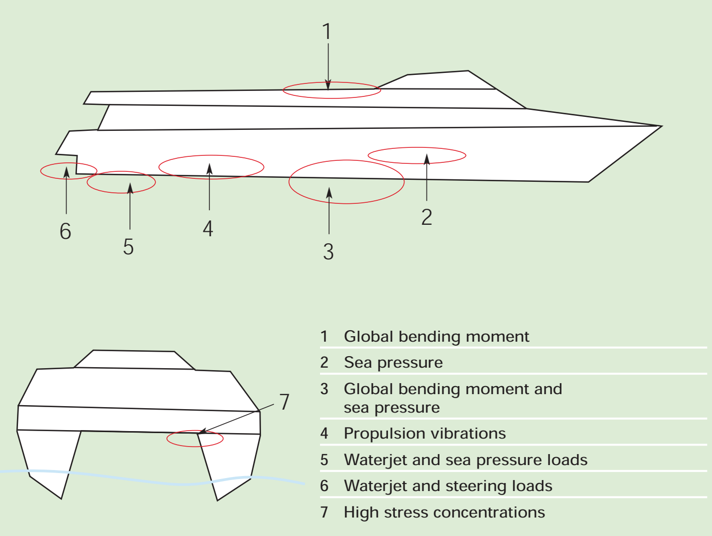


Figure 34

6. GENERAL COMMENTS ON THE FATIGUE OF METALS

Fatigue is a complex phenomenon that affects most normal metals including aluminium alloys. It occurs when structures undergo cyclical variations in load.

Experience shows that the levels of stress at which fatigue cracks (and fractures) are observed are generally much lower than the admissible stress calculated for static conditions.
Fatigue behaviour is determined by a number of relative parameters:

- the properties of the metals and alloys,
- the design,
- the workmanship,
- the loads, whose level will depend on the vessel's service conditions (its itinerary, frequency of loading/unloading and the weight of the cargo etc.).

Very many years of experience with fatigue in metal structures (steel, aluminium etc.) have shown that the two most important parameters are design and workmanship, including welding.

According to the design rules, it is only the configuration of the aluminium alloy weldment that is taken into consideration when determining fatigue life (FAT). The nature of the aluminium alloy is disregarded (7) even if its fatigue strength is known to be better, as is the case with *Sealium*® (8). The fact remains that by obeying the mandatory rules, this new alloy offers additional fatigue strength and hence enhanced safety in use.

(7) This is true for steels.

(8) Cf. Chapter 3, Section 6-2.

7. SPECIFICS OF THE FATIGUE BEHAVIOUR OF ALUMINIUM

Aluminium alloys differ from steel in a number of aspects. These include:

7.1 Fatigue limit

On a smooth test piece, aluminium has a linear decreasing S/N curve (figure 35). This means that the structural calculations must be verified for the level of stress below which there will be no crack propagation for a given period of time which is usually fixed at 2.10^6 cycles [9].

At this level, the fatigue limit determined on a "smooth" specimen of parent metal is 420 MPa for steel and 140 MPa for aluminium. In welded attachments, the ratio of admissible stresses (FAT) according to the calculation rules between steel and aluminium alloys is in fact closer to 2 (9) on a case by case basis.

7.2 The heat affected zone (HAZ)

Owing to the heat generated by welding, the mechanical properties of the HAZ are those of the annealed condition (O) for strain hardened alloys and of the quenched condition (T4) for age hardened alloys (figure 35), (10).

Welding has the opposite effect on steels, hardening the heat affected zone because of the rapid cooling (quench effect).

But as with steels, welding also lowers the threshold of admissible stresses under variable loads. These thresholds (FATs) are laid down by standards, calculation rules and classification societies (11).

7.3 Residual stresses

These stresses are lower in aluminium alloys than in steel because the heat affected zone is softened by the heat generated by welding.

(9) For example, for a 100% tested butt weld, (case 211 of the IWW), the steel FAT is 125 MPa and the aluminium alloy FAT is 50 MPa, or 40 % of the FAT of steel.

(10) In casting alloys, the fatigue strength of the welded joint is the same as the casting.

(11) FATs and the way in which they are determined may vary somewhat from one code or one regulation to another.

TYPICAL WÖHLER CURVES

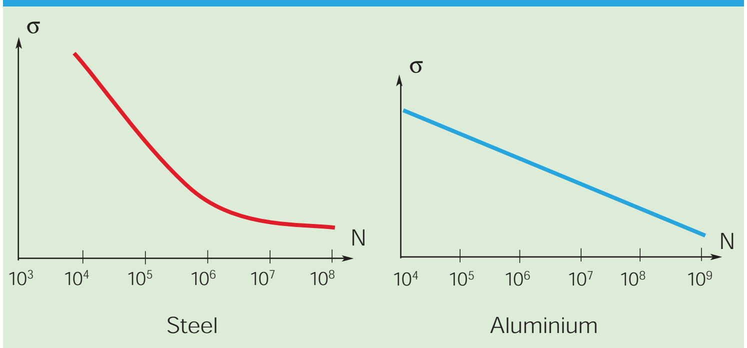


Figure 35

BULB FLATS IN *SEALIUM*® (*)

Type	H (mm)	Tw (mm)	H1 (mm)	Tw1 (mm)	Bf (mm)	R (mm)	S (mm^2)	Weight $kg.m^{-1}$	C (mm)	I (mm^4)	Sxx High (mm^3)	Sxx Low (mm^3)
P50	50	3	9	4,5	10	4	218	0,58	21,25	57 085	2 687	1 985
P60	60	3,3	9,6	4,8	12	4	284	0,76	24,86	107 947	4 342	3 072
P70	70	3,5	10	5	14,5	4	360	0,96	27,95	186 636	6 677	4 439
P80	80	3,7	10,4	8,2	16,6	4	436	1,16	31,34	296 312	9 455	6 089
P90	100	4,2	11,4	5,7	21	4	620	1,65	38,30	659 291	17 215	10 685
P100	120	4,6	12,2	6,1	26	4	833	2,21	44,47	1 271 697	28 600	16 836
P140	140	5,1	13,2	6,6	30,5	4,8	1 106	2,94	50,31	2 267 810	45 078	25 285
P170	170	5,8	14,6	7,3	37,5	5,8	1 580	4,20	58,99	4 717 199	79 966	42 493

(*) Cf figure 32.

Table 41

TYPICAL FATIGUE CROWTH RATE CURVE

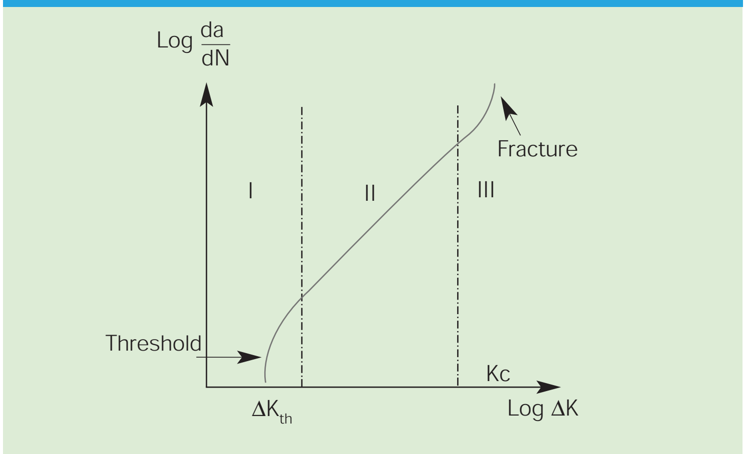
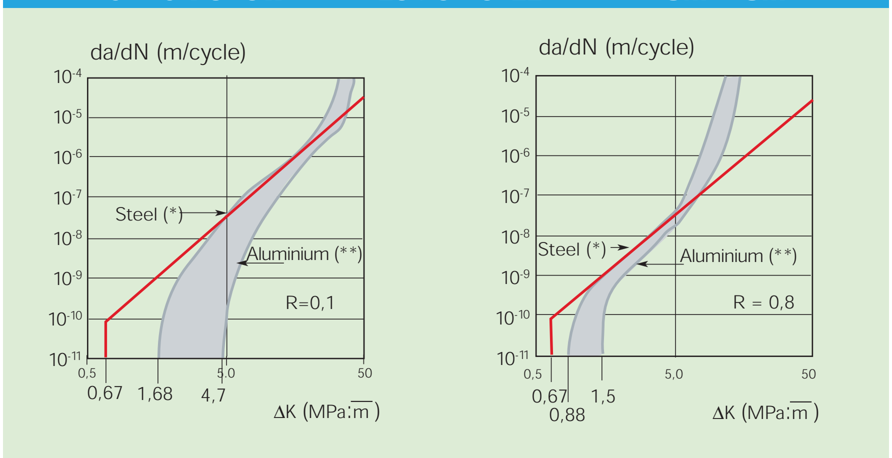


Figure 36

CRACK GROWTH RATES FOR STEEL AND ALUMINIUM



(*) Steel curve has been corrected by a factor x3 to take into account th density difference between aluminium and steel.

(**) 5000, 6000 et 7000 alloys .

7.4 Fracture mode

These stresses are lower in aluminium alloys than in steel because the heat affected zone is softened by the heat generated by welding.

7.5 Propagation threshold

There is a threshold with the value ΔK above which a crack will start to propagate (phase II in figure 36). For an admissible limit stress of 50 MPa (FAT 50), the limit size of the incipient fault in a weld is 0.5 mm, and a well-made weld is one that is free from defects of this size.

This size limit is relatively high for aluminium alloys, much higher than for steels, all other things being equal, i.e. the mass of the structural element subjected to a load and the level of that load (figure 37).

TEE SHAPES IN *SEALIUM*® (*)

Type	H (mm)	Tw (mm)	H1 (mm)	Tw1 (mm)	Bf (mm)	L (mm)	R (mm)	S (mm^2)	Weight $kg.m^{-1}$	C (mm)	I (mm^4)	Sxx Hight (mm^3)	Sxx Low (mm^3)
T50	50	3	10	5	30	4,5	4,6	299	0,80	16,74	84 662	5 057	2 546
T60	60	3,5	11	5,5	35	5,1	5,2	402	1,07	19,94	162 062	8 126	4 046
T70	70	4	12	6	40	6,1	6	536	1,42	22,69	287 200	12 657	6 071
T80	80	4,5	13	6,5	45	6,2	6,2	650	1,73	26,55	459 564	17 310	8 598
T100	100	5	14	7	50	6,4	6,4	830	2,20	34,62	927 952	26 805	14 193
T120	120	5,5	15	7,5	5	7,7	7,8	1 091	2,90	41,01	1 735 149	42 315	21 965
T140	140	6	16	8	60	8,7	8,8	1 367	3,64	47,89	2 942 592	61 442	31 947
T170	170	6,5	17	8,5	65	10,3	10,4	1 777	4,73	58,05	5 598 542	96 440	50 010

(*) Voir figure 32.

Table 42

8. CLASSIFICATION OF ALUMINIUM ALLOYS

As with steels, there is no relationship between the fatigue strength of aluminium alloys and their mechanical properties: ultimate tensile strength and proof stress.

As figure 38 illustrates, tests show that the fatigue limits are of the same order of magnitude when stresses attain 10^6 cycles.

This tends to confirm what experience suggests, i.e. that fatigue strength depends on the attachment – including the configuration of the weldment – and not on the basic alloy (or its temper). This is true of the 5000 and 6000 series alloys, and applies equally to steels (figure 39).

The fatigue behaviour of metals in general and of welded connections in particular can only be measured and assessed by tests and experience [10].

The nature of the semi-finished products (sheet, shapes, forgings etc.) made from the same alloy, and their shape, has no effect on fatigue resistance [11].

Surface condition is an important parameter on the other hand: surface scoring and marks encrusted by "iron" can act as the initiation sites for crack propagation (figure 40). The same applies to edge irregularities left behind by cutting tools.
Sawing is more favourable to fatigue resistance than plasma cutting because it leaves cut edges that are clean.

INFLUENCE OF THE TYPE OF ALLOY

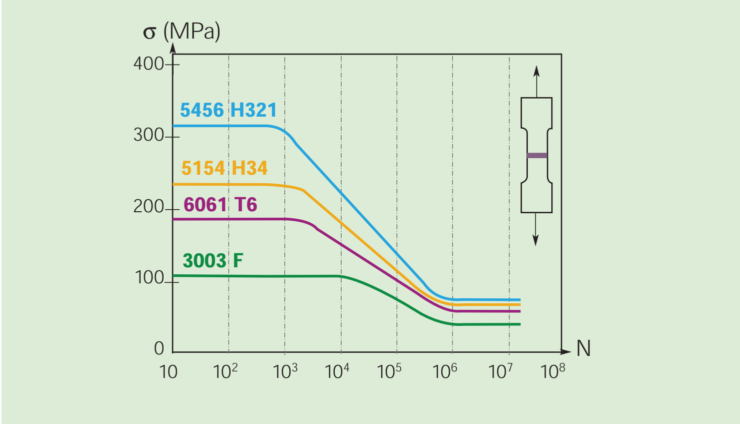


Figure 38

FATIGUE STRENGTH AT 5.10⁸ CYCLES

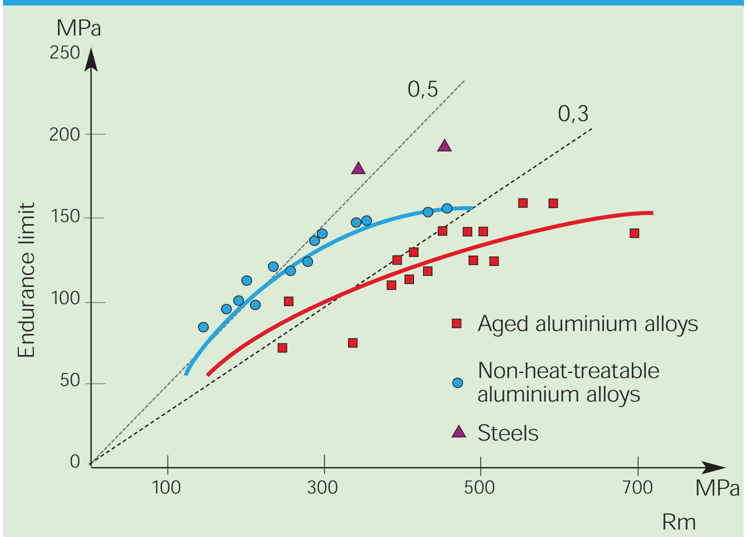


Figure 39

EFFECT OF SURFACE MARKS

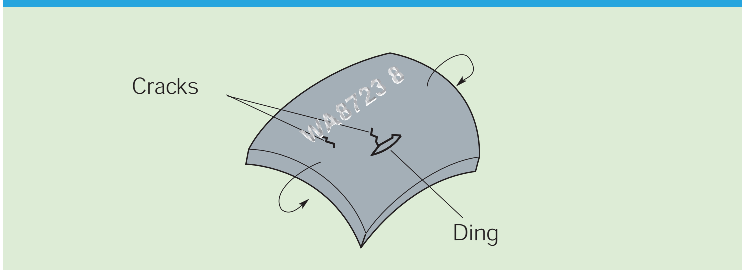


Figure 40

9. FATIGUE LIFE OF WELDMENTS

Experience shows that most fatigue cracks start from the weld bead, either at its beginning, its end or on its surface (around surface "wrinkles").The heat affected zone can also be an initiation site of fatigue cracks.

There are two main reasons for this:

- stress concentrations: the weld bead is the site of stresses due to its method of cooling [12]. Small surface craters form as the weld pool solidifies because of the decrease in volume (figure 41).
- defects (or imperfections) which form when the weldment is made. They are the site of stress concentrations (figure 42).

9.1 Weld defects

A weldment may present different types of defect (13): these can be external (misalignment etc.) or internal due to the execution of the weld (inclusions, porosity etc.), figure 43.

On principle, any defect will tend to reduce fatigue strength when it starts on a free surface and if its size - 2a - exceeds the limit above which a fatigue crack can grow (figure 36, p.62).

Calculations show that for an applied load of 50 MPa, the minimum size of the defect above which cracks grow is 0.5 mm. On weldments that have been correctly executed, the size of normal defects (porosity, shrinkage cracks etc.) varies from 0.01 to 0.40 mm (12, 13), a little less than the critical size (14).

It follows that not all of the types of defect mentioned affect fatigue strength in the same way.

(12) Cf. Chapter 6.

(13) Some of the causes of these defects are given in Chapter 6, Section11.

(14) The fatigue behaviour of a weldment depends on the growth rate of cracks (according to the laws of fracture mechanics).

CRATERS ON THE WELD BEAD

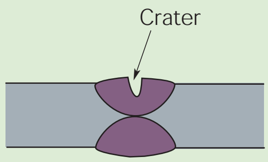
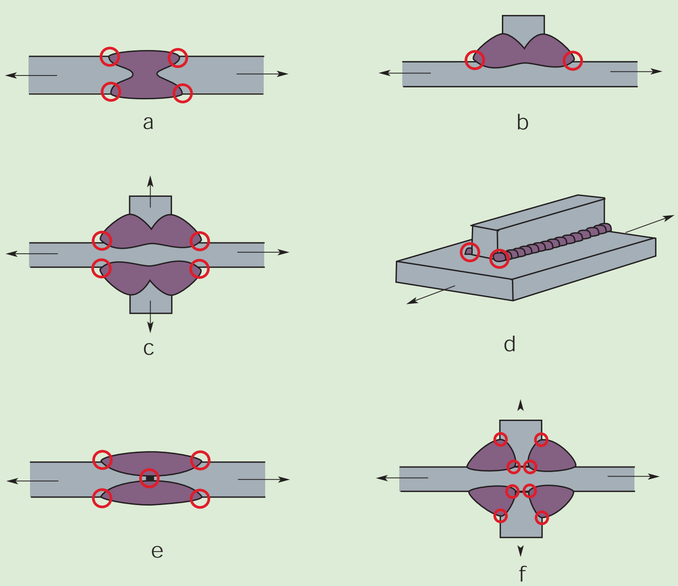


Figure 41

STRESS CONCENTRATIONS AT WELD DEFECTS



Weld toe : a, b, c, d

Weld toe + lack of penetration : e, f

Figure 42

Of the various weld defects, it is the lack of penetration (defect 5 in figure 43) which affects fatigue strength the most, which explains why the fatigue strength of fillet welds is less than that of butt welds, all other things being equal.

The toe angle "a" of the weld bead with the structure is another important factor affecting fatigue strength, for two reasons:

- geometrical, the change in direction which angle a marks,
- structural, due to any overfill overflowing the weld (figure 44).

The more obtuse angle a, the greater the fatigue strength. It is at its maximum when the weld is dressed flush: a = 180 °C (figures 45 and 46).

TYPICAL DEFECTS OF WELDMENTS

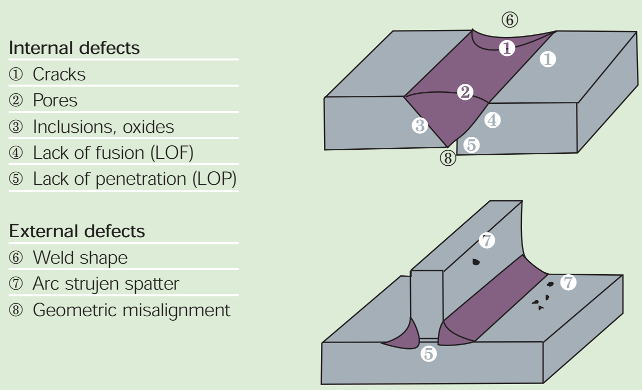


Figure 43

TOE ANGLE OF THE WELD

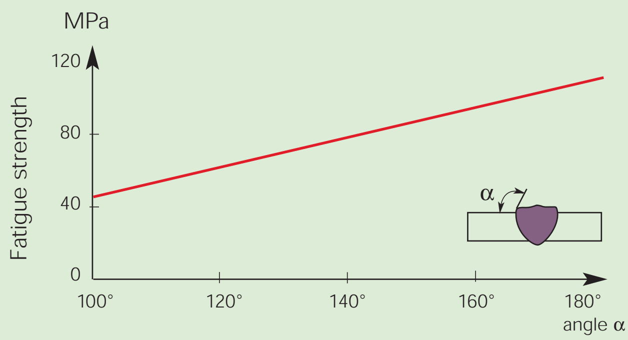


Figure 45

OVERLAP

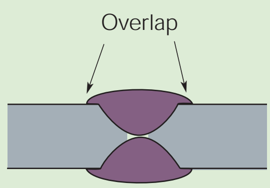


Figure 44

FLUSH DRESSING OF WELD

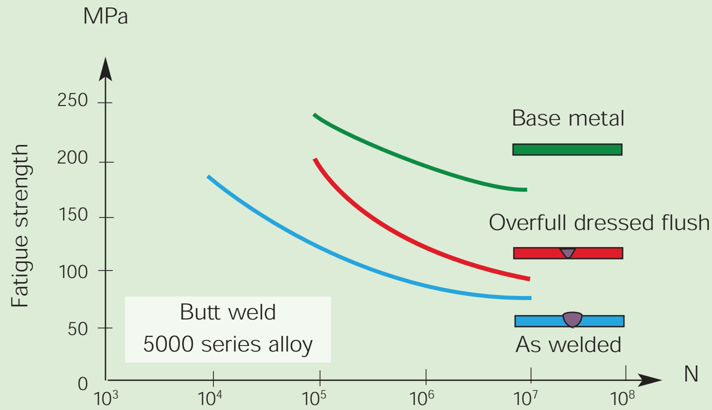


Figure 46

9.2 Classification of weldments

The limits of endurance (FAT) that are given in codes and regulations have been established on the basis of standard tests conducted on specimens taken from attachments and feedback on structures in service [14].

Eurocode 9 proposes limits of endurance (FAT 25 to 62 MPa) as a function of the size of the defects (figure 47) (misalignment, undercut, lack of root penetration, porosity, crack etc.) and the extent of controls corresponding to the desired level of FAT.

The influence of the size of four defects on the limits of endurance (FAT) is given in table 43 by way of example

Design codes and regulations confine themselves solely to the configuration of the weld to define the acceptable limit of endurance (FAT), as figures 48 to 50 illustrate.

FATIGUE STRENGTH (FAT) ACCORDING TO EUROCODE 9

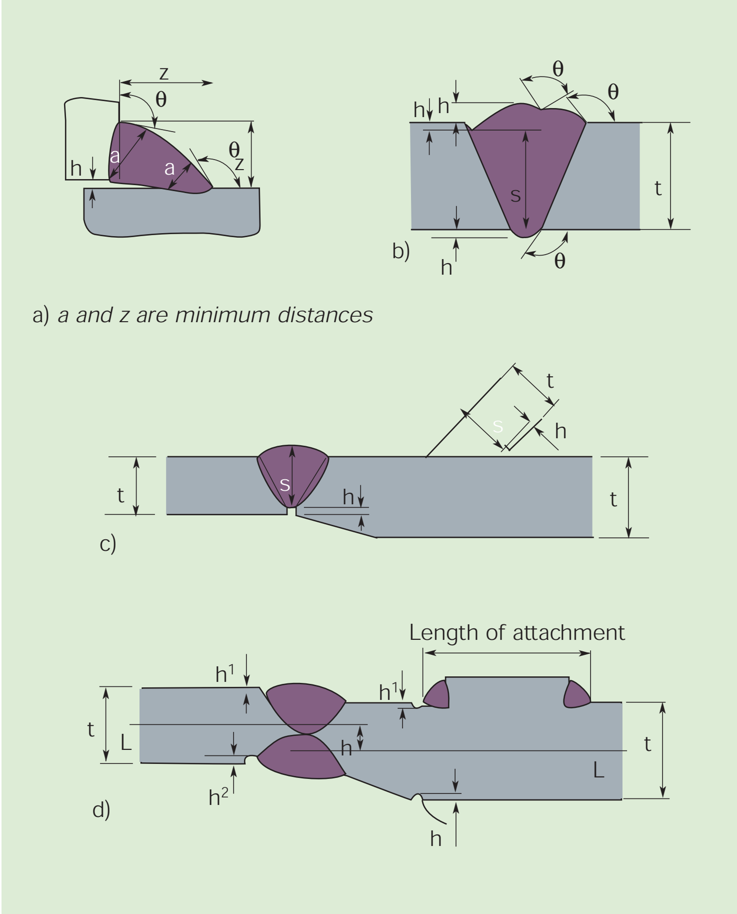
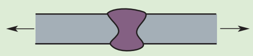


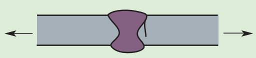
Figure 47

LIMIT OF ENDURANCE OF BUTT WELDS
(according to IIW Recommendations, Group XIII – XV, 1996)

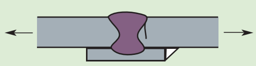
Case 211 : Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT (*)



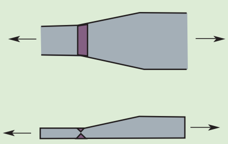
Case 212 : Transverse butt weld made in shop in flat position, toe angle ≤ 30°, NDT



Case 213 : Transverse butt weld, toe angle ≤ 50°



Case 215 : Transverse butt weld, toe angle ≤ 50°, or transverse butt weld on permanent backing bar

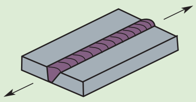


Case 223 : Transverse butt weld, NDT, with transition on thickness and width
Slope 1:5
Slope 1:3
Slope 1:2

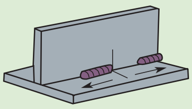
(*) Non destructive test.

Figure 48

FATIGUE STRENGTH (FAT) OF LONGITUDINAL WELDS
(recommendations of IIW, Group XIII - XV, 1996)



Case 313 : Longitudinal butt weld, without stop/start positions,
NDT 45
With stop/start position 36

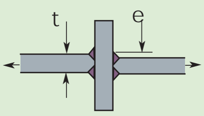


Case 324 : Intermittent longitudinal fillet weld (based on normal stress in flange σ and shear stress in web τ at weld ends).

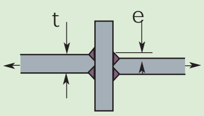
τ/σ = 0. 32
τ/σ = 0,0 – 0,2 28
τ/σ = 0,0 – 0,3 25
τ/σ = 0,0 – 0,4 22
τ/σ = 0,0 – 0,5 20
t/σ = 0,0 – 0,6 18
t/σ = 0,0 – 0,7 16
t/σ = > 0,7 14

Figure 49

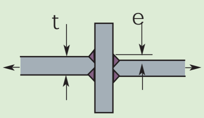
FATIGUE STRENGTH (FAT) OF CRUCIFORM WELDS
(recommendations of IIW, Group XIII - XV, 1996)



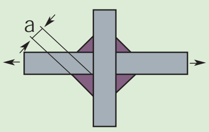
Case 411 : Cruciform joint or T-joint, K- butt welds, full penetration, no lamellar tearing, misalignment e < 0,15 t, weld toes ground, toe crack



Case 412 : Cruciform joint or T-joint, K- butt welds, full penetration, no lamellar tearing, misalignment e < 0,15 t, toe crack



Cas 413 : Cruciform joint or T-joint, fillet welds, or partial penetrating K- butt weld, misalignment e < 0,15 t, toe crack



Cas 414 : Cruciform joint or T-joint, fillet welds, or partial penetrating K- butt welds (including toe ground welds), weld root crack. Analysis based on stress in weld throat

Figure 50

ACCEPTANCE LEVEL OF INDUSTRIAL WELDS (*)

Defect	Weld	Weld direction (*)	Figures	Size of defect	FAT 25	FAT 31	FAT 39	FAT 49	FAT 62
Weld angle	all types	Transv. Longit	a, b a, b	θ ≥ θ ≥	120° 90°	150° 90°	165° 90°	175° 90°	- 175°
Excessive bead thickness	butt	Transv. Longit	b b	h ≤ h ≤	5 6	4 5	2 4	0,5 3	- 0,5
Misalignment	butt	Transv.	d	h ≤	D + 0,1 t	D + 0,05 t	D + 0,05 t	D + 0,05 t	-
Lack of root pen-tration	butt	Transv. Longit	c c	h ≤ h ≤	- D + 0,1 t	- D + 0,1 t	- D + 0,05 t	- D + 0,05 t	- -

D = dimension specified on drawings (*) From table D.2 Eurocode (9).

Table 43

10. INFLUENCE OF DESIGN AND FABRICATION ARRANGEMENTS

The fatigue behaviour of aluminium alloy ships depends
- on the design arrangements defined by the design consultancy
- on the execution of welds in the shipyard.

10.1 Design of welded attachments

This is a very important parameter: Design engineers must propose structures in which the stress concentrations are as low as possible, while keeping within acceptable cost limits. The "hot spot" method can be used to identify the sensitive zones [15].

The influence of the design arrangements of some typical welded structures is given in table 44.

10.2 Design of bolted and bonded attachments

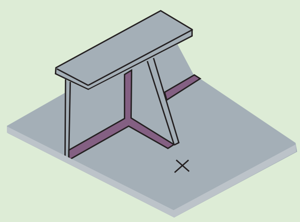
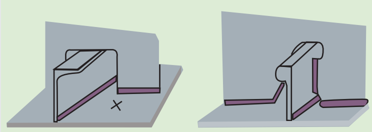
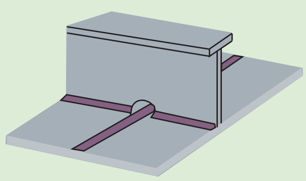
Bolted and bonded joints must be designed to offer good fatigue behaviour (Figures 51 and 52, p. 70). It is particularly important to ensure that the diameter of the bolts is proportional to the dimensions of the attachment.

10.3 Making weldments

Experience shows that the fatigue behaviour of welded aluminium alloy structures is more sensitive to weld defects than welded steel structures [].

This is why shipbuilding in particular, and aluminium fabrication in general, requires:
- better welding skills than are needed for steel fabrication,
- tighter control of weldments, at least those located in zones most stressed by fluctuations of load.

INFLUENCE OF WELDED STRUCTURES ON FATIGUE BEHAVIOUR [16, 17]

Example of Structure		Remarks
Gusset of floor plate on ship bottom.		The weld bead must be wrapped at the end of the gusset to avoid crack initiation.
Path of a longitudinal through a frame.		At left, torch cannot access beneath the shape and the weld bead cannot be wrapped, so there is a risk of cracking. At right, weld is correctly made, beads do not cross over, the sheet of the frame is welded to the flat side of the longitudinal.
Path of a stiffener over skin sheet.		Correct arrangement which avoids welds crossing over (which can destroy much of the underlying weld).

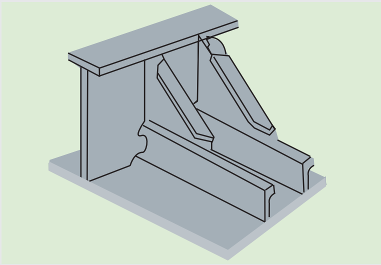
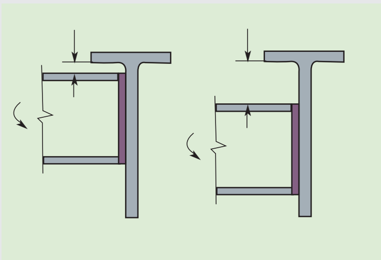
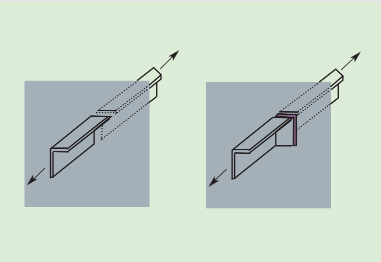
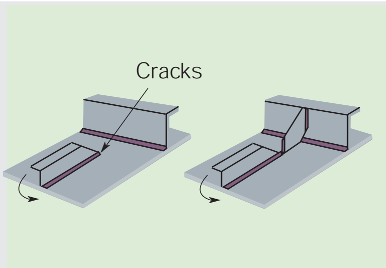
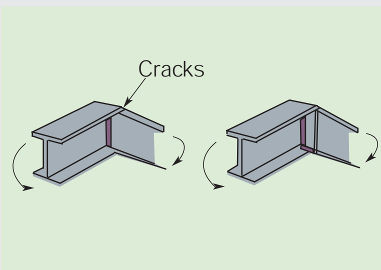
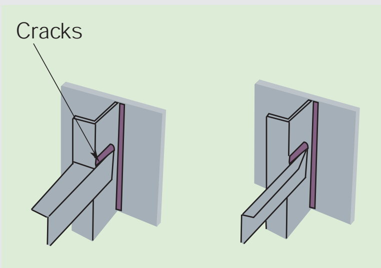
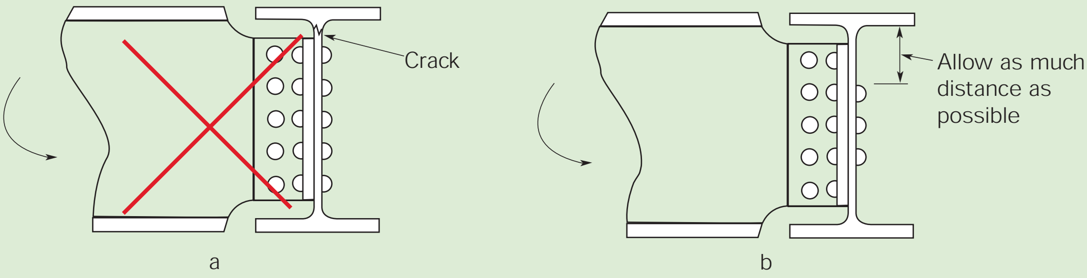
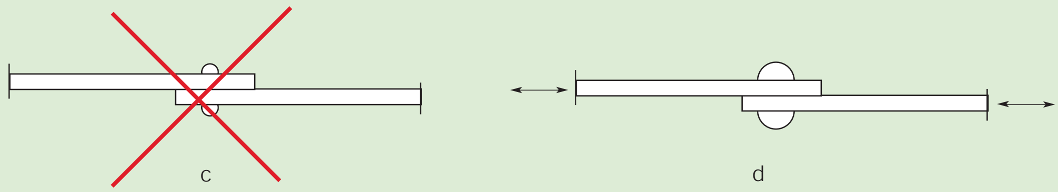
Example of Structure		Remarks
Deck flooring, junction of bar and reinforcement.		Assembly too tight, torch cannot reach the inside faces of the longitudinal reinforcements.
Connection of two shapes, e.g. longitudinal and bar.		Enough space must be left for the torch to enter everywhere and wrap around the transverse bar on the longitudinal.
Bulkhead crossing.		At left, with a shape on each side of the bulkhead, alignment will be poor and stresses will occur. At right, the shape passes through the bulkhead which is 'hung' on the shape.
Stiffeners on sheet.		At left, the stiffener stops in the middle of the sheet causing stresses, with the risk of tearing by bending. At right, the scallop in the reinforcement avoids welds crossing and distributes bending forces.
Connection of two shapes.		The change of direction creates bending and torsional stresses. These stresses are avoided by adding a plate to form a box.
Connection of a longitudinal and a bar to the sheet of the skin.		At left, the recess in the shape causes a stress concentration that is avoided by the arrangement on the right.

Table 44

BOLTED ATTACHMENTS IN SHEAR [13]



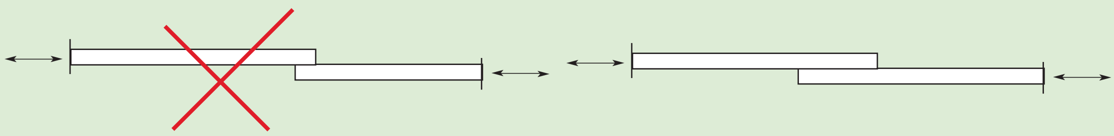
Bolts close to flange cause high local bending stresses in web (a).
A larger distance between fastener and flange allows web to flex, thereby reducing local stresses (b)



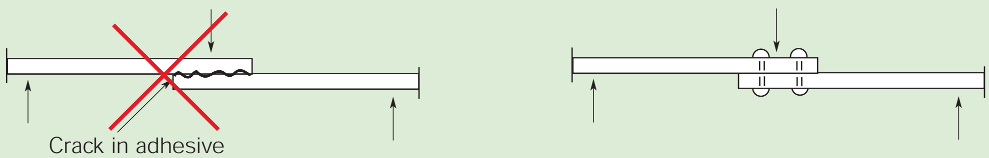
Small fastener in large parts allows fatigue failure in fastener at low nominal stress (c).
Fasteners that develop a high percentage of strength of parts shift fatigue failures to parts at higher stresses (d).

Figure 51

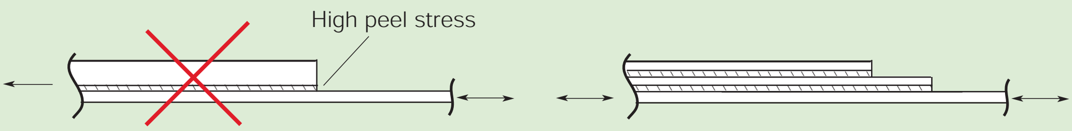
BONDED ATTACHMENTS [13]



Joints with short laps in which adhesive is stressed in inelastic range will fail at low fatigue lives. Longer laps so that adhesive is stressed elastically will result in much longer fatigue lives.



Joints with high cleavage or peel forces in the adhesive will fail at low static and fatigue loads. Use bolts or other fasteners with good tensile performance; supplement with adhesives if desired for much better fatigue performance.



Thick doublers on thin sheet causes high stress concentration at end of doubler. Stepped, thin doublers reduce stresses at end of doublers and improves fatigue.

Figure 52

11. REFERENCE STANDARDS AND REGULATIONS

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TALAT, EAA, Lecture 2405. Fatigue and Fracture in aluminium structures, prepared by Dimitris Kosteas, Technische Universität München, 1994, 40 pages

TALAT, EAA, Lecture 2406. Fatigue and Fracture in Aluminium Structures, prepared by Dimitris Kosteas, Technische Universität München, 1999, 5 pages

TALAT, EAA, Lecture 2406, Annex 1. Fatigue and Fracture in Aluminium Structures, prepared by Dimitris Kosteas, Technische Universität München, 1994, 6 pages

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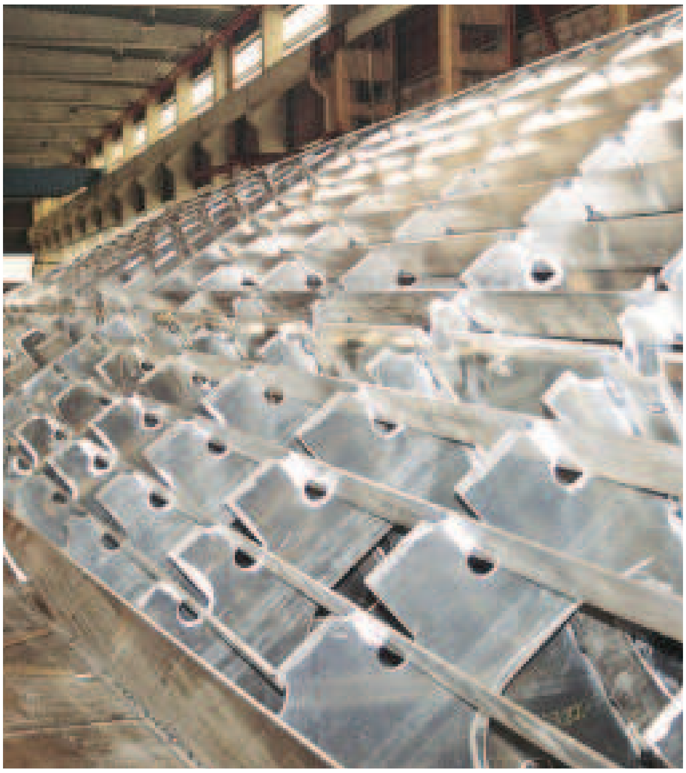

STRUCTURE OF MONOHULL