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Aluminium structures — Material and design — Ultimate limit state under static loading

*Structures en aluminium — Matériaux et conception — État limite ultime
sous charge statique*



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

- type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 11069, which is a Technical Report of type 1, was prepared by Technical Committee ISO/TC 167, *Steel and aluminium structures*, Subcommittee SC 3, *Aluminium structures*.

This Technical Report was proposed as a Draft International Standard but failed to obtain the required committee support. Reasons for the failure were primarily concerned with the attempt to promote the standard prepared by the ECCS. There was no serious technical disagreement; thus the grounds for the lack of support could not be resolved by addressing the technical content.

Aluminium finds wide application in load-carrying assemblies, such as building structures, vehicles and ships, to which the rules for strength design have general validity. This Technical Report deals with the resistance of aluminium structural elements, without regard to any specific product. Because of this broad target, such standards as those developed for steel in particular markets cannot provide a model. No single European standard is suitable for international acceptance; therefore the procedures

presented are compromises to satisfy the demands of both Europe and North America.

National standards include the required safety levels for the particular field treated. Because there is no specific field considered in the Report, there can be no values given for resistance factors or other safety margins. However, if the load spectrum and desired reliability are known, safe design procedures are readily obtained using the resistances provided.

Being intended for international use, no purpose is served by further delaying the issuing of the Report by waiting for the final ECCS recommendations, or the conflicting British Standard BS 8118, or the very distant CEN code for aluminium structures.

Design procedures have been based on the current techniques used for steel structures, adjusted to suit aluminium, and the presentation will be familiar to those using modern steel codes of practice, but may differ in some respects from the methods of earlier aluminium standards.

The Commentary to the Report gives only a limited review of the sources of the treatments proposed. Over the 16 years that the Committee has been meeting, a great deal of material has been produced which records the many aspects of each of the subjects that have been examined, and reveals the areas where compromise has been needed.

Annexes A and B of this Technical Report are for information only.

Introduction

Limit states design requires a knowledge of the ultimate load capacities of components and of the distortion of structural assemblies under the action of specified service loads. These two aspects of structural behaviour are in most cases unrelated and require independent treatment.

This Technical Report gives the ultimate load capacity of aluminium members and connections used in stressed applications, under the action of static loads. The types of component treated include bars, plates and panels; the types of connection are riveted, bolted and welded.

Under the action of static loads, some local buckling and local yielding, up to fully plastic behaviour, are acceptable prior to the attainment of the ultimate resistance.

No restriction is placed on the fields of application, as, in this Report, the component is treated in isolation from its use.

In every application, one design criterion is that the resistance of the part exceed the load effects. To ensure this in limit states design, the load is increased by a "partial factor on load" (load factor), and the ultimate resistance of the component is decreased by a "partial factor on resistance" (resistance factor). These factors, in combination, provide the desired reliability index for the assembly. As each application has its own load spectrum and required level of security, no general values for the partial factors are possible, and are thus not included in this Report. International Standard ISO 2394 deals with the manner in which suitable partial factors are to be determined.

Characteristic resistances obtained using this Report are, in general, the mean of test results less two standard deviations. The values may be factored to provide "safe", "working" or "rated" capacities in those applications which do not use limit states design.

Deformation and natural frequencies of components and assemblies are limited by the need to meet the dictates of the intended purpose. Such serviceability requirements are not treated in this Report.

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Aluminium structures — Material and design — Ultimate limit state under static loading

1 Scope

This Technical Report provides design expressions to determine the characteristic values for the ultimate resistances of components and connections in aluminium assemblies which are subjected to known static forces.

It is intended for general applications of structural aluminium alloys other than those used in aircraft and for other special purposes. All wrought product types are included, in all thicknesses suitable for load-carrying.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this Technical Report. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Technical Report are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 2394:1986, *General principles on reliability for structures*.

ISO 3898:1987, *Bases for design of structures — Notations — General symbols*.

ISO 8930:1987, *General principles on reliability for structures — List of equivalent terms*.

3 Symbols

The preferred symbols used in this Technical Report are based on ISO 3898 and ISO 8930, and are as follows:

<i>a</i>	dimension, weld throat	<i>A</i>	area
<i>b</i>	dimension	<i>C</i>	constant
<i>c</i>	distance	<i>E</i>	elastic modulus
<i>d</i>	distance, diameter	<i>F</i>	action
<i>e</i>	eccentricity, edge distance	<i>G</i>	shear modulus
<i>f</i>	stress	<i>H</i>	length
$\bar{f}$	normalized buckling stress = f_c/f_o	<i>I</i>	moment of inertia
<i>g</i>	fastener spacing, gap	<i>K</i>	factor
<i>h</i>	web depth	<i>L</i>	length
<i>i</i>	radius of gyration	<i>M</i>	moment
<i>k</i>	factor	<i>N</i>	force
		<i>R</i>	resistance
<i>m</i>	factor, number	<i>T</i>	torque
<i>n</i>	number	<i>V</i>	shear force
<i>r</i>	radius	<i>W</i>	section modulus
<i>s</i>	fastener spacing, stiffener spacing		
<i>t</i>	thickness		
<i>v</i>	shear flux		
<i>w</i>	width		
<i>x</i>	distance		
<i>y</i>	distance		
<i>z</i>	weld size		
α	factor, index, coefficient of thermal expansion	β	factor, angle
γ	partial factor	δ	imperfection
λ	slenderness	θ	angle
ν	Poisson's ratio	$\bar{\lambda}$	normalized slenderness $(f_o/f_e)^{1/2} = (\lambda/\pi)(f_o/E)^{1/2}$
η	ratio	ρ	density

The following suffixes are used:

b	bearing
c	compression, critical
d	design
e	elastic, Euler
f	factored, flange
g	gross
h	HAZ (heat-affected zone)
k	characteristic
l	lateral
m	maximum, material
n	net, normal
o	limiting
p	plastic, polar
r	resistance
s	shear
t	tension, torsion
u	ultimate
v	weak axis of angles, shear
w	warping, welded, web
x	axis (major)
y	yield, axis (minor)
z	axis

4 Documentation

4.1 Calculations

Calculations of the resistance of a component or connection shall include the alloy designation and temper, the guaranteed mechanical properties and any derived properties that are used, together with a complete geometric description of the component or connection, and the support conditions. Where the resistance is influenced by associated components, they shall also be fully described.

4.2 Testing

If the resistance is determined by testing, information shall be given on the method of support and load application, the number of tests, the number of parameters varied, the locations of points where strains or deflections are measured, the force/displacement relationships, and the mode of failure. Coupons shall be cut from the test specimens and the mechanical properties determined.

This information shall be sufficiently complete that a third party may interpret the results, and arrive at values for the characteristic resistances which relate to the probable strengths of the components with the same confidence as those predicted by the design expressions in this Technical Report.

5 Basic design principles

5.1 General

Components and connections are proportioned to provide a required ultimate resistance, and to perform within specified limits under service loads. All conditions arising during manufacture, transportation, assembly and construction, and the intended life in service, shall be considered in determining the suitability of the part.

5.2 Limit states

Limit states are classified as "serviceability" limit states and "ultimate" limit states.

Serviceability limit states are dictated by the function of the assembly and are treated in standards specific to the application.

Ultimate limit states are a matter of public concern. They correspond to the highest force that members, connections, assemblies or complete structures can sustain without uncontrolled distortion. The limit may be set by the need to avoid

- large deformations due to extensive yielding;
- rupture, including that due to fatigue;
- member instability;
- overall instability.

Deflection and other distortions, except insofar as they influence stability, are not considered at the ultimate limit state.

While such failure modes as overturning and foundation or anchorage failure need to be considered, they are not treated in this Technical Report, which is restricted to aluminium parts.

5.3 Design requirement

The joints, components and assemblies shall be proportioned to satisfy the inequality:

$$S_d \leq R_d$$

where

S_d is the design action (internal force) due to the factored load;

R_d is the design resistance (factored resistance).

5.4 Design load

Knowing the load spectrum for a particular application, characteristic loads are selected, usually based on a required return period.

The design load, F_d , is the product of the characteristic value of the load, F_k , and the partial factor on load (load factor), γ :

$$F_d = F_k \gamma$$

Values of γ are given in the applicable national standards.

The design action (internal force) is obtained from the analysis of the assembly when subjected to the design load (factored load), and is used to determine the required design resistance (factored resistance) of a component.

The design actions are expressed as follows:

N_{sd} is the design force

V_{sd} is the design shear force

M_{sd} is the design moment

T_{sd} is the design torque

5.5 Design resistance

The expressions provided in this Report give the values for the characteristic resistances, R_k .

The design resistance (factored resistance), R_d , is obtained using

$$R_d = R_k / \gamma_m$$

in which γ_m is the partial factor on resistance (resistance factor).

Values of γ_m are established for each particular application in conjunction with the partial factors on load (load factors), γ , to provide the required level of reliability. When values are not given in national standards, ISO 2394 provides guidance.

Predictors given in this Report have been targeted to give values for the characteristic resistance that are the mean value from test results less two standard deviations.

6 Basic considerations

6.1 Static actions

Characteristic values for the actions, to be used in the design, are specified in the standards appropriate to the application.

Direct actions are loads such as the weight of cargo, wind pressure and traffic. They may be static, quasi-static equivalents of impact forces, temporary, permanent, fixed, variable, planned or accidental. The type of action will determine, in part, the partial factor to be applied.

Indirect actions are those attributed to imposed changes in geometry such as are caused by expansion and settlement. In general, indirect load effects are to be avoided by using a suitable overall design, as, in normal circumstances, they are not readily predictable.

6.2 Materials

6.2.1 Aluminium alloys

In selecting an aluminium alloy for a stressed application, its suitability will be assessed on the basis of conformity to an International Standard, or European or national standard and on the following considerations, as applicable:

- strength: yield and ultimate;
- ductility: elongation and reduction in area;
- weldability and welded properties;
- corrosion resistance in the intended environment;
- formability;
- machinability;
- surface finish.

In general, extrusions will be of heat-treated alloys in T5 or higher temper, while sheet and plate may be of heat-treated or work-hardened alloys.

Where castings or forgings are to be used, there shall be close cooperation with the suppliers to establish the design properties. For foundry alloys, the values should be confirmed by tests of the finished casting.

6.2.2 Fasteners

Only bolts and solid rivets are treated in this Technical Report. Bolts may be of aluminium alloy, zinc- or cadmium-coated steel, or stainless steel. Solid rivets will preferably be of an aluminium alloy. If proprietary fasteners are used, the value of the ultimate resistance shall provide the same level of reliability as do connections proportioned according to this Report (see 6.4.2.1).

6.2.3 Welds

Welding electrodes and filler wire, and shielding gas shall be selected to suit the alloys to be joined and the method of welding (see clause 15).

6.2.4 Identification of material

All material shall be marked or stored such that the identification of the alloy and temper can be established at all stages of manufacture.

6.3 Geometrical parameters

Dimensions of profiles, members and overall assemblies shall be subject to the ruling commercial tolerances applicable to the product.

6.4 Properties

6.4.1 Physical properties

For strength design purposes, all aluminium alloys to which this Report applies shall be considered to have the following physical properties:

Elastic modulus, E	70 000 MPa
Elastic shear modulus, G	26 000 MPa
Poisson's ratio, ν	0,33
Density, ρ	2 700 kg/m ³
Coefficient of thermal expansion, α	0,000 024 per 1 °C

6.4.2 Mechanical properties

6.4.2.1 Specified properties

Yield strength, f_y , (0,2 % proof stress) is taken to be that stress in tension at which there is a 0,2 % strain offset in the stress/strain relationship.

Ultimate strength, f_u , is the highest force in tension, sustained by the test specimen, divided by the original cross-sectional area of the specimen.

Yield and ultimate strengths in tension are the basic mechanical properties specified, for each alloy and temper, in International Standards, or European or national standards. (To satisfy the requirements of the Aluminum Association, the values are expected to be exceeded in 99 % of the production, at a confidence level of 0,95.) Selected values of these strengths for some popular alloys are given in table A.1.

Yield strength in compression, yield and ultimate strengths in shear, and strength in bearing, may be established by a sufficient number of tests to provide the same level of confidence as that for the specified properties. When these values are not available, 6.4.2.2 shall be used.

6.4.2.2 Derived properties

6.4.2.2.1 Yield strength in compression

In compression, the yield strength shall be taken as the value in tension.

6.4.2.2.2 Yield and ultimate strengths in shear

For direct shear, the characteristic strengths shall be taken to be

- yield strength in shear, $f_{vy} = 0,6f_y$
- ultimate strength in shear, $f_{vu} = 0,6f_u$

6.4.2.2.3 Ultimate strength in bearing on fasteners

For bolts and rivets acting in bearing, the characteristic bearing strength of the connected material shall be taken to be

$$f_{bk} = 2f_u$$

This is subject to the further restrictions given in 14.3.2.

The bearing stress on the fastener itself need not be considered.

6.4.2.3 Welded properties

Full account shall be taken of the influence of welding on the properties of aluminium, as described in 8.2.

Table A.1 gives, for some popular alloys, the values of the yield and ultimate tensile strengths of the base metal and of the metal in the heat-affected zone (HAZ) at the weld, which are acceptable for design purposes.

Table A.2 gives, for some popular alloys, values for the ultimate tensile strengths of the weld beads which are acceptable for design purposes.

Higher values may be used if they are demonstrated and can be ensured in production.

When the properties of the heat-affected zone (HAZ) are not known, they may be taken to be equal to those in the solution-treated condition for heat-treated alloys and equal to those in the annealed condition for work-hardened alloys. Because the properties of the weld bead are a function of both the base metal alloy and the filler wire alloy, any combination for which the properties are not known shall be tested to establish the strength of the weld bead itself.

7 Methods of analysis

7.1 General

For individual components and connections, the design expressions in this Report give the ultimate resistance. Behaviour may be linear or non-linear. The values obtained are not related to the method of analysis; however, as the behaviour of individual parts can influence the overall behaviour of the assembly, the method of analysis may take cognizance of the force/deformation relationships of the components.

7.2 Elastic analysis

Elastic analysis is generally considered to provide a lower bound solution, and is permitted for all assemblies, without regard for the behaviour of the individual components up to the ultimate resistance, unless geometric distortions influence the stability of the assembly.

7.3 Plastic hinge analysis

Plastic hinge analysis may be used for rigid frames in which it can be demonstrated that the required rotation at the yield hinges is available, and the destabilizing influence of compression forces is taken into account. The limited deformation capacity at bolted joints and transverse welds shall be considered when determining whether plastic hinges can be developed.

7.4 Yield line theory

Yield line theory for plates may be used, but full account shall be taken of the influence of any welds or perforations for fasteners.

7.5 Redundant lattice structures

Non-linear analysis of redundant lattice structures is permitted only where the force/deformation relationships for the components are known and can be accurately or conservatively modelled.

8 Characteristic resistance in tension

8.1 Bolted construction

8.1.1 Concentric force

For a member subjected to a concentric axial tension force, the resistance is the lesser of the values given by

$$N_k = A_g f_y$$

$$N_k = A_n k f_u$$

where

f_y is the tensile yield strength (0,2 % proof stress) of the material;

f_u is the ultimate tensile strength of the material;

A_g is the area of the gross cross-section;

A_n is the area of the net cross-section;

k equals 1,0, unless it is demonstrated that a lower value applies for a particular alloy and temper.

8.1.2 Net sections

8.1.2.1 Where a chain of holes extends across a plate or element of a member subjected to tension, the area of the net section is given by

$$A_n = A_g - n(dt)$$

8.1.2.2 If the holes in the chain are staggered as in figure 1, the net area is given by

$$A_n = A_g - n(dt) + (n - 1) \left(\frac{s^2}{4g} \right) t$$

where

A_n is the area of the net section;

A_g is the area of the gross section;

n is the number of holes in the chain;

d is the hole diameter;

t is the plate thickness;

s is the longitudinal spacing of adjacent holes in the chain;

g is the transverse spacing of adjacent holes.

The staggered path governs when $s^2 < 2gd$.

8.1.3 Eccentric force

8.1.3.1 General case

When axial tension force is applied with an eccentricity, e , as in figure 2, the resistance shall be the lesser of the values given by

$$N_k = f_y / (1/A_g + e/W_g)$$

$$N_k = f_u / (1/A_n + e/W_n)$$

where, in addition to the symbols in 8.1.1

W_g is the elastic section modulus of the gross section;

W_n is the elastic section modulus of the net section.

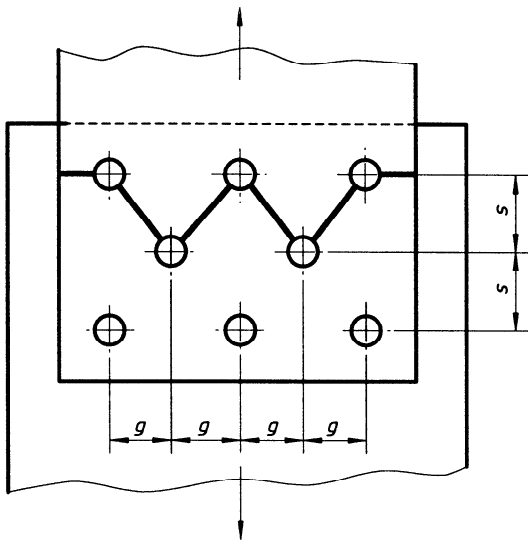


Figure 1 — Area of net section

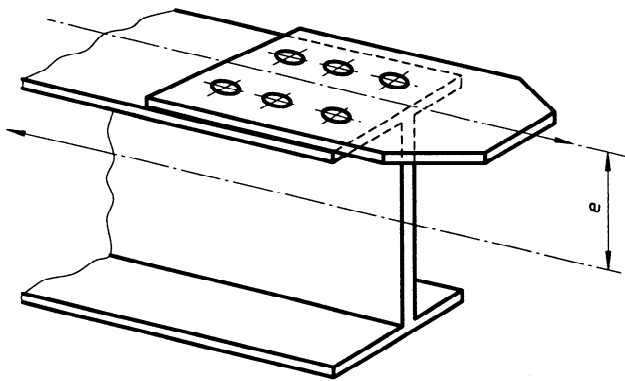


Figure 2 — Eccentric axial force

At bolted connections, the section modulus of the net section shall be calculated using

$$W_n = W_g - \sum (dt)_i y_i$$

where

- $(dt)_i$ is the area removed by a hole at a distance y_i from the centroid of the gross cross-sectional area;
- d is the hole diameter;
- t is the metal thickness.

The above expressions are based on the summation of stresses derived from elastic behaviour. Full plastic analysis at the limiting condition is permitted, using the yield stress on the gross section and the ultimate stress on the net section, as is the case in the following clauses (8.1.3.2 and 8.1.4). Such an analysis shall take account of any non-symmetry in the cross-section.

8.1.3.2 Special cases

8.1.3.2.1 Eccentrically loaded gusset plates

For a plate, as shown in figure 3, loaded eccentrically in tension, the resistance shall be the lesser of the values given by

$$N_k = [(4e^2 + b^2)^{1/2} - 2e]tf_y$$
$$N_k = [(4e^2 + b^2)^{1/2} - 2e - nd]tf_u$$

where

- e is the eccentricity of the force;
- b is the width of the plate;
- t is the thickness of the plate;
- d is the hole diameter;
- n is the number of holes in the transverse section.

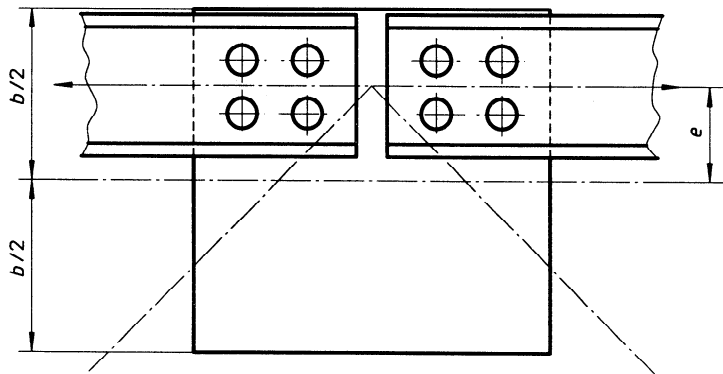


Figure 3 — Eccentrically loaded gusset plate

8.1.3.2.2 Single angles

For an isolated single angle member as in figure 4, connected at the end by a single bolt through one leg, the axial resistance in tension is the lesser of the values given by

$$N_k = (2e - d) t f_u$$

$$N_k = (b - d) t f_u$$

where

$$e \text{ (edge distance)} \geq 1,25d.$$

If $e \geq b/2$ and two or more bolts are used in the connected leg, the area of the net section may be increased by one-third of the area of the outstanding leg.

The addition of lug angles (cleats, clip angles) to attach the outstanding leg is, in general, of no benefit. If any advantage is claimed, it shall be demonstrated by tests.

8.1.3.2.3 Single channels, T-sections and double angles connected eccentrically

For a single channel connected by the web, T-sections connected by the flanges, and double angles connected to one side of a gusset, the effective gross area, A'_g , to be used in 8.1.1 shall be the area of the connected element plus half the area of the outstanding elements. The effective net area, A'_n , is the effective gross area less all the holes in line across the connected elements.

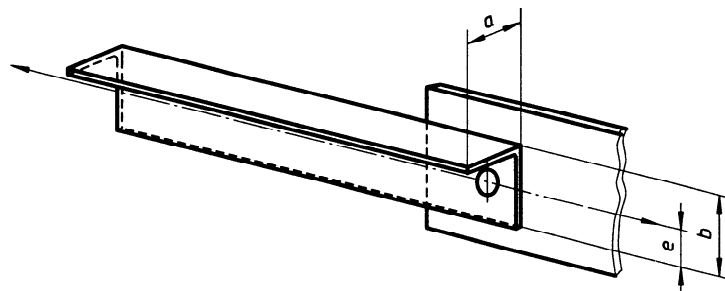


Figure 4 — Single angle connected by single bolt

8.1.4 Combined tension and bending

In the case of sections, bars, and plates, not subject to local or lateral buckling, bending in a plane of symmetry, the limiting condition is given by

$$(N_{sd}/N_d)^\alpha + (M_{sd}/M_d) = 1$$

where

N_{sd} is the factored axial force;

M_{sd} is the factored applied moment;

$N_d = A_g f_y / \gamma$ and $M_d = W_p f_y / \gamma$ or

$N_d = A_n f_u / \gamma$ and $M_d = W_n f_u / \gamma$

A_g is the gross area;

A_n is the net area;

W_p is the plastic section modulus of the gross section;

W_n is the plastic section modulus of the net section;

f_y is the yield strength;

f_u is the ultimate strength;

$\alpha = 2$ for solid sections, T, C, Z, H, and similar sections bending about the weak axis,
 $= 1,4$ for hollow sections and C, Z, H, and similar sections bending about the strong axis;

γ is the resistance factor.

8.2 Full penetration butt welded construction

8.2.1 Full width transverse welds

For full penetration, full width, transverse butt welded joints in tension, the tensile resistance is the least of the values given by the expressions:

$$N_k = t L f_y$$

$$N_k = t L f_{hu}$$

$$N_k = t L f_{wu}$$

where

t is the plate thickness;

L is the length of the butt weld;

f_y is the yield strength of the unaffected base metal;

f_{hu} is the ultimate tensile strength in the HAZ (table A.1 gives some values);

f_{wu} is the ultimate tensile strength in the weld bead (table A.2 gives some values).

Partial penetration butt welds are not recommended for engineered designs but, should the need arise, then t in 8.2.1 shall be replaced by the total effective throat.

8.2.2 Full width oblique welds

For a full width oblique weld, as shown in figure 5, if the angle θ between the direction of the weld and the direction normal to the applied stress is less than 45° , the dimension L shall be taken as the width of the welded element measured in a direction normal to that of the applied stress. For angles θ greater than 45° , the treatment for longitudinal welds (8.2.3) shall be used except that the resistance shall not exceed

$$N_k = tL f_{wu} / \sin 2\theta$$

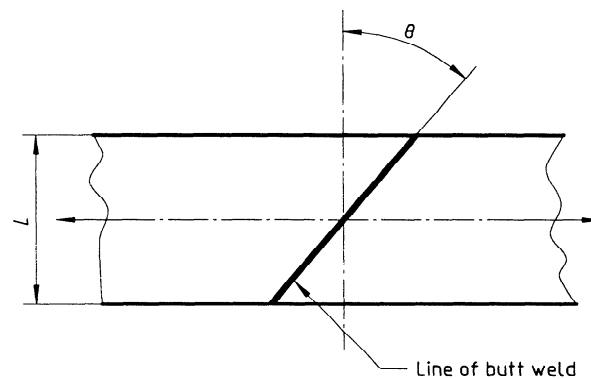


Figure 5 — Oblique butt weld in tension

8.2.3 Longitudinal welds

For members with longitudinal welds, and in other cases where only a portion of the cross-section is influenced by welding, the effective transverse section is obtained by reducing the thickness in the HAZ (15.2) to an effective thickness, t' , given by

$$t' = t(f_{hy}/f_y)$$

where

t is the original thickness;

f_y is the tensile yield strength in the unaffected base metal;

f_{hy} is the yield strength in the HAZ (table A.1).

9 Characteristic resistance in compression

9.1 Concentric force

For a member subjected to a concentric axial compressive force, the resistance is given by

$$N_k = A_g f_c$$

where

A_g is the gross area;

f_c is the buckling stress determined using 9.4.

9.2 Limiting stress

The maximum compressive stress at any point in a cross-section shall not exceed the limiting stress, f_o , appropriate to the situation, as follows:

- the yield strength of the base metal, f_y ;
- the yield strength of the HAZ at a transverse weld away from lateral supports, f_{hy} (15.8.2);
- the ultimate tensile strength of the HAZ at a transverse weld adjacent to a lateral support, f_{wu} ;
- the weighted average yield strength in a longitudinally welded member, f_o (9.5.2);
- the initial local buckling stress in an outstanding flange or other element where local buckling precipitates collapse, f_c (9.5.3);
- the mean post-buckling stress where local buckling does not lead to immediate collapse, $(f_y f_c)^{1/2}$ (9.5.4);
- the buckling stress of a chord in a lattice column, f_c (9.5.1).

9.3 Normalized slenderness

9.3.1 The normalized slenderness of a component which may buckle under the action of compressive stress is given by

$$\bar{\lambda} = (f_o/f_e)^{1/2} = (\lambda/\pi) (f_o/E)^{1/2}$$

where

- $\bar{\lambda}$ is the normalized slenderness;
- f_o is the limiting stress in compression;
- f_e is the elastic buckling stress equal to $\pi^2 E/\lambda^2$
- E is the elastic modulus;
- λ is the slenderness appropriate to the mode of buckling.

9.3.2 In other cases of buckling, the normalized slenderness may be expressed as

Columns

$$\bar{\lambda} = (N_o/N_e)^{1/2}$$

Beams

$$\bar{\lambda} = (M_o/M_e)^{1/2}$$

where

- N_o is the limiting axial force when $\lambda = 0$;
- M_o is the limiting moment when $\lambda = 0$;
- N_e is the theoretical axial force to cause elastic buckling;
- M_e is the theoretical moment to cause elastic buckling.

The value of $\bar{\lambda}$ shall be used in 9.4 to determine the normalized buckling stress, force or moment.

9.4 Normalized buckling stress

The highest mean axial stress sustained before instability occurs is the buckling stress. The ratio of the buckling stress, f_c , to the limiting stress, f_o , is the normalized buckling stress

$$\bar{f} = f_c/f_o$$

The relationship between the normalized buckling stress, $\bar{f}$, and the normalized slenderness, $\bar{\lambda}$, is given by

$$\bar{f} = \beta - (\beta^2 - 1/\bar{\lambda}^2)^{1/2}$$

where

$$\beta = [1 + \alpha(\bar{\lambda} - \bar{\lambda}_o) + \bar{\lambda}^2]/2\lambda^2$$

$\bar{\lambda}_o$ is the value of the normalized slenderness below which the limiting stress can be sustained, and will vary between different alloys, members and elements.

To reflect the different stress/strain relationships for work-hardened and heat-treated alloys, different values of α are used. Values of α may also be varied for columns, beams and plates, different shapes, and for symmetrical and asymmetrical profiles.

A review of suitable values for α and λ_o is given in annex A, together with some representative curves of the relationships.

If forces or moments are used rather than stress, the value of $\bar{f}$ given by the above expression represents the normalized buckling force, N_c/N_o , or the normalized buckling moment, M_c/M_o .

9.5 Flexural buckling of columns

9.5.1 General case

The slenderness of a column failing in pure flexure is given by

$$\lambda = KL/i$$

where

- L is the length between lateral restraints;
- i is the radius of gyration for the axis of flexure;
- K is the effective length factor.

This slenderness, in conjunction with the appropriate limiting stress, f_o (9.2), gives the normalized slenderness, $\bar{\lambda}$ (9.3). The normalized buckling stress, $\bar{f}$, shall then be obtained using 9.4.

The axial resistance of a compression member is given by

$$N_k = (\bar{f}f_o)A_g = f_cA_g$$

where

- f_o is the limiting stress;
- f_c is the buckling stress;
- A_g is the gross cross-sectional area of the column.

9.5.2 Influence of longitudinal welds

For compression members with longitudinal welds only, the limiting stress f_o is given by

$$f_o = f_y - (A_h/A_g)(f_y - f_{hy})$$

where

f_y is the yield strength of the base metal;

f_{hy} is the yield strength of the HAZ;

A_g is the area of the gross cross-section;

A_h is the area of the cross-section of the HAZ's (15.2).

This limiting stress shall be used in 9.3 to obtain $\bar{\lambda}$, which is then used in 9.4 to obtain $\bar{f}$.

The axial resistance of the compression member is then given by

$$N_k = k(\bar{f}f_o)A_g$$

where

$$k = 0,9 + |1 - \bar{\lambda}| \quad 0,1 \leq 1,0$$

($|1 - \bar{\lambda}|$ is the absolute value.)

9.5.3 Influence of local buckling that leads to failure

For pin-ended columns, the local buckling of outstanding flanges in I, Z and C sections, and of the walls of cylindrical tubes, shall be deemed to limit the capacity. The local buckling stress, f_{cr} , is obtained using 12.1 for flat elements, and 12.5 for curved walls.

This local buckling stress shall be taken as the limiting stress, f_o , in conjunction with the overall slenderness to calculate the normalized slenderness, $\bar{\lambda}$, in 9.3 for use in 9.4 to give the resistance of the column.

9.5.4 Influence of local buckling with post-buckling strength

Flat elements with both long edges supported can sustain a mean compressive stress in excess of that causing initial local buckling. The buckling stress, f_{cr} , is obtained from 12.1. The limiting stress, f_o , is then given by

$$f_o = (f_y f_{cr})^{1/2} = \bar{f}^{1/2} f_y$$

where

$\bar{f}$ is the normalized buckling stress.

This value of f_o shall be used in 9.3 and 9.4 to give the axial resistance of the column.

9.6 Torsional and torsional-flexural buckling of columns

9.6.1 Open sections symmetrical about one axis

In open sections with only one axis of symmetry, torsional buckling combines with flexure about the axis of symmetry. The slenderness to be used in 9.3 to obtain the normalized slenderness is given by

$$\lambda = [1 + 0,4(x_o/i_p)(\lambda_2/\lambda_1)^2]\lambda_1$$

where

λ_1 is the larger of λ_t and λ_f ;

- λ_2 is the smaller of λ_t and λ_f ;
- λ_f is the slenderness for flexural buckling about the axis of symmetry
 $= KL/i_x$,
- λ_t is the slenderness for torsional buckling
 $= 5(I_p/I_t)^{1/2}$ or as modified by 9.6.3;
- x_0 is the distance from the centroid to the shear centre of the cross-section;
- I_p is the polar moment of inertia about the shear centre
 $= I_x + I_y + Ax_0^2 = Ai_p^2$
- I_t is the St. Venant torsion constant;
- i_p is the polar radius of gyration about the shear centre;
- i_x is the radius of gyration for the axis of symmetry;
- A is the cross-sectional area;
- L is the length.

Calculation of the slenderness, λ_t , for built-up sections such as double angles, shall include the influence of shear according to 9.7.

9.6.2 Angles, T-sections and cruciform sections

In the case of single or multiple angles, T-sections and cruciform sections, all with equal legs, the slenderness for torsional buckling is given by

$$\lambda = 5b/t$$

where

- b is the leg length;
- t is the leg thickness.

For extruded sections, b shall be measured from the start of the root fillet radius. For shapes with no thickening at the root (e.g. cold-formed shapes), b shall be measured from the median line of the adjacent leg.

9.6.3 Influence of warping resistance

In open sections, such as channel or hat shapes, the resistance to torsional buckling is increased by the warping resistance of the section. The slenderness for torsional buckling of sections with one axis of symmetry is given by

$$\lambda_t = 5(I_p/I_t)^{1/2} / (1 + 25C_w/I_t L^2)^{1/2}$$

where

- C_w is the warping constant;
- L is the length between restraints.

This value of λ_t shall be used in 9.6.1.

9.6.4 Asymmetrical open sections

In the case of open sections with no axis of symmetry, flexure about both principal axes combines with torsion to give the buckling mode. If a design is required, reference shall be made to the literature to obtain the elastic buckling stress, f_e , for use in 9.3.

9.7 Built-up compression members

The resistance of built-up compression members composed of multiple bars, such as double angles and battened channels, connected together by widely spaced fasteners or welds, is determined in accordance with 9.5, using a slenderness given by

$$\lambda = (\lambda_1^2 + \lambda_2^2)^{1/2}$$

where

- λ_1 is the overall slenderness for the built-up section treated as a whole, for bending about the built-up axis;
- λ_2 is the slenderness of the individual bars between points of interconnection for bending about an axis parallel to that used to compute λ_1 .

The connections between the bars, at each location, shall be designed to resist a total shear force equal to 2,5 % of the total axial force. There shall be rigid connections between the bars at each end, and, preferably, there should be not less than two intermediate connections.

9.8 Lattice columns

To determine the axial compressive force to cause overall buckling of lattice columns, the limiting stress, f_o , shall be the buckling stress for an individual chord member, f_c . Design shall then be in accordance with 9.4. The influence of shear flexibility in lattice columns (λ_2 in 9.7) may be neglected.

The planes of diagonal bracing shall be designed to resist a total shear force across the mast equal to 2,5 % of the total axial force.

10 Bending

10.1 Moment resistance

The moment resistance of a member shall be given by the appropriate expression from the following cases:

10.1.1 For failure in the plane of bending

- a) Fully plastic: $M_k = W_p f_y$

With longitudinal welds (8.2.3): $M_k = W_{ep} f_y$

- b) Limited by first yield: $M_k = W f_y$

With longitudinal welds (8.2.3): $M_k = W_e f_y$

- c) Limited by the ultimate strength in tension at connections:

Bolted: $M_k = W_n f_u$

Welded transversely: $M_k = W_p f_{wu}$

- d) Limited by local buckling of outstanding flanges which leads to collapse [12.1.3.2]: $M_k = Wf_c$
- e) Limited by local buckling of elements with post-buckling reserve [12.2.2.2]: $M_k = W_e f_y$
- f) Limited by chord buckling in lattice beams (9.5): $M_k = Adf_c$

10.1.2 For failure by lateral-torsional buckling (10.2) $M_k = Wf_{cl}$

10.1.3 In 10.1.1 and 10.1.2, the symbols are as follows:

- M_k is the characteristic moment resistance;
- A is the total cross-sectional area of the compression chords;
- d is the depth of lattice beam;
- W is the elastic section modulus of the gross section;
- W_e is the elastic section modulus of the effective section (12.2.2 for local buckling, 8.2.3 for longitudinal welds);
- W_{ep} is the plastic section modulus for the effective section (8.2.3 for welded sections);
- W_n is the section modulus of the net section (8.1.3.1);
- W_p is the plastic section modulus of the gross section;
- f_y is the yield strength of the base metal;
- f_u is the ultimate tensile strength of the base metal;
- f_{wu} is the ultimate tensile strength at the weld;
- f_{hy} is the yield strength of the HAZ;
- f_c is the critical stress for buckling of chords (9.5) or of outstanding flanges, which leads to failure (9.5.3);
- f_{cl} is the critical stress for lateral-torsional buckling (10.2).

The fully plastic condition, given by 10.1.1 a), shall only be used where there is a demonstrable security against overall and local instability. In general, for cases controlled by yielding, the value obtained from 10.1.1 b) shall be used as the limiting condition.

10.2 Lateral-torsional buckling

10.2.1 For uniform moment, and where the maximum moment occurs in the span, the slenderness for lateral-torsional buckling, is given as follows:

- a) For beams between points of lateral restraint of the compression flange or points of torsional restraint:

$$\lambda = (W_x L)^{1/2} / [I_y (0,04 I_t + C_w / (KL)^2)]^{1/4}$$

- b) For beams with continuous lateral restraint to the tension flange and points of lateral restraint to the compression flange:

$$\lambda = (W_x L)^{1/2} / [I_y + (0,04 I_t + C_w / (KL)^2)]^{1/2}$$

In both a) and b),

W_x is the elastic section modulus about the axis of bending (X-axis);

I_y is the moment of inertia about the weak axis (Y-axis);

L is the distance between points of lateral restraint to the compression flange or to twisting;

I_t is the St. Venant torsion constant;

C_w is the warping constant;

K is a factor representing the restraint to warping at the ends, usually taken as 1.

The limiting stress, f_o , shall be one of those described in 9.2. The normalized slenderness (9.3) shall be used with the appropriate buckling curve for columns (9.4) to give the normalized buckling stress, $\bar{f}$, and the actual buckling moment:

$$M_k = (\bar{f}f_o)W$$

where W is the section modulus.

10.2.2 Linear moment gradients, with the maximum moment at an end, shall be treated as an equivalent uniform moment given as follows:

$$0,6M_1 + 0,4M_2 \geq 0,4M_1,$$

where the end moments are M_1 and M_2 , $|M_1| > |M_2|$, and M_2 is negative if it creates double curvature.

The maximum end moment is subject to the limits of 10.1.1.

11 Beam-columns

11.1 Moment with axial compressive force

For members subjected to combined axial and bending forces, the ultimate limit state shall be given by the more restrictive of the conditions in 11.1.1 and 11.1.2.

11.1.1 Failure in the plane of bending (about the X-axis)

a) Limited by yielding in compression:

$$N_{sd}/N_{dx} + M_{sd}/M_d(1 - N_{sd}/N_{ex}) = 1$$

b) Limited by an elastic extreme fibre compressive stress, such as local buckling in flanges and chord buckling in latticed masts:

$$N_{sd}/A + M_{sd}/W_x(1 - N_{sd}/N_{ex}) = f_o/\gamma_m$$

c) Limited by an extreme fibre tension stress:

$$M_{sd}/W_x(1 - N_{sd}/N_{ex}) - N_{sd}/A = f_o/\gamma_m$$

11.1.2 Failure by lateral-torsional buckling

$$N_{sd}/N_{dy} + M_{sd}/M_{dl}(1 - N_{sd}/N_{ex}) = 1$$

11.1.3 In 11.1.1 and 11.1.2, the symbols are as follows:

- A is the gross cross-sectional area;
- W_x is the elastic section modulus applicable to the fibre with the maximum compressive stress for case 11.1.1 b), and with the maximum tensile stress for case 11.1.1 c);
- N_{sd} is the design applied axial force;
- N_{dx} is the design axial resistance for buckling in the plane of bending, X-axis, (9.5);
- N_{dy} is the design axial resistance for buckling about the Y-axis, i.e. out of the plane of bending, (9.5);
- N_{ex} is the theoretical axial force for elastic flexural buckling in the plane of bending and is equal to $\pi^2 EI_x / (KL)^2$;
- M_{sd} is the design applied bending moment;
- M_{dl} is the design moment resistance limited by lateral-torsional buckling (10.2);
- M_d is the design moment resistance limited by yielding;
- f_o is the limiting stress at the extreme compression or tension fibre (9.2);
- γ_m is the partial factor on resistance.

If extensive plastification can take place in short members such as is permitted for combined tension and bending (8.1.4), a limiting combination demonstrated by test or by computer simulation may be used. The value of the compressive force, N , shall not exceed that given by 9.5 for overall flexural buckling about the Y-axis.

11.1.4 For axially loaded members subjected to moments about both principal axes, with the maximum moment in the span, in which torsion is not a consideration, and the most highly stressed fibre is the same for M_x and M_y , the ultimate limit state is given as follows:

a) Limited by yielding in compression:

$$N_{sd}/N_d + M_{sd}/M_{dx}(1 - N_{sd}/N_{ex}) + M_{sdy}/M_{dy}(1 - N_{sd}/N_{ey}) = 1$$

b) Limited by an elastic extreme fibre stress:

$$N_{sd}/A + M_{sd}/W_x(1 - N_{sd}/N_{ex}) + M_{sdy}/W_y(1 - N_{sd}/N_{ey}) = f_o/\gamma_m$$

In both a) and b),

- W_x, W_y are the elastic section moduli about the X- and Y-axes;
- N_{sd} is the design applied axial force;
- N_d is the design axial resistance;
- N_{ex}, N_{ey} are the theoretical axial forces for elastic buckling about the X- and Y-axes;
- M_{dx}, M_{dy} are the design moment resistances for bending about the X- and Y-axes;
- M_{sd}, M_{sdy} are the design applied moments about the X- and Y-axes;
- f_o is the limiting stress from 9.2;
- γ_m is the partial factor on resistance.

Torsional-flexural buckling under the action of axial force and biaxial moments shall be treated by a rational method which includes the influence of the axial force on the torsional as well as on the flexural components of the buckled mode.

11.2 Eccentrically loaded columns

11.2.1 General case

Eccentrically loaded columns shall be proportioned to satisfy 11.1.

11.2.1.1 For failure in the plane of bending:

- a) When limited by yielding in compression, 11.1.1 a) shall apply, using a design applied moment given by

$$M_{sd} = N_{sd}e$$

- b) When limited by elastic compressive stress, such as for local buckling and for chords in lattice columns, 11.1.1 b) shall apply, using an applied moment given by

$$M_{sd} = 1,2N_{sd}e$$

- c) When limited by tension stress, 11.1.1 c) shall apply, using a moment given by

$$M_{sd} = 1,2N_{sd}e$$

11.2.1.2 For failure by lateral-torsional buckling, 11.1.2 shall apply, using a moment given by

$$M_{sd} = N_{sd}e$$

where

N_{sd} is the design applied axial force;

e is the eccentricity.

11.2.2 Single angle struts

Discontinuous single angle compression members, loaded through one leg, as for internal bracing members, fail in a flexural-torsional mode. The slenderness used to calculate $\bar{\lambda}$, for direct entry into 9.4 to give the mean axial stress at failure, shall be given by

$$\lambda = (\lambda_t^2 + \lambda_v^2)^{1/2}$$

where

$$\lambda_t = 5b/t \text{ (See 9.6.2.)}$$

$$\lambda_v = KL/i_v$$

b, t are the larger leg width and thickness;

L is the length;

i_v is the radius of gyration about the minimum axis;

K is the effective length factor

= 0,8 for 1 bolt connection,

= 0,7 for 2 or more bolt connections.

The mean axial stress shall not exceed $0,5f_y$ for 1 bolt connections, or $0,67f_y$ for 2 or more bolt connections or welded connections.