ITER STRUCTURAL DESIGN CRITERIA FOR IN-VESSEL COMPONENTS

(SDC-IC)

FOREWORD

The Structural Design Criteria for ITER In-vessel Components (SDC-IC) contains interim rules for the structural design of the in-vessel components: first wall, shield / blanket, divertor and the diagnostic components located inside of vacuum vessel. The scope of these criteria is limited to design.

These criteria were developed because existing codes do not address the effects of irradiation on the in-vessel components, which include embrittlement of the material (low ductility and toughness), and may include swelling and creep. Also, the component classifications used with existing codes for the construction of Nuclear Power Plants do not necessarily apply to the in-vessel components.

This document, the result of that work, is a self-contained set of rules for design by analysis. Separate appendices contain analysis guidelines and justification of the rules. Substantial modifications are introduced to account for irradiation effects. The language of RCC-MR has been updated to be more relevant to fusion and more consistent with terminology used in other countries. This Criteria has been reviewed by the Working Group and it represents a working consensus. This is a living document subjected to review, modification, and extension by both the developers and users of these criteria.

This development was undertaken as a collaboration among the Home Teams of the European Union, Japan, the Russian Federation, and the United States. Consultants from laboratories and industry, organized into a Working Group, advised the ITER Joint Central Team on these criteria, with the objective of establishing design rules that would be acceptable to all Parties. The Working Group began with the French code, RCC-MR, as a starting point and made modifications as necessary to account for the requirements of the other countries.

ACKNOWLEDGEMENT

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[1] G 74 MA 10, Materials Assessment Report (MAR)

[2] G 74 MA 9, ITER Materials Properties Handbook for In-vessel Components (MPH-IC)

GENERAL CONTENT

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STRUCTURAL DESIGN CRITERIA FOR IN-VESSEL COMPONENTS

(SDC-IC)

IC 1000 NOMENCLATURE

IC 1001 SYMBOLS

E	Young's modulus
F	Peak Stress
h, h_c, h_t, h_k	Shell thicknesses
J_C, K_C	Critical J-integral and linear elastic fracture toughness
K_f	Fatigue strength reduction factor
$M_{\alpha\beta}, N_{\alpha\beta}$	Bending and membrane stress resultants for shells
N, N_d	Cycles and allowable fatigue cycles
n_j, N_j	Number of j-type cycles and allowable j-type fatigue cycles
P_m, P_L, P_b	General primary membrane, local primary membrane and primary bending stresses for single layer shell
P_m^*, P_L^*, P_b^*	General primary membrane, local primary membrane and primary bending effective stresses for multilayer shell
$\overline{P_m}, \overline{P_L}, \overline{P_b}$	General primary membrane, local primary membrane and primary bending stress intensities for single layer shell
Q, Q_L	Secondary and membrane secondary stresses
%RA	Per cent reduction in area
R, r, r_1, r_2, r_3	Elastic follow-up factors
r^*	Alternative elastic follow-up factor = r-1
S_d, S_e, S_m	Temperature and fluence-dependent, time-independent allowable stress intensities
S_t	Temperature, fluence, and time-dependent allowable stress intensity
S_u, S_y	Temperature and fluence-dependent ultimate tensile and yield strengths
$S_{u,k}, S_{y,k}$,	Temperature and fluence-dependent ultimate tensile and yield strengths for k-th layer

S_u^*, S_y^*	Effective ultimate tensile and yield strengths for multilayer shell
t, t_s	time, allowable time
t_r	times to creep rupture
T, T_m	Temperature, thickness averaged temperature
TF	Triaxiality factor
U_t, U_ε	Time based and strain based creep usage fractions
V, V_j	Fatigue usage fractions
W_t	Time based creep rupture usage fraction
x_i (i=1 to 3)	Cartesian coordinates
Δe	Offset of in-plane resultant force for multilayer shell
α	Triaxiality factor for uniform elongation
$\overline{\Delta\varepsilon}$	Equivalent strain range
$(\Delta\notin_m)_p$	Increment of significant mean plastic strain
$(\Delta\notin_m)_c$	Increment of significant mean creep strain
$\overline{\Delta\sigma}$	Stress intensity range
ε, $\bar{\varepsilon}$	Strain (total strain - thermal plus swelling strains) and equivalent strain
$\notin$, $\notin^*$	Significant strain for single layer shell and effective significant strain for multilayer shell
$\notin_m$, $\notin_b$	Significant membrane and significant bending strains
ε_c, ε_{ctr}	creep ductility and true strain at rupture for creep
ε_{ij}, γ_{ij}	normal and engineering shear strain components
$(\varepsilon_{ij})_m$, $(\varepsilon_{ij})_b$	Membrane and bending components of strain
$(\varepsilon_{ij})_{nl}$	Non-linearly distributed components of strain
ε_{tr}, ε_u	True strain at rupture and uniform elongation
ε_u^*	Effective uniform elongation for multilayer shell
ϕt, ϕt_m	Neutron fluence, thickness-averaged neutron fluence. Here and through all document, this parameter is referred to neutron damages of materials, i.e. displacement dose, D_d in dpa, as given in ASTM 170-97a.

$\sigma, \sigma_{el}, \bar{\sigma}$	Stress, elastic stress, and stress intensity
σ_ι, σ_H	Principal stresses (i=1 to 3) and hydrostatic stress
$\sigma_{ij}, \sigma_{\alpha\beta}$	3-D and 2-D stress tensor components
$(\sigma_{ij})_m, (\sigma_{ij})_b$	Membrane and bending components of stress
$(\sigma_{ij})_{nl}$	Non-linearly distributed components of stress

IC 1002 ACRONYMS

SDC-IC	ITER Structural Design Criteria for In-vessel Components
ASME	American Society of Mechanical Engineers
RCC-MR	French Design Code for Liquid Metal Fast Breeder Reactor
DRG	Design Requirements and Guidelines

IC 1100 GENERAL

IC 1110 INTRODUCTION - FEATURES UNIQUE TO ITER IN-VESSEL COMPONENTS

The structure and the environment of the in-vessel components of ITER have a number of unique features that require special consideration. In particular,

1. Plasma disruptions (centered disruption, vertical disruption, or Vertical Displacement Events) cause transient dynamic stresses (due to electromagnetic loads) and transient thermal stresses with extremely high heat fluxes (due to the thermal energy deposited on the first wall). However, these stresses are characterized by two important features: first, they are of short duration, and second, the high thermal stresses in a bare metal are restricted to a thin skin. The cyclic and frequent nature of disruption-induced stresses are expected to make fatigue the dominant failure mechanism for in-vessel components.
2. The first wall will experience moderate doses of high energy (14 MeV) neutrons. This irradiation has a number of effects on material properties, including:
   - embrittlement of the material (reduced ductility and fracture toughness),
   - possible swelling (depending on the temperature),
   - irradiation-induced creep,
   - time dependent material properties.

   Swelling, creep, and time dependent properties cause time-dependent stresses, but these in themselves do not require fundamental changes in the design rules when compared with existing codes. With reduced ductility, however, secondary and peak stresses become more important. Existing codes rely on sufficient ductility to simplify the analysis, ignoring secondary and peak stresses apart from their effect on strain ratcheting and fatigue. The SDC-IC includes direct limits on secondary and peak stresses that account for both the stress and strain limits of the material.
3. The geometry is non-axisymmetric:
   - The general configuration of the vacuum vessel and blanket is non-axisymmetric because of the use of double-walled and rib-reinforced structures and numerous large penetrations (ports).
   - The local configuration of the components, e.g., the shape of the modules and the arrangement of the cooling channels, is also non-axisymmetric.
   - Distribution of thermal and electromagnetic loads will also be non-axisymmetric.

   Simplified rules based on axisymmetric pipes and pressure vessels are not necessarily adequate.
4. The in-vessel components are experimental components for which no safety credit is taken. The need for performing accurate design analyses has to do with investment protection rather than public safety.

IC 1120 SCOPE

SDC-IC provides rules for the design evaluation and stress analyses of in-vessel mechanical components of ITER. These components include the first wall, the shield/blanket, and the divertor.

The purpose of these rules is to ensure that required safety margins, specified in the *PDS*[3], the *PSR*[4] and the DRG1[5] are maintained relative to the types of mechanical damage which might occur as a result of imposed loadings. The various types of damage are listed and discussed in IC 2100. The design rules to prevent the damage are listed and discussed in IC 3000 and IC 4000.

These rules do not cover measures needed to prevent other types of damage resulting, for example, from erosion or corrosion.

These rules do not cover the steps to be taken to ensure correct operation of components comprising mechanisms or moving parts (such as pumps or valves).

3 G A0 SP 2, Plant Design Specification (PDS)

4 G 81 RI 7, Plant Safety Requirements (PSR)

5 G A0 GDRD 2, Design Requirements and Guidelines, Level 1 (DRG1)

IC 2000 DEFINITIONS AND CLASSIFICATIONS

IC 2100 DAMAGES AND FAILURE MODES

IC 2110 M-type damage

"M-type damage" denotes damage in a structure which can result from the application of a steadily and regularly increasing loading, a constant loading, or the loading corresponding to the first quarter cycle of a cyclic load. M refers to Monotonic. In unirradiated structural alloys, M-type damages generally occur in a ductile mode, i.e., accompanied by significant plastic deformation. In irradiated materials, the potential for fracture modes with little or no plastic deformation increases.

IC 2111 Ductile damage modes

IC 2111.1 Immediate plastic collapse

If a structure made of an elastic and ductile material is subjected to a proportional and steadily increasing loading, initially the structure behaves elastically and the deformation is reversible. At higher loading, irreversible plastic deformations occur such that, if the loading were removed, the structure would not return to its original dimensions or shape. If the loading were continually increased, the structure would ultimately reach plastic collapse. This is an overall structural behavior, as opposed to a local material instability, as described below.

IC 2111.2 Immediate plastic instability

Immediate plastic instability is a phenomenon of material instability which, in the case of a tensile test, is called “necking.” If a structure is loaded well into the plastic regime, the response in a local region of the structure depends on its change in geometry and the strain hardening behaviour of the material. These two effects are often counteracting, i.e., any change in geometry generally tends to reduce the load carrying capability of the structure (by reduction in area for example), whereas an increase in the yield strength of the material tends to increase it. As long as the geometrical effect is dominated by the strain hardening effect, the structure deforms in a stable manner. When the geometrical effect becomes dominant, deformation becomes unstable and fracture can ensue if the loading is maintained. Necking can also be considered as a plastic strain localization phenomenon.

Plastic instability considered here is a phenomenon at the continuum level on a scale that is large compared to grain size and microstructure but small compared to the component or structure being analyzed. Plastic instability must not be confused with ductile tearing which is controlled by phenomena at the microstructural level. The latter is a form of fast fracture and must be examined separately.

IC 2112 Non-ductile damage modes

The neutron irradiation environment in ITER will create a number of potential damage or failure modes that are not considered in the fission reactor codes. These damage or failure modes will result primarily from the loss of ductility and strain hardening capability of the material that occurs when it is subjected to neutron irradiation. Further, the use of multilayer heterogeneous structures will introduce a number of potential failure modes not considered in the fission reactor codes.

IC 2112.1 Immediate plastic flow localization

In a material with very low strain hardening capability, plastic strain may not be readily homogenized, and the structure may fail by the localization of plastic flow. Plastic flow localization appears as a large strain within a narrow band, inclined at an angle to the load. It is a type of plastic instability (under load-control), precipitated by small surface notches or irregularities. Like necking, plastic flow localization is essentially a nonlinear phenomenon and must be avoided even under strain-controlled loading. This type of damage may lead to early cracking even when the material has significant local ductility as measured by reduction in area.

Both necking and plastic flow localization are affected by the strain hardening capability of a material, which is closely tied to its uniform elongation. Both appear in an irradiated material with low uniform elongation.

IC 2112.2 Immediate local fracture due to exhaustion of ductility

Reduced ductility is associated with a low elongation (strain) at rupture. This can precipitate cracking in regions of high elastic follow up or stress concentration, such as the root of a notch, where the strains may be locally high. This type of damage must be distinguished from the damage of "fast fracture" (below). Exhaustion of ductility is a limit of a continuum analysis of a homogeneous material. Fast fracture is associated with propagation of cracks.

IC 2112.3 Fast Fracture

The term "fast fracture" is used in this document to denote any fracture which initiates from an existing defect or defects under monotonic loading and is not preceded by an appreciable plastic deformation of the material. Fast fracture is generally caused by unstable propagation of a crack. Two types of fast fracture are generally considered. One occurs by ductile tearing and the other by brittle or semi-brittle tearing.

- **Ductile tearing** occurs when a small volume (process-zone) of highly stressed material at the tip of the defect fractures through plastic instability, while the bulk of the structure behaves elastically and is otherwise able to withstand the applied loadings.
- **Brittle tearing** is the result of the material cracking without detectable local plastic deformation. In reality, a certain degree of microscopic plastic deformation always precedes this type of tearing but it is usually restricted to a microscopic volume of material.

The flaws that initiate a fast fracture may or may not be present at a given position in an actual structure. The existence and distribution of such flaws are statistical phenomena. The probability of finding a flaw of critical size in the region of highest stress may be extremely low. Therefore, fast fracture is not “damage” that is predictable in a deterministic stress analysis. The discipline of fracture mechanics is used herein as protection only against low probability hypothetical flaws. The assessment of flaw tolerance gives additional assurance beyond that provided by a conventional stress analysis.

IC 2113 Thermal creep

Although inducing no immediate damage when applied, a loading can, because of creep, induce plastic material instability if maintained over a sufficiently long period of time. This type of damage is called time-dependent plastic instability. It is analogous to the immediate plastic instability (necking) described in IC 2111.2, except that it is time dependent.

Many structural materials, at relatively high ($\approx 0.5\ T_m$) homologous temperatures, experience internal damage due to thermal creep, with or without environmental interactions, by a variety of mechanisms, such as grain boundary cavitation, grain boundary oxidation, etc. Generally, the manifestation of such damage at the macroscopic level is a reduction of ductility as measured in creep rupture tests. Reduction in ductility caused by creep (under constant load or stress) can lead to time- or rate-dependent fracture. Because of potentially significant reduction in the elongation at rupture, fracture may occur even under constant strain (stress relaxation) loading before stresses can be relaxed by creep.

IC 2120 C-type damage

"C-type damage" denotes damage that results from repeated (Cyclic) application of loadings.

IC 2121 Progressive deformation (ratcheting)

If a structure is subjected to cyclic loading, the structure may show signs of permanent deformation at the end of the first cycle. During subsequent cycles, two cases may arise:

- After a few cycles, the overall permanent deformation is constant, i.e., there is no further progressive permanent deformation with cycles. If the cyclic deformation is elastic (or elasto-plastic), elastic (or elasto-plastic) shakedown is said to be achieved. The term shakedown without any qualifier is often used in the context of elastic shakedown.
- The overall permanent deformation continues to increase with every loading cycle, and the structure gradually changes from its original shape. This is called progressive deformation, or ratcheting.

IC 2122 Fatigue (progressive cracking)

IC 2122.1 Time independent fatigue

When the loading applied to a structure varies in a cyclic fashion, the material is subjected to cyclic deformation. If the number of cycles and their amplitudes are sufficiently large, they can cause the material to crack. The damage is initiated by small microscopic cracks or structural imperfections. These cracks or imperfections do not initially compromise the integrity of the structure with regard to other types of damage (e.g., M-type damage), but they may grow with repeated cycles, eventually leading to fracture.

IC 2122.2 Time dependent fatigue

If the temperature is sufficiently high, creep deformation may occur during each cycle, accelerating the appearance of cracks by the process of creep-fatigue interaction. This phenomenon is associated with thermal creep. Irradiation-induced creep, discussed in IC 2151, affects the stress-strain field but not the material damage.

Time-dependent fatigue can also be the result of interactions between fatigue or creep-fatigue with the environment, e.g., corrosion fatigue.

IC 2130 Buckling

Buckling is a phenomenon associated with compressive or shear loading of the structures. It consists of the development of deformation modes or patterns which are different in shape from those that manifest themselves at low loading levels. Typical buckling patterns include bows, bulges, or wrinkles. Buckling is a form of instability that, depending on the geometry, may result in immediate collapse or may result in a new, stable configuration. If the latter, then additional loading beyond the point of buckling can cause general instability as well as large deformation or large variations in local deformation.

Strictly speaking, buckling is not a type of damage, but its appearance generally induces damage such as elastoplastic instability, excessive deformation or fatigue. Geometrical imperfections resulting from acceptable manufacturing tolerances are likely to accelerate and aggravate buckling, particularly in shells.

IC 2131 Load-controlled buckling

Buckling is said to be load controlled if it is the result of externally imposed loads which are not reduced by the deformations associated with buckling. It is characterized by continued application of an applied load in the post-buckling regime leading to failure. An example is the collapse of a tube under external pressure. Other external (imposed displacements) or internal (temperatures) loadings may act simultaneously to modify the imposed loading leading to buckling.

IC 2132 Strain-controlled buckling

Buckling is said to be strain controlled if the externally imposed loads, whatever their intensity, cannot on their own produce it. It is self-limiting and characterized by the immediate reduction of internal, strain-controlled loads upon initiation of buckling. In all other cases, buckling is said to be load-controlled. Even though it is self-limiting, strain-controlled buckling must be avoided to guard against failure by fatigue, excessive strain (ratcheting), and interaction with load-controlled instability.

IC 2133 Time-dependent buckling

Under irradiation or at high temperatures, sustained loadings may lead to time-dependent buckling. Time-dependent changes in the material properties and the shape of the structure can cause an amplification of geometrical defects, which can cause an initially stable structure to become unstable.

IC 2140 Excessive deformations affecting functional adequacy

If a structure undergoes large deformation due to elastic, plastic, thermal creep, or irradiation-induced creep strain during operation, the functional adequacy of the component may be compromised. The maximum permissible deformation for each component should be specified in the Component Data File.

IC 2150 Irradiation effects

Neutron flux can modify a material's crystal structure by various mechanisms, such as transmutations, ion implants, atomic displacements, and lattice defects. It enhances the precipitation of impurities and phase modifications, often inducing detrimental effects on material properties. The detailed mechanisms are very complex, but, from a macroscopic viewpoint, three phenomena are important: irradiation-induced creep, swelling, and changes in material properties.

IC 2151 Irradiation- induced creep

Irradiation-induced creep, caused by atomic displacements, is similar to thermal creep in that it leads to permanent deformation of the material. However, irradiation-induced creep is widely held to be non-damaging and is not limited by ductility. Nevertheless, the strains caused by irradiation-induced creep should be taken into account. Irradiation creep strains affect the distribution of stresses, which in turn can influence other damage mechanisms such as fatigue and excessive deformation of the structure. Irradiation-induced creep may have a beneficial effect of relaxing residual or strain-controlled stresses. On the other hand, this relaxation may result in a stress reversal when thermal loadings are removed.

IC 2152 Irradiation- induced swelling

Irradiation can induce gross structural distortions by swelling in isotropic materials or by growth in anisotropic materials. This phenomenon is irreversible and may lead to high stresses when the swelling is constrained or spatially varying. Such stresses are strain controlled, and the beneficial relaxation effects of irradiation-induced creep should be considered in the calculation of the constrained swelling stresses.

IC 2153 Irradiation- induced changes in material properties

Large changes in materials properties due to irradiation can be induced by atomic displacements, nuclear transmutation, and gas formation (He). Irradiation effects in copper alloys and austenitic stainless steels include significant irradiation-induced hardening, loss of ductility, loss of strain-hardening capability, and reduction in fracture toughness at a relatively low neutron damages (displacement dose ~ 0.3 to 10 dpa).

IC 2160 Other effects

IC 2161 Elastic follow-up

It is possible for a small part of a structure to undergo inelastic deformation whereas the rest of the structure remains elastic. The bulk of the structure then acts as a spring with respect to the small inelastic part of the structure. The strain energy in the elastic structure can impose large strains on the small inelastic part, in the same manner as elastic spring-back can cause a fracture surface to separate. The "inelastic" zones can become the seats of strain concentrations likely to damage them. A classical example of elastic follow-up is that created by a pipe acting on an expansion loop when the loop is considerably more heavily stressed than the rest of the pipe.

Existing codes simplify the analysis of secondary stresses (IC 2525) and peak stresses (IC 2526) by assuming that the material is sufficiently ductile to accommodate constrained inelastic deformations (caused by secondary and peak stresses) without immediate damage. In a material with reduced ductility, such as irradiated stainless steels, elastic follow up can cause local plastic strains to exceed the ductility limit (see IC 2112.2). To account for reduced ductility, the SDC-IC explicitly accounts for elastic follow-up in the elastic analysis rules for secondary and peak stresses. This is accomplished with the aid of a parameter “r,” as described below.

The amount of elastic follow-up depends on the geometry and loading of the structure (see C 3024.1.3 of Appendix C). Its effect can be quantified using an elastic follow-up factor “r”, which is defined as the maximum in the structure of the following ratio R:

$$R = \frac{E\varepsilon - \sigma}{\sigma_{el} - \sigma}$$

where

σ_{el} = elastically calculated stress,

σ and ε = actual stress and total strain.

The value of r depends on the geometry of the structure, the material stress-strain law, and the load level. Conservative values of r can be determined in advance and then used to express the allowable stress as a function of both a stress limit and a strain limit. Methods for the determination of r are discussed in Appendix B, B 3024.1.3.

Note that the above definition of r is consistent with that used in Japanese codes but is different from the definition used in papers by Roche (he uses r* = r - 1). The above definition for elastic follow-up factor r, which has been adopted for SDC-IC, gives a simpler form of the rules.

IC 2162 Corrosion and Erosion

If the component is subject to in-service thinning resulting from surface corrosion, surface erosion, the effects of handling, or environmental conditions, the component should be protected by providing either a certain additional thickness or protective cladding or tiles. The additional thickness, called a “corrosion allowance,” compensates for thinning during the specified service life of the component. The corrosion allowance need not be the same for all areas of the component if different rates of attack are expected in different areas. The thickness remaining in the absence of the corrosion allowance is called the “minimum thickness.”

The structural analysis and the evaluation of the rules of these criteria should treat the corrosion allowance in the most conservative manner. In general, the analysis must check the behavior of the structure in both its original condition and in the condition resulting from total or partial consumption of the corrosion allowances. In practice, the nominal thickness (including corrosion allowance) shall be used for checking ratcheting and fatigue damage, and the "minimum thickness" shall be used for checking other damages, particularly the primary membrane stress limit. If local corrosion is likely to occur, the stress report must justify the thickness adopted for the analysis. The justification must include the tests conducted to ensure the non-degradation of the material.

IC 2163 Multilayer Effects

Multilayer structures are particularly vulnerable to flaws and cracks that may lead to delamination or other types of damage. The analysis of these type of structures, with or without flaws, is usually complex and currently there is no industry-wide consensus as to how these structures should be designed. Therefore, new rules for designing unflawed multilayer structures were developed and included in the current edition of the SDC-IC.

IC 2200 OPERATING CONDITIONS

During operation, a component may be subjected to various operating conditions (including loading conditions). These conditions may be classified into several categories based on various considerations, including probability of occurrence and consequences of failure. Each operating and loading condition and plausible combination thereof must be identified and classified as I (Operational), II (Likely), III (Unlikely) and IV (Extremely Unlikely) [6]. These loading classifications (I, II, III and IV) are related to criteria levels in this document, A, C and D, which are used to categorise allowable stresses and other limits that will be applied in the analysis of the respective loading conditions. The correspondence between loading conditions and criteria levels is given in IC 2220.

The list and classification of operating conditions must be defined in the Component Data Files. Each Component Data File should specify what loadings are belong to category I, II, III or IV, and which sections of SDC-IC and other codes apply to the specific component.

IC 2210 Loading considerations

There is a set of environments (pressures, forces, magnetic fields, vacuum, heat flux, irradiation, corrosion, etc.) corresponding to each operating condition. Depending on the

[6] G A0 MA 1, Load Specification and Combination (LS). Annex to DRG1

component deformation, those that produce mechanical work are referred to as loads. Sets of simultaneous loads are referred to as loadings. The general rules for specification of loading conditions for each component are given in Annex to DRG1, Load Specification and Combination (LS) [6].

IC 2211 Loads

The loads include, but are not limited to, the following:

a) Internal and external pressures (pressure, P).

b) Electromagnetic loads due to:
   - disruptions,
   - Vertical Displacement Events,
   - Magnet faults.

   These loads include reaction forces at the support points, including dynamic effects.

c) The weight of the component and its contents, and the static and dynamic loads due to its contents (fluid interaction) under each condition analyzed.

d) Forces resulting from weight, thermal expansion, pressure and dynamic loads (anchor displacements) which originate outside the zone studied and which are applied at its boundaries.

e) Loads resulting from earthquakes and consequent vibrations, if any.

f) Temperature effects, either constant or transient.

g) Irradiation-induced swelling effects.

h) Pressure of explosion, if occurs in the vacuum vessel (including dynamic effects).

IC 2220 Categories of loading conditions

The loading conditions are linked with the events category and are named the same as events specified for ITER. Rules for the specification of loading conditions or a set of loading conditions into categories are defined in the DRG1 [5] and in LS [6]. The correspondence between the loading categories used in the LS and the terminology used in the SDC-IC is shown Table IC 2220-1.

Loading Category	Category Conditions (Damage Limits)	SDC-IC Criteria Level
I Operational Loading	Normal	A
II Likely Loading	Upset	A
III Unlikely Loading	Emergency	C
IV Extremely Unlikely Loading	Faulted	D

Table IC 2220-1: SDC-IC criteria levels vs. loading categories and damage limits

The criteria levels used to evaluate the above loadings are described in IC 2300. Note that the criteria level B is missing and has been replaced with A in the above table. This is because normal and upset damages are evaluated against the same level A criteria (as explained in IC 2300).

From the safety standpoint, it is acceptable to apply level D criteria to a safety important class (SIC) component under category III loading. The component designer is always free to specify more conservative limits in the Component Specification. The component designer may choose not to accept damage for reasons other than safety.

The philosophy of the SDC-IC is more conservative than is required for safety alone. The SDC -IC requires that a loading of a given category (I and II = normal or upset condition, III = emergency condition, IV = faulted condition) must be evaluated according to criteria limit of that category or better. That is, a Category C loading must be evaluated with Level C or A criteria.

IC 2221 Normal and upset category conditions

Normal category conditions include start-up, hot standby, operation with plasma-on and plasma-off cycles, system shutdown, and any other loading which the component may be subjected in the performance of its specified service function. Upset category conditions include incidents of moderate frequency such as plasma disruptions, operator error, control malfunctions, loss of power, and any other loading which the component must withstand without damage requiring repair. The level A criteria shall be met for the normal and upset category conditions.

IC 2222 Emergency category conditions

Emergency category conditions include events which may necessitate shutdown of system and removal of the component from service for inspection or repair of possible damage to the component or support. The criteria to be met for emergency category conditions shall be at least as severe as those of level C. Unlike in the ASME code or RCC-MR, fatigue is considered as a possible damage mechanism in level C, and there is no limit on the total number of level C incidents over the life of the component.

IC 2223 Faulted category conditions

The criteria to be met for faulted category conditions shall be at least as severe as those of level D. These set of limits permit gross general deformations with some consequent loss of dimensional stability and damage requiring repair, which may require removal of the component from service.

IC 2224 Design conditions

Design loadings are simplified, envelope loadings used to quantify the capability of the component. They are used for various purposes, including the definition of test loadings (see below) and pressure relief valve settings. The specific loading parameters for design loadings shall equal or exceed those of the most severe combination of coincident pressure, temperature, and forces specified under events corresponding to normal or upset category conditions. For the design loadings conditions, the criteria to be met are those of criteria level A in IC 2320.

IC 2225 Testing conditions

Test loadings are pressure loadings which occur during hydrostatic tests, pneumatic tests and leak tests.

Test pressure shall be defined to meet the local regulation requirements.

The criteria to be met for testing loading conditions are the pressure testing limitations of IC 3230.

IC 2230 Loading history

During operation, structures are subjected to mechanical and thermal loadings which may vary periodically with time and which, consequently, can induce fatigue and progressive deformation damage (C-type damage) with or without creep. The variations of these loadings are defined in the Component Data File by a list of steady state or transient loading states. This list is used to determine the history of loading for evaluating fatigue and progressive deformation damage.

The loading history should define a variation in the loadings according to the following general scheme:

- steady state,
- variation of effects: transient condition,
- return to steady state.

Guidelines for defining the loads to be considered, the numbers of occurrences, and the way in which to combine loads in different categories are given in the Load Specification and Combination Document[6]. Guidelines for combining and counting cycles to be used in a fatigue analysis, given a random history of stress or strain, are given in B 2752.1 of Appendix B.

IC 2231 Strain cycles

Strain cycles correspond to variations in the strain tensor as a function of time. In the simplest case, strain cycles would start from an initial value and return periodically to the same initial value. In more complex cases the stress-strain state may never return to the same value, in which case algorithms are provided in B 2752.1 of Appendix B for identifying cycles. In some cases, the number of strain cycles can be deduced from the number of load cycles which cause them to occur. It should be noted that a given type of loading may result in several types of strain cycles.

In the presence of progressive deformation or cyclic hardening (or softening) prior to achieving stable cyclic state, it may not be possible to identify cycles unambiguously. In such cases, the method used to determine strain cycles shall be justified.

IC 2232 Stress cycle

The notion of stress cycle is similar to that of strain cycle, defined in IC 2231, except that the stress tensor is used instead of the strain tensor.

IC 2300 CRITERIA LEVELS

Three criteria levels are use for in-vessel components A, C, and D. The main objectives of these criteria levels are given in General Section of Structural Design Criteria for ITER (SDC-G[7]).

The specific damage prevented is listed in the following sections.

Some fission codes introduce level B criteria for upset loadings, but level B is not included in the SDC-IC for reasons that follow. For example, the ASME Code, Section III includes level B criteria that are identical to level A criteria except that the allowable primary stresses may be increased to 110% of their level A values when an Upset pressure loading exceeds the Design pressure. In ASME Code Case N-47 and in RCC-MR, there is no difference between level A and level B criteria. RCC-MR and the SDC-IC remove the distinction completely. In the case of the SDC-IC, pressure is not the dominant loading, and the Design conditions are defined to envelope the level B transients. This is a simpler and more conservative approach.

IC 2310 Design conditions criteria

(will be issued at a later date)

IC 2320 Level A criteria

The aim of level A criteria is to protect the component against the following damage:

- immediate plastic collapse,
- immediate plastic instability,
- immediate plastic flow localization,
- fast fracture,
- local fracture due to exhaustion of ductility,
- ratcheting,
- fatigue,
- thermal creep,
- buckling.

The satisfaction of level A criteria is intended to ensure the safety levels required by the DRG1 document [5] with regard to these types of damage for the specified operation throughout the life of the component.

IC 2330 Level C criteria

The aim of level C criteria is to protect the component against the same damage as level A but with lower safety margins. The safety margins are set so that local permanent deformation and small levels of overall deformation could occur, while the component is limited with reasonable confidence against the damage of immediate fracture. Consequently, it may be necessary to inspect an apparatus subjected to these types of loading before re-using it.

It is noted that contrary to RCC-MR and ASME Code Section III, level C criteria in the SDC-IC do offer protection against C-type damage. Consequently, there is no limit on the number

[7] G 74 MA 6, Structural Design Criteria for ITER, General Section.

of cycles associated with stresses corresponding to this category of loadings and which are limited only by level C criteria.

IC 2340 Level D criteria

The aim of level D criteria is to protect the component against the same M-type damage (i.e., excluding fatigue and ratcheting) as level C but with lower safety margins. The safety margins are set so that gross overall deformations could occur, although some protection is still provided against the damage of immediate fracture. It will not always be possible to return to service a component which has been subjected to a loading limited only by level D criteria.

IC 2350 Testing conditions criteria

(will be issued at a later date)

IC 2400 STRUCTURE TYPES AND DETAILS

IC 2410 General single-layer homogeneous structures

IC 2411 Continuous structures

These include single-layer structures, with or without non-structural surface protection tiles or layers (IC 2440), away from structural discontinuities (IC 2412). The stresses in such structures act over significant volumes of the structure and their average values have to be limited for protection from gross deformations and damage.

IC 2412 Structural discontinuities

A **gross structural discontinuity** is a geometric or material discontinuity which affects the distribution of stresses and/or strains throughout the entire structure thickness. Examples of gross structural discontinuities are flange-to-shell junctions, nozzles and junctions between shells of different diameters, thicknesses and materials.

A **minor or local structural discontinuity** is a geometric or material discontinuity which only affects the distribution of stresses or strains in a small part of the structure thickness. The stress distribution resulting from this type of discontinuity causes very localized deformations and has no significant effect on the overall deformation of the structure. Examples of minor structural discontinuities are small fillet radius, small attachments, and partial penetration welds.

A **geometrical discontinuity** is an area in which the radius of curvature cannot be clearly defined and can reach extremely small values making it impossible to define stresses at this point. This includes all areas of parts containing a sharp notch due to design or manufacture. An example is shown in Figure IC 2412-1. Geometrical discontinuities should be avoided in the design because they introduce stress concentrations that may be the source of premature failure, particularly through fatigue, and they invalidate the results of a conventional stress analysis. If a geometrical discontinuity is unavoidable, then the verification of the structure shall be performed using experiments and/or the principles of fracture mechanics.

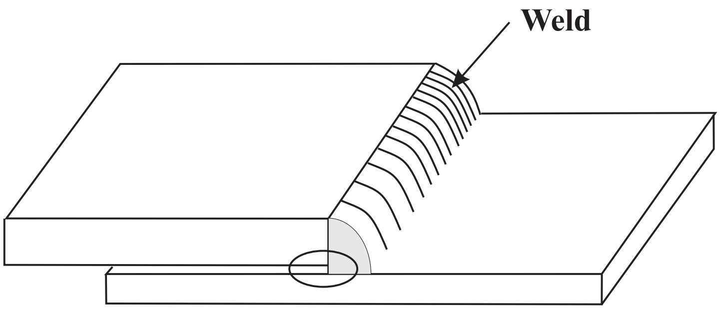


Figure IC 2412-1: Geometrical discontinuities

IC 2420 Joints

Special attention must be paid to the design, analysis and manufacture of joints assembled by welding or other bonding methods between materials which do not have the same mechanical properties.

These properties comprise thermal expansion, swelling rate, creep rate, ductility, toughness and fatigue strength. Typical examples of these types of junctions are welds between dissimilar materials, brazing, bolted flanges and other mechanical assemblies. When a joint of this type is subjected to cyclic temperature variations above and below the creep range, inelastic deformation may lead to strain concentrations close to the location of the sudden change in the mechanical properties.

IC 2421 Welded Joints

Rules for designing welded joints are given in section IC 3600. The requirements for manufacturing, assembling, and inspection of welded assemblies in the ITER in-vessel components will be developed and included in the SDC-IC in the future. In the interim, procedures such as found in RCC-MR and the ASME boiler and pressure vessel code should be adopted, as appropriate.

IC 2422 Brazed Joints

(will be issued at a later date)

IC 2423 Bolted Joints

The bolted joint should be located in regions of sufficiently low neutron fluence where irradiation-induced embrittlement is not a concern. The bolt pre-load should be sufficient to maintain a joint surface compression load during all loading conditions. Particular attention should be paid to the loss of bolt pre-load due to thermal strain, irradiation-induced creep and plastic deformation of the bolt and/or the flange due to initial pre-load and service loading.

If the bolted joint does not have a sealing function, it will primarily serve to transfer the electromagnetic loads due to plasma disruption, seismic and gravity loads and the bolt cross-sectional area will be controlled primarily by the disruption or/and seismic load. On the other hand, if the joint is required to seal a coolant pressure, a minimum bolt cross-sectional area is provided using a more conservative allowable stress to resist the hydrostatic end forces.

The initial tightening of the bolts is a pre-stressing operation, and the amount of bolt stress developed must be within proper limits to ensure, on the one hand, that it is adequate to protect against all conditions that tend to produce a leaking joint and, on the other hand, that it is not so excessive that yielding of the bolts and/or flanges can produce relaxation that can also result in leakage.

Because of the cyclic temperature and mechanical loadings expected during ITER operation, fatigue analysis of the bolts is required. The bolt pre-load acts to reduce the alternating component of stress due to externally applied forces and moments (e.g., due to coolant pressure and electromagnetic load during disruptions) without increasing the maximum stress. The pre-load should be sufficient to minimize fatigue damage. However, the alternating component of stress due to cyclic thermal loading and the high mean stress due to bolt pre-loading must be considered in the fatigue analysis.

An assessment of the fatigue damage generally requires a detailed analysis that considers the discontinuity at the interface and the flexibility of the flanges in addition to the bolts (Appendix B 3800). In this assessment, allowance must be made for the possibility of relaxation of bolt pre-load due to irradiation-induced or thermally-induced creep of the bolt or relaxation of the gasket, if any.

Seizing is potentially a problem for bolts operating in ITER environment. Seizing can be minimized by maintaining an adequate difference in hardness between the nut and the bolt (e.g., by heat treatment).

IC 2430 Heterogeneous general structures

The plasma facing components (first wall, divertor plate, etc.) of the ITER are primarily heterogeneous multilayer structures. At the present time, there is no industry wide consensus on how such structures should be designed. Therefore, new rules were developed and included in the SDC-IC to deal with the integrity of the layers. Currently, the various layers in the ITER first wall blanket modules are proposed to be joined by a hot isostatic pressure (HIP) technique. Rules pertaining to integrity (e.g., delamination) of such joints will be developed in the future on the basis of tests to be conducted under the ITER R&D program.

IC 2440 Protection Layers

The primary purpose of the protection layers (e.g., claddings, tiles, coating, etc.) provided in the ITER first wall and divertor is to reduce plasma contamination by sputtering erosion during normal operation and to reduce melting and evaporation during plasma disruptions. The protection layers can be either a low-Z material for minimising plasma contamination or a high-Z martial for increased resistance to sputtering erosion by energetic particles. A secondary purpose of the protection layer, which is of interest to structural design, is to prevent melting or other damage from occurring in the first wall structure.

No structural strength shall be attributed to the cladding or tiles for satisfying the primary stress limits. However, the presence of cladding or tiles must be considered in the thermal analysis, in the stress analysis for satisfying the secondary and peak stress limits, and in the fatigue analysis of the structure. In particular, the designer should beware of stress concentrations at discontinuities (e.g., discrete tiles and edge effects).

If the cladding or tile is of the integrally bonded type and the nominal thickness of the cladding or tile is 10% or less of the total thickness of the component, the presence of the cladding may be neglected.

Assessment of whether cracks are contained within the coating and justification that the metal substrate (the primary structure) is not affected by cracks in the coating shall be provided by the designer. Tests may be necessary to justify the last two points.

IC 2450 Attachments

Plugs, brackets, hooks, stiffeners pads and other attachments may be welded, bolted, or screwed to the internal or external component walls. The effects of attachments on thermal stresses, on stress concentrations and their possible deformation-limiting effects on pressure-retaining parts shall be taken into account when checking that the requirements of this chapter are met. A fatigue analysis of the zones affected by these attachments is essential and must be carried out in accordance with the rules of the present Design Criteria.

From a structural standpoint, it is preferable to grind off temporary attachments after they are used, but, if it is necessary to keep them for disassembly, their effects on the structural behaviour of the component must be analysed.

B 2460 Bellows

(will be issued at a later date)

IC 2500 STRESS DEFINITIONS AND CLASSIFICATIONS

To apply the present design criteria, it is necessary to define in all parts of the structure a median surface. The term “structure thickness” refers to the direction perpendicular to this surface. The concept of resolving stresses into membrane, bending, and peak stress components applies equally to all slender structures including pipes and beams. For general three-dimensional structures, the designer must use judgment to define the appropriate analog, depending on the nature of the loading and how the load is transmitted through the structure. These general principles are equally applicable to single-layer homogeneous structures as well as multilayer heterogeneous structures.

IC 2510 Breakdown of stresses (homogeneous structure)

IC 2511 Supporting line segment

In a single layer homogeneous structure, line integration through the thickness of the structure is used to resolve stresses into membrane (IC 2513), bending (IC 2514), and peak (IC 2516) components. The line along which this integration is carried out is defined as the supporting line segment. Away from discontinuities, the supporting line segment is a line perpendicular to the mid-surface of the structure, and its length is equal to the thickness of the wall. In discontinuity zones, the line support segment is the shortest line joining the two surfaces of the wall. In all cases, the length of the supporting line segment will be called h (Figure IC 2511-1). For a definition of the origin of the x_3 axis which contains the supporting line segment, see IC 2513.

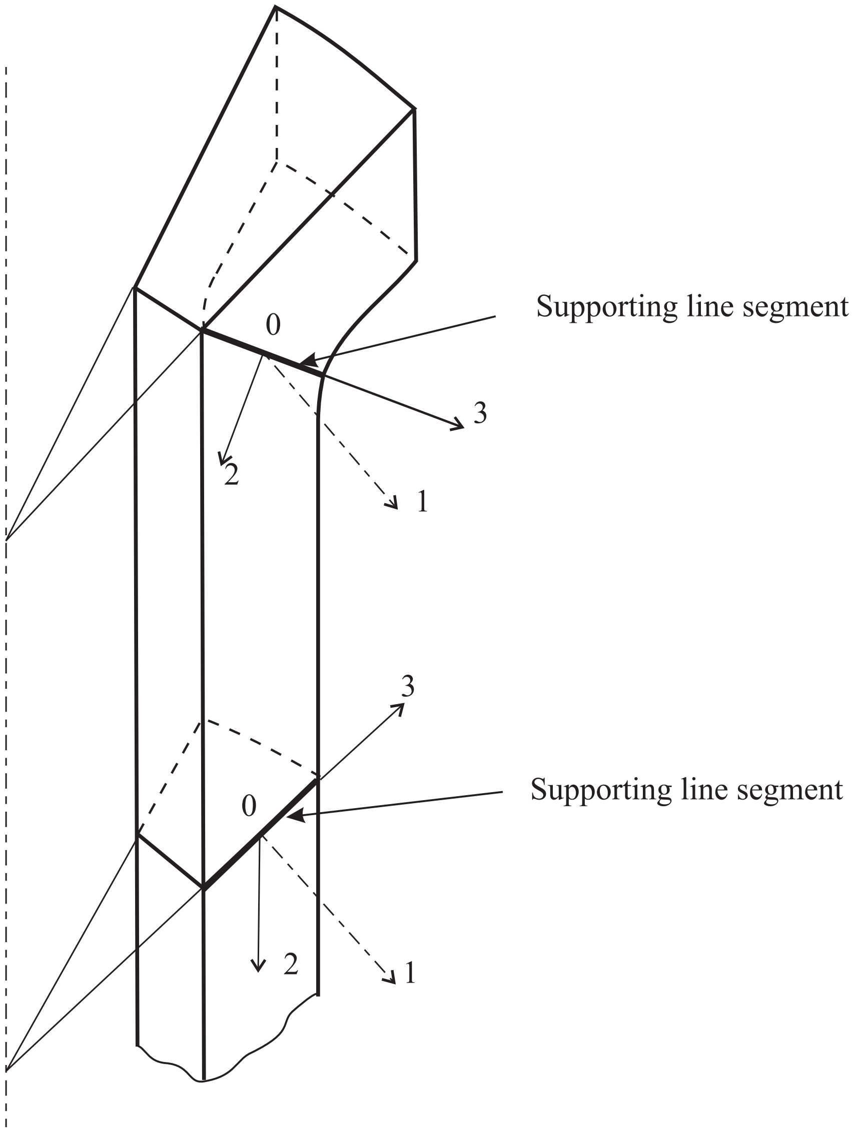


Figure IC 2511-1: Supporting Line Segment

IC 2512 Total stress

The total stress σ_{ij} is the stress value obtained at the given point under the effect of all the loadings to which the apparatus is subjected.

IC 2513 Membrane stress

Given a total stress tensor with components σ_{ij} in the Cartesian frame of reference 0123 (Figure IC 2511-1), the membrane stress tensor is the tensor whose components $(\sigma_{ij})_m$ are equal to the mean value of stresses σ_{ij} along the support line segment. For a single-layer homogeneous shell, these components $(\sigma_{ij})_m$ can be defined by the following equation:

$$\left(\sigma_{ij}\right)_m = (1/h) \int_{-h/2}^{+h/2} \sigma_{ij} \, dx_3$$

where h = thickness of shell.

The notations are given in Figures IC 2511-1 (above) and IC 2514-1 (below). Axis x_3 contains the supporting line segment of length h. The origin of axis x_3 is taken at the midpoint of the supporting line segment. The abscissa of a point of the supporting line segment is denoted by x_3. The above formula for membrane stress applies to each component of the tensor, i.e., indices i and j may assume values 1, 2, and 3.

Note: For more complex shaped cross-sections of the structure, e.g., first wall containing coolant channels running along one direction separated by regularly-spaced webs, see discussion in B 2513 of Appendix B.

IC 2514 Bending stress

Given a total stress tensor with components σ_{ij} in the Cartesian frame of reference 0123 (figure IC 2511-1), the bending stress tensor is that tensor whose components $(\sigma_{ij})_b$ vary linearly along the supporting line segment and which, when integrated along the supporting line segment, have the same bending moment as the original tensor σ_{ij}. For a single-layer homogeneous shell, the bending stress tensor is given (as a function of x_3) by the following equation:

$$\left(\sigma_{ij}\right)_b = \left(12\,x_3/h^3\right) \int_{-h/2}^{+h/2} \sigma_{ij}\; x_3\; dx_3$$

The notations are given in figures IC 2511-1 and IC 2514-1.

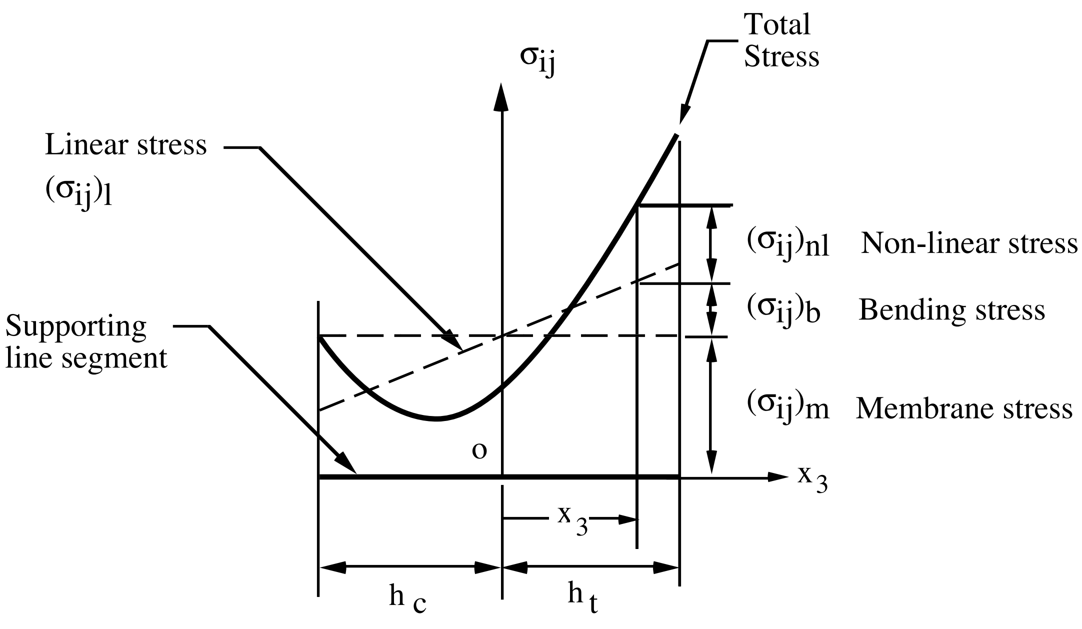


Figure IC 2514-1: Stress breakdown

Note: For more complex shaped cross-sections of the structure, e.g., first wall containing coolant channels running along one direction separated by regularly-spaced webs, see discussion in B 2513 of Appendix B.

IC 2515 Linearly distributed stress

The linearly distributed stress tensor is that portion of the total stress tensor which varies linearly along the supporting line segment. It is the sum of the membrane and bending stress tensors. Its components $(\sigma_{ij})_l$ are given (as a function of x_3) by the following equation:

$$\left(\sigma_{ij}\right)_l = \left(\sigma_{ij}\right)_m + \left(\sigma_{ij}\right)_b$$

The quantities $(\sigma_{ij})_m$ and $(\sigma_{ij})_b$ are the components of the membrane stress tensor and the bending stress tensor, respectively. $(\sigma_{ij})_m$ is a constant, and $(\sigma_{ij})_b$ is a function of x_3.

IC 2516 Non-linearly distributed stress

The non-linearly distributed stress is the difference between the total stress σ_{ij} and the linearly distributed stress $(\sigma_{ij})_l$. Its components $(\sigma_{ij})_{nl}$ are given (as a function of x_3) by the following equation:

$$\left(\sigma_{ij}\right)_{nl} = \sigma_{ij} - \left[\left(\sigma_{ij}\right)_m + \left(\sigma_{ij}\right)_b\right]$$

The quantities $(\sigma_{ij})_m$ and $(\sigma_{ij})_b$ are the components of the membrane stress tensor and the bending stress tensor, respectively. $(\sigma_{ij})_m$ is a constant, and $(\sigma_{ij})_b$ is a function of x_3.

IC 2520 Classification of stresses (elastic analysis)

If elastic analysis is to be used, the rules of this code require that the total stress be broken down into constituent parts, also known as “stress categories,” as defined in the following paragraphs. Table IC 2520, below, illustrates the breakdown. These stress categories, either alone or in various combinations, are compared with various limits in satisfying these criteria. It should be noted that, in all of these stress categories, the stress constituents are functions of position in the structure. The maximum value (at any position) of a sum of the constituents, rather than a sum of the maximums, is compared against a limit.

Total Stress σ				
Primary Stress		**Non Primary Stress**		
Primary membrane stress	**Primary bending stress**	**Peak stress**	**Secondary stress**	**Additional Local membrane stress**
P_m	P_b	**F**	**Q**	L_m

with $\sigma = P_m + P_b + Q + F$ {if $L_m = 0$}

or $\sigma = P_L + P_b + Q + F$ with $P_L = P_m + L_m$

TABLE IC 2520-1: Classification of stresses

IC 2521 Primary stress

a) Definition

The primary stress is defined as that portion of the total stress which is required to satisfy equilibrium with the applied loading and which does not diminish after small scale permanent deformation. Small scale deformation is taken to mean deformation which does not lead either to appreciable change in geometry (large displacements) or to significant stretching (large local deformation).

b) Comments

Within a structure, any stress field which balances the volumetric forces and the loads applied on the surface (mechanical loads: pressure, forces, etc.) is an upper bound to the primary stress. This property is useful in practice because the exact value of the primary stress is not always easy to determine. Thus, the upper bound will, more often than not, be used instead of the true primary stress. The exact value of the primary stress may be obtained by taking the smallest stress field which balances the forces, that is, that which leads to the lowest value of the maximum stress intensity in the structure.

When there is no risk of elastic follow-up (see IC 2161), thermal stresses are not considered as primary stresses.

In most cases, the structures under consideration are formed by thin-wall shells in which the stresses are further subdivided into membrane stresses and bending stresses, as described below.

IC 2522 General primary membrane stress: P_m

The general primary membrane stress is the thickness-averaged value of the primary stress tensor. The general primary membrane stress, defined at all points of the structure, is obtained by applying the procedure given in IC 2513 to the primary stress tensor. Because of elastic follow-up (IC 2161), and unless it can be shown that they will be relaxed after small scale yielding, it is prudent to classify all membrane stresses into this stress category.

IC 2523 Primary bending stress: P_b

Primary bending stress designates the stress distributed linearly through the thickness which has the same moment as the primary stress. The primary bending stress, defined at all points within the structure, is obtained by applying the procedure given in IC 2514 to the primary stress tensor.

IC 2524 Local primary membrane stress: P_L

A stress denoted by L_m is defined as an additional membrane stress, over and above the general primary membrane stress, that is caused by mechanical loads applied to a gross structural discontinuity (as defined in IC 2412), or simply by the presence in the structure of a gross structural discontinuity. Elastic follow-up from strains in external components should be included among the applied mechanical loads. For example, an additional membrane stress could be caused by

a. a mechanical load acting on a nozzle, or

b. the presence of a stiff support boss that creates a local stress concentration.

Generally, the additional membrane stresses are highest near the discontinuity and diminish rapidly at distances away from the discontinuity, at a scale commensurate with the size of the discontinuity.

The local primary membrane stress, P_L, is defined as the sum of the general primary membrane stress P_m and the additional membrane stress L_m:

$$P_L = P_m + L_m$$

Although it does not have all the characteristics of a primary stress, prudence dictates that this stress P_L be classified as a primary stress.

IC 2525 Secondary stress: Q

Secondary stress is that portion of the total stress (minus peak stresses, as defined below), which can be relaxed as a result of small scale permanent deformation. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can eliminate the conditions which cause the stress to occur.

The stress classification "Q" includes only the constant (membrane) and linearly varying (bending) part of the secondary stress. Q is calculated by applying the procedure of sections IC 2513 and IC 2514 to the secondary stress tensor and summing the membrane and bending parts. The non-linearly varying part of secondary stress, not included in Q, is classified as peak stress "F" (see below).

Where there is no risk of elastic follow-up (IC 2161), all thermal stresses, swelling stresses, and stresses due to imposed displacements or deformations are classified as secondary stresses. However, only a part of the mechanical stresses can be classified in this category.

The fabrication-induced residual stresses in heterogeneous multilayer structures should be considered as secondary stresses.

IC 2526 Peak stress: F

Peak stress is the increment of stress which is additive to the primary-plus-secondary stresses by reason of local discontinuities or local thermal stresses including the effects, if any, of stress concentrations. This additional stress, generally very localized and redistributed by plasticity, cannot cause an overall deformation of the structure. For ductile materials, it is objectionable only as a possible source of fatigue cracking or fast fracture damage and, at high temperature, of local cracking damage due to creep or creep-fatigue. However, for materials with reduced ductility, such as irradiated stainless steels, local cracking due to exhaustion of ductility is a possible damage mode and must be guarded against.

The following are examples of peak stress:

- the non-linear portion of the stresses distributed within the thickness (IC 2516),
- thermal stress within the stainless steel cladding of a carbon steel structure,
- certain thermal stresses which can cause fatigue but no deformation,
- stresses due to any minor discontinuity,
- skin stresses, caused by thermal shocks and, more generally, local thermal stresses.

The peak stress "F" may be calculated as the non-linearly varying part of the total stress on a cross section, using the formula in IC 2516. The constant and linearly varying portions of the total stress, not included in F, are classified as primary membrane, primary bending, or secondary stresses Q. When applying the rules for elastic analysis, F is always considered as a part of the total stress ($P_L + P_b + Q + F$), so the separation of F as a distinct component is not necessary.

IC 2530 Breakdown of stresses (heterogeneous structure)

The multilayer shell theory requires a consideration of both local stresses in each layer and global stress resultants obtained by integrating the known stress distributions through the full thickness (Fig. IC 2530-1). An orthogonal curvilinear coordinate system (x_1, x_2 and x_3) is used with the coordinates x_1-x_2 running along the midsurface of the shell (Fig. IC 2530-1). The position of a material fibre away from the midsurface is denoted by its distance x_3 from the midsurface, x_3 being positive towards the external normal. Thus, the top and bottom free surfaces of the shell element are located at x_3 = h/2 and -h/2, respectively. The layers are numbered from bottom to top, with k=1 denoting the bottom layer and k=n denoting the top layer where n is the number of layers. The thickness of the kth layer is denoted by h_k. Therefore, the total thickness of the multilayer structure is given by

$$h = \sum_{k=1}^{k=n} h_k$$

The stress distribution through the thickness of the multilayer structure is assumed to be known. It can be determined from shell theory (e.g., using multilayer shell elements in a finite element program) or by any other means. Rules for determining the various membrane and bending stress resultants on the basis of known distribution of stresses through the thickness of the shell are given in this section.

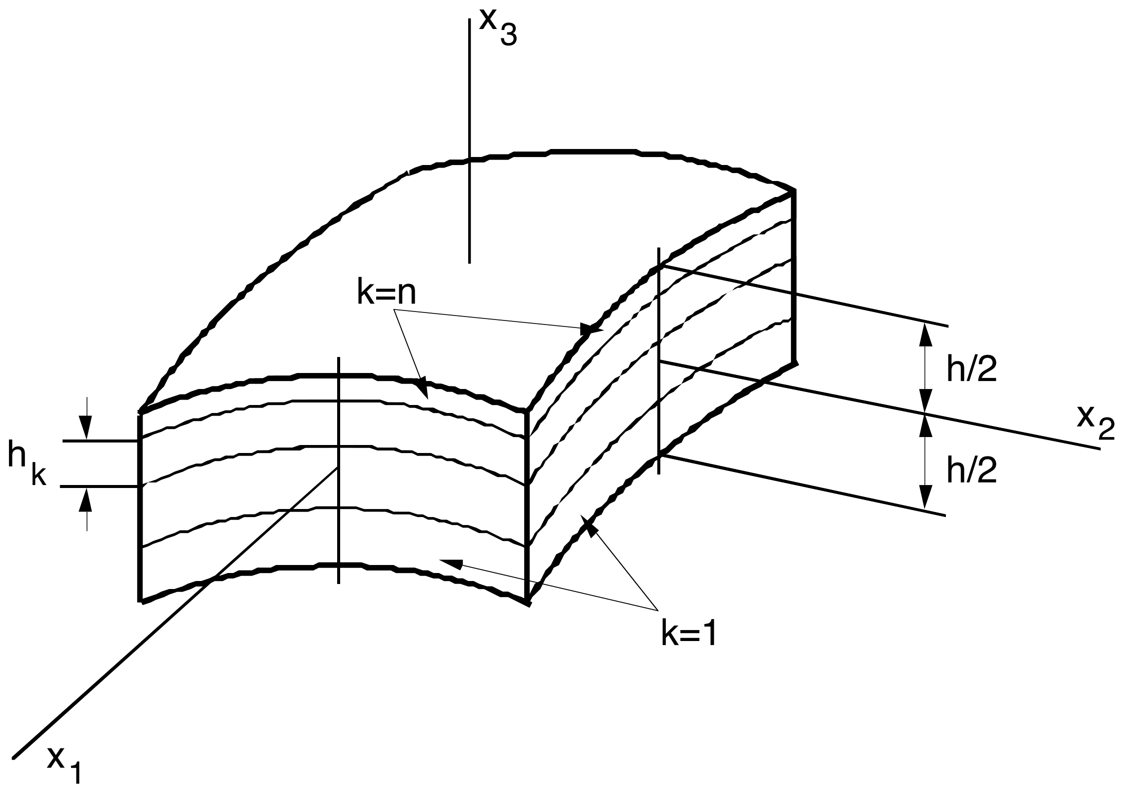


Figure IC 2530-1

IC 2531 Membrane stress resultants for multilayer structure

Given the distribution of stresses in the various layers through the thickness of the multilayer shell structure, the membrane stress resultants (Fig. IC 2531-2) are defined by the following integral:

$$N_{\alpha\beta} = \int_{-h/2}^{h/2} \sigma_{\alpha\beta} dx_3 \qquad \alpha,\beta = 1,2$$

where

$\sigma_{\alpha\beta}$ = in-plane stress tensor which varies through the thickness, and

h = total thickness of the multilayer structure

Note: For more complex shaped cross-sections of the structure, e.g., first wall containing coolant channels running along one direction separated by regularly-spaced webs, see discussion in B 2513 of Appendix B.

IC 2532 Bending stress resultants for multilayer structure

Given the distribution of the stresses in the various layers through the thickness of the multilayer shell structure, the bending stress resultants (Fig. IC 2531-2) are defined by the following integral:

$$M_{\alpha\beta} = \int_{-h/2}^{h/2} \sigma_{\alpha\beta} x_3 dx_3 \qquad \alpha,\beta = 1,2$$

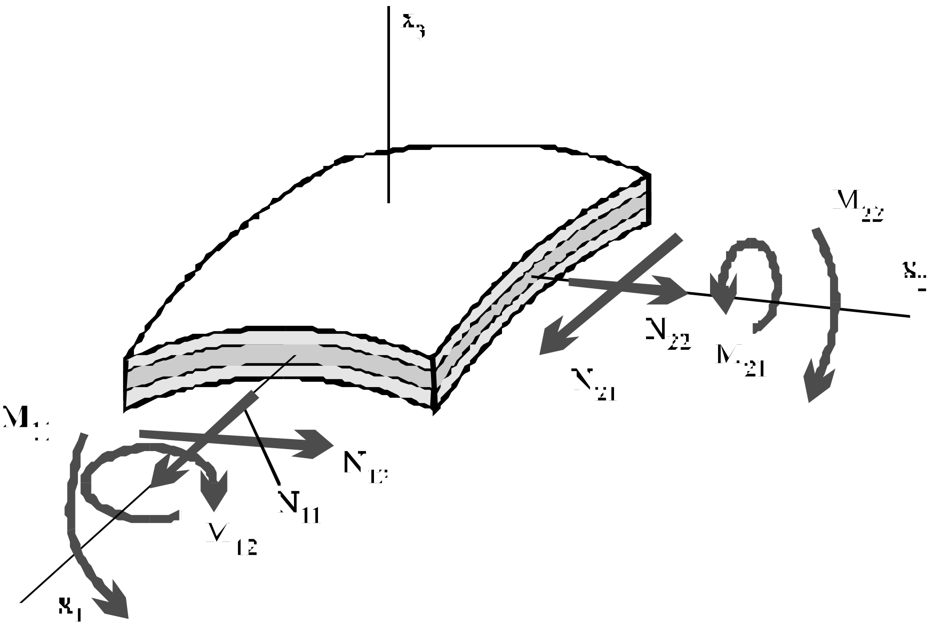


Figure IC 2531-2

Note: For more complex shaped cross-sections of the structure, e.g., a first wall containing coolant channels running along one direction separated by regularly-spaced webs, see discussion in B 2513 of Appendix B.

IC 2540 Stress Intensities / Equivalent stresses

The stress state at each point is represented by a tensor (Cartesian components σ_{11}, σ_{22}, σ_{33}, σ_{12}, σ_{23}, σ_{31} and principal components σ_1, σ_2, σ_3). This is true for the total stress as well as for the various stress categories or combinations of categories. The limits imposed on either the stress state, or its variation with time are scalar quantities. It is thus necessary to define scalar quantities corresponding to the stress state and its variation with time.

At any given point, the stress intensity, $\overline{\sigma}$, is a scalar derived from the stress tensor, σ, at that point. The stress intensity range $\overline{\Delta\sigma}$ is similarly defined from the variation of the stress tensor with time. To apply the rules of this code, the stress intensity is determined, as required, using one of the following two optional methods:

- maximum shear stress (or Tresca) method,

$$\overline{\sigma} = \max\left(\left|\sigma_1 - \sigma_2\right|, \left|\sigma_2 - \sigma_3\right|, \left|\sigma_3 - \sigma_1\right|\right)$$

where σ_1, σ_2, and σ_3 are the principal stresses

- octahedral shear stress (or von Mises) method.

$$\overline{\sigma} = \sqrt{1/2}.\left\{\left(\sigma_{11} - \sigma_{22}\right)^2 + \left(\sigma_{22} - \sigma_{33}\right)^2 + \left(\sigma_{33} - \sigma_{11}\right)^2 + 6\left(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2\right)\right\}^{1/2}$$

Details of how to apply the maximum shear stress and octahedral shear stress theories to the calculation of the stress intensity, including the calculation of the principle stresses, are described in B 2540.1 and B 2540.2 of Appendix B.

IC 2541 Hydrostatic stress (σ_H)

Hydrostatic stress is defined as the trace of the stress tensor divided by 3, i.e.,

$$\sigma_H = \frac{1}{3}\left[\sigma_1 + \sigma_2 + \sigma_3\right]$$

IC 2541.1 Triaxiality factor (TF)

The triaxiality factor **TF** is equal to the ratio of hydrostatic stress (IC 2541) to octahedral shear stress (IC 2540) normalized to unity for uniaxial loading, i.e.,

$$TF = \frac{\sqrt{2}\left(\sigma_1 + \sigma_2 + \sigma_3\right)}{\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right]^{1/2}}$$

where σ_1, σ_2 and σ_3 are the principal stresses.

IC 2542 General primary membrane stress intensity: $\overline{P_m}$

This stress intensity is evaluated in accordance with IC 2540 on the basis of the tensor of the general primary membrane stresses P_m defined in IC 2522.

IC 2542.1 Effective general primary membrane stress for multilayer structure: P_m^*

The effective general primary membrane stress in a multilayer structure, which is based on the octahedral shear stress (IC 2540) of a homogeneous shell in pure membrane loading, is defined in terms of the general primary membrane stress resultants as follows:

$$P_m^* = \frac{1}{h}\sqrt{N_{11}^2 - N_{11}N_{22} + N_{22}^2 + 3N_{12}^2}$$

where the membrane stress resultants $N_{\alpha\beta}$ (α, β =1, 2) are defined in IC 2531 and h is the total thickness.

IC 2543 Local primary membrane stress intensity: $\overline{P_L}$

This stress intensity is evaluated in accordance with IC 2540 on the basis of the tensor of the local primary membrane stresses P_L defined in IC 2524.

IC 2543.1 Effective local primary membrane stress for multilayer structure: P_L^*

The effective local primary membrane stress in a multilayer structure is defined in terms of the local primary membrane stress resultants using the same equation as given in IC 2542.1.

IC 2544 Primary membrane plus bending stress intensity: $\overline{P_{m,L} + P_b}$

Here the notation $P_{m,L}$ refers to either the general primary membrane stress tensor P_m [IC 2522] or the local primary membrane stress tensor P_L [IC 2524], whichever is applicable. P_b refers to the primary bending stress tensor [IC 2523]. The bar is placed over the entire quantity, indicating that the stress intensity is evaluated in accordance with IC 2540 on the basis of the stress tensor obtained by summing the individual stress tensors.

In a heterogeneous multilayer structure the primary membrane plus bending stress intensity for the kth layer can be obtained by translating the origin of the x_3 axis to the midsurface of the kth layer and restricting the integrals in IC 2513 and IC 2514 to the kth layer, i.e., replacing h by h_k.

IC 2544.1 Effective primary bending stress for multilayer structure: P_b^*

The effective primary bending stress in a multilayer structure, which is based on the octahedral shear stress (IC 2540) at the extreme fibre of a homogeneous shell, is defined in terms of the primary membrane and bending stress resultants as follows:

$$P_b^* = \frac{6}{h^2}\sqrt{\left(M_{11}^*\right)^2 - M_{11}^* M_{22}^* + \left(M_{22}^*\right)^2 + 3\left(M_{12}^*\right)^2}$$

where

$$M_{\alpha\beta}^* = M_{\alpha\beta} - N_{\alpha\beta}\Delta e,$$

$N_{\alpha\beta}$ and $M_{\alpha\beta}$ $(\alpha, \beta = 1, 2)$ are the primary membrane and bending stress resultants as defined in IC 2531 and IC 2532, respectively,

h is the total thickness, and

Δe = offset of the resultant force of the in-plane stresses in the various layers at collapse from the midsurface of the shell, positive if towards the top free surface. It is defined as follows:

$$\Delta e = \frac{\sum_{k=1}^{k=n}\left[S_{y,k}(T_k, \phi t_k)\left\{-\frac{h_k^2}{2} + h_k \sum_{j=1}^{j=k} h_j\right\}\right]}{h S_y^*} - \frac{h}{2}$$

where

$S_{y,k}$ is the minimum yield strength of the kth layer (IC 2721),

S_y^* is the effective yield strength of a multilayer structure (IC 2721.1),

T_k is the average temperature of the kth layer,

ϕt_k is the average fluence of the kth layer,

h is the total thickness of the multilayer structure, and

h_k is the thickness of the kth layer.

IC 2545 Primary plus secondary membrane stress intensity: $\overline{P_L (\text{or } P_m) + Q_L}$

This stress intensity is evaluated in accordance with IC 2540 on the basis of the primary plus secondary membrane stresses tensor. This is the membrane stress tensor (IC 2513) of the sum of the local primary stress tensor P_L [IC 2524] and the secondary stress tensor Q [IC 2525]. The notation Q_L refers to the membrane part of the secondary stress tensor, although Q_L does not have to be evaluated separately.

IC 2546 Primary plus secondary stress intensity: $\overline{P_L (\text{or } P_m) + P_b + Q}$

This stress is evaluated in accordance with IC 2540 on the basis of the primary plus secondary stresses tensor. This tensor is equal to the sum of the tensors of the local primary membrane stress, the bending stress, and the secondary stress.

IC 2547 Total stress intensity: $\overline{P_L + P_b + Q + F}$

This stress intensity is evaluated in accordance with IC 2540 on the basis of the total stress tensor defined in IC 2512. The total stress tensor, by definition, is equal to the sum of the tensors of the local primary membrane stresses, the primary bending stresses, the secondary stresses and the peak stresses. If a finite-element analysis is used, the total stress is known directly. The breakdown is not needed to calculate it.

IC 2550 Stress intensity ranges / Equivalent stress ranges

Analogous to the stress intensity, the stress intensity range at any point in the structure must be determined in order to check the rules for C-type damage for time varying (e.g., cyclic) stresses.

In the simplest possible case, if the components of the stress tensor vary during the cycle in direct proportion to a time-dependent scalar parameter P, then the stress intensity range $\overline{\Delta\sigma}$ can be calculated from a reference value of the stress intensity $\bar{\sigma}_{ref}$ and the range of the scalar parameter:

$$\overline{\Delta\sigma} = \frac{\bar{\sigma}_{ref}\left(P_{max} - P_{min}\right)}{P_{ref}}$$

where

P_{ref} = a reference value of the parameter P,

$\bar{\sigma}_{ref}$ = the stress intensity corresponding to P_{ref},

P_{max} = the maximum value of P during the cycle, and

P_{min} = the minimum value of P during the cycle.

A more general procedure, to be used when the variation of the stress tensor is not so simple, is given below:

- Calculate the time history of the stress tensor
- Subdivide the time history into cycles (Appendix B 2752.1)
- Within a cycle, calculate the tensor differences between the stress tensors σ(t) and σ(t') for every pair of times t and t'.
- Calculate the stress intensity of the tensor differences.
- The stress intensity range the maximum for all pairs of times t and t', of the stress intensity of the tensor differences.

The stress intensities in question can be calculated in accordance with one of the following two optional methods:

- maximum shear stress (or Tresca) method
- octahedral shear stress (or von Mises) method

Details of how to apply the maximum shear stress and octahedral shear stress theories to the calculation of the stress intensity range are described in B 2550.1 and B 2550.2 of appendix B.

IC 2551 Range of secondary stresses: $\overline{\Delta Q}$

This stress intensity range is evaluated in accordance with IC 2550 on the basis of the secondary stress tensor defined in IC 2525.

IC 2552 Range of primary and secondary stresses: $\overline{\Delta(P_L + P_b + Q)}$

This stress intensity range is evaluated in accordance with IC 2550 on the basis of the stress tensor equal to the sum of the local primary membrane stresses, the primary bending stresses, and the secondary stresses defined in IC 2522, IC 2523, IC 2524, and IC 2525.

IC 2553 Range of total stresses: $\overline{\Delta(P_L + P_b + Q + F)}$

This stress intensity range is evaluated in accordance with IC 2550 on the basis of the total stresses tensor defined in IC 2512. The total stress tensor, by definition, is equal to the sum of the tensors of the local primary membrane stresses, the primary bending stresses, the secondary stresses and the peak stresses. If a finite-element analysis is used, the total is known directly. The breakdown is not needed to calculate it.

IC 2600 STRAIN DEFINITIONS AND CLASSIFICATIONS

IC 2610 Breakdown of strain components (homogeneous structure)

The local strain at a point is represented by a tensor, e, which is henceforth called the total strain tensor. The components of this tensor are denoted by e_{ij}. The shear components of e must not be confused with "engineering shear strains" γ_{ij} ($\gamma_{ij} = 2\ e_{ij}$, $i \neq j$). The strain tensor has nine components, whereas the engineering strain has six components that are treated as a vector.

IC 2611 Total strain

The total strain corresponds to the total deformation from all the loadings to which the apparatus is subjected, including mechanical, thermal expansion, swelling, and creep. The total strain tensor, denoted by e, corresponds to the total stress (IC 2530.2).

IC 2612 Reduced strain

The reduced strain tensor is equal to the total strain tensor minus the swelling strain and the thermal expansion strain tensors. The reduced strain tensor is denoted by ε and in this code, henceforth, it is abbreviated to the term "strain tensor". Since thermal and swelling strains are not by themselves damaging, damage is correlated to the reduced strain alone.

The reduced strain tensor is the sum of the elastic, plastic, and creep strain tensors.

IC 2613 Membrane strain

The membrane strain tensor ε_m is the tensor whose components $(\varepsilon_{ij})_m$ are equal to mean value along the supporting line segment of the components ε_{ij} of the strain tensor. The components $(\varepsilon_{ij})_m$ for a single layer homogeneous shell are defined by the following equation:

$$\left(\varepsilon_{ij}\right)_m = (1/h) \int_{-h/2}^{+h/2} \varepsilon_{ij}\ dx_3$$

where h= thickness of shell

The notations are identical to those of figures IC 2511-1 and IC 2514-1 except that σ is replaced by ε. The origin of the x_3 axis is determined in the same way as that for the membrane stress, discussed in IC 2513.

Note: For more complex shaped structures, see discussion on membrane stress in B 2513 and define membrane strains by analogy.

IC 2614 Bending strain

The bending strain tensor ε_b is defined as that portion of the total strain tensor ε_{ij} whose components $(\varepsilon_{ij})_b$ vary linearly along the supporting line segment and which have the same first moments as the total strain tensor. By analogy with IC 2514, the bending strain tensor for a single-layer homogeneous shell is given (as a function of x_3) by the following equation:

$$\left(\varepsilon_{ij}\right)_b = \left[\frac{12 x_3}{h^3}\right] \int_{-h/2}^{+h/2} \varepsilon_{ij}\ x_3\ dx_3$$

The notations are identical to those of figures IC 2511-1 and IC 2514-1, except that σ is replaced by ε.

Note: For more complex shaped structure, see discussion on bending stress in B 2514 and define bending strains by analogy.

IC 2615 Non-linearly distributed strain

The non-linearly distributed strain is the difference between the total stain ε_{ij} and the linearly distributed portion of the strain. Its components $(\varepsilon_{ij})_{nl}$ are given (as a function of x_3) by the following equation:

$$\left(\varepsilon_{ij}\right)_{nl} = \varepsilon_{ij} - \left[\left(\varepsilon_{ij}\right)_m + \left(\varepsilon_{ij}\right)_b\right]$$

The quantities $(\varepsilon_{ij})_m$ and $(\varepsilon_{ij})_b$ are the components of the membrane strain tensor and the bending strain tensor, respectively. $(\varepsilon_{ij})_m$ is a constant, and $(\varepsilon_{ij})_b$ is a function of x_3.

IC 2616 Significant strains ($\not\varepsilon$):

a) The significant mean strain $\not\varepsilon_m$ is the greatest positive principal strain of the membrane strain tensor ε_m defined in IC 2613.

b) The significant linear strain is the greatest positive principal strain of the tensor equal to the sum of the membrane strain ε_m and bending strain ε_b tensors defined in IC 2613 and IC 2614.

c) Significant strain $\not\varepsilon$ is the greatest positive principal strain of the reduced strain tensor (IC 2612).

IC 2620 Breakdown of strain components (heterogeneous multilayer structure)

IC 2621 Effective membrane strain for multilayer structure

Given the distribution of strains in the various layers through the thickness of the multilayer shell structure, the effective membrane strains are defined by the following integral:

$$\left(\varepsilon_{ij}\right)_m^* = (1/h) \int_{-h/2}^{+h/2} \varepsilon_{ij} \, dx_3$$

where h= total thickness of shell

IC 2622 Effective bending strains for multilayer structure

Given the distribution of the strain in the various layers through the thickness of the multilayer shell structure, the effective bending strains are defined by the following integral:

$$\left(\varepsilon_{ij}\right)_b^* = \left[\frac{12 x_3}{h^3}\right] \int_{-h/2}^{+h/2} \varepsilon_{ij} \, x_3 \, dx_3$$

IC 2623 Effective significant strains ($\not\varepsilon^*$) for multilayer structure

a) The effective significant mean strain $\not\varepsilon_m^*$ is the greatest positive principal strain of the effective membrane strain tensor ε_m^* defined in IC 2621.

b) The effective significant linear strain is the greatest positive principal strain of the tensor equal to the sum of the effective membrane strain ε_m^* and effective bending strain ε_b^* tensors defined in IC 2621 and IC 2622.

IC 2625 Equivalent strain ($\bar{\varepsilon}$)

Equivalent strain is a scalar measure of the strain (plastic or total) tensor which is compared with the uniaxial ductility of the material to determine if cracking due to exhaustion of ductility occurs. It is defined using the octahedral shear strain criterion as follows:

$$\bar{\varepsilon} = \frac{\sqrt{2}}{3} . \left\{ [\varepsilon_{11} - \varepsilon_{22}]^2 + [\varepsilon_{22} - \varepsilon_{33}]^2 + [\varepsilon_{33} - \varepsilon_{11}]^2 + 6\left[\varepsilon_{12}^2 + \varepsilon_{23}^2 + \varepsilon_{31}^2\right] \right\}^{1/2}$$

IC 2630 Equivalent strain range ($\overline{\Delta\varepsilon}$)

The equivalent strain range at a point is used to compute the fatigue usage fraction from a uniaxial fatigue curve and is defined using the octahedral shear strain criterion.

In the simplest possible case, if the components of the strain tensor vary during the cycle in direct proportion to a scalar parameter P, then the equivalent strain range can be calculated as:

$$\overline{\Delta\varepsilon} = \frac{\bar{\varepsilon}_{ref}\left(P_{max} - P_{min}\right)}{P_{ref}}$$

where

P_{ref} = a reference value of the parameter P,

$\bar{\varepsilon}_{ref}$ = the equivalent strain corresponding to P_{ref}, calculated according to B 2620

P_{max} = the maximum value of P during the cycle, and

P_{min} = the minimum value of P during the cycle.

A more general procedure, when the components of the strain tensor do not vary in direct proportion to a scalar, is given in B 2630 of appendix B.

IC 2700 TERMS RELATED TO LIMIT QUANTITIES

IC 2705 Stress-strain curves

IC 2705.1 Monotonic stress-strain curve

Monotonic stress-strain curves are determined from tensile tests conducted at a given temperature and strain rate and are reported as functions of strain rate, temperature, and fluence.

IC 2705.2 Cyclic stress-strain curve

Cyclic stress-strain curves are typically determined by connecting the tips of the cyclically stable stress-strain hysteresis loops at half lives of strain-controlled fatigue tests conducted at a given strain range, strain rate, temperature, and fluence. If cyclic stability is not achieved during the tests, the cyclic stress-strain curves corresponding to half lives are often reported as cyclic stress-strain curves.

IC 2706 Tensile creep curves

Tensile creep curves are determined from constant-load, constant temperature creep tests. A typical experimentally determined creep curve plotted as strain against time, schematically shown in Fig. IC 2706-1, generally consists of the following stages:

(1) the loading strain, which is the combined elastic plus plastic strain on initial loading at time t=0,

(2) primary creep, which occurs at a decreasing rate with time,

(3) secondary or steady-state creep, which usually occupies the longest time during the test, and

(4) tertiary creep, which represents the final stage when creep rate increases until rupture occurs.

However, not all materials display all of the above stages. The time to rupture t_r and total creep strain at rupture ε_c are used in defining the various creep and creep rupture usage fractions (IC 2764, IC-2765, IC-2766).

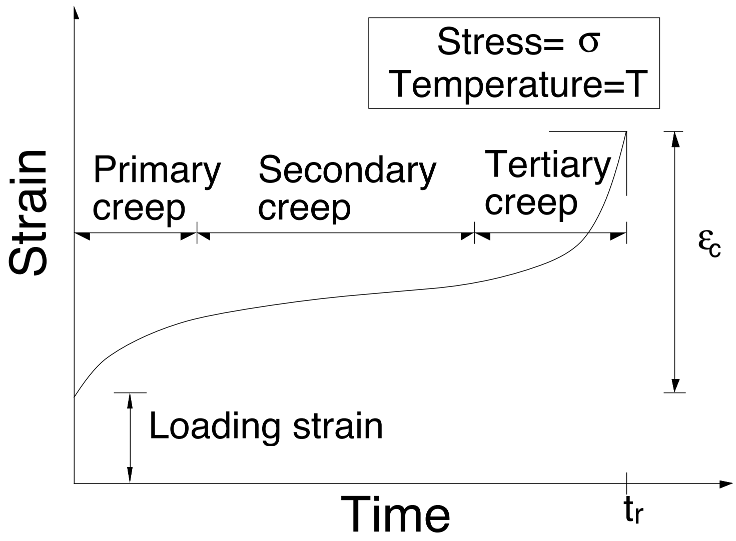


Figure IC 2706-1

IC 2707 Isochronous stress-strain curves

Isochronous stress-strain curves (Fig. IC 2707-1) are derived from tensile and creep curves at a given temperature. The purpose of the isochronous curves is to provide a general procedure for calculating either the creep strain increment at a constant stress (going horizontally) or the stress relaxation at constant strain (going vertically) from the same set of curves. This is particularly useful in creep fatigue analysis where one often has to consider stress or strain holds.

Each isochronous stress-strain curve corresponds to a given time t and temperature T. To determine the isochronous stress-strain curve at a given time t and temperature T, the following step by step approach should be followed:

- select a stress σ
- from the tensile stress-strain curve (IC 2705.1) at a temperature T and a relatively rapid strain rate (~10^{-3}/s), obtain the total strain ε_t, i.e., the sum of the elastic and plastic strain components, corresponding to a stress σ
- from a tensile creep curve (IC 2706) conducted at a stress σ and temperature T, obtain the creep strain ε_c (primary plus secondary plus tertiary creep strains but excluding loading strain at time t=0) corresponding to time t.
- add up the strain components $\varepsilon_t + \varepsilon_c$ and plot it against the stress σ
- repeat with a different stress

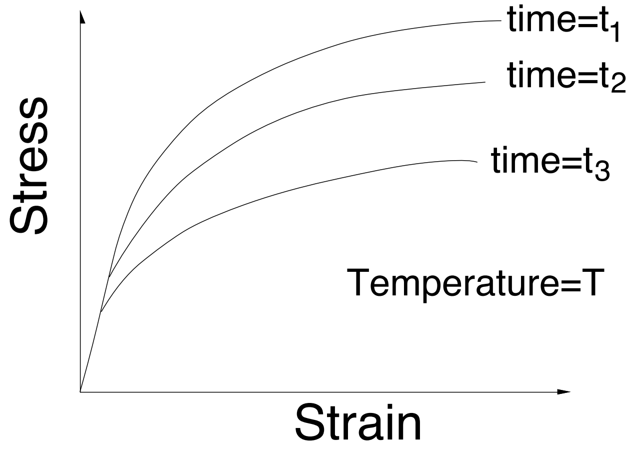


Fig. IC 2707-1

IC 2710 Nominal and minimum value

The nominal value of any mechanical property is defined as the mean value of the property.

The minimum value of any mechanical property is determined by an appropriate statistical analysis of the data such that a property value below the minimum would be unlikely. In the case of austenitic stainless steels, the minimum strength is defined as the mean minus 1.96 standard deviations, which corresponds to a 97.5% probability of a sample exceeding the minimum, given an infinite number of samples. For other materials, a different definition may be used. See Appendix A for the details of each material.

Note that the definition of minimum strength as a function of temperature used in the ASME code is based on passing a trend curve through the specified minimum strength at room temperature such that the ratio of the mean to the minimum is a constant along the curve. The approach used here, based on RCC-MR, is to use an appropriate statistical analysis of the data, without being specific and without tying the definition to a material specification. The intent is the same, but the RCC-MR approach provides more flexibility.

IC 2720 Terms related to stress limits

IC 2721 Nominal and minimum yield strength $\left(S_y, S_{y,min}\right)$

The 0.2% offset yield strength is determined in a uniaxial tension test at a given temperature and at a given strain rate, specified as a time-dependent function of neutron fluence. Nominal and minimum are defined in IC 2710 and tabulated for all materials in A.MAT.3.2 of Appendix A.

IC 2721.1 Effective yield strength for multilayer structure S_y^*

The effective yield strength for a multilayer structure is the average through the thickness of the minimum yield strengths of all the layers. It is defined as follows:

$$S_y^* = \frac{1}{h}\sum_{k=1}^{k=n}\left[h_k S_{y,k}(T_k, \phi t_k)\right]$$

where

h = total thickness of multilayer structure,

h_k = thickness of kth layer,

$S_{y,k}(T_k, \phi t_k)$ = minimum yield strength at the average temperature and fluence of the kth layer,

T_k is the average temperature of the kth layer, and

ϕt_k is the average fluence of the kth layer.

IC 2722 Nominal and minimum ultimate tensile strength $\left(S_u, S_{u,min}\right)$

The engineering stress at the point of maximum load in a uniaxial tension test at a given temperature and at a given strain rate, specified as a time-dependent function of fluence. Nominal and minimum are defined in IC 2710 and tabulated for all materials in A.MAT.3.3 of Appendix A.

IC 2722.1 Effective ultimate tensile strength for multilayer structure (S_u^*)

The effective ultimate tensile strength for a multilayer structure is the average through the thickness of the minimum ultimate tensile strengths of all the layers. It is defined as follows:

$$S_u^* = \frac{1}{h}\sum_{k=1}^{k=n}\left[h_k S_{u,k}(T_k, \phi t_k)\right]$$

where

h = total thickness of multilayer structure,

h_k = thickness of kth layer,

$S_{u,k}(T_k, \phi t_k)$ = minimum ultimate tensile strength at the average temperature and neutron fluence of the kth layer,

T_k is the average temperature of the kth layer, and

ϕt_k is the average neutron fluence of the kth layer.

IC 2723 Allowable primary membrane stress intensity (S_m)

Materials other than bolts

S_m is a temperature (T) and neutron fluence (Φt) dependent allowable stress intensity defined as the least of the following quantities for all metallic materials except bolts:

Materials other than annealed Austenitic stainless steels	**Annealed Austenitic stainless steels**
1/3 $S_{u,min}$(RT, 0)	1/3 $S_{u,min}$(RT, 0)
1/3 $S_{u,min}$(T, 0)	1/3 $S_{u,min}$(T, 0)
1/3$S_{u,min}$(T, Φt)	1/3$S_{u,min}$(T, Φt)
2/3 $S_{y,min}$(RT, 0)	2/3 $S_{y,min}$(RT, 0)
2/3 $S_{y,min}$(T, 0)	0.90 $S_{y,min}$(T, 0)
2/3$S_{y,min}$(T,Φt)	0.90 $S_{y,min}$(T, Φt) for $S_u/S_y \geq 2.0$, 2/3$S_{y,min}$(T,Φt) for $S_u/S_y < 2.0$

If the material is susceptible to softening due to thermal aging, fully softened values of the strength quantities should be used in above. Note that if a material hardens due to irradiation, the value of S_m is controlled by the unirradiated value if the time of loading is not specified. On the other hand, if it softens due to irradiation, the value of S_m is controlled by the irradiated value.

Values of S_m for all materials are tabulated in A.MAT.5.1 of Appendix A.

In a heterogeneous multilayer structure, the allowable primary stress intensity for the kth layer, $S_{m,k}$, is determined from the tensile properties at the average temperature (T_k) and fluence (Φt_k) of the kth layer.

Bolts

For bolts, the design stress intensity S_m at any temperature is the least of the following, with credit being granted for enhancement of properties by heat treatment:

(1) Two-thirds of the specified minimum yield strength at room temperature,

(2) Two-thirds of the yield strength at temperature.

Note 1: The S_m values provided in Appendix A for the bolting materials are based on unirradiated properties and assume that bolts in ITER are located in low neutron fluence regions where irradiation effects on yield strength are small. If there is a loss of strength

>5% due to the expected fluence at the end of life, the S_m values should be reduced accordingly.

Note 2: To keep the definition of S_m for bolts consistent with those for other materials used in the SDC-IC, the S_m values for bolts listed in appendix A are twice those used in the ASME Code or RCC-MR. However, the rules are changed correspondingly to keep the allowable stress values the same.

IC 2724 Allowable primary plus secondary membrane stress intensity (S_e)

S_e is a temperature (T_m) and neutron fluence (ϕt) dependent allowable stress for the primary plus secondary membrane stress intensity $\overline{P_L (\text{or } P_m) + Q_L}$ (IC 2545) defined as follows:

$$S_e = \frac{1}{3}\left[S_{u,min}(T_m,\phi t) + \frac{E\alpha_1}{r_1}\left(\varepsilon_u(T_m,\phi t) - 0.02\right)\right] \qquad \text{if } \varepsilon_u\,(T_m,\,\phi t) \geq 2\%$$

and

$$S_e = \frac{1}{3}S_{u,min}(T_m,\phi t) \qquad \text{if } \varepsilon_u\,(T_m,\,\phi t) < 2\%$$

where

$S_{u,min}$	=	minimum ultimate tensile strength, defined in IC 2722 and given in A.MAT.3.3 of Appendix A, for the thickness averaged temperature and neutron fluence,
E	=	Young's modulus, at the thickness averaged temperature and neutron fluence, given in A.MAT.2.2 of Appendix A,.
ε_u	=	minimum uniform elongation, defined in IC 2731 and given in A.MAT.3.4 of Appendix A, for the thickness averaged temperature and neutron fluence,
T_m	=	thickness-averaged temperature,
ϕt	=	thickness-averaged neutron fluence,
α_1	=	0.5,
r_1	=	elastic follow-up factor (IC 2161).

For level A criteria, values of S_e, using a conservative value of $r_1 = 4$, for all materials are tabulated as a function of fluence and temperature in Table A.MAT.5.3 of Appendix A. Higher values may be used if a lower value of r_1 can be justified (see B 2411.3 of appendix B). The S_e values of Table A.MAT.5.3 are increased for other criteria levels by using multilplicative factors given in Table IC 3220-1. For ductile (low fluence) materials, the numerical values of S_e are usually orders of magnitude higher than the maximum stresses expected in ITER. Under these conditions, the S_e limit need not be satisfied and the Table A.MAT.5.3 in Appendix A indicates this by the entry "no limit". The S_e values are provided only for sufficiently embrittled materials for which the limits can become controlling.

IC 2725 Allowable total stress intensity (S_d)

S_d is a temperature (T_m), neutron fluence (ϕt), and r-factor dependent allowable stress for the total stress intensity, defined as follows:

$$S_d = \frac{2}{3}\left(S_{u,min}(T_m,\phi t) + \frac{E}{r}\frac{\varepsilon_{tr}(T_m,\phi t)}{TF} \right)$$

where $S_{u,min}$, E, T_m and ϕt are defined in IC 2724 and

ε_{tr} = minimum true strain at rupture, defined in IC 2732 and given in A.MAT.3.6 of Appendix A, for the thickness averaged temperature and neutron fluence,

TF = triaxiality factor, defined in IC 2541,

r = elastic follow-up factor (IC 2161). Its value is r_2 when peak stress due to stress concentration is included, $\overline{P_L + P_b + Q + F}$ (IC 2547) and r_3 when it is excluded, $\overline{P_L + P_b + Q}$ (IC 2546).

<u>Including peak stress (</u>$\overline{P_L + P_b + Q + F}$)

r_2 = Max {K_T and 4}

where K_T is the elastic stress concentration factor.

<u>Excluding peak stress (</u>$\overline{P_L + P_b + Q}$)

$$r_3 = \begin{cases} \infty \text{ for } \varepsilon_u \le .02 \quad [2\%] \\ 4 \text{ for } \varepsilon_u > .02 \end{cases}$$

where ε_u is defined in IC 2724.

Two sets of S_d allowables for criteria level A are tabulated as functions of fluence and temperature for all materials in A.MAT.5.4 of Appendix A. These sets of S_d are increased for other criteria levels by using multiplicative factors given in Table IC 3220-1. One set, corresponding to $r=r_2$, is applicable when peak stress is included in the total stress and the other, corresponding to $r=r_3$, is applicable when peak stress is excluded from the total stress. In the tables, the value of K_T is assumed equal to 4 for calculating the S_d limit for $\overline{P_L + P_b + Q + F}$. If K_T is significantly greater than 4, the designer should recalculate the allowable stresses using a higher value of r.

Note that the r-factor for thermal bending stresses can be close to 1, irrespective of the strain hardening capability of the material. Therefore, if a major component of the total stress is a secondary stress Q of the thermal bending type, the designer may be able to justify (see B 3024.1.4 of Appendix B for guidance) a lower value of r and thus use higher allowable stresses than the tabulated values.

For ductile (low fluence) materials, the numerical values of S_d are usually orders of magnitude higher than the peak stresses expected in ITER. Under these conditions, the S_d limit need not be satisfied and the Table A.MAT.5.4 in Appendix A indicates this by the entry "no limit". The S_d values are provided only for sufficiently embrittled materials for which the limits can become controlling.

IC 2726 Time-dependent allowable stress intensity (S_t)

S_t is a time-dependent allowable stress intensity for primary stresses, which accounts for certain creep effects (see below) at elevated temperature. S_t, which is applicable to constant stress and constant temperature loading, is extended to time dependent stress or temperature by means of a usage fraction U_t (see IC 2764).

S_t is a function of the time t and temperature T of the loading period. It is derived from experimentally measured tensile creep curves (IC 2706) and is defined as the least of the following:

(1) two thirds of the minimum stress corresponding to average creep rupture time t at temperature T ,

(2) 80% of the minimum stress corresponding to time t and temperature T for onset of tertiary creep,

(3) minimum stress to cause a creep strain of min[1%, ε_C/5] in time t and temperature T, where ε_C is the minimum creep ductility (IC2761).

Values of S_t for all materials are plotted and tabulated in A.MAT.5.9 of Appendix A.

IC 2730 Terms related to strain limits

IC 2731 Minimum Uniform Elongation (ε_u)

The uniform elongation is defined as the plastic component of the engineering strain at the time when necking begins. By theoretical arguments, this may be taken as the time of maximum load in a uniaxial tension test at a given temperature, strain rate, and fluence. The minimum value of the uniform elongation, as defined in IC 2710 is specified as a function of temperature, strain rate, and fluence in A.MAT.3.4 of Appendix A.

IC 2731.1 Effective uniform elongation for multilayer structure (ε_u^*)

The effective uniform elongation for a multilayer structure is the average, through the thickness, of the uniform elongations of all the layers. It is defined as follows:

$$\varepsilon_u^* = \frac{1}{h}\sum_{k=1}^{k=n}\left[h_k \varepsilon_{u,k}(T_k, \phi t_k)\right]$$

where

h = total thickness of multilayer structure

h_k = thickness of kth layer

$\varepsilon_{u,k}(T_k, \phi t_k)$ = minimum uniform elongation at the average temperature and neutron fluence of the kth layer

IC 2732 Minimum true strain at rupture (ε_{tr})

The true strain at rupture is defined as :

$$\varepsilon_{tr} = \ln\left(\frac{100}{100 - \%RA}\right) ,$$

where %RA is the reduction in area (%) as determined in a uniaxial tension test at a given temperature, strain rate, and neutron fluence. The minimum value of the true strain at rupture, as defined in IC 2710, is specified as a function of temperature, strain rate, and neutron fluence in A.MAT.3.6 of Appendix A.

IC 2740 Terms related to fracture mechanics limits

IC 2741 Minimum fracture toughness (K_C)

An elastically calculated measure of the fracture toughness of the material in the presence of a sharp flaw. Given a fracture toughness specimen with an "initial crack," which consists of a machined notch with a small fatigue crack at its tip, K_C is the stress intensity factor K corresponding to the lowest load at which the initial crack is extended by 2% of its initial length. K_C shall be specified as a function of temperature, loading rate, and neutron fluence. Unless a higher value can be justified by tests, the minimum plane strain fracture toughness under mode I (tensile) loading in a plane strain specimen, K_{IC} shall be used for K_C. Alternatively, K_{JC}, which is derived from the elasto-plastic J_{IC}, may be used for K_C. Values of K_C are given in A.MAT.5.8 of Appendix A.

IC 2742 Minimum critical J-integral (J_C)

An inelastically calculated measure of the toughness of a material in the presence of a sharp flaw, expressed in terms of the J-integral. J_C is determined by the point at which there is a marked change in slope of a plot of J vs. crack extension, signifying a transition from crack tip blunting to crack advance. J_C shall be specified as a function of temperature, loading rate and fluence. Unless a higher value can be justified by tests, the minimum J-integral under mode I (tensile) loading in a plane strain specimen, J_{IC}, shall be used for J_C. Values of J_C are given in A.MAT.5.8 of Appendix A.

IC 2750 Terms related to fatigue limits

IC 2751 Allowable fatigue cycle (N_d)

In order to design a component subjected to cyclic loading, design fatigue curves, expressed as allowable number of cycles vs. strain range, are needed. The design allowables are derived from strain-controlled fatigue tests that are normally conducted at a fixed temperature and at a fixed strain range. To derive the allowable number of fatigue cycles, a safety factor of 2 on strain range and 20 on life, whichever gives a shorter life, is usually applied to the mean of the fatigue life data. The allowable number of cycles (N_d) as functions of strain range and temperature are plotted as graphs and also tabulated in A.MAT.5.5 and A.MAT.5.6 of Appendix A.

IC 2752 Fatigue usage fraction V

Design fatigue curves provided in appendix A were derived from uniaxial fatigue tests conducted at a fixed strain (or stress) range at a fixed temperature. A typical component, on the other hand, experiences variable strain (or stress) cycles at variable temperatures. The concept of fatigue usage fraction provides an analytical means of calculating the damage due to such a generalised loading. It is based on Miner's linear damage rule which can be simply stated as follows:

- if the loading can be divided into M-types of cycles and the jth (j = 1 to M) type of cycle consists of n_j number of cycles at a fixed strain range $\overline{\Delta\varepsilon_j}$ and a maximum temperature T_j, and mean neutron fluence ϕt_j during the cycle j,
- if the number of allowable cycles under a fixed strain range $\overline{\Delta\varepsilon_j}$ at a fixed temperature T_j and fixed neutron fluence ϕt_j is N_j (Fig. IC 2752.1),
- then the fatigue usage fraction V_j for the jth type of cycles is defined by n_j/N_j,
- and the cumulative fatigue usage fraction is given by the following sum:

$$V = \sum_{j=1}^{M} V_j = \sum_{j=1}^{M} \left(n_j / N_j \right)$$

In a design application, more than one type of strain cycle may occur during any one type of loading variation, e.g., multiple vibrations caused by a dynamic load. All strain cycles must be taken into account when evaluating the cumulative fatigue usage fraction V. Procedures for combining cycles are discussed in B 2752.1. Miner’s rule states that the design lifetime is exhausted when V = 1.0 (failure would be predicted with nominal data).

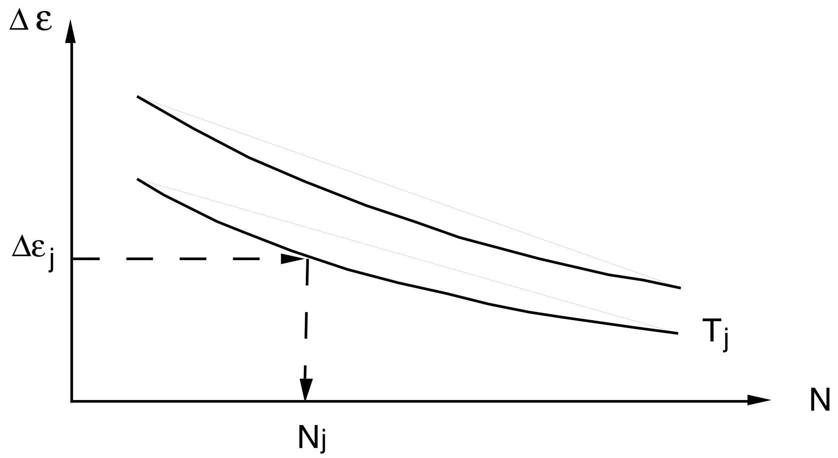


Figure IC 2752-1: Fatigue Curve

IC 2753 Fatigue strength reduction factor (K_f)

Fatigue strength reduction factor is an effective strain concentration factor which accounts for the effect of a local structural discontinuity (stress concentration) on the fatigue strength. In the absence of experimental data, the theoretical elastic stress concentration factor may be used. For bolts or other threaded members, unless it can be shown by tests or analysis that a lower value is appropriate, the fatigue strength reduction factor shall not be less than 4.

Note: The fatigue strength reduction factor is applied on the strain range and not on the fatigue life.

IC 2760 Terms related to creep limits

IIC 2761 Minimum creep ductility (ε_c)

Creep ductilities are the total elongations at rupture determined from uniaxial tensile creep tests (IC 2706) conducted under a constant temperature and constant load conditions.

IC 2762 Minimum true strain at rupture for creep (ε_{ctr})

The true strain at rupture for creep is defined as :

$$\varepsilon_{ctr} = \ln\left(\frac{100}{100 - \%RA}\right) ,$$

where %RA is the reduction in area (%) as determined in a uniaxial tensle creep test at a given temperature, load, and fluence. The minimum value of the true strain at rupture for creep, as defined in IC 2710, is specified as a function of temperature, stress, and neutron fluence in A.MAT.3.6 of Appendix A.

IC 2763 Average and minimum time to creep rupture (t_r, $t_{r,min}$)

Time to rupture curves are determined from uniaxial tensile creep tests (IC 2706) conducted under a constant temperature and constant load conditions. The same curves are also referred to as stress rupture curves S_r.

IC 2764 Creep usage fraction for primary stress, (U_t)

The creep usage fraction for primary stress, U_t, provides a means of generalising the use of S_t (IC 2726) (which is applicable to a constant-stress, constant-temperature loading) to cases in which the stress or temperature depends on time. S_t, in turn, provides a safety margin against the following effects of thermal creep:

- creep rupture
- onset of tertiary creep
- creep strains exceeding a given amount

See IC 2726 for details of the definition of S_t. At any point in a component, the creep usage fraction U_t is computed and compared with limits imposed by IC 3521.1.

The creep usage fraction U_t can be estimated by the following procedure which is applicable at a given point of the structure to any stress tensor which varies with time, with or without temperature variation.

- The operating time concerned (t) is divided into N time intervals. the time intervals must be chosen in such a way that the operating temperatures and stresses are approximately constant throughout the interval. Only time intervals for which the temperature is greater than that defined in A.MAT.4.1 (negligible creep curve) shall be used.
- For each interval j of duration t_j, the highest operating temperature T_j as well as the highest stress intensity $\overline{\sigma}_j$ reached during the interval j are calculated.

- The maximum allowable time $t_{s,j}$ at any stress $\overline{\sigma}_j$ and temperature T_j can be obtained from the S_t curves (IC 2726) given in Section A.MAT.5.9 of Appendix A, as indicated in figure IC 2764-1.
- If $t_{s,j}$ is greater than 3×10^5 hours, its value shall be determined by a linear extrapolation of the curves. The maximum extrapolation time shall be limited to three times the maximum duration time of creep tests used for obtaining the property data.
- The creep usage fraction for time interval j is equal to the ratio of application time t_j to the maximum allowable time $t_{s,j}$. The cumulated creep usage fraction U_t is the sum of the usage fractions for all N intervals, as indicated below:

$$U_t = \sum_{j=1}^{N} \left(t_j / t_{s,j}\right)$$

Since the creep usage fraction is calculated using the stress intensity $\overline{\sigma}$, it will be denoted by $U_t\ (\overline{\sigma})$.

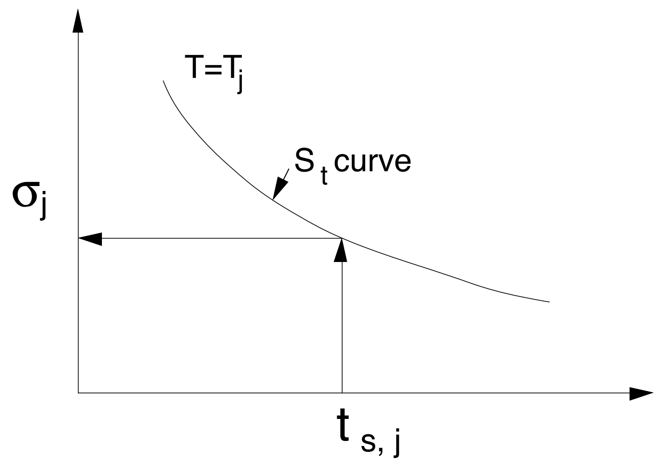


Fig. IC 2764-1

IC 2765 Creep strain usage fraction (U_ε)

The creep strain usage fraction, U_ε, is used in a ratcheting analysis (IC 3532.3) to satisfy Test No. B-1 (Bree diagram). U_ε is calculated using the following procedure:

- The operating time concerned (t) is divided into N time intervals. The time intervals must be chosen in such a way that the operating temperatures and stresses are approximately constant throughout the interval. Only time intervals for which the temperature is greater than that defined in A.MAT.4.1 (negligible creep curve) shall be used.
- For each interval k of duration t_k, calculate the highest operating temperature T_k as well as the highest stress intensity $\overline{\sigma}_k$ reached during the interval.
- Calculate the creep strain increment $\overline{\varepsilon_k}$ at a stress $\overline{\sigma}_k$ and temperature T_k during the time duration t_k. The creep strain increment for each interval can be evaluated separately as follows (see Fig. IC 2765-1):

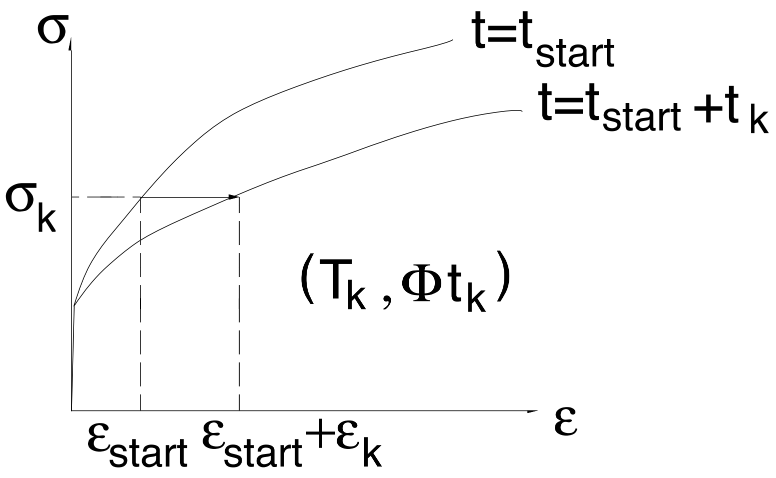


Fig. IC 2765-1

a. Select (or construct by interpolation) an isochronous stress strain curve (IC 2706.1) at temperature T_k and neutron fluence Φt_k that passes through the coordinates
(1) the initial strain accumulated throughout the prior loading history $\overline{\varepsilon_{start}}$ and
(2) the stress $\overline{\sigma}_k$ during the interval.
That point lies on an isochronous stress-strain curve corresponding to a fictitious time, t_{start}.

b. Construct a horizontal line through that point parallel to the strain axis at the given stress $\overline{\sigma}_k$. Extend this line to the right until it intersects another isochronous curve corresponding to time $t_{start} + t_k$ (use interpolation as necessary).

c. Locate the strain, $\overline{\varepsilon_{start}} + \overline{\varepsilon_k}$ corresponding to $t_{start} + t_k$.

- the maximum allowable creep strain ε_{ck} at a stress $\overline{\sigma}_k$ and temperature T_k is equal to min [1%, $\varepsilon_c/5$], where ε_c is the minimum creep ductility (IC 2761) given in section A.MAT. 3. 9 of Appendix A. Each curve gives the minimum creep ductility as a function of stress determined from tests conducted at a given temperature.
- The creep usage fraction for a time interval k is equal to the ratio of the creep strain increment $\overline{\varepsilon_k}$ to the maximum allowable creep strain ε_{ck}. The cumulative creep usage fraction based on strain fraction U_ε is the sum of the usage fractions for all N intervals, as indicated below:

$$U_\varepsilon = \sum_k \frac{\overline{\varepsilon_k}}{\varepsilon_{ck}}$$

Since the creep usage fraction based on strain fraction is calculated using the stress intensity $\overline{\sigma}$, it will be denoted by $U_\varepsilon(\overline{\sigma})$.

IC 2766 Creep rupture usage fraction (W_t)

To estimate the creep damage in a structure as a function of time, temperature, and loading, a creep rupture usage function is computed and compared with the limits imposed by IC 3521 and IC 3522. The creep rupture usage fraction at a given point of the structure is determined by the following procedure:

- the operating time (t) is divided into N time intervals,
- for each time interval k of duration t_k, the highest operating temperature T_k and the highest stress intensity $\overline{\sigma}_k$ reached during the interval k are calculated.

In order to make an accurate estimation of the creep rupture usage fraction, the time intervals must be chosen in such a way that the temperatures and stresses during the intervals are approximately constant. Only time intervals for which the temperature T_k is greater than that defined in A.MAT.4.1 (negligible creep curve) shall be used.

For calculating the creep rupture usage fraction W_t, the following steps should be followed:

- the maximum allowable time $t_{r,\,k}$ at a stress $\overline{\sigma}_k$ and temperature T_k is obtained from the minimum isothermal creep rupture curves t_r (IC 2763) given in section A.MAT.3.8 of Appendix A. Each curve gives the minimum creep rupture time $t_{r,k}$ at a given stress $\overline{\sigma}_k$ as determined from tests conducted at a given temperature T_k.

  If $t_{r,k}$ is greater than 3 x 10^5 hours, its value should be determined by linear extrapolation of the curves. The maximum extrapolation time shall be limited to three times the maximum duration time of creep tests used for obtaining the property data.
- The creep rupture usage fraction for a time interval k is equal to the ratio of application time t_k to the maximum allowable time $t_{r,k}$. The cumulative creep rupture usage fraction based on time fraction W_t is the sum of the usage fractions for all N intervals, as indicated below:

  $$W_t = \sum_k \left(t_k / t_{r,k}\right)$$

  Since the creep rupture usage fraction based on time fraction is calculated using the stress intensity $\overline{\sigma}$, it will be denoted by $W_t(\overline{\sigma})$.

Note: When the trace tr of the stress tensor is known, a more accurate (and less conservative) determination of creep rupture usage fraction can be made by replacing $\overline{\sigma}_j$ by either of the following:

NB: The trace of a stress tensor σ is the sum of the three normal components of the stress tensor, remembering that a normal stress is considered positive when it is tensile,

$$tr = \sigma_{11} + \sigma_{22} + \sigma_{33}$$

1) $\overline{\sigma}_j$ can be replaced by

$$0.867\ \overline{\sigma}_j + 0.133\ tr_j$$

2) $\overline{\sigma}_j$ can be replaced by

$$\overline{\sigma_j} \exp\left[C\left(\frac{tr_j}{S_{s_j}} - 1\right)\right]$$

where S_s is defined in terms of the principal stresses by

$$S_s = \left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2\right]^{1/2}$$

The constant C is equal to 0.24 for types 304 and 316 type stainless steels.

IC 2770 Collapse load

IC 2771 Limit analysis

The deformation of a structure made of a rigid, perfectly plastic, material increases without bound at a loading level called the collapse load. Limit analysis methods can be used to calculate the collapse load or a lower bound to the collapse load.

A given loading is less than or equal to the collapse load if there is a stress distribution which satisfies the laws of equilibrium at all points that does not violate the material yield criterion at any point. This theorem allows a lower bound to be defined for the collapse load.

In the case of elasto-plastic analysis and experimental analysis, the collapse load, by convention, is defined as the loading for which the overall permanent deformation of the structure equals the deformation which would occur by purely elastic behaviour.

IC 3000: DESIGN RULES FOR GENERAL SINGLE LAYER HOMOGENEOUS STRUCTURES

IC 3010 General

IC 3011 Scope of application

The following design rules apply to single layer homogeneous structures constructed from materials the properties of which are given in these criteria. The stress analyses required for applying the rules should be conducted using the loading data given in the component data file for the particular component and with mechanical properties and design limits for the materials given in Appendix A.

IC 3012 Purpose of the rules

The purpose of the rules is to ensure by analysis that, if the rules are satisfied, then a component does not undergo any damage beyond that described in the general criteria, IC 2300, when subjected to the categories of loadings specified in the component data file. For each category of loading condition, this requirement is satisfied by compliance with rules of the applicable criteria level, given in IC 3100 through IC 3500, at any time and at any location of the structure.

IC 3020 Methods of analysis

Analyses consist of verifying compliance with applicable rules, as described in IC 3030, which are selected on the basis of the Criteria Level, the method of analysis, and the type of damage. In the course of this verification, practical methods of analysis are used to determine significant quantities and to compare these quantities with maximum acceptable values.

Three methods of analysis are acceptable in defining the significant quantities used in the criteria:

- elastic analysis,
- inelastic analysis,
- experimental analysis

The term elastic analysis designates analyses carried out on the assumption that the material is linear-elastic and that there are no initial or residual stresses.

The term inelastic analysis designates all other methods (including elasto-plastic analysis, limit analysis, visco-plastic analysis, etc.) except for experimental analysis.

Some loadings such as electromagnetic loading during plasma disruptions (categories II or III events) or/and earthquake are generally dynamic in nature. The determination of loads for components and component supports shall account for dynamic amplification of structural response, both in the component and in the system.

Experimental analysis consists of subjecting models representing the component or some of its elements to loadings in order to determine the deformation and stresses or margins with regard to the damage under study.

Guidance for conducting elastic and inelastic analyses are given in appendix B 3020. The definition and computation of limit quantities are given in IC 2700. An overview of the relationship between rules and failure modes and of the flow of structural evaluation is given in IC3030.

IC 3030 Applicable rules - Flow of analysis

The rules to be satisfied differ according to:

- the level of criteria: A, C, or D,
- the method of analysis: elastic, inelastic, or experimental,
- the damage envisaged: M-type damage, C-type damage, buckling, or excessive deformation affecting functional adequacy,
- the temperature experienced by the component : absence (low temperature) or presence (high temperature) of thermal creep effects.

These rules (or their limits) also depend on three factors: temperature, time (or neutron damages), and possibly neutron flux. First, they depend upon temperature because material properties (allowable stresses, fatigue curves, etc.) are often temperature-dependent. Second, they depend upon time or neutron fluence because of material phenomena including thermal creep (time dependent, negligible at sufficiently low temperatures), irradiation induced creep or swelling (fluence dependent) and variations of material properties with fluence. Fluence-dependent material properties are transformed to time-dependent stresses and strains in the analysis. A dependence on the neutron flux or its spectrum may exist in the material property correlations.

The test given in IC 3050 defines the condition for the absence of significant thermal creep. Under these conditions, (1) the effects of thermal creep in stress analysis can be neglected and (2) only the low temperature design rules (IC 3100-3422) need be satisfied. On the other hand, if the negligible creep test is not satisfied, then (1) the effects of thermal creep in stress analysis must be considered and (2) only the high temperature design rules (IC 3500-3540) need be satisfied.

Since irradiation-induced creep at low temperatures is widely held to be non-damaging, no specific rule is proposed to limit its value. However, if irradiation-induced creep is significant, its effects on stress, strain, and displacement must be considered. Most analysis for ITER will be conducted on the assumption of infinitesimal strain and displacement. The designer should use judgement to ensure that this assumption is reasonable. A test to determine whether finite deformation effects (due to irradiation-induced creep and swelling) should be considered in the analysis is given in B 3021 of Appendix B.

ITER operating conditions are expected to cause negligible swelling in the structural components. A negligible swelling test is provided in B 3022 to verify that swelling effects are indeed negligible. If not, the designer should use judgement in deciding whether swelling-induced stress should be considered in the analysis. Even a large swelling strain does not necessrily cause any stress if it is unconstrained. On the other hand, a relatively small constrained swelling strain or swelling strain gradient (e.g., due to temperature gradient) may induce significant stresses in the structure and must be considered in the analysis. The designer may include the relaxing effects of irradiation-induced creep for calculating the swelling-induced stresses (see B 3024.1.1.1 of Appendix B for guidance on swelling-induced stress).

A flow chart for satisfying the design rules is given in Figure IC 3030-1, below. A flow chart for satisfying the low-temperature design rules for a given operating condition is given in Figure IC 3030-2.

[high temperature rules – will be prepared at a later date]

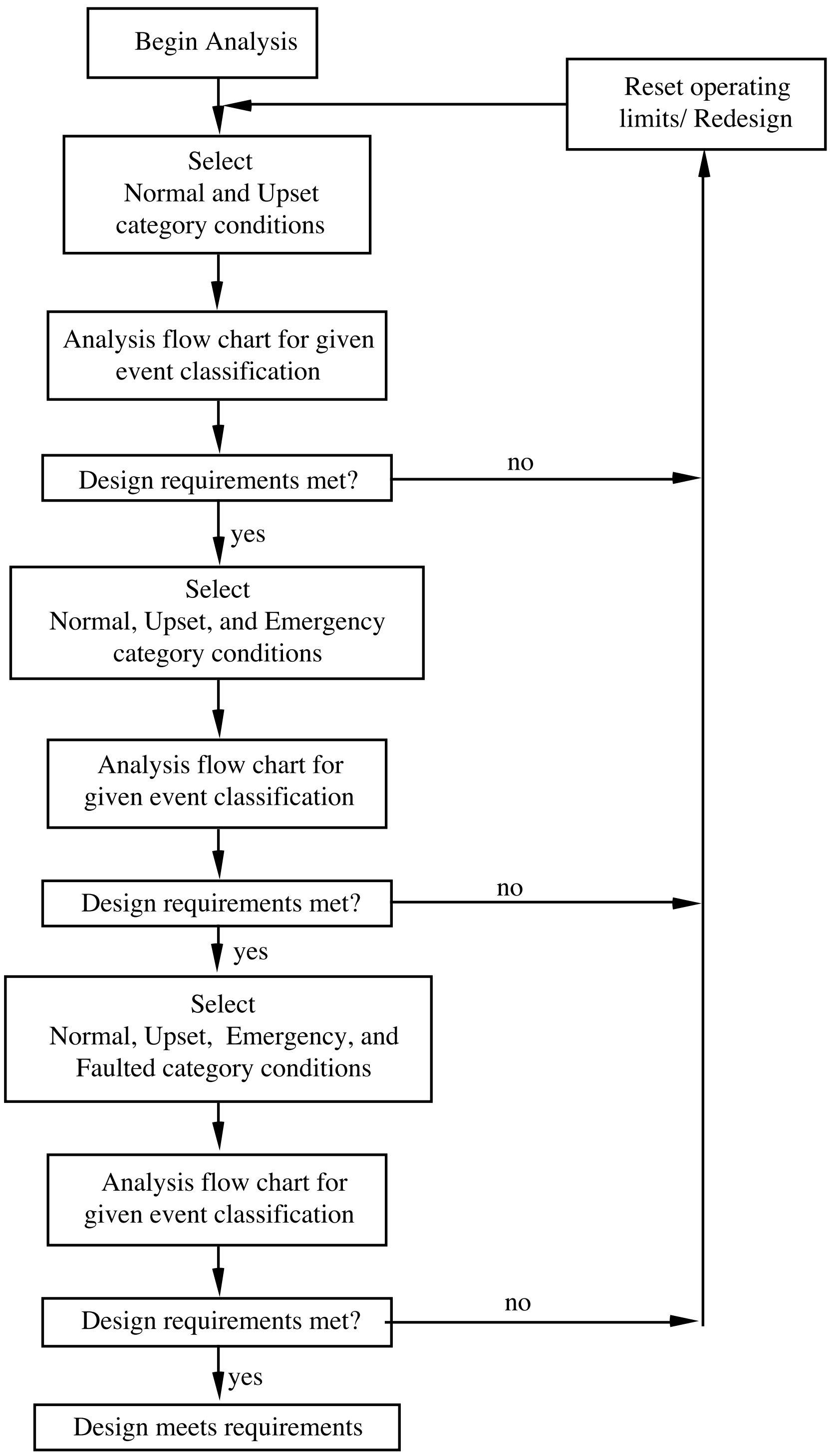


Figure IC 3030-1: Design flowchart for various operating conditions

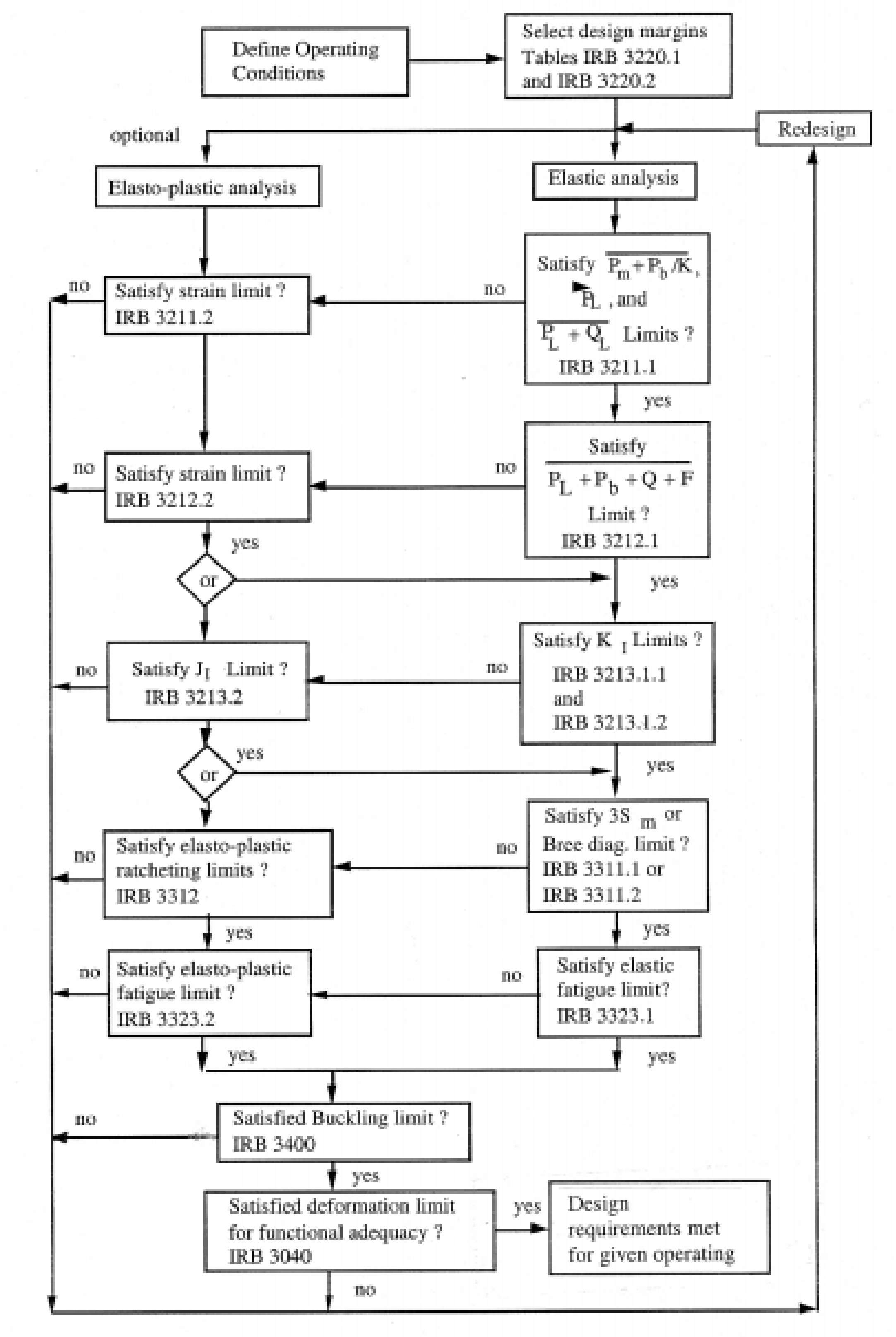


Figure IC 3030-2: Analysis flow chart for satisfying low temperature design rules for given operating conditions

IC 3040 Rules for the prevention of excessive deformations affecting functional adequacy

Any deformation limits specified in the component specification for all specified service loadings shall be satisfied. Proper account must be taken of the effects of irradiation-induced creep and swelling on deformations, if they are deemed to be significant. Guidelines for determining when such effects are negligible are given in B 3022 and B 3101 of Appendix B.

IC 3050 Negligible thermal creep test

For a component or a part of a component, thermal creep is negligible over the total operating period if the following summation limit is satisfied.

- The total operating period is divided into N intervals of time. For each interval i, of a duration t_i, the maximum temperature reached is noted T_i,

$$\sum_{i=1}^{N} \left(\frac{t_i}{t_{c_i}} \right) \leq 1$$

where t_{ci} is the allowable time at temperature T_i , given in A.MAT.4.1 of Appendix A.

If the conditions of the negligible thermal creep test (IC 3050) are satisfied, the applicable design rules are referred to as "low-temperature rules" and are given in IC 3100-3400.

If the conditions of the negligible thermal creep test (IC 3050) are not satisfied, the applicable design rules are referred to as "high-temperature rules" and are given in IC 3500.

IC 3100 LOW-TEMPERATURE RULES

If the conditions of the negligible thermal creep test (IC 3050) are satisfied, the following low temperature rules are applicable:

M-type damage	level A	IC 3210
	levels C and D	IC 3220
Testing conditions criteria		IC 3230
C-type damage	levels A and C	IC 3300
	level D	None
Buckling	levels A, C, and D	IC 3400

Note: At low temperatures, non-negligible time- (or fluence-) dependent strains may occur due to irradiation-induced creep, with or without swelling (see IC 3030 for guidelines on when swelling-induced stresses can be ignored). A test for determining when effects of irradiation-induced creep are negligible is given in B 3101 of Appendix B. If irradiation-induced creep is non-negligible, generally an elasto-visco-plastic analysis (see B 3024.4 of Appendix B) is needed and the limits for inelastic analysis should be satisfied. However, the designer may choose to satisfy the elastic analysis limits after accounting for time- (or rate-) dependent effects using a simplified elastic-irradiation-induced creep analysis (e.g., see B 3024.1.1 of Appendix B).

IC 3200 RULES FOR THE PREVENTION OF M-TYPE DAMAGE

The rules of this article are aimed at providing sufficient safety margins with regard to M-type damage (IC 2110), excluding buckling phenomenon (IC 2130) and excessive deformation affecting functional adequacy (IC 2140). The rules to prevent buckling and excessive deformations affecting functional adequacy are dealt with in IC 3400 and IC 3040, respectively.

The stress intensity and fracture toughness limits used in this article are:

S_m	=	allowable stress, a function of temperature and fluence, given in A.MAT.5.1 of appendix A,
$S_{y,min}$	=	minimum conventional 0.2 % offset yield strength, a function of temperature and fluence, given in A.MAT.3.2 of appendix A,
S_e	=	allowable stress (defined in IC 2724), a function of temperature and fluence given in A.MAT.5.3 of Appendix A for all materials,
S_d	=	allowable stress (defined in IC 2725), a function of temperature and fluence, given in A.MAT.5.4 of Appendix A for all materials,
K_C	=	material toughness, a function of temperature and fluence, given in A.MAT.5.8 of Appendix A,
J_{IC}	=	minimum critical J-integral under mode I, defined in IC 2742 and given in A.MAT.5.8 of Appendix A.

IC 3210 Level A criteria

At level A, the following rules for protection against M-type damage are applicable:

- immediate plastic collapse and plastic instability (IC 3211)
- immediate plastic flow localization (IC 3212)
- local fracture due to exhaustion of ductility (IC 3213)
- fast fracture (IC 3214)

IC 3211 Immediate plastic collapse and plastic instability

To prevent global fracture due to immediate plastic collapse and plastic instability, the following limits have to be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified.

Note: Either the limits based on elastic analysis or the limits based on elastic-plastic analysis need to be satisfied.

IC 3211.1 Elastic analysis (Immediate plastic collapse and plastic instability)

To apply the limits of this section, results from a linear elastic analysis of the component are needed. Expressions for the limits on different stress quantities are given below. The notation of the limits and references to the values of the limits are given in IC 3211.1.1.

IC 3211.1.1 Notations and values for elastic stress limits

In sections, IC3211.1.2 and IC3211.1.3, the notations used to express the stress limits are as follows. Values of the limits are given in the referenced sections of appendix A.

S_m = allowable stress, defined in IC 2723 and given in A.MAT.5.1 of Appendix A, for the thickness-averaged temperature and neutron fluence calculated along the supporting line segment,

$S_{y,min}$ = minimum tensile yield strength, defined in IC 2721 and given in A.MAT.3.2 of Appendix A for the thickness averaged temperature and neutron fluence,

T_m = thickness-averaged temperature,

ϕt_m = thickness-averaged neutron fluence,

R = $(R_1 + R_2)/2$,

h = $(h_1 + h_2)/2$,

h_1 and h_2 = minimum thicknesses of the zones examined,

R_1 and R_2 = minimum radii of curvature associated with the zones examined, determined at the level of the mean fibre.

IC 3211.1.2 Primary membrane and bending stress (Immediate plastic collapse and plastic instability)

$$\boxed{\overline{P_m} \leq S_m(T_m, \phi t_m)} \qquad (1)$$

$$\boxed{\overline{P_L + P_b} \leq K_{eff}\, S_m(T_m, \phi t_m)} \qquad (2)$$

where

$\overline{P_m}$ = general primary membrane stress intensity [IC 2542]

P_L = local primary membrane stress tensor [IC 2523]

P_b = primary bending stress tensor [IC 2524].

$\overline{P_L + P_b}$ = stress intensity of the sum of the tensors P_L and P_b. The tensor sum is obtained first, and then the stress intensity is calculated for the combined tensor in accordance with IC 2540.

K_{eff} = an effective bending shape factor, which accounts for the increased maximum bending moment carrying capability of an elastic-plastic material with limited ductility as compared to that of an elastic-brittle material. For unirradiated materials with unlimited ductility, $K_{eff} = K$ where K is the usual bending shape factor used in the RCC-MR and the ASME Code. Values of K for various cross-sections are given in Figures IC 3211-1 through -3. K_{eff} may be calculated from $K_{eff,rect}$, which is the K_{eff} for a solid rectangular section, using the following equation

$$K_{eff} = 1 + 2\,(K - 1)\,(K_{eff,rect} - 1)$$

Values of $K_{eff,rect}$ of a solid rectangular section, which may be reduced due to loss of ductility with irradiation, are tabulated as a function of fluence and temperature for each material in A.MAT.5.2 of Appendix A.

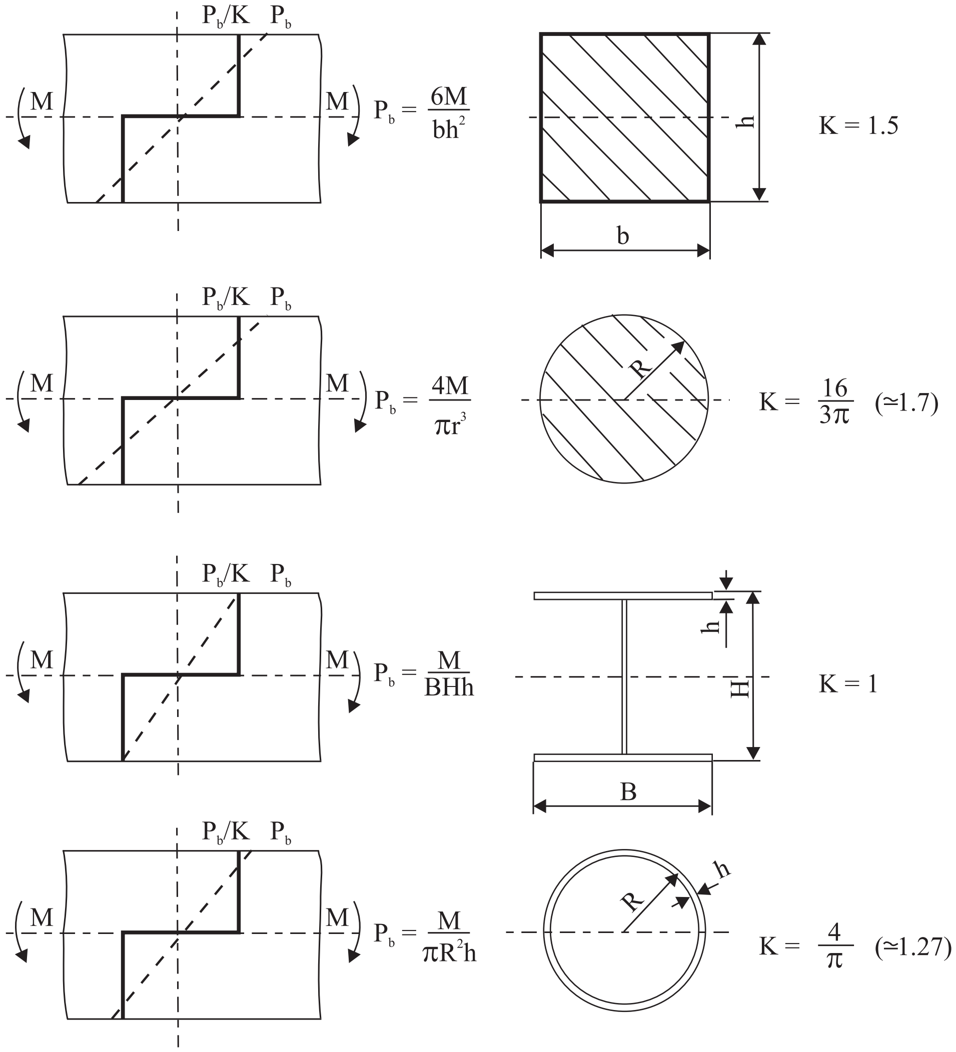


Figure IC 3211-1: Bending shape factor (K) for standard cross-sections

A cross-section of interest to ITER First Wall / Blanket, shown in Figure IC 3211-2, consists of two plates of thicknesses h_1 and h_2 separated by coolant channels of height $h_c$where h_1, h_2 and h_c are of comparable dimension. The bending shape factors for such a section (if the bending stiffness effects of the webs separating the coolant channels can be ignored, which is a conservative assumption) are given parametrically in Figure IC 3211-3.

If the two plates are separated by a large distance, (for example, as for the vacuum vessel or cryostat of ITER) the bending shape factor may be 1. See Appendix B, section B 3211.1.1, for a discussion of this geometry.

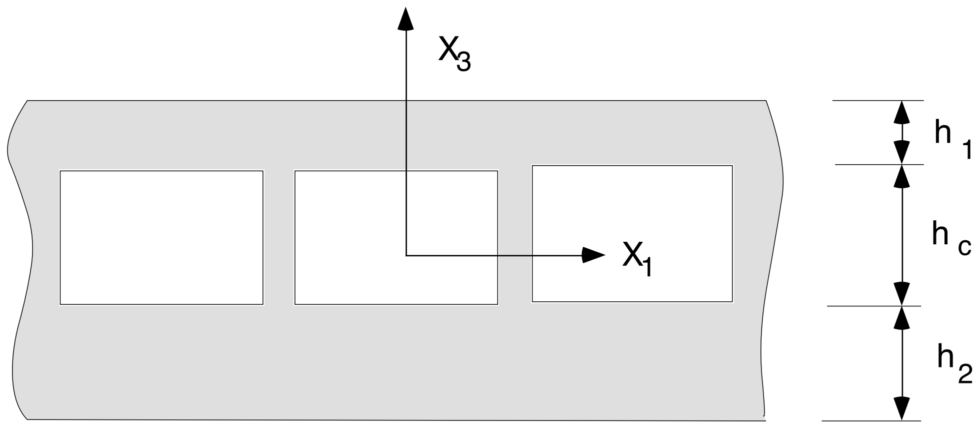


Figure IC 3211-2: First wall cross-section

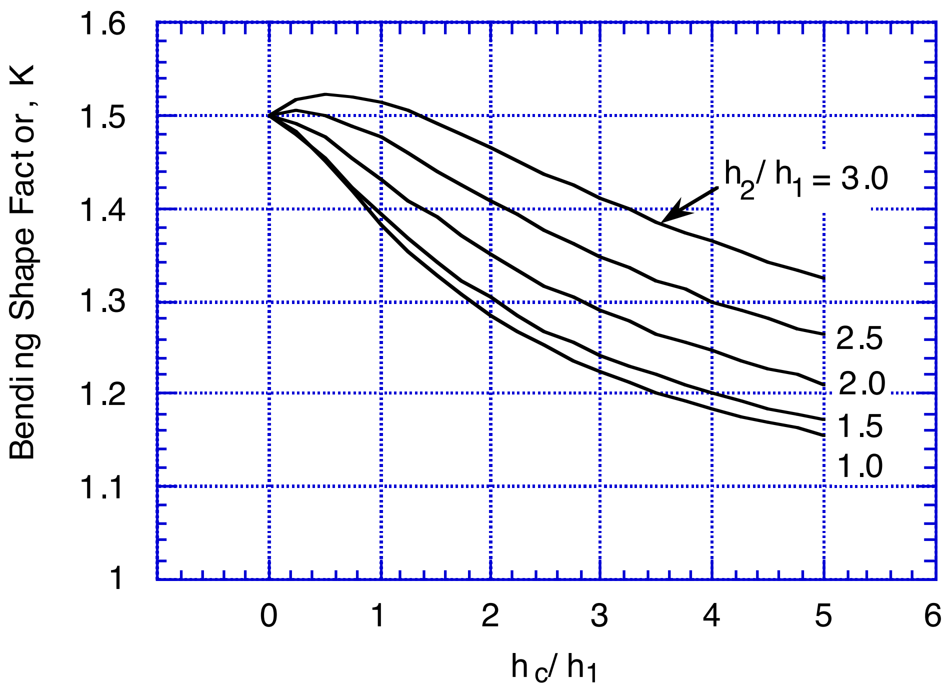


Figure IC 3211-3: Bending shape factor (K) for first wall cross-section

IC 3211.1.3 Local primary membrane stress (Immediate plastic collapse and plastic instability)

In local, non-overlapping areas,

$$\boxed{\overline{P_L} \le \min \left[1.5\, S_m(T_m, \phi t_m),\, S_{y,min}(T_m, \phi t_m)\right]} \qquad (3)$$

where

$\overline{P_L}$ = local primary membrane stress intensity (IC 2543).

In overlapping areas,

$$\boxed{\overline{P_L} \le 1.1\, S_m(T_m, \phi t_m)} \qquad (4)$$

In the case of a shell of revolution, a zone can be considered as local if the axisymmetric distributions of the membrane stresses exceeding 1.1 S_m are at most 2.5 $\sqrt{(Rh)}$ apart in the meridian direction and have a meridian length that does not exceed $\sqrt{(Rh)}$.

IC 3211.2 Elasto-plastic analysis (Immediate plastic collapse)

If elasto-plastic analysis is performed (for guidance, see B 3024 of Appendix B), it must be demonstrated that the specified mechanical loadings do not exceed the elasto-plastic analysis collapse load divided by the load factor of Γ_{1L} = 1.5 (for criteria level A). For the purpose of this rule, the elasto-plastic analysis collapse load is defined as the least of the loads at which the following conditions are satisfied:

- The significant mean (membrane) plastic strain (IC 2616) is equal to the significant mean elastic strain,

$$\boxed{(\varepsilon_m)_{pl} = (\varepsilon_m)_{el}} \qquad (1)$$

- The significant linear (membrane plus bending) plastic strain (IC 2616) is equal to the significant linear elastic strain, or

$$\boxed{(\varepsilon_{m+b})_{pl} = (\varepsilon_{m+b})_{el}} \qquad (2)$$

An equivalent procedure based on the analysis of loads and displacements is as follows:

- In the stress analysis, apply the mechanical loading with a monotonically increasing scalar load factor, beginning at zero load;
- Plot the load (or load factor) as a function of the maximum displacement;
- Draw a straight line from the origin (zero load) tangent to the load-deflection curve. This line, representing the elastic response, will be at an angle θ from the load axis;

- Draw a second straight line from the origin an angle 2θ from the load axis;
- The intersection of the second (2θ) line with the load-deflection curve is the assumed collapse point.
- The loading at this assumed collapse point should be at least a factor Γ_1 (Table IC 3220-2) greater than the specified loading.

IC 3212 Immediate plastic flow localization

To prevent cracking due to immediate plastic flow localization, the following limits must be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified.

Note: Either the limits based on elastic analysis or the limits based on elastic-plastic analysis must be satisfied.

IC 3212.1 Elastic analysis (Immediate plastic flow localization)

To apply the limits of this section, results from a linear elastic analysis of the component are needed.

IC 3212.1.1 Primary plus secondary membrane stress (Immediate plastic flow localization)

The limit for the sum of the primary and secondary membrane stress intensities depends on elastic follow-up, as described in IC 2161, and is given by:

$$\boxed{\overline{P_L + Q_L} \le S_e(T_m, \phi t_m)} \qquad (1)$$

where

$\overline{P_L + Q_L}$ = primary plus secondary membrane stress intensity (IC 2546)

$S_e\ (T_m, \phi t_m)$ = allowable stress intensity (IC 2724) dependent on temperature and fluence tabulated in A.MAT.5.3 of Appendix A for all materials.

T_m = thickness-averaged temperature,

ϕt_m = thickness-averaged neutron fluence.

IC 3212.2 Elasto-plastic analysis (Immediate plastic flow localisation)

If elasto-plastic analysis is performed, it must be demonstrated that the specified load-controlled and strain-controlled loadings do not cause damage due to plastic flow localisation (including necking). The procedure for doing this is as follows:

- Multiply mechanical loadings by the load factor Γ_{2L} (Table IC 3220-2)

- Multiply thermal and other deformation-controlled loadings (e.g., swelling-induced stress, if any) by the strain factor Γ_{2S} (Table IC 3220-2). For guidance on swelling-induced stress, see B 3024.1.1.1 of Appendix B.
- Apply both of the above loadings concurrently to the structure and perform an elasto-plastic analysis. For guidance, see B 3024 of appendix B.
- the significant mean plastic strain $\left(\notin_m\right)_{pl}$ (IC 2616) at all times must satisfy the following limit:

$$\boxed{\left(\notin_m\right)_{pl} \le \frac{\varepsilon_u(T_m, \phi t_m)}{2}} \quad (1)$$

where

ε_u	=	minimum uniform elongation, dependent on temperature and fluence, defined in IC 2731 and given in A.MAT.3.4 of Appendix A,
T_m	=	thickness-averaged temperature,
ϕt_m	=	thickness-averaged neutron fluence.

IC 3213 Immediate local fracture due to exhaustion of ductility

To prevent local fracture due to exhaustion of ductility, the following limits must be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified.

Note: Either the limits based on elastic analysis or the limits based on elastic-plastic analysis must be satisfied.

IC 3213.1 Elastic analysis (Local fracture, exhaustion of ductility)

To apply the limits of this section, results from a linear elastic analysis of the component are needed. Then, the total stress, including peak stress, is limited by

$$\boxed{\overline{P_L + P_b + Q + F} \le S_d(T, \phi t, r_2)} \quad (1)$$

and the total stress, excluding peak stress, is limited by

$$\boxed{\overline{P_L + P_b + Q} \le S_d(T, \phi t, r_3)} \quad (2)$$

where

$\overline{P_L + P_b + Q + F}$	= total primary plus secondary stress intensity including peak stresses (IC 2547),
$\overline{P_L + P_b + Q}$	= total primary plus secondary stress intensity excluding peak stresses (IC 2546),

S_d (T, ϕt, r)	= allowable stress intensity (IC 2725), dependent on the r-factor, temperature, and fluence given in A.MAT.5.4 of Appendix A for all materials,
T	= temperature of point under consideration,
ϕt	= neutron fluence of point under consideration.

Note: Two sets of allowable S_d values (B 2725 of Appendix B) for the total stress are tabulated in Appendix A, one corresponding to r=r_2 applicable if peak stresses are included ($\overline{P_L + P_b + Q + F}$) and the other corresponding to r=r_3 applicable if peak stresses are excluded ($\overline{P_L + P_b + Q}$).

IC 3213.2 Elasto-plastic analysis (Local fracture, exhaustion of ductility)

If elasto-plastic analysis is performed, it must be demonstrated that the specified load-controlled and strain-controlled loadings do not cause local damage due to exhaustion of ductility. The procedure for doing this is as follows:

- Multiply mechanical loadings by the load factor Γ_{3L} (Table IC 3220-2)
- Multiply thermal and other deformation-controlled loadings (e.g., swelling-induced stress, if any) by the strain factor Γ_{3S} (Table IC 3220-2). For guidance on swelling-induced stress, see B 3024.1.1.1 of Appendix B.
- Apply both of the above loadings concurrently to the structure and perform an elasto-plastic analysis. For guidance, see B 3024 of appendix B.
- The significant local plastic strain $(\bar{\varepsilon})_{pl}$ (IC 2616) at all times must satisfy

$$\boxed{(\bar{\varepsilon})_{pl} \leq \frac{\varepsilon_{tr}(T,\phi t)}{TF}} \qquad (1)$$

where

ε_{tr}	=	minimum true strain at rupture, dependent on temperature and fluence, defined in IC 2732 and given in A.MAT.3.6 of Appendix A,
T	=	temperature of point under consideration,
ϕt	=	neutron fluence of point under consideration,
TF	=	triaxiality factor, defined in IC 2541.1.

IC 3214 Fast fracture

To prevent failure caused by insufficient fracture toughness, either the elastic analysis limits of IC 3214.1 or the elasto-plastic analysis limit of IC 3214.2 must be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified.

The following definitions are used:

$K_C (T_m,\Phi t_m)$ = minimum fracture toughness defined in IC 2741 and given in A.MAT.5.8 of Appendix A

$J_{IC} (T_m,\Phi t_m)$ = minimum critical J-integral under mode I, defined in IC 2742 and given in A.MAT.5.8 of Appendix A

T_m = thickness-averaged temperature,

ϕt_m = thickness-averaged neutron fluence.

a_0 = postulated crack depth = max $[4a_u , h/4]$, $4a_u < h$

a_u = largest undetectable crack length

h = wall thickness or characteristic size

K_I = mode I (tensile) stress intensity factor associated with $P_L + Q_L$ or $P_L + P_b + Q + F$ loading and maximum crack length a_o

J_I = mode I J-integral due to all loading and maximum crack length a_o

IC 3214.1 Elastic analysis (fast fracture)

In all cases, a (tensile) stress intensity factor K_I has to be calculated for a postulated surface crack of depth a_o and minimum length $10a_o$ subjected to the prescribed loading. If the postulated crack is embedded inside a yielded region, elastic analysis rules do not apply and the elasto-plastic limit of IC 3214.2 has to be applied.

IC 3214.1.1 Global fast fracture

To prevent global fast fracture, the following limit has to be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified. The maximum mode I (tensile) stress intensity factor, K_I, due to all primary plus secondary membrane loadings ($P_L + Q_L$), including disruption loading, must be limited by the following:

$$\boxed{K_I \leq \gamma_1 \; K_C\left(T_m, \Phi t_m\right)} \qquad (1)$$

where

γ_1 = safety factor = 0.33 for criteria level A

IC 3214.1.2 Local fast fracture

To prevent localized cracking or crack extension, the following limit shall be satisfied at all times during the life of the component subjected to all loadings for which level A criteria is specified. The maximum mode I (tensile) stress intensity factor, K_I, due to all primary and secondary loadings, including peak ($P_L + P_b + Q + F$), must be limited by the following:

$$\boxed{K_I \leq \gamma_2 \; K_C(T_m, \Phi t_m)} \qquad (2)$$

where

γ_2 = safety factor = 0.67 for criteria level A

IC 3214.1.2 Local fast fracture

To prevent localized cracking or crack extension, the following limit shall be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified. The maximum mode I (tensile) stress intensity factor, K_I, due to all primary and secondary loadings, including peak (P_L +P_b +Q +F), must be limited by the following:

$$\boxed{K_I \leq \gamma_2 \; K_C(T_m, \Phi t_m)} \qquad (2)$$

where

γ_2 = safety factor = 0.67 for criteria level A

IC 3214.2 Elasto-plastic analysis (fast fracture)

If the postulated crack for the global or local fast fracture analysis is embedded in a yielded region, elastic-plastic fracture mechanics methodology should be used. The J-integral is an acceptable criterion for such cases and, if used, its maximum value due to all loadings (P_L + Pb +Q +F) shall be limited by the following:

$$\boxed{J_I \leq \gamma_3 \; J_c(T_m, \Phi t_m)} \qquad (3)$$

where

γ_3 = safety factor = 0.67 for criteria level A

IC 3215 Special Stress Limits

The following deviations from the basic stress limits are provided to cover special conditions or configurations.

IC 3215.1 Bearing Loads

The average bearing stress for resistance to crushing under the maximum design load shall be limited to the yield strength S_y at temperature except that, when the distance to a free edge is greater than the distance over which the bearing load is applied, a stress of l.5 S_y at temperature is permitted. For clad surfaces, the yield strength of the base metal may be used if, when calculating the bearing stress, the bearing area is taken as the lesser of the actual contact area or the area of the base metal supporting the contact surface.

When bearing loads are applied on parts having free edges, such as at a protruding edge, the possibility of a shear failure shall be considered. In the case of load stress only, the average shear stress shall be limited to $0.6S_m$. In the case of load stress plus secondary stress, the average shear stress shall not exceed $0.5S_y$.

When considering bearing stresses in pins and similar members, the S_y -at-temperature value is applicable, except that a value of $1.5S_y$ may be used if no credit is given to bearing area within one pin diameter from a plate edge.

IC 3215.2 Pure Shear

The average primary shear stress across a section loaded under design conditions in pure shear (for example, keys, shear rings, screw threads) shall be limited to $0.6S_m$. The maximum primary shear under design conditions, exclusive of stress concentration at the periphery of a solid circular section in torsion, shall be limited to $0.8\ S_m$.

IC 3220 Level C and D criteria, M-Type Damage

At levels C and D, the same set of rules as for level A, but with different safety factors, and load factors (see below), are applicable for protection against the following M-type damage:

- immediate plastic collapse (IC 3211) (not required for criteria level D)
- immediate plastic instability and strain localization (IC 3212)
- local fracture due to exhaustion of ductility (IC 3213)
- fast fracture (IC 3214)

As in level A, either the limits based on elastic analysis or the limits based on elasto-plastic analysis need to be satisfied. The applicable stress allowables, safety factors and load factors for elastic analysis rules and elasto-plastic analysis rules are given in tables IC 3220-1 and IC 3220-2, respectively.

Table IC 3220-1 S_m, S_e, S_d and safety factors for elastic analysis rules for M-type damage

Damage	Level A	Level C	Level D
Immediate plastic collapse and instability (IC 3211.1)	$S_m(T_m, \phi t_m)$	$\min\begin{cases}1.2S_m(T_m,\phi t_m)\\ S_{y,min}(T_m,\phi t_m)\end{cases}$	$\min\begin{cases}2.4S_m(T_m,\phi t_m)\\ 0.7S_{u,min}(T_m,\phi t_m)\end{cases}$
Immediate plastic strain localization (IC 3212.1)	$S_e(T_m, \phi t_m)$	$1.2S_e(T_m, \phi t_m)$	$2.0S_e(T_m, \phi t_m)$
Immediate local fracture due to exhaustion of ductility (IC 3213.1)	$S_d(T, \phi t)$	$1.2S_d(T, \phi t)$	$1.35S_d(T \phi t)$
Fast fracture Global (IC 3214.1.1) Local (IC 3214.1.2)	$\gamma_1 = 0.33$ $\gamma_2 = 0.67$	$\gamma_1 = 0.40$ $\gamma_2 = 0.80$	$\gamma_1 = 0.67$ $\gamma_2 = 0.90$

Table IC 3220-2 Load factors (Γ_{iL}), strain factors (Γ_{iS}), and safety factor (γ_3) for elasto-plastic analysis rules for M-type damage

Damage	Level A	Level C	Level D
Immediate plastic collapse (IC 3211.2)	$\Gamma_{1L}=1.5$	$\Gamma_{1L}=1.2$	Analysis not required
Immediate plastic instability and strain localization (IC 3212.2)	$\Gamma_{2L} = 2.5$ $\Gamma_{2S} = 1.5$	$\Gamma_{2L} = 2.0$ $\Gamma_{2S} = 1.2$	$\Gamma_{2L} = 1.35$ $\Gamma_{2S} = 1.0$
Immediate local fracture due to exhaustion of ductility (IC 3213.2)	$\Gamma_{3L} = 2.5$ $\Gamma_{3S} = 1.5$	$\Gamma_{3L} = 2.0$ $\Gamma_{3S} = 1.2$	$\Gamma_{3L} = 1.35$ $\Gamma_{3S} = 1.0$
Fast fracture (IC 3214.2)	$\gamma_3 = 0.67$	$\gamma_3 = 0.80$	$\gamma_3 = 0.90$

IC 3230 Testing conditions criteria

IC 3231 Pressure testing

The following definitions are used in sections IC 3231.1 and IC 3231.2

P_d = design pressure,

T_d = design temperature

P_t = test pressure

T_t = test temperature

S_m = allowable stress, a function of temperature and fluence, given in A.MAT.5.1 of appendix A,

S_y = minimum conventional 0.2 % offset yield strength, a function of temperature and fluence, given in A.MAT.3.2 of appendix A,

$\overline{P_m}$ = general primary membrane stress intensity [IC 2542]

P_L = local primary membrane stress tensor [IC 2523]

P_b = primary bending stress tensor [IC 2524].

$\overline{P_L + P_b}$ = stress intensity of the sum of the tensors P_L and P_b. The tensor sum is obtained first, and then the stress intensity is calculated for the combined tensor in accordance with IC 2540.

IC 3231.1 Hydrostatic test

A manufactured component designed for internal pressure shall be subjected to a hydrostatic test pressure which, at every point in the component, is not less than the specified test pressure P_t as defined below,

$$P_t = 1.25 P_d \frac{S_m(T_t)}{S_m(T_d)} \quad (1)$$

where

$S_m(T_t)$ = design stress intensity value for the test temperature T_t,

$S_m(T_d)$ = design stress intensity value for the design temperature T_d.

If the test pressure at any point in the component exceeds the required test pressure P_t by more than 6%, the upper limit of the test pressure shall be restricted to meet the following stress intensity limits for all loadings that may exist during the test:

- The general primary membrane stress intensity shall not exceed the following limit:

$$\boxed{\overline{P_m} \leq 0.9 S_y(T_t)} \quad (2)$$

- The local primary membrane plus bending stress intensity shall not exceed the following limit:

$$\begin{aligned} \left(\overline{P_L + P_b}\right) &\le 1.35 S_y(T_t) && \text{if } \overline{P_L} \le 0.67 S_y(T_t) \\ \left(\overline{P_L + P_b}\right) &\le 2.15 S_y(T_t) - 1.2\overline{P_L} && \text{if } 0.67 S_y(T_t) < \overline{P_L} \le 0.9 S_y(T_t) \end{aligned} \tag{3}$$

where

$S_y(T_t)$ = minimum yield strength at test temperature T_t.

IC 3231.2 Pneumatic test

A pneumatic test may be used in lieu of the hydrostatic test only if either of the following two conditions apply to the component under consideration:

1) the component cannot be safely filled with water.
2) traces of testing liquid cannot be tolerated in the component.

The pneumatic test pressure shall be not less than the specified test pressure P_t as defined below:

$$P_t = 1.15 P_d \frac{S_m(T_t)}{S_m(T_d)} \tag{4}$$

If the test pressure at any point in the component exceeds the required test pressure by more than 6%, the upper limit of the test pressure shall be restricted to meet the following stress intensity limits for all loadings that may exist during the test:

- The general primary membrane stress intensity shall not exceed the following limit:

$$\boxed{\overline{P_m} \le 0.8 S_y(T_t)} \tag{5}$$

- The local primary membrane plus bending stress intensity shall not exceed the following limit:

$$\begin{aligned} \left(\overline{P_L + P_b}\right) &\le 1.2 S_y(T_t) && \text{if } \overline{P_L} \le 0.67 S_y(T_t) \\ \left(\overline{P_L + P_b}\right) &\le 1.87 S_y(T_t) - \overline{P_L} && \text{if } 0.67 S_y(T_t) < \overline{P_L} \le 0.9 S_y(T_t) \end{aligned} \tag{6}$$

IC 3231.3 External pressure test

- The external pressure shall not exceed 135% of the maximum pressure allowed by the design rules of IC 4400 (buckling).

IC 3232 Vacuum testing

(will be issued at a later date)

IC 3300 RULES FOR THE PREVENTION OF C-TYPE DAMAGE (LEVELS A AND C)

The rules of this article are aimed at providing sufficient safety margins with regard to C-type damages (IC 2120) and are applicable only if the rules for the prevention of M-type damage have been satisfied.

These rules apply to all loadings for which level A or level C criteria are specified. They do not apply to loadings corresponding to level D criteria, as such loadings are presumed to be extremely unlikely and the cycles few in number.

The complete time history of combined loadings for which the levels A and C criteria are specified must be taken into account in the analysis of C-type damage. After subjecting the structure to the history of loadings, the following criteria must be satisfied at all points of the structure.

- progressive deformation or ratcheting (IC 3310)
- time-independent fatigue (IC 3320)

To simplify the analysis, the complete time history may be subdivided into separate operating periods, each of which may include one or more types of cycles. The way in which the operating periods are combined depends on the specific limits being evaluated, and are discussed in B 2752.1 of Appendix B.

IC 3310 Progressive deformation or ratcheting

Either the rule for elastic analysis (IC 3311) or the rule for elasto-plastic analysis (IC 3312) must be applied.

IC 3311 Elastic analysis (Progressive deformation or ratcheting)

The elastic analysis rules for progressive deformation depend on the range of the stress or strain during a cycle but not the number of cycles and must be satisfied for each individual operating period. It may be shown that the limits are satisfied by considering only bounding cases.

To apply the rules of this paragraph, the maximum values of the following seven quantities over the time for each operating period need to be determined first:

- maximum thickness-averaged temperature: T_m,
- a maximum thickness-averaged neutron fluence : ϕt_m
- maximum primary membrane stress intensity (excluding plasma disruption loadings): Max $\overline{P_m}$,
- maximum local primary membrane plus bending stress intensity (excluding plasma disruption loadings): Max $\left(\overline{P_L + P_b}\right)$,
- maximum range of stress intensity due to disruption loadings: $\overline{\Delta P}$
- maximum in the thickness secondary stress intensity range: $\overline{\Delta Q}$.
- maximum in the thickness stress intensity range: $\Delta\left[\overline{P} + \overline{Q}\right]_{max} = \overline{\Delta P} + \overline{\Delta Q}$.

It is important that the stress state be identical at the beginning and at the end of the operating period concerned.

To prevent the occurrence of progressive deformation on the basis of elastic analysis, either of the following two methods may be used:

a) 3 S_m rule (IC 3311.1)

b) Bree- diagram rule (IC 3311.2)

IC 3311.1 3S_m rule

For each operating period, the following criteria must be satisfied at all points of the structure:

$$\boxed{\mathrm{Max}\left(\overline{P_L + P_b}\right) + \Delta\left[\overline{P} + \overline{Q}\right]_{max} \leq 3S_m(T_m, \phi t_m)} \qquad (1)$$

where

S_m = allowable stress, defined in IC 2723 and given in A.MAT.5.1, for the maximum thickness-averaged temperature and neutron fluence during the operating period calculated along the supporting line segment.

$\Delta\left[\overline{P} + \overline{Q}\right]_{max}$ = maximum range of cyclic primary plus secondary stress intensities

IC 3311.2 Bree-diagram rule

This rule is defined in terms of the following quantities:

$$X = \frac{\overline{P_m}}{S_y} \quad \text{or} \quad X = \frac{\overline{P_L + \frac{P_b}{K}}}{S_y}, \text{ as applicable,}$$

and

$$Y = \frac{\Delta\left[\overline{P} + \overline{Q}\right]}{S_y}$$

Where:

K = the bending shape factor defined in IC 3211.1.

S_y = average of the minimum yield strengths (defined in IC 2721 and given in A.MAT.3.2 of Appendix A), evaluated at the minimum and maximum thickness-averaged temperatures and fluences during the cycle calculated along the supporting line segment.

For each operating period, the following criteria must be satisfied at all points of the structure:

$$\boxed{Y \leq \frac{1}{X} \text{ for } 0 \leq X \leq 0.5} \qquad (2a)$$

$$\boxed{Y \leq 4(1-X) \text{ for } 0.5 \leq X \leq 1.0} \qquad (2b)$$

IC 3312 Elasto-plastic analysis (Progressive deformation or ratcheting)

The following rules for progressive deformation using elasto-plastic analysis are based on the total plastic strain accumulated over the complete loading history for which level A or level C criteria are specified. To calculate the accumulated strain , an incremental cyclic elasto-plastic analysis should be conducted until cyclic stabilization, giving either the exact value or an upper bound to the strains resulting from all the cycles envisaged.

Two forms of limits are given on the accumulated plastic strain, depending on the ductility of the material. For a material with high ductility, the limit is expressed simply as a maximum allowable strain. For a material with reduced ductility, the limit is expressed in incremental form to account for the effect of time-varying ductility. This gives the designer the option to take credit for the fact that incremental strains that occur while the material is ductile are less damaging than incremental strains that occur while the ductility is reduced.

In the incremental form of the rule, the complete operating history is divided into N blocks of time. Each block may include several loading and stress-strain cycles. The length of a block is determined by the time period in which the ductility can be assumed constant. Within each block, the strain limits are defined as the lowest values that may occur during that time interval. Optionally, the analyst may elect to use only one block, in which case the strain limit shall correspond to the lowest value during the entire loading history. For each block i, the following definitions are used:

$\varepsilon_{tr}(T_i, \phi t_i)$ = minimum true strain to rupture, defined in IC 2732 and given in A.MAT.3.6 of Appendix A, for the temperature T_i and neutron fluence Φt_i of the point under consideration with T_i and Φt_i defined such that ε_{tr} has the lowest value during the interval i,

$\varepsilon_{tr,min}$ = minimum value of ε_{tr} at any time during the total operating period,

$\varepsilon_u(T_{mi}, \phi t_{mi})$= minimum uniform elongation, defined in IC 2731 and given in A.MAT.3.4 of Appendix A, for the thickness averaged temperature T_{mi} and neutron fluence Φt_{mi}, with T_{mi} and Φt_{mi} defined such that ε_u has the lowest value during the interval i,

$\varepsilon_{u,min}$ = minimum value of ε_u at any time during the total operating period,

T_{mi} = thickness-averaged temperature during interval i,

Φt_{mi}	=	thickness-averaged neutron fluence during interval i,
T_i	=	temperature of point under consideration during interval i
ϕt_i	=	neutron fluence of point under consideration during interval i
t_i	=	duration of interval i
$(TF)_i$	=	maximum triaxiality factor (IC 2541.1) during interval i.
Δ	=	symbol preceding a strain quantity that refers to the increment in that strain quantity during the interval i, noting that interval i may include several stress-strain cycles.

IC 3312.1 Significant mean plastic strain (Elasto-plastic, ratcheting)

The significant mean plastic strain at all times must satisfy one of the following two limits, Eq. (1) or (2). First, check if the following more conservative limit is satisfied:

$$\boxed{\left(\bar{\varepsilon}_m\right)_{pl} \leq 0.5\,\lambda_1\,\varepsilon_{u,min}} \qquad (1)$$

where

λ_1	=	a safety factor dependent on the criteria level (Table IC 3312-1)
$\left(\bar{\varepsilon}_m\right)_{pl}$	=	significant mean plastic strain (IC 2616)

If Eq. 1 above cannot be satisfied, the time history may be subdivided into blocks, and the significant mean plastic strain increments, at all times must satisfy the following summation limit:

$$\boxed{\sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{\left(\Delta\bar{\varepsilon}_m\right)_{pl,i}}{\varepsilon_u\left(T_{mi},\Phi t_{mi}\right)} \leq 0.5\,\lambda_1} \qquad (2)$$

where

$\left(\Delta\bar{\varepsilon}_m\right)_{pl,i}$	=	significant mean plastic strain increment (IC 2616) during ith block.

The strain increment is the total strain increment that occurs during period of time where the ductility (ε_u), which is a function of temperature T and a fluence of irradiation, may be considered constant. The N is number of blocks for this period of time.

IC 3312.2 Significant local plastic strain (Elasto-plastic, ratcheting)

The significant local plastic strain at all times must satisfy one of the following two limits, Eq. (3) or (4). First, check if the following more conservative limit is satisfied:

$$\boxed{(\not\varepsilon)_{pl} \;\leq\; \min\left[5\%, \lambda_2\, \varepsilon_{tr,min}\right]} \qquad (3)$$

where

λ_2 = a safety factor dependent on the criteria level (Table IC 3312-1)

$(\not\varepsilon)_{pl}$ = significant local plastic strain (IC 2616)

If Eq. 3 above cannot be satisfied, the time history may be subdivided into blocks, and the significant local plastic strain increments at all times must satisfy the following summation limit:

$$\boxed{\sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{(\Delta\not\varepsilon)_{pl,i}}{\varepsilon_{tr}(T_i, \Phi t_i)\;/(TF)_i} \;\leq\; \lambda_2} \qquad (4)$$

where

$(\Delta\not\varepsilon)_{pl,i}$ = the increment of significant local plastic strain (IC 2616) during ith block.

Table IC 3312-1 Safety factors for elasto-plastic analysis rules for progressive deformation or ratcheting (IC 3312).

	Level A	Level C	Level D
Base metal	$\lambda_1 = 0.3$ $\lambda_2 = 0.3$	$\lambda_1 = 0.6$ $\lambda_2 = 0.6$	Analysis not required

weld	$\lambda_1 = 0.15$ $\lambda_2 = 0.15$	$\lambda_1 = 0.3$ $\lambda_2 = 0.3$	Analysis not required

IC 3320 Time-independent fatigue

IC 3321 Scope

The rules of IC 3320 apply only if the rules of IC 3310 (progressive deformation) have been satisfied.

These rules are applicable neither to zones containing geometrical discontinuities (IC 3221) nor to bolts.

The following definitions are used in section IC 3322 and IC 3323:

E	=	Young's modulus (A.MAT.2.2 of Appendix A), evaluated at temperature T_{max} and neutron fluence ϕt_{max},
K_ε, K_ν	=	plastic strain amplification coefficients, functions of total stress range $\overline{\Delta\sigma_{tot}}$, temperature T_{max} and neutron fluence ϕt_{max} and are tabulated in A.MAT.5.7 of appendix A,
N_j	=	allowable fatigue cycles (A.MAT.5.5 and A.MAT.5.6 of Appendix A) corresponding to strain range $\overline{\Delta\varepsilon}_j$, temperature $(T_{max})_j$, and neutron fluence $(\Phi t_{max})_j$ for the point during cycle j,
$(T_{max})_j$	=	maximum temperature at the point during cycle j,
$\overline{\Delta P}_{eff}$	=	cyclic primary stress intensity $\overline{\Delta\left[P_m + 0.67\left(P_b + P_L - P_m\right)\right]}$(IC 2550, IC 2522-2524),
$\overline{\Delta\varepsilon}_j$	=	equivalent strain range (IC 2630) corresponding to cycle j,
$\overline{\Delta\sigma}_{tot}$	=	total stress range $\overline{\Delta(P + Q + F)}$ (IC 2553),
$(\Phi t_{max})_j$	=	maximum neutron fluence at the point during the cycle j,
ν	=	Poisson's ratio (A.MAT.2.3 of Appendix A).

IC 3322 Limits on fatigue damage

The rules for fatigue damage depend on both the range of the stress or strain and the number of cycles. The operating periods for fatigue damage analysis must account for the complete lifetime of the component and all cycles to which the component is subjected, without duplicate counting of cycles. The rules of this section must be satisfied by combining the cycles from all operating periods.

Guidelines for subdividing an operating period into cycles are given in B 2752.1 of appendix B. Guidelines for calculating the stress intensity range for each cycle are given in B 2550.1 and B 2550.2 of Appendix B. Guidelines for calculating the equivalent strain range are given in B 2630 of Appendix B.

When the component examined is not subjected to progressive deformation, the effects of the loading variations on fatigue damage accumulation can be estimated by the fatigue usage fraction (IC 2752). The fatigue usage fraction at a given point of the structure is calculated using the following procedure:

- the strain cycles (described in IC 2231) that occur in the operating period i are classified into M_i types of cycles,
- the number of cycles n_j corresponding to each type of cycle j (j=1 to M_i) is given in the component data file,
- The procedure for combining cycles so that the fatigue usage fraction due to an arbitrary sequences of cycles can be estimated conservatively is described in B 2752.1 of appendix B.
- the equivalent strain range $\overline{\Delta\varepsilon}_j$ (IC 2630) corresponding to each type of cycle j is determined by analysis in accordance with IC 3323.
- the allowable number of cycles N_j corresponding to the strain range $\overline{\Delta\varepsilon}_j$ and the maximum temperature $(T_{max})_j$ and neutron fluence $(\phi t_{max})_j$ in the cycle is determined from fatigue curves in A.MAT.5.5 of Appendix A. If fatigue data on irradiated materials are not yet included in A.MAT.5.6 of Appendix A, a procedure for accounting for irradiation effects on fatigue life is given in appendix B 3322.2.
- the fatigue usage fraction (IC 2752) $V_j\left(\overline{\Delta\varepsilon}_j\right)$ produced by this jth type of cycles is calculated as

$$V_j\left(\overline{\Delta\varepsilon}_j\right) = \frac{n_j}{N_j\left(\overline{\Delta\varepsilon}_j\right)}$$

- The cumulative fatigue usage fraction (IC 2752) V is calculated as the sum of the fatigue usage fractions for all (M_i) types of cycles, over all (N) operating periods:

$$V = \sum_{i=1}^{N} \sum_{j=1}^{M_i} V_j\left(\overline{\Delta\varepsilon}_j\right)$$

The cumulative fatigue usage fraction V at all points of the structure and for all cycles requiring compliance with levels A and C criteria over all operating periods must be less than 1:

$$\boxed{V \le 1} \qquad (1)$$

IC 3323 Calculation of equivalent strain range $\overline{\Delta\varepsilon}$:

IC 3323.1 Elastic Analysis (Time-independent fatigue)

To apply the rules of this section, first the total stress intensity range and then the corresponding elastic strain range at the point under consideration must be calculated elastically for each of the cycles. These ranges can be obtained either by a sufficiently detailed calculation of the region concerned or by using an appropriate stress concentration factor. Next, given the elastic strain range, corrections are made for the effects of plasticity to estimate the total strain range.

IC 3323.1.1 Elastic strain range

- using the procedure outlined in IC 2550 and IC 2553, calculate the total stress intensity range for the cycle,

$$\overline{\Delta\sigma}_{tot} = \overline{\Delta(P+Q+F)}\ .$$

- calculate an <u>elastic</u> strain range $\overline{\Delta\varepsilon}_1$ corresponding to the total stress intensity range from

$$\overline{\Delta\varepsilon}_1 = \frac{2}{3}(1+\nu)\left(\overline{\Delta\sigma}_{tot}/E\right)$$

Note: The elastic strain range thus obtained generally underestimates the total strain range, because it does not account for plastic strains which would occur if the real behavior of the material were taken into consideration.

IC 3323.1.2 Corrections for effects of plasticity

To account for the effects of plasticity, the following corrections are generally needed.

IC 3323.1.2.1 Cyclic Primary Stress

If all or some of the primary stresses are cyclic, they may induce additional plastic strains. The additional plastic strain range $\overline{\Delta\varepsilon}_2$ can be determined as follows:

- calculate the cyclic primary stress intensity,

$$\overline{\Delta P}_{eff} = \overline{\Delta\left[P_m + 0.67\left(P_b + P_L - P_m\right)\right]}$$

- calculate the additional plastic strain range $\overline{\Delta\varepsilon}_2$ corresponding to the $\overline{\Delta P}_{eff}$ using the cyclic stress-strain curve given in appendix A. Detailed guidelines for calculating $\overline{\Delta\varepsilon}_2$ are given in Appendix B 3323.1.2.

- The corrected total strain range at this point is represented by $\overline{\Delta\varepsilon}_1 + \overline{\Delta\varepsilon}_2$.

IC 3323.1.2.2 Local Plastic Strain Amplification Coefficients

Two additional amplifications of the plastic strain range must be considered. These are calculated by means of amplification coefficients described below.

$K_{\varepsilon}\left(\overline{\Delta\sigma_{tot}}, T_{max}, \Phi t_{max}\right)$	the effect of elastic follow-up
$K_{\nu}\left(\overline{\Delta\sigma_{tot}}, T_{max}, \Phi t_{max}\right)$	the effect of multiaxial Poisson's ratio

Both K_{ε} and K_{ν} are functions of total stress range $\overline{\Delta\sigma_{tot}}$, temperature T_{max} and neutron fluence ϕt_{max} during the cycle and are tabulated in A.MAT.5.7 of Appendix A for each material. Details of the procedures used for determining K_{ε} and K_{ν} are given in B-3323.1.2 of appendix B.

IC 3323.1.2.3 Equivalent Strain Range

Using the results of the calculations performed above, the value of the equivalent strain range $\overline{\Delta\varepsilon}$ is given by:

$$\overline{\Delta\varepsilon} = \left(K_{\varepsilon} + K_{\nu} - 1\right)\left(\overline{\Delta\varepsilon_1} + \overline{\Delta\varepsilon_2}\right)$$

IC 3323.2 Elasto-plastic analysis (Time-independent fatigue)

Determination of the equivalent strain range ($\overline{\Delta\varepsilon}$) using elasto-plastic analysis for a load cycle is carried out as follows:

- An elasto-plastic analysis following the procedure given in appendix B 3024 gives the variations of the strain components during the load cycle. The values of $\overline{\Delta\varepsilon}$ for all the strain sub-cycles of the load cycle concerned are then deduced in accordance with appendix B 2630 and B 2752.1.

  In order to ensure cyclic stabilisation of the stress-strain behaviour, it is recommended that the load cycle be repeated several times in succession during the elasto-plastic analysis.

IC 3400 BUCKLING RULES (LEVELS A, C, AND D)

Buckling, as defined in IC 2130, consists of the appearance, beyond a certain level of loading, of deformation modes or patterns which are different in shape from those that manifest themselves at low loading levels. Along with these deformation modes, the stresses and strains will change, increasing the risk of damage from immediate plastic collapse, fatigue, and progressive deformation. Buckling may be accelerated or amplified by geometrical imperfections permitted by the manufacturing tolerances.

The objective of the present criteria is to ensure that the applied loading is below the buckling load with a sufficient design margin. General rules are given below. Buckling limits are given in IC 3420.

IC 3410 Buckling rules - general

IC 3411 Calculation of buckling load (or strain)

The structures considered in this section are thin shells, i.e., structures that can be represented by a mean surface and a thickness.

When an ideal linear elastic structure with perfect geometry is gradually loaded in compression or shear such that the applied loads are increased in proportion to a scalar load factor Γ, initially the load-displacement curve is unique. However, beyond a certain value of Γ, there may exist two or more displacement shapes that are in equilibrium with the loads. The branching of a single load-displacement curve into two or more curves is called bifurcation. This generally occurs when Γ exceeds a certain critical value Γ_C, called the bifurcation load factor. The bifurcation load factor is an upper bound to the true buckling load factor (Γ_I). The displacement shape with the lowest potential energy is an approximation to the true buckling shape. Displacement shapes with higher energy are unstable. The post-buckled shape may be stable or unstable, depending on the structure.

The true buckling load is generally smaller than the bifurcation load for a number of reasons: nonlinear material effects (e.g., plastic deformations), large displacement effects (e.g., due to lateral loading or prebuckling deformations), and initial imperfections in the geometry. In general, the problem of buckling requires a large displacement, elasto-plastic structural analysis, increasing the loading in proportion to a scalar “load factor” (or strain factor) until buckling is observed in the analysis. In a nonlinear analysis, buckling may occur not as an abrupt instability, but as a gradually increasing displacement. Guidelines for estimating the buckling load with a nonlinear analysis are given in B 3420 of Appendix B.

However, in many cases the manufacturing tolerances are sufficiently tight so that the true shape of the structure is fairly close to it's nominal geometry, and it is possible to estimate the buckling load by elastic analysis as follows:

- determine the bifurcation load by solving an elastic eigenvalue problem for a structure with nominal geometry.
- using factors based on geometrical tolerances and elastic-plastic material properties, adjust the bifurcation load downward to estimate the buckling load.

Guidelines for performing the above elastic analysis are given in B3400, appendix B. Other methods may be used provided they are justified or validated.

In the final step, the scalar factor for the buckling load is compared with the design load (or strain) factor, as defined in IC 3420.

IC 3412 Effect of inelastic deformations on buckling (level A and C criteria)

The rules of IC 3310 (Progressive deformation or ratcheting) have been purposely set to be more conservative than those of either the ASME Code or RCC-MR and should allow the accumulation of less ratcheting strain than permitted in either of the two codes. On the other hand, since the strain due to irradiation-induced swelling and creep has not been limited, they may induce sufficient deformation in the structure to adversely affect its buckling load.

Consequently it may be necessary to account for the reduction of the instability load due to the effects of irradiation-induced swelling and creep and/or cyclic loadings, or to limit the amount of irradiation-induced swelling and creep strains and/or the variation in these cyclic loadings in order to ensure that they do not lead to a significant reduction in the instability load.

IC 3413 Effect of buckling on fatigue (level A and C criteria)

Non-linear phenomena associated with buckling, including large displacements and plastic strains at loadings below the elastic instability limit, could affect the evaluation of quantities used in the calculation of fatigue damage (strain range, stress range). Conservative load factors (for load-controlled buckling) and strain factors (for strain-controlled buckling) are provided in these criteria to minimize such effects. However, if in the judgment of the designer these non-linear effects are important, the effects of buckling on fatigue must be considered.

IC 3414 Load-controlled vs. strain-controlled buckling

Details of the analysis and the limits depend on whether the buckling is load-controlled or strain-controlled, as explained in IC 2131 and IC 2132, respectively.

- Load-controlled buckling is characterized by continued application of an applied load in the post-buckling regime. The rules of IC 3421 apply.
- Strain-controlled buckling is characterized by the immediate reduction of strain-induced load upon initiation of buckling. The rules of IC 3422 apply.

When the classification is in doubt, or when both types of loading are involved, the buckling shall be classified as load-controlled.

IC 3420 Buckling limits

IC 3421 Load-controlled buckling limits

The rules of this section shall be used when:

- The buckling is load controlled.
- Strain-controlled and load-controlled loadings are combined, or their effects interact.
- Conditions exist where significant elastic follow-up may occur.

The calculation of the buckling load (elastic or elasto-plastic) shall consider the following:

- the effects of initial geometrical imperfections and tolerances,
- the largest geometrical imperfections permitted by the imposed tolerances,
- the minimum thicknesses, subtracting the corrosion allowance, if any (see IC 2162),
- the minimum tensile properties of the material at temperature (appendix A),
- the possible reduction of the instability load due to the effects of irradiation-induced creep and swelling strains or the presence of cyclic stresses, e.g., cyclic thermal stresses.

Guidelines for determining the buckling load are given in B 3421 of appendix B. Given the buckling load, the “load factor (Γ_I)” for buckling is calculated as

$$\Gamma_I = \frac{\text{Load that would cause buckling at the design or service temperatures}}{\text{Load that occurs in design or service conditions}}$$

The buckling load factor (Γ_I) calculated above must be greater than or equal to the design load factors (Γ_L) tabulated in Table IC 3421-1.

Table IC 3421-1: Time-independent load factors (Γ_L) for load-controlled buckling

Loading Conditions	Load factor
Design	3.0
Level A	3.0
Level C	2.5
Level D	1.5
Test	2.25

IC 3422 Strain -controlled buckling limits

The rules of this section shall be used when:

- the buckling is strain controlled,
- there is no interaction with load-controlled loadings,
- conditions do not exist where significant elastic follow-up could occur.

For purely strain-controlled buckling, the effects of geometrical imperfections and tolerances, whether initially present or induced by service, need not be considered in the calculation of the buckling strain.

The calculation of the buckling strain (elastic or elasto-plastic), according to guidelines in B 3422, appendix B, shall consider the following:

- the minimum thicknesses, subtracting the corrosion allowance, if any (see IC 2162),
- the minimum tensile properties of the material at temperature (Appendix A),
- the possible reduction of the instability load due to the presence of cyclic stresses, e.g., cyclic thermal stresses.

To determine the buckling strain for thermally-induced strain loading, it is necessary to artificially induce high thermal strains concurrent with the use of realistic stiffness properties. "Adjusting" the thermal expansion coefficient, rather than the temperature, is one technique for enhancing the applied strains without affecting the associated stiffness properties.

Given the buckling strain, the “strain factor" (Γ_I) for buckling is calculated as

$$\Gamma_I = \frac{\text{Strain that would cause buckling at the design or service temperatures}}{\text{Strain that occurs in design or service conditions}}$$

The buckling strain factor (Γ_I) calculated above must be greater than or equal to the design strain factors (Γ_S) tabulated in Table IC 3422-1.

Table IC 3422-1 Time-independent strain factors (Γ_S) for strain-controlled buckling

Loading Condition	Strain factor
Design	1.67
Level A	1.67
Level C	1.4
Level D	1.1
Test	1.67

IC 3500 HIGH-TEMPERATURE RULES

If the conditions of the negligible thermal creep test (IC 3050) are not satisfied, the following low-temperature rules as well as the high-temperature rules of this section are applicable:

Damage Type	Criteria Level	Low-temperature rules	High-temperature rules
M-Type	Level A	IC 3211, IC 3212, IC 3213, IC 3214	IC 3520
	Levels C and D	IC 3220	IC 3520, IC 3525
	Pressure testing	IC 3231	IC 3527
C-Type	Levels A and C	None	IC 3530
	Level D	None	None
Buckling	Levels A, C, and D	IC 3400	IC 3540

IC 3510 RULES FOR THE PREVENTION OF M-TYPE DAMAGE

IC 3520 Levels A and C criteria

The following limits have to be satisfied at all times during the life of the component subjected to all loadings for which criteria levels A and C are specified. Either the elastic analysis or the elasto-visco-plastic analysis rules need be satisfied.

Note: For rapid dynamic phenomena (earthquakes, disruption events, etc.), creep is considered to be negligible and consequently the limits established by this article do not apply.

IC 3521 Elastic analysis

To apply the rules of this section, results from a linear elastic analysis of the component are needed. Before applying the rules of this section, the low temperature rules to prevent M-type damages as given in sections IC 3211.1, IC 3212.1, IC 3213.1, and IC 3214.1 for level A loading and IC 3220 for level C loading should be satisfied. Any adverse effect of long time exposure at temperature and stress (thermal creep) on the short-term ductility, strength and fracture properties of the material must be taken into account for satisfying these criteria.

The limits of IC 3521.1 have to be satisfied at all times during the life of the component subjected to all loadings for which criteria levels A and C are specified. However, for rapid dynamic loadings such as those due to plasma disruptions and earthquake, creep is negligible and therefore, the limits of this article do not apply.

IC 3521.1 Primary membrane and bending stress (creep effects)

$$\boxed{U_t(\overline{P_m}) \leq 1} \qquad (1)$$

$$\boxed{U_t(\overline{P_L + P_b/K_t}) \leq 1} \qquad (2)$$

where

U_t = creep usage fraction for primary stress [IC 2764] using wall-averaged temperatures for determining the allowable times T_j

P_m = general primary membrane stress tensor [IC 2522]

P_L = local primary membrane stress tensor [IC 2523]

P_b = primary bending stress tensor [IC 2524].

K_t = creep bending shape factor, defined as $(K_{eff} + 1)/2$

K_{eff} = an effective bending shape factor, which accounts for the increased maximum bending moment carrying capability of an elastic-plastic material with limited ductility as compared to that of an elastic-brittle material. For unirradiated materials with unlimited ductility, $K_{eff} = K$ where K is the usual bending shape factor used in the RCC-MR and the ASME Code. Values of K for various cross-sections are given in Figures IC 3211-1 through -3. K_{eff} may be calculated from $K_{eff,rect}$, which is the K_{eff} for a solid rectangular section, using the following equation

$K_{eff} = 1 + 2 (K - 1) (K_{eff,rect} - 1)$

Values of $K_{eff,rect}$ of a solid rectangular section, which may be reduced due to loss of ductility with irradiation, are tabulated as a function of fluence and temperature for each material in A.MAT.5.2 of Appendix A.

Note: If there is a risk of elastic follow up (IC 2161), membrane stresses from all sources should be included with P_m for satisfying Eq. (1).

IC 3522 Elasto-visco-plastic analysis

Guidance for elasto-visco-plastic analysis is given in B 3024.4 of Appendix B.

IC 3522.1 Elasto-visco-plastic analysis (time-dependent plastic collapse)

It must be demonstrated that the specified mechanical loadings do not exceed the elasto-visco-plastic analysis collapse load divided by the load factor Γ_{1L} (Table IC 3220-2). For the purpose of this rule, the elasto-visco-plastic analysis collapse load is defined as the least of the loads at which the following conditions are satisfied:

- the significant (IC 2616) mean (membrane, IC 2613) inelastic (plastic plus creep) strain is equal to the significant mean elastic strain,

$$\boxed{(\bar{\varepsilon}_m)_{p+c} = (\bar{\varepsilon}_m)_{el}} \qquad (1)$$

or

- the significant (IC 2616) linear (membrane plus bending, IC 2614) inelastic (plastic plus creep) strain is equal to the significant linear elastic strain,

$$\boxed{\left(\varepsilon_{m+b}\right)_{p+c} = \left(\varepsilon_{m+b}\right)_{el}} \tag{2}$$

An equivalent procedure based on the analysis of loads and displacements is given in IC 3211.2.

IC 3522.2 Elasto-visco-plastic analysis (exhaustion of membrane ductility)

It must be demonstrated that the specified load-controlled and strain-controlled loadings do not cause global damage due to time-dependent exhaustion of membrane ductility. The procedure for doing this is as follows:

- Multiply mechanical loadings by the load factor Γ_{2L} (Table IC 3220-2)
- Multiply thermal and other deformation-controlled loadings (e.g., swelling-induced stress, if any) by the strain factor Γ_{2S} (Table IC 3220-2). For guidance on swelling-induced stress, see B 3024.1.1.1 of Appendix B.
- Apply both loadings concurrently to the structure and perform an incremental elastic-plastic-creep analysis. For guidance, see B 3024.4 of appendix B.
- the time history should be subdivided into N blocks, and the significant mean plastic strain increments $\left(\Delta\varepsilon_m\right)_{p,i}$ (IC 2616), significant mean creep strain increments $\left(\Delta\varepsilon_m\right)_{c,i}$ (IC 2616), and stress intensity $\overline{\sigma}$ at all times must satisfy the following limits:

$$\boxed{\sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{\left(\Delta\varepsilon_m\right)_{p,i}}{\varepsilon_u\left(T_i,\Phi_i t_i,\overline{\sigma_i}\right)} + \sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{\left(\Delta\varepsilon_m\right)_{c,i}}{\varepsilon_C\left(T_i,\Phi_i t_i,\overline{\sigma_i}\right)} \leq 0.5} \tag{1}$$

where

ε_u = minimum uniform elongation, defined in IC 2731 and given in A.MAT.3.4 of Appendix A, for the thickness averaged temperature T_i and neutron fluence $\Phi_i t_i$, with T_i and $\Phi_i t_i$ defined such that ε_u has the lowest value during the interval i,

ε_c = minimum creep ductility, defined in IC 2761 and given in A.MAT.3.9 of Appendix A, for the thickness averaged temperature T_i , neutron fluence $\Phi_i t_i$, and stress intensity $\overline{\sigma_i}$ with T_i , $\Phi_i t_i$, and $\overline{\sigma_i}$ defined such that ε_c has the lowest value during the interval i,

IC 3522.3 Elasto-visco-plastic analysis (Local cracking by creep)

It must be demonstrated that the specified load-controlled and strain-controlled loadings do not cause local cracking due to accumulation of creep damage. The procedure for doing this is as follows.

- Multiply mechanical loadings by the load factor Γ_{3L} (Table IC 3220-2).
- Multiply thermal and other deformation-controlled loadings (e.g., swelling-induced stress, if any) by the strain factor Γ_{3S} (Table IC 3220-2). For guidance on swelling-induced stress, see B 3024.1.1.1 of Appendix B.
- Apply both loadings concurrently to the structure and perform an incremental elastic-plastic-creep analysis. For guidance, see B 3024.4 of appendix B.
- The time history should be subdivided into N blocks, and the stress intensity $\bar{\sigma}$ at all times must satisfy the following limit

$$\boxed{W_t(\bar{\sigma}) \leq 1} \qquad (2)$$

where

$W_t(\bar{\sigma})$ = creep rupture usage function defined in IC 2766.

IC 3525 Level D criteria

The rules defined in IC 3525.1, or IC 3525.2 may be applied. However, other validated methods may be used.

IC 3526 Elastic analysis

The creep rupture usage fraction W_t (IC 2766) associated with:

- the sum of the primary local membrane stresses and primary bending stresses divided by factor K_t defined in IC 3521.1, multiplied by the load factor 1.35,
- and all loadings relating to levels A, C and D criteria,

must satisfy the following condition:

$$\boxed{W_t\left(1.35 \,.\left(\overline{P_m + \frac{P_b}{K_t}}\right)\right) \leq 1}$$

IC 3527 Visco-plastic analysis

For elasto-plastic analysis, the following criteria must be satisfied :

- all loadings for which compliance with levels A, C and D criteria is required, are taken into account;

- the creep rupture usage fraction W_t (IC 2766) under loadings obtained by multiplying the mechanical loading by the load factor 1.35, considering the actual application time, must be lower than 1.

$$\boxed{W_t\left(1.35\,\overline{\sigma}\right) \leq 1}$$

where $\overline{\sigma}$ is the total stress tensor.

IC 3530 Testing conditions criteria

IC 3531 Pressure testing

(Will be issued at a later date)

IC 3535 RULES FOR THE PREVENTION OF C-TYPE DAMAGE (LEVELS A AND C)

The rules of this article are aimed at providing sufficient safety margins with regard to C-type damages (IC 2120) and are applicable only if the rules for the prevention of M-type damage have been satisfied.

These rules apply to all loadings for which level A or level C criteria are specified. They do not apply to loadings corresponding to level D criteria, as such loadings are presumed to be extremely unlikely and the cycles few in number.

The complete time history of combined loadings for which the levels A and C criteria are specified must be taken into account in the analysis of C-type damage. After subjecting the structure to the history of loadings, the following criteria must be satisfied at all points of the structure.

- progressive deformation or ratcheting (IC 3531)
- time-dependent fatigue (IC 3535)

To simplify the analysis, the complete time history may be subdivided into separate operating periods, each of which may include one or more types of cycles. The way in which the operating periods are combined depends on the specific limits being evaluated and are discussed in B 2752.1 of Appendix B.

IC 3540 Progressive deformation or ratcheting

Either the rule for elastic analysis (IC 3541) or the rule for elasto-plastic analysis (IC 3542) must be applied.

IC 3541 Elastic analysis

To apply the rules of this paragraph, the maximum values of the following five quantities over the time for each operating period need to be determined first:

- maximum thickness-averaged temperature: T_m,
- a maximum thickness-averaged neutron fluence : ϕt_m
- maximum primary membrane stress intensity (excluding plasma disruption loadings): Max $\overline{P_m}$,
- maximum local primary membrane plus bending stress intensity (excluding plasma disruption loadings): $\left(\overline{P_L + P_b / K_t}\right)_{max}$ and $\text{Max}\left(\overline{P_L + P_b}\right)$,
- maximum range of stress intensity due to disruption loadings: $\overline{\Delta P}$
- maximum secondary stress intensity range in the thickness: $\overline{\Delta Q}$.
- maximum stress intensity range in the thickness: $\Delta\left[\overline{P} + \overline{Q}\right]_{max} = \overline{\Delta P} + \overline{\Delta Q}$

It is important that the stress state be identical at the beginning and at the end of the operating period concerned.

Any one of the tests given in sections IC 3541.1 (Test No. A-1), IC 3541.2 (Test No. A-2), IC 3541.3 (Test No. A-3) or IC 3541.4 (Test No. B-1) needs to be satisfied. In general, Tests A-

1 and A-2 are the most conservative followed in decreasing order of conservatism by Tests A-3 and B-1.

The following general requirements are applicable to Test Nos A-1 through A-3.

(1) At least one cycle must be defined that includes the maximum cyclic primary plus secondary stress intensity range and the maximum value of ($P_L + P_b/K_t$) which occurs during all level A and C service loadings.

(2) Any number of cycles may be grouped together and evaluated according to the rules of this section.

(3) The rules are defined in terms of the following quantities:

$$X = \frac{\left(\overline{P_L + \frac{P_b}{K_t}}\right)_{max}}{S_y},$$

and

$$Y = \frac{\Delta\left[\overline{P} + \overline{Q}\right]_{max}}{S_y}$$

Where:

K_t = the creep bending shape factor defined in IC 3521.1.

S_y = average of the minimum yield strengths (defined in IC 2721 and given in A.MAT.3.2 of Appendix A), evaluated at the minimum and maximum thickness-averaged temperatures and fluences during the cycle calculated along the supporting line segment.

$\Delta\left[\overline{P} + \overline{Q}\right]_{max}$ = maximum range of cyclic primary plus secondary stress intensities

IC 3541.1 Test No. A-1

$$\boxed{X + Y \le S_a/S_y} \tag{1}$$

where S_a is the lesser of

(a) $1.25S_t$ (IC 2726) using the highest wall-averaged temperature during the cycle and a time of 10^4 h, and

(b) the average of two S_y values associated with the maximum and minimum wall-averaged temperatures during the cycle.

IC 3541.2 Test No. A-2

$$\boxed{X + Y \le 1} \tag{2}$$

for those cycles during which the average wall temperature at one of the stress extremes defining the maximum cyclic primary plus secondary stress range is below the temperature given in A.MAT.4.1 (negligible creep curve).

IC 3541.3 Test No. A-3

This test can be applied if the following conditions are first met:

(a) the low temperature $3S_m$ rule (IC 3311.1) is satisfied,

(b) the low temperature Bree diagram rule (IC 3311.2) is satisfied,

(c) $W_t\left[1.5S_y(T_m)\right] \leq 0.1$

where W_t is the creep rupture usage fraction (IC 2766) evaluated using a stress 1.5 times the average yield strength at the maximum wall-averaged temperature T_m during each interval

(d) $\sum_i \varepsilon_i\left[1.25S_y(T_{m,i})\right] \leq 0.2\%$

where ε_i is the creep strain at a stress of 1.25 times the average yield strength at the maximum wall averaged temperature $T_{m,i}$ during interval i. When the design life is separated into several time periods, the service life time must not exceed the sum of all the time periods.

If the above conditions (a) through (d) are met, then

$$\boxed{\text{Max}\left(\overline{P_L + P_b}\right) + \Delta\left[\overline{P} + \overline{Q}\right]_{max} \leq \overline{3S_m}} \qquad (3)$$

where $\overline{3S_m}$ is the lesser of $3S_m(T_m, \phi t_m)$ and

$1.5S_m + 1.5\ S_{rH}$ if only one extreme of the stress cycle occurs at a temperature above the limit given in A.MAT.4.1 (negligible creeep curve), and

$S_{rH} + S_{rL}$ if both extremes of the stress cycle occur at temperatures above the limit given in A.MAT.4.1 (negligible creep curve);

S_{rH} and S_{rL} are the relaxation strengths associated with the "hot" and "cold" extremes of the stress cycle. Both the hot and cold times are the portions of service time when the wall-averaged temperatures exceed the limits given in A.MAT.4.1. Hot temperature condition is defined as the maximum operating temperature of the stress cycle. The cold temperature condition is defined as the colder of the two temperatures corresponding to the two extremes in the stress cycle;

S_m is the allowable stress, defined in IC 2723 and given in A.MAT.5.1 of Appendix A, for the maximum thickness-averaged temperature T_m and neutron fluence ϕt_m during the cycle calculated along the supporting line segment.

If Test No. A-3 is used, the total service life may not be further subdivided into time-temperature blocks. The two relaxation strengths, S_{rH} and S_{rL}, may be determined by performing a purely uniaxial relaxation analysis starting with an initial stress of $1.5S_m$ at the hot (or cold) temperature and holding the initial strain and temperature constant throughout the time interval equal to the time of service above the limit of A.MAT.4.1.

IC 3541.4 Test No. B-1 (Bree diagram)

For this test to be applicable, the following conditions must be met first:

(a) the structure must be either axisymmetric with axisymmetric loading away from any local structural discontinuity or general structure in which the peak through wall thermal stress is negligible, i.e., thermal through wall stress distribution is approximately linear,

(b) the individual cycles defined in the design specification cannot be split into subcycles. Earthquakes, disruptions and other transient conditions should be uniformly distributed over the life time for the strain evaluation,

(c) secondary stresses with elastic follow up (i.e., pressure-induced membrane and bending stresses and thermal-induced membrane stresses) should be classified as primary stresses. Alternatively, strains due to such stresses may be calculated separately and added to that obtained from Test No B-1. If the latter is done, stresses with elastic follow up should be treated as secondary for evaluating the effective creep stress σ_c.

(d) at least one extreme of the stress cycle occur at a temperature below the limit given in A.MAT.4.1 (negligible creep curve).

(e) load combinations in the R_1 and R_2 ratcheting regimes in Fig. IC 3541-1 are not permitted.

If the above conditions (a) through (e) are satisfied,

- divide the service life into N time-temeperature blocks.
- determine effective creep stress $\sigma_{c,k}$ for the kth (k = 1 to N) time-temperature block using the formula

  $$\sigma_c = Z\, S_{yL}$$

  where S_{yL} is the S_y value at the "low" temperature extreme of the cycle and Z is a creep stress parameter for any combination of loading given in Fig. IC 3541-1. Z may be calculated as follows.

  In regimes S_2 and P, $Z = X \bullet Y$ (4)

  In regime S_1, $Z = Y + 1 - 2\sqrt{(1 - X)Y}$ (5)

  In regime E, $Z = X$ (6)

  where the definitions of X and Y are the same as given in IC 3532, except that S_y value is replaced by S_{yL}.

- Test No. B-1 (Eq. 7) is applicable only if σ_c values calculated above for all the blocks are less than their corresponding hot yield stress S_{yH} which is the S_y value at the "high" temperature extreme of the cycle.
- multiply each value of $\sigma_{c,k}$ by 1.25, and evaluate the creep strain usage fraction U_ε (IC 2765) associated with the stress $1.25\sigma_{c,k}$ held constant throughout the time-temperature history of the particular time-temperature block.
- limit the maximum value of the accumulated creep usage fraction U_ε to 1

$$\boxed{\sum_{k} U_{\varepsilon}(1.25\sigma_{c,k}) \leq 1} \qquad (7)$$

Note: As an alternative to Test No. B-1, the inelastic strains due to any number of selected operational cycles may be evaluated separately using detailed inelastic analysis. The resulting creep strain usage fraction (IC 2765) based on computed inelastic strain increments added to the usage fractions due to the rest of the operational cycles must satisfy Eq. (7).

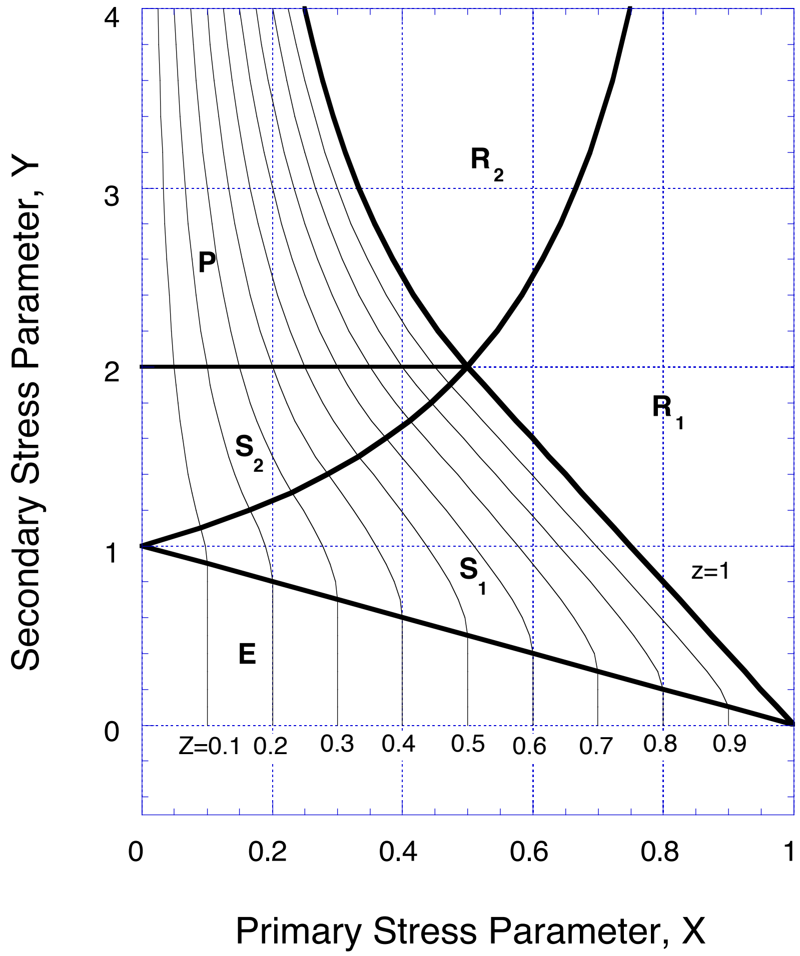


Fig. IC 3541-1

IC 3542 Elasto-visco-plastic analysis

The following rules for progressive deformation using elasto-visco-plastic analysis are based on the total plastic and creep strain accumulated over the complete loading history for which level A or level C criteria are specified. To calculate the accumulated strain , an incremental cyclic elasto-visco-plastic analysis should be conducted until cyclic stabilization, giving either the exact value or an upper bound to the strains resulting from all the cycles envisaged. For guidance on elasto-visco-plastic analysis, see B 3024.4 of Appendix B.

The complete operating history is divided into N blocks of time. Each block may include several loading and stress-strain cycles. The length of a block is determined by the time period in which the tensile and creep ductilities can be assumed constant. Within each block, incremental strains are calculated and compared against strain limits. The strain limits that are used must be the lowest limits that apply at any time during that time interval. Optionally, the analyst may elect to use only one block, in which case the strain limit shall be the lowest limit that applies at any time during the whole operating history.

A number of strain limits are used in the following rules. Some of them are defined in IC 3312. Others are defined in the following sections.

IC 3542.1 Significant mean inelastic strain (Elasto-visco-plastic, ratcheting)

The significant mean plastic $\left(\bar{\varepsilon}_m\right)_p$ and creep strain $\left(\bar{\varepsilon}_m\right)_c$ (IC 2616) at all times must satisfy the following incremental inequality. To achieve this, the time history may be subdivided into blocks, and the significant mean plastic and creep strain increments $\left(\Delta\bar{\varepsilon}_m\right)_{p,i}$ and $\left(\Delta\bar{\varepsilon}_m\right)_{c,i}$ (IC 2616), at all times must satisfy the following summation limit:

$$\boxed{\sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{\left(\Delta\bar{\varepsilon}_m\right)_{p,i}}{\varepsilon_u\left(T_{mi},\Phi t_{mi}\right)} + \sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{\left(\Delta\bar{\varepsilon}_m\right)_{c,i}}{\varepsilon_C\left(T_{mi},\Phi t_{mi},\overline{\sigma_i}\right)} \leq 0.5\lambda_1} \qquad (1)$$

where

λ_1 = a safety factor dependent on the criteria level (Table IC 3312-1)

ε_c = minimum creep ductility, defined in IC 2761 and given in A.MAT.3.9 of Appendix A, for the thickness averaged temperature T_{mi} and neutron fluence Φt_{mi} with T_{mi} and Φt_{mi} defined such that ε_c is the lowest value during the interval i,

IC 3542.2 Significant local inelastic strain (Elasto-visco-plastic, ratcheting)

The significant local plastic $\left(\bar{\varepsilon}\right)_p$ and creep strain $\left(\bar{\varepsilon}\right)_c$ (IC 2616) at all times must satisfy the following incremental inequality. The time history may be subdivided into blocks, and the significant local plastic and creep strain increments $\left(\Delta\bar{\varepsilon}\right)_{p,i}$ and $\left(\Delta\bar{\varepsilon}\right)_{c,i}$ (IC 2616) at all times must satisfy the following summation limit:

$$\sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{\left(\Delta\varepsilon\right)_{p,i}}{\varepsilon_{tr}\left(T_i,\Phi t_i\right)/(TF)_i} + \sum_{\substack{i=1\\ \text{blocks}}}^{N} \frac{\left(\Delta\varepsilon\right)_{c,i}}{\varepsilon_{ctr}\left(T_i,\Phi t_i\right)/(TF)_i} \leq \lambda_2 \qquad (2)$$

where

λ_2 = a safety factor dependent on the criteria level (Table IC 3312-1)

ε_{ctr} = minimum true strain at rupture for creep, defined in IC 2762 and given in A.MAT.3.10 of Appendix A, for the temperature T_i and neutron fluence Φt_i of the point under consideration with T_i and Φt_i defined such that ε_{ctr} is the lowest value during the interval i,

IC 3545 Time-dependent fatigue

(Will be prepared at a later date.)

IC 3546 Elastic analysis

IC 3547 Elastio-visco-plastic analysis

IC 3550 BUCKLING RULES (LEVELS A, C, AND D)

(Will be prepared at a later date.)

IC 3600 RULES FOR WELDED JOINTS

IC 3605 NOMENCLATURE

J_C, K_C	Critical J-integral and linear elastic fracture toughness
J_J, J_K, J_M	Weld material strength property coefficients
J_f	Weld fatigue strength reduction factor
n	Efficiency coefficient for welded joint
$N_\perp$	Normal component of force on the fillet weld throat
S_d, S_e, S_m	Allowable time-independent stress intensities
S_y	Yield strength
$V_{//}$, $V_\perp$	Shearing components of force on the fillet weld throat
$\sigma_\perp$, $\tau_{//}$, $\tau_\perp$	Normal and tangential stresses in fillet weld throat
τ_h, τ_{th}	Shear stresses in bolt head and thread

IC 3610 WELDED ASSEMBLY

IC 3611 Manufacturing and inspection requirements

This section contains recommended design practices for welded joints in the ITER in-vessel components. Detailed requirements for manufacturing, assembling, and inspection will be developed and included in the SDC-IC in the future. In the interim, procedures such as found in RCC-MR and the ASME boiler and pressure vessel code should be adopted, as appropriate.

The following recommendations are provided as good design practices:

a) Crossing of weld lines assembling various parts of a main shell should be avoided.

b) The distance between any two adjacent longitudinal butt welds in a shell should be greater than the minimum distance shown in Table IC 3610-1.

c) The distance from the edge of a main weld to the edge of a weld of an accessory part or the edge of a drilled hole should be greater than the minimum distance shown in Table IC 3610-1.

Inspection method	Minimum distance between welds [see (b) and (c) above]
100% Radiography	The smaller of: • twice largest thickness of sections to be welded • 40 mm
Other	The larger of: • five times largest thickness of sections to be welded • 100 mm

Table IC 3610-1 Separation of Welds

d) Welded joints should be located as far away as possible from gross shape discontinuities, in particular those assembling materials with different thermal expansion coefficients.

e) Access should be provided for performing back welding as required in IC 3612.2 and radiographic or ultrasonic inspections as necessary.

- If such access is permanently blocked at some stage of the assembly, the welding and/or inspection should be performed before the access is blocked.
- If such access is technically impossible to achieve, then either

1. the weld can be degraded to a lower class, with reduced allowable stress, in accordance with IC 3612.3, or

2. alternative inspection methods may be employed, provided that it is justified in coupon tests that these alternative inspection methods can detect and size the flaws of interest.

f) Welds in high fluence zones should be avoided.

IC 3612 Classifications of welded joints

IC 3612.1 Organization of weld classifications

Welded joints are organized below into different "Weld Categories" (A, B, C, D, and E) based on their intended use. In addition, joints are organized into different "Weld Types" (I, II, III, IV, V, VI, VII) based on the configuration of the weld. The types include butt welds, fillet welds, one- or two-sided access, full or partial penetration, etc. For code-stamped pressure vessels, there are specific requirements concerning which weld types can be used to make welds in the different use categories. For example, in a longitudinal weld joining sections of a cylindrical pressure vessel (category A), the only welds permitted are a full penetration butt welds with no permanent backing strip (types I.1, I.2, I.3, and II.1).

In most cases, the in-vessel components of ITER are not pressure vessels, and they have unique design challenges with regard to access for fabrication and inspection. Therefore, the relationship between weld categories and weld types is reduced herein to a recommendation rather than a requirement. This may be modified as specific welds are adopted and qualified by R&D.

In addition, this section contains a procedure for calculating the strength or the fatigue life of weld joints of different weld types. These are given in terms of the properties of the base metal and "knock down" factors based on material, weld process, and weld type. The allowable stresses for a weld (the knock down factors) are intimately related both to the qualification of the process and the inspection of the weld after fabrication. The inspection procedures are not yet included in the SDC-IC, but procedures such as found in RCC-MR and the ASME boiler and pressure vessel code should be adopted.

IC 3612.2 Weld types

Table IC 3612-1 shows different types of welds, without reference to specific uses. The types of welded joints shown in Table IC 3612-1 are not intended to be a compendium of all permissible welded assembly details for ITER but are used as generic types of welded joints which can be used as basis for defining the various weld categories and the stress and fatigue allowables. Recommendations on which weld types should be used for different use categories are given in IC 3612.3.

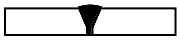
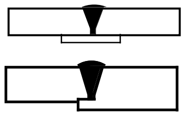
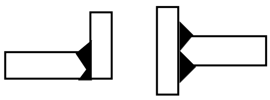
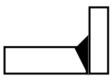
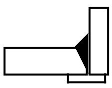
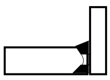
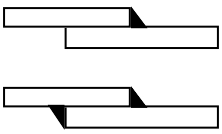
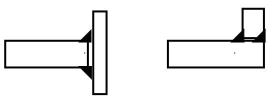
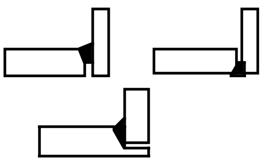
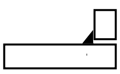
Examples	Definitions of types of welded joints				
	I.1	butt welding	full penetration	two sides accessible	back welding
	I.2	butt welding	full penetration	two sides accessible	gaseous back protection with or without insert
	I.3	butt welding	full penetration	two sides accessible	temporary backing strip can be inspected after removal of the strip
	II.1	butt welding	full penetration	back side inaccessible	gaseous protection with or without insert
	II.2	butt welding	full penetration	back side inaccessible	permanent backing strip
	III.1	fillet or T	full penetration	two sides accessible	back weld or back machining
	III.2	fillet or T	full penetration	back side inaccessible	gaseous back protection
	III.3	fillet or T	full penetration	back side inaccessible	permanent backing strip
	IV.1	fillet or T	partial penetration	double opening preparation	double bead
	IV.2	butt welding	partial penetration	double opening preparation	double bead
	IV.3	Single or double fillet lap joint	partial penetration		
	V	fillet or T	partial penetration or no penetration	straight edges or single opening preparation	double bead
	VI	fillet or T butt welding, socket welding	partial penetration	single opening preparation	single bead
	VII	fillet or T	no penetration	straight edge preparation	single bead

Table IC 3612-1 Types of welded joint

IC 3612.3 Weld use categories

A summary of the recommended types of welds for different use categories, based on those given in RCC-MR and the ASME Boiler and Pressure Vessels Code, is included in Table IC 3612-2 If an intended use is not reflected in this table, then it would be appropriate to consider an analogous pressure vessel application.

All welded joints for assemblies directly related to the mechanical function of the structure should be categorized as A or B and should be butt welded joints obtained by full penetration welding, with or without back welding, and without the use of permanent backing plates (types I.1, I.2, I.3, II.1 of Table IC 3612-1). Assemblies connecting flanges, internal support shells, tube plates, etc. to the main shell should be categorized as C, and assemblies connecting nozzles to the main shell should be categorized as D. Category C and D welds may be full penetration fillet or T joints without permanent backing plate (type III.1). However, the back side being inaccessible for type III.2 joint, is not permitted for category C but is permitted for category D welded joints.

Weld use category	Description of uses	Types of welds recommended
A	• longitudinal welds in pressure vessels. • all welded joints in a sphere • all welded joints in a flat or dished head • girth joints connecting hemispherical heads to a main shell	I.1, I.2, I.3, II.1
B	• girth joints in a cylindrical vessel • girth joints connecting a dished or flat head to a cylinder • structural assemblies	I.1, I.2, I.3, II.1
C	• joints connecting flanges, tube sheets, or flat heads to main shell	I.1, I.2, I.3, II.1, III.1
D	• joints connecting nozzles to main shells, to spheres, to heads, etc.	I.1, I.2, I.3, II.1, III.1, III.2
E	• Non-pressure-retaining attachments to pressure vessels, stiffeners, etc.	I.1, I.2, I.3, II.1, II.2, III.1, III.2, III.3, IV.1, IV.2, IV.3
None	• None	V, VI,VII are not recommended

Table IC 3612-2 Recommended weld types for weld uses of various categories

IC 3612.4 Partial penetration joints

Partial penetration joints similar to types V, VI and VII are not recommended for primary structural welds but are acceptable:

- for permanent accessory welds,
- when assembling tubes to tube sheets.

These areas must be subjected to fatigue analysis using a high value of fatigue strength reduction factor (Table IC 3660-1).

IC 3615 THICKNESS TRANSITIONS

IC 3616 General

Tapered transition should be provided between sections that differ in thickness by more than one-fourth of the thickness of the thinner section or by more than 3 mm (1/8 in.). The transition may be formed by any process that will provide a uniform taper. If the difference in thickness is not the result of a lower allowable stress intensity of the thicker section, the transition may be made either by machining the thicker section (Figure IC 3615-1a), or by increasing the thickness of the thinner section by adding metal (Figure IC 3615-1b). If the difference in thickness is a result of a lower allowable stress intensity of the thicker section, only the second option is acceptable, subject to the requirements of nondestructive examination.

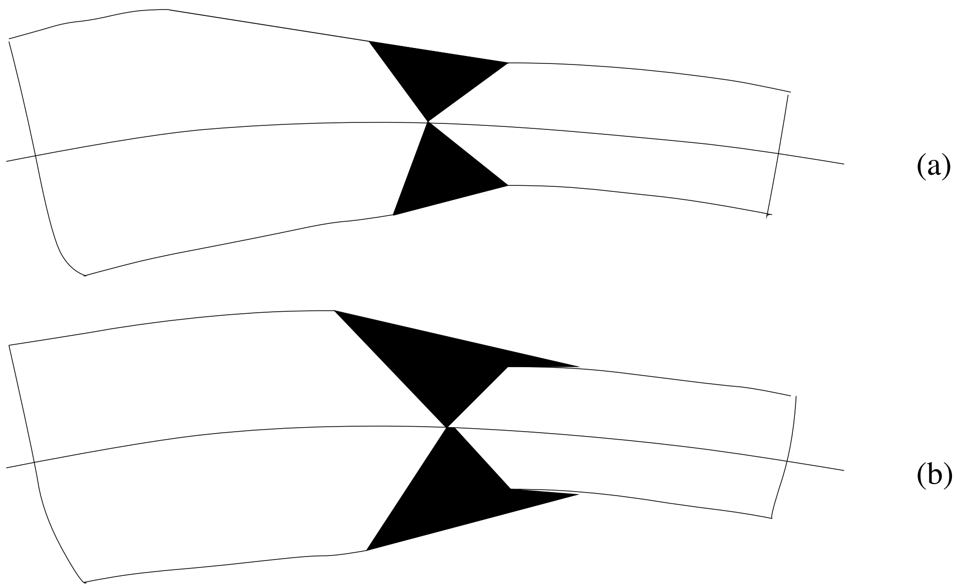


Figure IC 3615-1 Thickness transitions

If the weld is in a thickness transition zone, the stress concentration effects may be neglected if the maximum slope does not exceed 1/4; otherwise, it has to be justified by calculations.

IC 3617 Girth joints

In the case of girth joints (circumferential and aligned butt welding of cylinders, cones and dished parts) between sections of different thicknesses, the mid-surfaces of the sections may be offset with respect to one another. However, the offset should not be so large as to violate the alignment of the external or internal surfaces (excluding manufacturing tolerances), see Figure IC 3615-2.

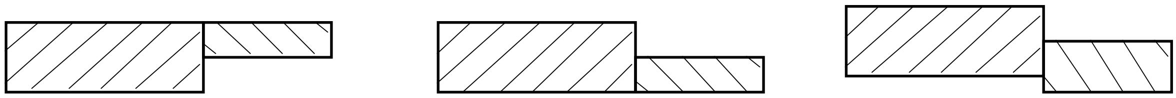


Figure IC 3615-2 Permissible offsets in girth joints

The transition slope may be less than or equal to 1/3; alternatively, a transition with a fillet radius of at least equal to the thickness of the thinner section may be used (Figure IC 3615-3).

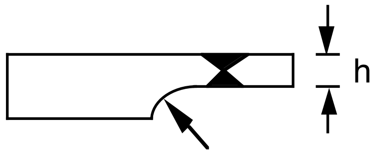


Figure IC 3615-3 Thickness transition with fillet

IC 3620 NEGLIGIBLE THERMAL CREEP TEST

In satisfying the rules of IC 3620, reference should be made to the negligible thermal creep rule of IC 3050. For the purposes of satisfying this rule, the values of t_{ci} for the weld could be assumed to be the same as those for the base metal. If the negligible thermal creep test is satisfied, the rules of IC 3625 are applicable; otherwise the rules of IC 3670 must be satisfied.

IC 3625 LOW-TEMPERATURE RULES FOR WELDED JOINTS

IC 3630 RULES FOR THE PREVENTION OF M-TYPE DAMAGE

The rules of this article are intended to provide sufficient safety margin against M-type damage (IC 2110) excluding elastic or elasto-plastic buckling. The rules related to buckling (IC 2130) are provided in IC 3665.

In satisfying the rules of IC 3630, reference should be made to IC 3200.

The rules of this article are to be applied in the vicinity of the welds, defined by ±3 times the thickness to either side of the weld center line.

Either the rules for elastic analysis or the rules for elasto-plastic analysis must be applied.

IC 3635 Elastic analysis rules

In the case of elastic analysis as per B 3023 of Appendix B, the stress-strain response of the structure can be calculated assuming that the mechanical properties of the weld and the heat affected zone are the same as those of the base metal. Stress intensities in welded joints may be calculated in accordance with article IC 3295.3. The calculated maximum stress intensities can then be compared with the allowable stress intensities specific to the joints.

For welded joints, the rules to be checked are those of IC 3211.1, IC 3212.1, IC 3213.1, and IC 3214.1. The requirements for IC 3212.1 and IC 3213.1 are satisfied with the allowable stress intensities (S_e and S_d) of the base metal. However, for meeting the requirements for IC 3211.1, the allowable primary membrane stress intensity S_m of the base metal is replaced by that of the welded joint. The allowable primary membrane stress intensity of the welded joint is related to that of the base metal by the efficiency coefficient (Table IC-3635-1) which depends on the quality of the weld and its mechanical characteristics. In general, it is obtained by the following formula :

$$S_m(\text{welded joint}) = S_m(\text{weld}) \times n \qquad (1)$$

where

$$S_m(\text{weld}) = S_m(\text{base metal}) \times J_m, \qquad (2)$$

n is the efficiency coefficient (Table IC 3635-1) which takes into account the type of joint and the nature and extent of the nondestructive examination used (IC 4463), and

J_m is a weld material property coefficient

The rule of IC 3214.1 for fast fracture has to be checked with the same postulated crack size a_0 (see Note 3 below) given in IC 3214, the same coefficients γ_1 and γ_2 given in Table IC 3220-1, and with the fracture toughness K_C for the weld which can be obtained from that of the base metal by the following formula:

$$K_C(\text{weld}) = J_K K_C(\text{base metal})$$

where

J_K is a weld material property coefficient

Note 1: For all welding using covered electrode or TIG with filler material of type 316 LN austenitic stainless steel satisfying the specifications of RCC-MR (Appendix A9) or the ASME Boiler and Pressure Vessels Code (Section IX), $J_m = 1$, i.e. base metal properties for S_m as given in A.MAT.5.1 of Appendix A may be used.

Note 2: For all welding using covered electrode or TIG with filler material of type 316 LN austenitic stainless steel satisfying the specifications of RCC-MR (Appendix A9) or the ASME Boiler and Pressure Vessels Code (Section IX), $J_K = 1$, i.e., the elastic and elasto-plastic fracture toughness (irradiated and unirradiated) for the welded joint can be assumed to be the same as those of the base metal, i.e., can be obtained from A.MAT.5.8 of Appendix A of SDC-IC.

Note 3: In case of partial penetration welds, the postulated crack size should be increased to the thickness not penetrated by the weld if it is greater than a_0 as given in IC 3214.

<table>
<tr><th>Type of welded joint
Examinations</th><th>I.1, I.2, I.3, III.1</th><th>II.1, III.2</th><th>II.2, III.3, IV, V, VI, VII</th></tr>
<tr><td>Volumetric examination[1] + Surface examination[2] after welding (both sides)</td><td>1.0</td><td colspan="2"></td></tr>
<tr><td>Surface examination[2] during welding + Surface examination[2] after welding (one side)</td><td colspan="2">0.85</td><td>0.5</td></tr>
<tr><td>Surface examination[2] after first pass + Surface examination[2] after welding (one side)</td><td colspan="2">0.7</td><td>0.5</td></tr>
<tr><td>Surface examination[2] after welding (one side)</td><td colspan="2">0.5</td><td>0.5</td></tr>
</table>

1 radiography or ultrasonic

2 liquid penetrant (for components not exposed to high vacuum) or magnetic particle

Table IC 3635-1 Joint efficiency coefficient n. Shaded areas denote weld types that cannot be examined by the indicated nondestructive technique because of lack of accessibility.

IC 3640 Elasto-plastic analysis rules

In the case of elasto-plastic analysis as per B 3024 of Appendix B, it is not necessary to analyze a detailed model (i.e., base metal, weld, heat affected zone, etc.) of the welded joint but it is sufficient to evaluate the welded joint using a global model of the structure and the stress-strain curve of the base metal and limiting the allowable ductilities of the weld to be half those of the base metal. The objective of the inelastic analysis is to obtain a correction to the elastic stress-strain field due to inelastic effects. The degree of conservativeness sought is comparable to that achieved in elastic analysis by the use of the efficiency coefficient.

The rules to be checked are those of IC 3211.2, IC 3212.2, and IC 3213.2, provided that the allowable ductilities are replaced by one half of those of the base metal, given in Appendix A.

The rule of IC 3214.2 for fast fracture has to be checked with the same postulated crack size a_0 given in IC 3214, the same coefficient γ_3 given in Table IC 3220-1, and with the fracture toughness J_C for the weld obtained from that of the base metal by the following formula:

$$J_C(\text{weld}) = J_J J_C(\text{base metal})$$

where

J_J is a weld material property coefficient

Note: For all welding using covered electrode or TIG with filler material of type 316 LN austenitic stainless steel satisfying the specifications of RCC-MR (Appendix A9) or the ASME Boiler and Pressure Vessels Code (Section IX), $J_J = 1$, i.e., the elastic and elasto-plastic fracture toughness (irradiated and unirradiated) for the welded joint can be assumed to be the same as those of the base metal, i.e., can be obtained from A.MAT.5.8 of Appendix A of SDC-IC.

IC 3645 Determination of stresses in welds

IC 3646 Full penetration welds

IC 3646.1 No geometrical discontinuity

In cases of no geometrical discontinuity (full penetration welds without permanent backing plates), i.e., for types I.1, I.2, I.3, II.1, III.1, and III.2 welding, the stresses are calculated assuming that the two assembled sections are joined to form a single continuous seamless section. The allowable primary stress intensity S_m (IC 2723) for the joint may be reduced from that of the weld material (i.e., efficiency coefficient ≤ 1) depending on the type and level of inspection. The fatigue strength reduction factor (IC 2753) is usually unity except in the case of as-welded (i.e., surface not dressed flush) joint.

IC 3646.2 With geometrical discontinuity

In cases of full penetration welds with geometrical discontinuity (e.g., using permanent backing plate), i.e., for types II.2 and III.3, the stresses are also computed assuming that the two assembled sections are joined to form a single continuous seamless section, ignoring the backing plate. Because of the presence of the permanent backing plate, the efficiency coefficient for the joint is 0.5 and the fatigue strength reduction factor is 4.

IC 3647 Partial penetration fillet welds

Stresses in partial penetration fillet welds are evaluated across the weld throat cross section, also known as the "weld area" (Figure IC 3645-1). These are the stresses $\sigma_\perp$, $\tau_{//}$ and $\tau_\perp$ calculated from the forces acting on the weld determined from a global analysis of the joint as follows:

- the normal stress $\sigma_\perp$ is given by

$$\sigma_\perp = \frac{N_\perp}{\text{Throat Area}},$$

where

$N_\perp$ = component of force acting normal to the throat area

- the tangential stress $\tau_{//}$, which is the component parallel to the weld axis, is given by

$$\tau_{//} = \frac{V_{//}}{\text{Throat Area}},$$

where

$V_{//}$ = shearing force component acting parallel to the weld axis.

- the tangential stress $\tau_\perp$, which is the component perpendicular to the weld axis, is given by

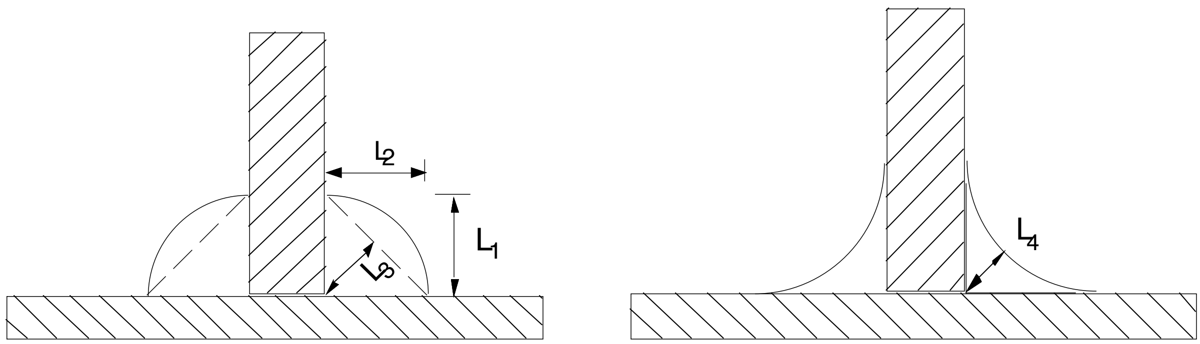
$$\tau_\perp = \frac{V_\perp}{\text{Throat Area}},$$

where

$V_\perp$ = shearing force component acting perpendicular to the weld axis.

The stress intensity in the fillet weld can be expressed by the following formula:

$$\bar{\sigma} = \sqrt{\sigma_\perp{}^2 + 3\left(\tau_\perp{}^2 + \tau_{//}{}^2\right)}$$



Throat Area = Min { L_1, L_2, L_3, L_4 } x l ,
where l is the length of the weld bead

Figure IC 3645-1 Throat area in fillet weld

IC 3650 RULES FOR THE PREVENTION OF C-TYPE DAMAGE

The rules of this article are intended to provide sufficient safety margin against C-type damage (IC 2120). The rules defined below in IC 3655 and IC 3660 are only applicable if the rules for the prevention of M-type damage are satisfied. They apply to all loadings for which Level A and level C criteria are specified.

As a general rule, reference should be made to IC 3300, taking into account the requirements given in this article IC 3630.

The rules of this article are to be applied in the vicinity of the welds, defined by ±3 times the thickness to either side of the weld centre line.

IC 3655 Progressive deformation or ratcheting

Either the rules for elastic analysis or the rules for elasto-plastic analysis must be applied.

IC 3656 Elastic analysis

Reference should be made to IC 3311. Either the $3S_m$ rule of IC 3311.1 or the Bree diagram rule of IC 3311.2 should be satisfied using the S_m and S_y values for the base metal.

IC 3657 Elasto-plastic analysis

Reference should be made to IC 3312. Following stress-strain analysis using the procedures of IC 3640, the requirements of IC 3312.1 and IC 3312.2 shall be satisfied. The allowable strains in the direction of and perpendicular to the joint should be taken as half the allowable strain for the base metal.

IC 3660 Time-independent fatigue

Reference should be made to IC 3320. Either the rules for elastic analysis or the rules for elasto-plastic analysis must be applied.

IC 3661 Elastic analysis

For welded joints, the rules of IC 3323.1 should be applied, with the following modifications.

- The stress range $\overline{\Delta\sigma}$ used is multiplied by a fatigue strength reduction factor f (Table IC 3606-1) which depends on the type of joint and the inspection used. This factor is intended to account for the local strain concentrations in the welded joint.

  For welded joints containing discontinuities (e.g., partial penetration fillet welds), $\overline{\Delta\sigma}$ is obtained by analysis using the true resisting cross-section (see IC 3605.3.2) of the weld but not taking into account the local effect of the discontinuity.
- The fatigue curve of the welded joint may be obtained by dividing the ordinates of the design fatigue curve of the base metal by the weld fatigue strength reduction factor, J_f.

Note: For all welding using covered electrode or TIG with filler material of type 316 L(N) austenitic stainless steel satisfying the specifications of RCC-MR (Appendix A9) or the ASME Boiler and Pressure Vessels Code (Section IX), $J_f = 1.25$. The cyclic stress-strain curves, K_ε, and K_v for the welded joint can be assumed to be the same as those of the base metal, i.e., obtained from A.MAT.5.7, A.MAT.5.7.1, and A.MAT.5.7.2, respectively of Appendix A.

Type of welded joint / Examinations, surface finishing	I.1, I.2, I.3, III.1	II.1, III.2	II.2, III.3, IV, V, VI, VII
Volumetric examination[1] or surface examination[2] during welding (between passes). Dressed flush welds.	1.0	1.0	
Volumetric examination[1] or surface examination[2] during welding (between passes). As-welded joints.	1.25	1.25	
Surface examination[2] after welding (both sides)	1.25		
Surface examination[2] after welding (both sides)	1		
Other examinations	2	2	4

[1] radiography or ultrasonic

[2] liquid penetrant (for components not exposed to high vacuum) or magnetic particle

Table IC 3660-1 Weld fatigue strength reduction factor, J_f. Shaded areas denote weld types that cannot be examined by the indicated non-destructive technique because of lack of accessibility.

IC 3662 Elasto-plastic analysis

Reference should be made to IC 3323.2. To satisfy the fatigue requirements, stress-strain analysis should be conducted using the procedure of IC 3640 and the requirements of IC 3323.2 should be satisfied after modifying the design fatigue curve as indicated in IC 3661.

IC 3665 BUCKLING RULES (LEVELS A, C, AND D)

Rules of IC 3400 are applicable. The effects of welded joints on the stress-strain distribution in the structure can be ignored.

IC 3670 HIGH-TEMPERATURE RULES FOR WELDED JOINTS

(Will be prepared at a later date.)

IC 3700 RULES FOR BRAZED JOINTS

(Will be prepared at a later date.)

IC 3800 RULES FOR BOLTED JOINTS

IC 3805 NOMENCLATURE

d	Bolt diameter
L_m	Distance from bolt axis to free edge
p	Nominal contact pressure in bolted joint
p_h, p_{th}	Bearing pressure on bolt head and thread
S_u	Ultimate tensile strength
τ_h, τ_{th}	Shear stress in bolt head and thread

IC 3810 GENERAL REQUIREMENTS

If high strength (tensile strength > 700 MPa) bolts are used, the following geometrical requirements are recommended to minimize fatigue damage:

- threads shall be of the V-type having a root radius no smaller than 0.1 mm (0.003 in.),
- fillet radii at the end of the shank shall be such that the ratio of the fillet radius to shank diameter is not less than 0.06.

The following recommendations are given as sound design practices:

- The minimum distance L_m of the bolt axis from the free edge of an assembled part should satisfy each of the following:

  1. $L_m/d \geq 0.5 + 1.43(p/S_u)$
  2. $L_m/d \geq 1.2$
  3. $p/S_u \leq 1.5$

  where

  d = nominal bolt diameter

  p = nominal contact pressure

  S_u = minimum tensile strength of the bolting element

- The maximum distance L_M from the axis of any bolt to the closest free edge of the assembled part should be less than the following.

  1. 12 times thickness of the thinnest assembled part
  2. 152 mm for bolts with d ≤ 76 mm
  3. 2d for bolts with d > 76 mm

- The minimum distance between drilled hole centers should be greater than 3 times the bolt diameter.
- For assemblies requiring leak tightness, the maximum bolt spacing should be ≤ 7d.
- Avoid shear loads on the screws and studs.
- Minimize thermal strain mismatch between the screws and assembled parts due either to different temperature or to different thermal expansion coefficient.
- Use screws with rolled threads rather than lathe machined threads.
- Provide careful guidance for pre tightening of bolts.
- If studs or screws are used, a minimum engagement length of 0.8 times the bolt diameter should be chosen.

IC 3811 Scope of application

The design rules of this article apply to metallic bolts (screws, nuts and washers), studs, and tie rods of bolted junctions. The stress analyses required for applying the rules should be conducted using the loading data given in the component data file for the particular component and with mechanical properties and design limits for the materials given in Appendix A.

IC 3812 Purpose of the rules

The purpose of the rules is to ensure by analysis that a bolt will not fail by fatigue and fast fracture, or the joint will not become loose due to excessive plastic deformation of the bolt. For each category of loading condition, the rules of the applicable criteria level, given in IC 3825 through IC 3860, have to be satisfied.

IC 3813 Methods of analysis

Analyses consist of verifying compliance with applicable rules, which are selected on the basis of the Criteria Level. In the course of this verification, practical methods of analysis are used to determine significant quantities and to compare these quantities with maximum acceptable values.

Before the stresses in the screw core, threads and heads can be determined, a stress analysis of the bolted assembly will be required to determine the forces and moments on each bolt, screw, or stud.

Average and bending stresses in bolts should be calculated using the actual total cross sectional area of bolts at the root of thread or section of the least diameter under stress.

Guidance for conducting elastic, simplified elastic, and inelastic analyses are given in appendix B 3800.

Because of the complexities and uncertainties associated with bolted joints, the preferred analysis method is elastic analysis. Inelastic analysis rules should be applied only if the elastic analysis rules cannot be satisfied.

Note: Current industry practice is to preload the bolts to a high fraction of the yield strength. Thus, the actual maximum service stresses in bolts and flanges, such as those produced by preload, pressure load, disruption load, and differential thermal expansion should be determined by analysis to ensure that allowable stresses are not exceeded.

IC 3814 Calculation of shear stress and contact pressure

The screwed-in threads and the screw head are subjected to shearing force and contact pressure. Rigorous stress analysis for such loadings would be highly complex. For satisfying the stress limits of SDC-IC, the shear stress and the contact pressure should be calculated in the following simplified way:

- The shear stress (τ_{th}) in the screw threads is calculated as the mean value of the shear stress on all the threads calculated at the pitch diameter, with the provision that the thread length used in the calculation cannot exceed 0.8 times the mean diameter of the threading. This restriction on the length is provided to keep the maximum plastic deformation of the threads to a negligible value. When the yield strength of the female part is less than that of the male part, a longer length (not exceeding the actual length screwed in) may be used provided disassembly is not required and small plastic deformation can be tolerated.
- the shear stress (τ_h) in the head of a screw is equal to the mean value of the shear stress on the thickness of the head calculated at the blank part beneath the head.
- the contact pressure (p_{th}) between the threads of the screw and those of the nut (or part) is equal to the mean value of the contact pressure calculated on the surface between the external diameter of the screw and the internal diameter of the nut (or of the hole of the threaded part). A minimum engagement length of 0.8 times the bolt diameter should be chosen.
- the contact pressure (p_h) between the head of the screw and the assembled part is equal to the mean value of the contact pressure calculated on the surface between the perimeter of the hole in the part and the corresponding circle inscribed in the head of the screw.

IC 3815 SET-UP STRESS LIMIT FOR BOLTS

This article provides guidance for initial tightening of bolts for all bolted joints. During initial tightening of the bolts, the membrane stress intensity should not exceed $0.8S_y(T_{RT})$, where $S_y(T_{RT})$ is the minimum yield strength at the set-up temperature T_{RT}.

IC 3820 NEGLIGIBLE THERMAL CREEP TEST

For a bolt, thermal creep is negligible over the total operating period if the summation limit given in IC 3050 is satisfied.

If the conditions of the negligible thermal creep test (IC 3050) are satisfied, the applicable design rules are referred to as "low-temperature rules" and are given in IC 3825.

If the conditions of the negligible thermal creep test (IC 3050) are not satisfied, the applicable design rules are referred to as "high-temperature rules" and are given in IC 3860.

IC 3825 LOW-TEMPERATURE RULES FOR BOLTED JOINTS

If the conditions of the negligible thermal creep test (IC 3820) are satisfied, the low temperature rules in Table 3825-1 are applicable:

Minimum bolt cross-sectional area	levels A and C	IC 3831 (required only for leak-tight joint)
	level D	none
Minimum dimensions of screw-threads and heads	levels A and C	IC 3832 (required only for leak-tight joint)
	level D	none
Primary stress limit	levels A and C	IC 3833 (required for non-leak-tight joint)
	level D	none
M-type damage	levels A, C and D	IC 3835 (all joints)
C-type damage	levels A and C	IC 3850 (all joints)
	level D	None

Table IC 3825-1 Low temperature rules for bolted joint

Note: At low temperatures, non-negligible time- (or fluence-) dependent strains may occur due to irradiation-induced creep, with or without swelling. These effects may lead to significant change in the bolt preload.

IC 3030 gives guidelines on when swelling-induced stresses can be ignored, and B 3101 of Appendix B gives guidelines for determining when effects of irradiation-induced creep are negligible. These tests, however, are based on stresses in a continuous medium, not bolted structures. For bolted structures, even a very small amount of irradiation-induced creep can lead to significant loss of bolt preload. Loss of preload for a bolted structure should be assessed by a detailed analysis of the swelling and creep strains, not by these tests.

If irradiation-induced creep is non-negligible, generally an elasto-visco-plastic analysis (see B 3024.4 of Appendix B) is needed, and the limits for inelastic analysis should be satisfied. However, the designer may choose to satisfy the elastic analysis limits after accounting for time- (or rate-) dependent effects using a simplified elastic-irradiation-induced creep analysis (e.g., see B 3024.1.1 of Appendix B).

IC 3830 GENERAL RULES

IC 3831 Minimum bolt cross-sectional area

This article provides rules for the determination of minimum bolt cross-sectional area for leak-tight bolted flanged joints. Only stresses due to coolant pressure and externally applied forces and moments due to levels A and C loading (excluding preload) need be considered for satisfying the rules of this article. If a leak-tight joint is required, the rules contained in IC 3831-IC 3832 need be applied. If a leak-tight joint is not required, only rules contained in IC 3833 need be applied to determine the size and number of bolts. However, bolts in the resulting joint may be particularly susceptible to high stresses and fatigue damage if gaps are developed during loading.

IC 3831.1 Nomenclature

The nomenclature defined below is used in the equations of IC 3831.2 and IC 3831.3.

a_b = actual cross-sectional area provided for a bolt at root of thread or section of least diameter under stress,

a_m = minimum required cross-sectional area of a bolt at root of thread or section of least diameter under stress, as calculated by the formula in IC 3831.3.

b = effective gasket or joint contact surface seating width,

b_0 = basic gasket seating width (Fig. IC 3831-3),

G = diameter at location of gasket load reaction (Fig. IC 3831-2),

H = total hydrostatic end force due to pressure P,

H_p = minimum allowed interface compression load needed for a tight joint during operation, which is a function of the operating pressure.

m = an empirical "gasket factor" used to calculate H_p.

P = maximum coolant pressure (Fig. IC 3831-1),

M = bending moment on the bolted assembly (Fig. IC 3831-1),

N = axial load on the bolted assembly (Fig. IC 3831-1),

n = number of bolts,

R = radius of the bolt circle at the flange,

S_1 = $S_m/2$ for bolt at maximum coolant temperature,

S_2 = $S_m/2$ for bolt at ambient temperature,

w_{m1} = minimum required bolt load (per bolt) sufficient to resist hydrostatic end force due to maximum coolant pressure, externally applied force and moment on the assembly, and gasket or joint contact surface compression force,

w_{m2} = minimum required bolt load (per bolt) sufficient for gasket seating at ambient condition,

y = minimum ambient gasket seating pressure

IC 3831.2 Bolt loads used for calculating minimum area

The actual bolt load depends on the geometry of the bolted assembly, the loads applied, and the pre-load. In the case of circular flange, fictitious bolt loads are used in calculating the minimum bolt cross-sectional area. These are determined as stipulated in IC 3831.2.1 and IC 3831.2.2 below, ignoring the effects of the bolt pre-loads. It is necessary to seat bolting and to pre-tighten them sufficiently to satisfy both the requirements, each one being investigated individually.

IC 3831.2.1 Pressure, externally applied, and joint compression loads

The bolt load w_{m1} consists of contributions from the hydrostatic end force (H) exerted by the maximum coolant pressure on the area bounded by the diameter of the gasket reaction, the maximum axial load (N), and maximum bending moment (M) on the assembly (Fig. IC IC 3831-1) for which compliance with level A and level C criteria are required, and the compression load (H_p) on the gasket or joint interface needed to ensure a tight joint. The contributions from the hydrostatic end force and the applied axial load N are given by the following:

$$\frac{H+N}{n} = \frac{\pi G^2 P/4 + N}{n}$$

The contribution of the applied bending moment M to the maximum bolt load can be conservatively obtained by assuming that the section remains flat (subject to later verification) and that the initial location of the neutral axis is unchanged by the application of M. It is given for the most heavily loaded bolt in joints with an even number of bolts by the following formula:

$$\frac{M}{0.5nR}$$

Note: This equation really applies only to a large number of bolts, so they approximate a uniform cylinder. For the odd (and small) number of bolts another formula should be derived. However within this criteria is recommended to limit only even number of bolts.

The minimum allowed interface pressure, H_p, is given as an empirical function of the operating pressure P by:

$$H_p = \text{(pressure)(gasket area)(gasket factor m)} = 2b\pi GmP$$

The contribution of the compression force H_p to the bolt load is:

$$\frac{H_p}{n} = \frac{2b\pi GmP}{n}$$

The value of m, which depends on the gasket material and construction, is given in Table IC 3831-1. The effective gasket or joint contact surface seating width b is related to the basic gasket seating width b_0 (Fig. IC 3831-3) as follows:

$$b = \begin{cases} b_0 \text{ for } b_0 \le 6 \text{ mm (1/4 in.)} \\ 2.5\sqrt{b_0}\text{, mm } (0.5\sqrt{b_0}\text{, in.) for } b_0 > 6 \text{ mm (1/4 in.)} \end{cases}$$

Adding the contributions of the components to the bolt load, the maximum bolt load (a ficticious load used for sizing) is given by

$$w_{m1} = \frac{\pi G^2 P/4 + N + M/0.5R + 2b\pi GmP}{n}$$

Note: If the bolt is in a zone of neutron environment, the load w_{m1} should be increased to $w_{m1} / (1-\alpha)$, where α represents the fractional loss in preload due to irradiation-induced creep. The values of α as a function of fluence for all bolt materials are given in Appendix A.

IC 3831.2.2 Initial gasket seating load

To obtain a tight joint, it is necessary to seat the gasket or joint contact surface properly by applying a minimum initial load under ambient condition before applying the internal pressure. This minimum initial bolt load w_{m2}, which is a function of the gasket material and the effective gasket area to be seated, is determined as follows:

$$w_{m2} = (\pi Gby)/n$$

where y is the minimum gasket seating pressure (Table IC 3831-1).

Note 1: For joints without gaskets, m = y = 0 and G should be replaced by the mean diameter of the bolt circle.

Note 2: In the case of a rectangular flange, the area and perimeter of the rectangle should replace the area and circumference of the circle in the above equations. The moment should be first divided into two orthogonal principal components and the load contribution from both components should be added after calculating them by means of a moment equilibrium formula on the assumption that the section remains flat (subject to later verification).

IC 3831.3 Minimum required bolt area

The minimum required bolt area (per bolt) is given by the following:

$$a_m = \max\begin{cases} \dfrac{w_{m1}}{S_1} \\ \dfrac{w_{m2}}{S_2} \end{cases}$$

where S_1 and S_2 are the allowable bolt stresses ($S_m/2$, Appendix A.MAT.5.1) at maximum coolant temperature and ambient temperature, respectively.

A selection of number of bolts n and bolt diameter to be used shall be made such that the actual cross-sectional area of a bolt a_b is not less than a_m,

$$a_b \geq a_m$$

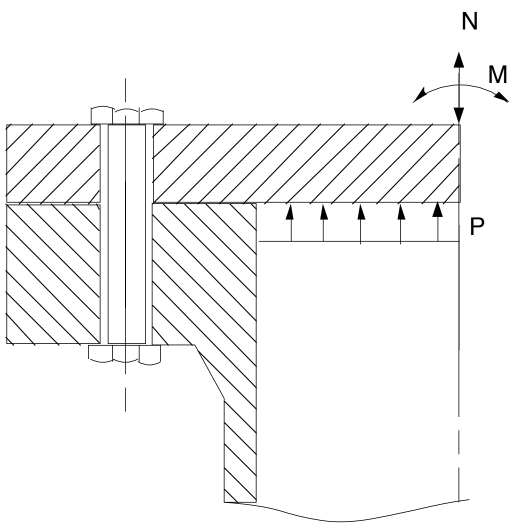


Fig. IC 3831-1 Bolted assembly with applied loads

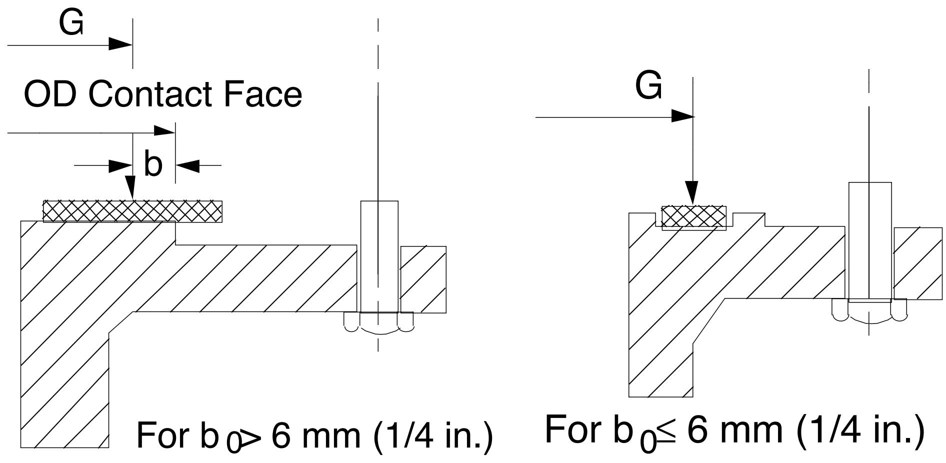


Fig. IC 3831-2 Location of gasket load reaction

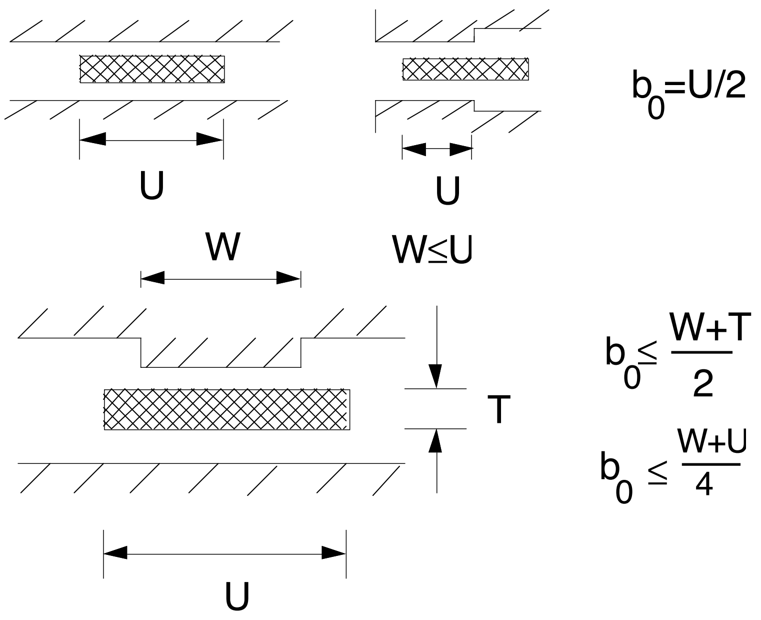


Fig. IC 3831-3 Basic gasket seating width b_0

Gasket material	Gasket Factor, m[1]	Min. Seating Pressure, y[1]
Solid flat metal		
Soft copper or brass	4.75	90 MPa (13 ksi)
Iron or soft steel	5.50	125 MPa (18 ksi)
Stainless steel	6.50	180 MPa (26 ksi)
Grooved metal		
Soft copper or brass	3.50	45 MPa (6.5 ksi)
Iron or soft steel	3.75	50 MPa (7.6 ksi)
Stainless steel	4.25	70 MPa (10.1 ksi)

[1] When sealing is effected by seal weld instead of a gasket, m = y = 0.

Table IC 3831-1 Gasket factor m and minimum seating pressure y

IC 3832 Minimum dimensions of screw threads and heads

The minimum dimensions of the screw threads and heads are determined by ensuring that the limits of IC 3832.1 and IC 3832.2 are satisfied. The loading is the same as considered for bolt loads in IC 3831.2.

The following definitions for stress limits are used in IC 3832.1, IC 3832.2, IC 3833, and IC 3834:

S_m = allowable membrane stress, a function of temperature (T_m), given in A.MAT.5.1 of appendix A,

S_y = minimum yield strength, a function of temperature (T_m), given in A.MAT.5.2 of appendix A,

S_u = minimum ultimate tensile strength, a function of temperature (T_m), given in A.MAT.5.3 of appendix A,

IC 3832.1 Shear stress limits

The value of the average shear stress τ_{th} in the threads of the screw and average shear stress τ_h in the head of the screw must be limited to the followings:

$$\boxed{\tau_{th} \le 0.3 S_m(T_m)} \qquad (1)$$

and

$$\boxed{\tau_h \le 0.3 S_m(T_m)} \qquad (2)$$

IC 3832.2 Contact pressure limits

The value of the average contact pressure (p_{th}) between the threads of the screw and those of the nut (or part) and the average contact pressure (p_h) between the head of the screw and the assembled part should not exceed half the value of the yield strength

$$\boxed{p_{th} \le 0.5 S_y(T_m)} \qquad (3)$$

and

$$\boxed{p_h \le 0.5 S_y(T_m)} \qquad (4)$$

IC 3833 Primary stress limit for bolts

The purpose of the rule in this article is the determination of minimum bolt cross-sectional area (number and diameter) for bolted flanged joints which do not have to satisfy leak-tightness. If a leak tight joint is required, the rules contained in IC 3831-IC 3832 instead of IC 3833 need to be applied. Only stresses due to coolant pressure and externally applied forces and moments due to levels A and C loading (excluding pre-load), need be considered for satisfying the rule of this article.

Note: The primary stress here is fictitous because the stress due to pre-load is ignored. Thus, a detailed rigorous analysis of the joint satisfying equilibrium and compatibility of deformation is not necessary for this evaluation. Any system of bolt loads in equilibrium with the pressure loading and applied mechanical forces and moments on the joint can be used as the primary loads for this evaluation.

<u>Levels A and C</u>

$$\boxed{\overline{P_L} \le S_m(T_m)} \qquad (1)$$

where

$\overline{P_L}$ = primary stress obtained by dividing the axial primary load by the minimum cross-sectional area of the bolt at the root of the thread,

S_m = allowable primary membrane stress intensity for the bolt material (IC 2723), a function of temperature (T_m), given in A.MAT.5.1 of appendix A.

IC 3835 RULES FOR THE PREVENTION OF M-TYPE DAMAGE

The rules of IC 3840-3842 are to be applied to all joints, leak-tight or not, and are aimed at providing sufficient safety margins with regard to M-type damage (IC 2110). Rules to prevent buckling and excessive deformations affecting functional adequacy are not required for bolts.

Note: Current rules assume that bolts are located in low fluence regions where irradiation effects on strength and ductility are small. Therefore, rules for preventing immediate flow localisation and immediate local fracture due to exhaustion of ductility are not included.

At levels A, C, and D, the following rules for protection against M-type damage are applicable:

- immediate excessive plastic deformation (leading to loss of bolt preload)
- fast fracture (IC 3214)

Because of the complexity and uncertainty of bolted joints, the elastic analysis rules should be applied first. The limits based on elasto-plastic analysis should be applied only if the elastic analysis rules cannot be satisfied. The applicable safety factors and load factors for elastic analysis rules and elasto-plastic analysis rules for the various criteria levels are given in Tables IC 3220-1 and 3220-2, respectively.

The stress intensity and fracture toughness limits used in this article are:

S_m = allowable membrane stress, a function of temperature (T_m), given in A.MAT.5.1 of appendix A,

S_y = minimum yield strength, a function of temperature (T_m), given in A.MAT.5.2 of appendix A,

S_u = minimum ultimate tensile strength, a function of temperature (T_m), given in A.MAT.5.3 of appendix A,

K_C = fracture toughness, a function of temperature (T_m), given in A.MAT.5.8 of Appendix A,

J_{IC} = minimum critical J-integral under mode I, a function of temperature (T_m), defined in IC 2742 and given in A.MAT.5.8 of Appendix A **[** This may be replaced by R6 rules]**

IC 3840 Immediate excessive plastic deformation

To prevent loss of bolt preload due to immediate excessive plastic deformation, the following limits have to be satisfied at all times during the life of the bolt subjected to all loadings for which criteria levels A, C, and D are specified.

IC 3841 Elastic analysis (Immediate excessive plastic deformation)

To apply the limits of this section, results from a linear elastic analysis of the bolted connection are needed. The calculated stresses must include the effects of all loads, including bolt preload. See Section B 3811 of appendix B for guidelines on methods to analyze bolted connections.

Expressions for the limits on different stress quantities are given below. The notations of the limits and references to the values of the limits are given in IC 3835, IC 2540, and IC 3814.

IC 3841.1 Average stress limit

The maximum value of the stress intensity due to all loading obtained from stresses averaged across the bolt cross section and neglecting stress concentrations shall not exceed the following limits:

<u>Levels A and C</u>

$$\boxed{\overline{P_L + Q_L} \leq S_m(T_m)} \tag{1}$$

<u>Level D</u>

$$\boxed{\overline{P_L + Q_L} \leq \begin{cases} 0.7 S_u(T_m) \\ S_y(T_m) \end{cases}} \tag{2}$$

IC 3841.2 Maximum stress limit

The maximum value of the stress intensity at the periphery of the bolt cross section due to all loading resulting from direct tension plus bending and neglecting stress concentrations shall not exceed the following limits:

Levels A and C

$$\boxed{\overline{P_L + P_b + Q} \le 1.5\, S_m(T_m)} \qquad (3)$$

Level D

$$\boxed{\overline{P_L + P_b + Q} \le S_u(T_m)} \qquad (4)$$

IC 3841.3 Shear stress limits (screw threads and heads)

The value of the average shear stress τ_{th} in the threads of the screw and average shear stress τ_h in the head of the screw shall not exceed the following limits:

Levels A and C

$$\boxed{\tau_{th} \le 0.6 S_m(T_m)} \qquad (1)$$

and

$$\boxed{\tau_h \le 0.6 S_m(T_m)} \qquad (2)$$

Level D

$$\boxed{\tau_{th} \le \begin{cases} 0.42 S_u(T_m) \\ 0.6 S_y(T_m) \end{cases}} \qquad (3)$$

and

$$\boxed{\tau_h \le \begin{cases} 0.42 S_u(T_m) \\ 0.6 S_y(T_m) \end{cases}} \qquad (4)$$

IC 3841.4 Contact pressure limits (screw threads and heads)

The value of the average contact pressure (p_{th}) between the threads of the screw and those of the nut (or part) and the average contact pressure (p_h) between the head of the screw and the assembled part shall not exceed the following limits:

Levels A and C

$$\boxed{p_{th} \le S_y(T_m)} \qquad (5)$$

and

$$\boxed{p_h \le S_y(T_m)} \qquad (6)$$

Level D

$$\boxed{p_{th} \le 2.1S_u(T_m)} \qquad (7)$$

and

$$\boxed{p_h \le 2.1S_u(T_m)} \qquad (8)$$

IC 3842 Elasto-plastic analysis (Immediate excessive plastic deformation)

If elasto-plastic analysis is performed (for guidance, see B 3024 of Appendix B), it must be demonstrated that the specified mechanical loadings do not exceed the elasto-plastic analysis collapse load divided by the load factor of Γ_{1L} (see Table IC 3220-2). For the purpose of this rule, the elasto-plastic analysis collapse load is defined as the least of the loads at which the following conditions are satisfied:

- The significant mean (membrane) plastic strain (IC 2616) is equal to the significant mean elastic strain,

$$\boxed{\left(\bar{\varepsilon}_m\right)_{pl} = \left(\bar{\varepsilon}_m\right)_{el}} \qquad (1)$$

- The significant linear (membrane plus bending) plastic strain (IC 2616) is equal to the significant linear elastic strain,

$$\boxed{\left(\bar{\varepsilon}_{m+b}\right)_{pl} = \left(\bar{\varepsilon}_{m+b}\right)_{el}} \qquad (2)$$

An equivalent procedure based on the analysis of loads and displacements are given in IC 3211.2.

IC 3845 Fast fracture

To prevent failure caused by insufficient fracture toughness, either the elastic analysis limits of IC 3214.1 or the elasto-plastic analysis limit of IC 3214.2 must be satisfied at all times during the life of the bolt subjected to all loadings for which criteria levels A, C and D are specified.

The following definitions are used:

$K_C(T,\Phi t)$ = minimum fracture toughness defined in IC 2741 and given in A.MAT.5.8 of Appendix A

$J_{IC}(T,\Phi t)$ = minimum critical J-integral under mode I, defined in IC 2742 and given in A.MAT.5.8 of Appendix A

a_0 = postulated crack depth = max $[4a_u , d/4]$

a_u = largest undetectable crack length

d = bolt diameter

K_I = mode I (tensile) stress intensity factor associated with $P_L + Q_L$ or $P_L + P_b + Q$ loading and maximum crack length a_o

J_I = mode I J-integral (tensile) due to all loading and maximum crack length a_o

IC 3846 Elastic analysis (Fast fracture)

In all cases, a mode I (tensile) stress intensity factor K_I has to be calculated for a postulated thumbnail crack of depth a_o subjected to the prescribed loading. If the postulated crack is embedded inside a yielded region, elastic analysis rules do not apply and the elasto-plastic limit of IC 3847 has to be applied.

To prevent fast fracture, the following limit has to be satisfied at all times during the life of the bolt subjected to all loadings. The maximum mode I (tensile) stress intensity factor, K_I, due to all primary plus secondary loadings ($P_L + P_b + Q$), including disruption loading, must be limited by the following:

$$\boxed{K_I \le \gamma_1 \; K_C(T_m)} \qquad (1)$$

where

γ_1 = criteria level-dependent safety factor (Table IC 3220-1)

IC 3847 Elasto-plastic analysis (Fast fracture)

If the postulated crack for the global or local fast fracture analysis is embedded in a yielded region, elastic-plastic fracture mechanics methodology should be used. The J-integral is an acceptable criterion for such cases and, if used, its maximum value due to all loadings ($P_L + P_b + Q$) shall be limited by the following:

$$\boxed{J_1 \le \gamma_3 \; J_c(T_m)} \qquad (2)$$

where

γ_3 = criteria level-dependent safety factor (Table IC 3220-2)

IC 3850 RULES FOR THE PREVENTION OF C-TYPE DAMAGE (LEVELS A AND C)

The rules of IC 3850 and IC 3851 are to be applied to all joints, leak-tight or not, and are aimed at providing sufficient safety margins with regard to C-type damage (IC 2120) and are applicable only if the rules for the prevention of M-type damage have been satisfied.

These rules apply to all loadings for which level A or level C criteria are specified. They do not apply to loadings corresponding to level D criteria, as such loadings are presumed to be extremely unlikely and the cycles few in number.

The complete time history of combined loadings for which the levels A and C criteria are specified must be taken into account in the analysis of C-type damage. After subjecting the structure to the history of loadings, the following criterion must be satisfied at all points of the bolt.

- time-independent fatigue (IC 3320)

A criterion for progressive deformation or ratcheting need not be satisfied for the bolts because the $3S_m$ rule is always satisfied by IC 3841.1.2.

IC 3855 Time-independent fatigue

IC 3856 Limits on fatigue damage

The rules for fatigue damage depend on both the range of the stress or strain and the number of cycles. The operating periods for fatigue damage analysis must account for the complete lifetime of the bolt and all cycles to which the bolt is subjected, without duplicate counting of cycles. The rules of this section must be satisfied by combining the cycles from all operating periods.

Guidelines for stress analysis of bolts with preloads are given in B 3800 of appendix B. Guidelines for subdividing an operating period into cycles are given in B 2752.1 of appendix B. Guidelines for calculating the stress intensity range for each cycle are given in B 2550.1 and B 2550.2 of appendix B. The procedure for calculating the equivalent strain range for bolts is given below in IC 3851.2.1. Additional guidelines for calculating the equivalent strain range are given in B 2630 of appendix B.

The effects of the loading variations on fatigue damage accumulation can be estimated by the fatigue usage fraction (IC 2752). The fatigue usage fraction at a given point of the structure can be calculated using the procedure given in IC 3322.

The cumulative fatigue usage fraction V at all points of the bolt and for all cycles requiring compliance with levels A and C criteria over all operating periods must be less than 1, i.e.

$$\boxed{V \leq 1} \qquad (1)$$

IC 3857 Calculation of equivalent strain range for bolts $\overline{\Delta\varepsilon}$:

IC 3857.1 Elastic Analysis (Time-independent fatigue)

To apply the rules of this section, first the total stress intensity range and then the corresponding elastic strain range at the point under consideration must be calculated elastically for each of the cycles. These ranges can be obtained by a sufficiently detailed calculation of the region concerned, as indicated in Appendix B. Next, given the elastic strain range, corrections are made for the effects of plasticity to estimate the total strain range. Detailed instructions for making such corrections are given in IC 3323.1. However, since the stress distribution in a bolt is simpler than in a general structure, some simplified calculations can be made. The following sections describe these simplifications and, in addition, provide a procedure for accounting for the mean stress of the pre-load.

IC 3857.1.1 Nominal elastic strain range

- using the procedure outlined in IC 2552, calculate the nominal total stress intensity range for the cycle,

$$\Delta\sigma_N = \overline{\Delta\left(P_L + P_b + Q\right)} \ .$$

- calculate a nominal <u>elastic</u> strain range $\Delta\varepsilon_N$ corresponding to the nominal total stress intensity range from

$$\Delta\varepsilon_N = \frac{\Delta\sigma_N}{E}$$

where

E = Young's modulus (A.MAT.2.2 of Appendix A) at the maximum temperature T_m during the cycle,

Note: The elastic strain range thus obtained generally underestimates the total strain range, because it does not account for stress concentration effects of the threads and plastic strains which would occur if the real behavior of the material were taken into consideration .

IC 3857.1.2 Correction for stress concentration and plasticity

To account for the effects of plasticity at the notch root, Neuber's rule, as described in C 3024.1.2 of Appendix C, together with the cyclic stress-strain curve (IC 2705.2) of the material, are used to calculate the actual stress ($\Delta\sigma$) and strain ($\Delta\varepsilon$) ranges at the root of the notch

$$\Delta\sigma.\Delta\varepsilon = K_F^2.\Delta\sigma_N.\Delta\varepsilon_N$$

where K_F is the fatigue strength reduction factor (IC 2753). For bolts or other threaded members, unless it can be shown by tests or analysis that a lower value is appropriate, the fatigue strength reduction factor shall not be less than 4.

The values of $\Delta\sigma$ and $\Delta\varepsilon$ are determined by the intersection of the hyperbola $\Delta\sigma.\Delta\varepsilon$ = constant and the cyclic stress strain curve. The equivalent strain range $\Delta\varepsilon$ and equivalent stress range $\Delta\sigma$ thus determined can be used to determine the allowable fatigue cycles for the cycles under consideration after implementing the following mean stress correction.

IC 3857.1.3 Correction for mean stress

Since bolts normally operate under a very high tensile mean stress, a mean stress correction is needed for fatigue life. The mean stress correction should be made for the highest mean stress during the life of the bolt, ignoring any relaxation effects due to cycling or creep.

The correction for mean stress should be implemented by the modified Goodman approach, which is to calculate the equivalent stress range $\overline{\Delta\sigma}$ at zero mean stress and thus the equivalent strain range $\overline{\Delta\varepsilon}$ which, in turn, can be used for obtaining the allowable fatigue cycle N_d from Appendix A. The Goodman equation is:

$$\overline{\Delta\sigma} = \frac{\Delta\sigma}{1 - \sigma_m / S_u(T_m)}$$

where

S_u = minimum ultimate tensile strength, defined in IC 2722 and given in A.MAT.3.3 of Appendix A for the section averaged temperature,

σ_m = min $[S_y(T_m), K_F\sigma_{pre}]$

K_F = fatigue strength reduction factor (IC 2753)

σ_{pre} = maximum average tensile stress in bolt during loading cycle,

S_y = minimum yield strength, defined in IC 2721 and given in A.MAT.3.2 of Appendix A for the section- averaged temperature, and

$\overline{\Delta\sigma}$ = equivalent stress range at zero mean stress

IC 3857.2 Elasto-plastic analysis (Time-independent fatigue)

Determination of the equivalent strain range ($\overline{\Delta\varepsilon}$) using elasto-plastic analysis for a load cycle is carried out as follows:

- An elasto-plastic analysis following the procedure given in appendix B 3024 gives the variations of the strain components during the load cycle. The values of $\overline{\Delta\varepsilon}$ for all the strain sub-cycles of the load cycle concerned are then deduced in accordance with appendix B 2630 and B 2752.1.

  In order to ensure cyclic stabilization of the stress-strain behavior, it is recommended that the load cycle be repeated several times in succession during the elasto-plastic analysis.

IC 3860 HIGH-TEMPERATURE RULES FOR BOLTED JOINTS

(Will be issued at a later date.)

IC 4000: DESIGN RULES FOR MULTILAYER HETEROGENEOUS STRUCTURES

IC 4010 General

IC 4011 Scope of application

The following design rules apply to multilayer heterogeneous structures constructed from materials the properties of which are given in these criteria. The stress analyses required for applying the rules should be conducted using the loading data given in the component data file for the particular component and with mechanical properties and design limits for the materials given in Appendix A.

IC 4012 Purpose of the rules

The purpose of the rules is to ensure by analysis that, if the rules are satisfied, then a component does not undergo any damage beyond that described in the general criteria, IC 2300, when subjected to the categories of loadings specified in the component data file. For each category of loading condition, this requirement is satisfied by compliance with rules of the applicable criteria level, given in IC 4100 through IC 4500, at any time and at any location of the structure.

IC 4020 Methods of analysis

Analyses consist of verifying compliance with applicable rules, as described in IC 4100 and IC 4500, which are selected on the basis of the criteria level, the method of analysis, and the type of damage. In the course of this verification, practical methods of analysis are used to determine significant quantities and to compare these quantities with maximum acceptable values.

Three methods of analysis are acceptable in defining the significant quantities used in the criteria:

- elastic analysis,
- inelastic analysis,
- experimental analysis

See IC 3020 for a discussion on the various types of analysis.

Guidance for conducting elastic and inelastic analyses are given in appendix B 4020. The definition and computation of limit quantities are given in IC 2700. An overview of the relationship between rules and failure modes and of the flow of structural evaluation is given in IC3030.

A critical problem in the design of all multi-layer structure is the occurrence of elastic stress singularities at the junctions of interfaces with a free surface and the consequent potential for failure by delamination. Currently, there is no established procedure for taking these stress singularities into account in design. Therefore, the design rules given in the ISDC do not address this failure mode. The acceptability of such interfaces should be established by experiments.

IC 4040 Rules for the prevention of excessive deformations affecting functional adequacy

Any deformation limits specified in the component specification for all specified service loadings shall be satisfied. Proper account must be taken of the effect of irradiation-induced creep and swelling on deformations, if they are deemed to be significant. Guidelines for determining when such effects are negligible are given in B 3022 and B 3101 of Appendix B.

IC 4050 Negligible thermal creep test

For a multilayer heterogeneous component or a part of a component, thermal creep is negligible over the total operating period if the following summation limit is satisfied for each layer.

- The total operating period is divided into N intervals of time. For each interval i, of a duration t_i, the maximum temperature reached in the kth layer is noted $T_{i,k}$,

$$\sum_{i=1}^{N} \left(\frac{t_i}{t_{c_i,k}} \right) \leq 1, k = 1, 2, ..., n.$$

where $t_{ci,k}$ is the allowable time at temperature $T_{i,k}$, given in A.MAT.4.1 of appendix A.

If the conditions of the negligible thermal creep test (IC 4050) are satisfied, the applicable design rules are referred to as "low-temperature rules" and are given in IC 4100-4400.

If the conditions of the negligible thermal creep test (IC 4050) are not satisfied, the applicable design rules are referred to as "high-temperature rules" and are given in IC 4500.

IC 4100 LOW-TEMPERATURE RULES FOR MULTILAYER HETEROGENEOUS STRUCTURES

If the conditions of the negligible thermal creep test (IC 3050) are satisfied, the following low temperature rules are applicable:

M-type damage	level A	IC 4210
	levels C and D	IC 4220
Testing conditions criteria		IC 4230
C-type damage	levels A and C	IC 4300
	level D	None
Buckling	levels A, C, and D	IC 4400

Note: At low temperatures, non-negligible time- (or neutron fluence) dependent strains may occur due to irradiation-induced creep, with or without swelling (see IC 3030 for guidelines on when swelling-induced stresses can be ignored). A test for determining when effects of irradiation-induced creep are negligible is given in B 3101 of Appendix B. If irradiation-induced creep is non-negligible, generally an elasto-visco-plastic analysis (see B 3024.4 of Appendix B) is needed and the limits for inelastic analysis should be satisfied. However, the designer may choose to satisfy the elastic analysis limits after accounting for time- (or rate-) dependent effects using a simplified elastic-irradiation-induced creep analysis (e.g., see B 3024.1.1 of Appendix B).

IC 4200 RULES FOR THE PREVENTION OF M-TYPE DAMAGE

The rules of this article are aimed at providing sufficient safety margins with regard to M-type damage (IC 2110), excluding buckling phenomenon (IC 2130) and excessive deformation affecting functional adequacy (IC 2140). The rules to prevent buckling and excessive deformations affecting functional adequacy are dealt with in IC 3400 and IC 4040, respectively.

IC 4210 Level A criteria

At level A, the following rules for protection against M-type damage are applicable:

- immediate plastic collapse (IC 4211)
- immediate plastic instability (IC 4212)
- immediate local fracture due to exhaustion of ductility (IC 4213)
- fast fracture (IC 4214, later)

IC 4211 Immediate plastic collapse

To prevent global fracture due to immediate plastic collapse, the following limits have to be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified.

Note: Either the limits based on elastic analysis or the limits based on elastic-plastic analysis need be satisfied.

IC 4211.1 Elastic analysis (Immediate plastic collapse)

To apply the limits of this section, results from a linear elastic analysis of the multilayer component are needed. Expressions for the limits on different stress quantities are given below.

$$\boxed{P^*_{m,L} + \frac{P^*_b}{K_{ms}} \leq \frac{2}{3} S^*_y} \qquad (1)$$

where

$P^*_{m,L}$ = effective primary (general and local) membrane stress for multilayer structure (IC 2542.1 and IC 2543.1),

P^*_b = effective primary bending stress for multilayer structure (IC 2544.1),

S^*_y = effective yield strength for multilayer structure, defined in IC 2723.1

$$= \frac{1}{h} \sum_{k=1}^{k=n} \left[h_k S_{y,k}(T_k, \phi t_k) \right]$$

h = total thickness of multilayer structure

h_k = thickness of kth layer

$S_{y,k}(T_k, \phi t_k)$ = minimum yield strength at the average temperature and neutron fluence of the kth layer, given in A.MAT.3.2 of appendix A,

K_{ms} = A bending coefficient for multilayer structure defined in terms of the collapse bending moment, collapse membrane force, and the total thickness (h) of the multilayer structure as follows:

$$K_{ms} = \frac{6M_L}{hN_L}$$

N_L = collapse membrane force

$$= \sum_{k=1}^{k=n} \left[h_k S_{y,k}(T_k, \phi t_k) \right]$$

M_L = collapse bending moment

Note: A general procedure for calculating the collapse bending moment M_L of a multilayer structure is given in B 4211 of Appendix B. For a two layer heterogeneous structure,

$$K_{ms} = 1.5\left[\frac{1-\alpha\beta}{1+\beta} + \frac{2\alpha\beta}{1+\alpha\beta}\right]$$

where

$$\alpha = \frac{\left(S_{y,min}\right)_2}{\left(S_{y,min}\right)_1} \text{ and } \beta = \frac{h_2}{h_1} \text{ if } \alpha\beta \le 1$$

and

$$\alpha = \frac{\left(S_{y,min}\right)_1}{\left(S_{y,min}\right)_2} \text{ and } \beta = \frac{h_1}{h_2} \text{ if } \alpha\beta > 1$$

IC 4211.2 Elasto-plastic analysis (Immediate plastic collapse)

IC 4211.2.1 Immediate plastic collapse

If elasto-plastic analysis is performed (for guidance, see B 3024 of appendix B), it must be demonstrated that the specified mechanical loadings do not exceed the elasto-plastic analysis collapse load divided by the load factor of Γ_{1L} = 1.5 (for level A). For the purpose of this rule, the elasto-plastic analysis collapse load is defined as the least of the loads at which the following conditions are satisfied.

- The effective significant mean (membrane) plastic strain (IC 2623) is equal to the effective significant mean elastic strain of the multilayer structure,

$$\boxed{\left(\bar{\varepsilon}^*_m\right)_{pl} = \left(\bar{\varepsilon}^*_m\right)_{el}} \qquad (1)$$

- The effective significant linear (membrane plus bending) plastic strain (IC 2623) is equal to the effective significant linear elastic strain of the multilayer structure, or

$$\left(\varepsilon^*_{m+b}\right)_{pl} = \left(\varepsilon^*_{m+b}\right)_{el} \qquad (2)$$

An equivalent procedure based on the analysis of loads and displacements is given in IC 3211.2.

IC 4212 Immediate plastic instability

To prevent global fracture due to immediate plastic instability, the following limit has to be satisfied at all times during the life of the component subjected to all loadings for which criteria level A is specified.

Note: Either the limit based on elastic analysis or the limit based on elastic-plastic analysis need be satisfied.

IC 4212.1 Elastic analysis (Immediate plastic instability)

To apply the limits of this section, results from a linear elastic analysis of the multilayer component are needed. Expressions for the limits on different stress quantities are given below.

$$P^*_m \leq \frac{1}{3} S^*_u \qquad (1)$$

where

$P^*_{m,L}$ = effective primary (general and local) membrane stress for multilayer structure (IC 2542.1 and IC 2543.1),

S^*_u = effective ultimate tensile strength for multilayer structure, defined in IC 2723.1

$$= \frac{1}{h}\sum_{k=1}^{k=n}\left[h_k S_{u,k}(T_k, \phi t_k)\right]$$

$S_{u,k}(T_k, \phi t_k)$ = minimum ultimate tensile strength at the average temperature and neutron fluence of the kth layer, given in A.MAT.3.3 of appendix A,

h_k = thickness of kth layer

IC 4212.2 Elasto-plastic analysis (Immediate plastic instability)

If elasto-plastic analysis is performed, it must be demonstrated that the specified load-controlled and strain-controlled loadings do not cause damage due to plastic instability (necking). The procedure for doing this is as follows:

- Multiply mechanical loadings by the load factor Γ_{2L} (Table IC 3220-2)

- Multiply thermal and other deformation-controlled loadings (e.g., swelling-induced stress, if any) by the strain factor Γ_{2S} (Table IC 3220-2). For guidance on swelling-induced stress, see B 3024.1.1.1 of Appendix B.
- Apply both of the above loadings concurrently to the structure and perform an elasto-plastic analysis. For guidance, see B 3024 of Appendix B.
- The effective significant mean plastic strain $\left(\bar{\varepsilon}_m^*\right)_{pl}$ (IC 2623) at all times must satisfy the following limit:

$$\boxed{\left(\bar{\varepsilon}_m^*\right)_{pl} \le \frac{\varepsilon_u^*}{2}} \qquad (1)$$

where

ε_u^* = Effective uniform elongation (IC 2731.1) of the multilayer structure

$$= \frac{1}{h}\sum_{k=1}^{k=n}\left[h_k \varepsilon_{u,k}(T_k, \phi t_k)\right]$$

$\varepsilon_{u,k}$ (T_k, Φt_k) = minimum uniform elongation, defined in IC 2731 and given in A.MAT.3.4 of Appendix A, for the thickness averaged temperature and fluence of the kth layer.

IC 4213 Immediate local fracture due to exhaustion of ductility

To prevent local fracture due to exhaustion of ductility, the following limits must be satisfied by all the layers at all times during the life of the component subjected to all loadings for which criteria level A is specified.

Note: Either the limits based on elastic analysis or the limits based on elastic-plastic analysis must be satisfied. For the purposes of satisfying the limits of this section, any singular stresses or strains arising at the interfaces between various layers need not be considered. However, designers should be aware that nonsingular residual stresses created during cooldown after fabrication due to mismatches in thermal expansion coefficients of various layers may be important for highly embrittled materials. If taken into account in elastic analysis, these stresses may be considered as secondary.

IC 4213.1 Elastic analysis (Local fracture, exhaustion of ductility)

To apply the limits of this section, results from a linear elastic analysis of the component are needed. Then, the total stress for each layer k (k = 1 to n), including peak stress, is limited by

$$\boxed{\left(\overline{P_L + P_b + Q + F}\right)_k \le S_{d,k}(T_k, \phi t_k, r_2)} \qquad (1)$$

and the total stress for each layer k (k = 1 to n), excluding peak stress, is limited by

$$\boxed{\left(\overline{P_L + P_b + Q}\right)_k \leq S_{d,k}(T_k, \phi t_k, r_3)} \qquad (2)$$

where

$\left(\overline{P_L + P_b + Q + F}\right)_k$ = total primary plus secondary stress intensity including peak stresses (IC 2547) for the kth layer,

$\left(\overline{P_L + P_b + Q}\right)_k$ = total primary plus secondary stress intensity excluding peak stresses (IC 2546) for the kth layer,

$S_{d,k}$ (T_k, ϕt_k, r) = An allowable stress (IC 2725) for the material of the kth layer, dependent on the r-factor, for the temperature and fluence of the point under consideration, given in A.MAT.5.4 of Appendix A for all materials.

Note: Two sets of allowable $S_{d,k}$ values (B 2725 of Appendix B) for the total stress are tabulated in Appendix A for the material of the kth layer, one corresponding to r=r_2 applicable if peak stresses are included ($\overline{P_L + P_b + Q + F}$)$_k$ and the other corresponding to r=r_3 applicable if peak stresses are excluded ($\overline{P_L + P_b + Q}$)$_k$.

IC 4213.2 Elasto-plastic analysis (Local fracture, exhaustion of ductility)

If elasto-plastic analysis is performed, it must be demonstrated that the specified load-controlled and strain-controlled loadings do not cause local damage in each layer due to exhaustion of ductility. The procedure for doing this is as follows.

- Multiply mechanical loadings by the load factor Γ_{3L} (Table IC 3220-2)
- Multiply thermal and other deformation-controlled loadings (e.g., swelling-induced stress, if any) by the strain factor Γ_{3S} (Table IC 3220-2). For guidance on swelling-induced stress, see B 3024.1.1.1 of Appendix B.
- Apply both of the above loadings concurrently to the structure and perform an elasto-plastic analysis. For guidance, see B 3024 of appendix B.
- The significant local plastic strain $(\notin)_{pl,k}$ (IC 2616) of the kth layer at all times must satisfy

$$\boxed{(\notin)_{pl,k} \leq \frac{\varepsilon_{tr,k}(T_k, \phi t_k)}{(TF)_k}} \qquad (1)$$

where

$\varepsilon_{tr,k}$ = minimum true strain at rupture for the material of the kth layer, defined in IC 2732 and given in A.MAT.3.6 of Appendix A, for the temperature and neutron fluence of the point under consideration,

$(TF)_k$ = Triaxiality factor for the kth layer, defined in IC 2541.1

IC 4214 Fast fracture

(Will be issued at a later date)

IC 4220 Level C and D criteria, M-Type damage

At levels C and D, the same set of rules as for level A, but with different safety factors and load factors (see below), are applicable for protection against M-type damage:

- immediate plastic collapse (IC 4211) (not required for level D)
- immediate plastic instability (IC 4212)
- fast fracture (IC 4214)

Damage mechanism	Analysis	Section reference	Safety & load factors
immediate plastic collapse	Elastic Inelastic	IC 4211.1 IC 4211.2 *	Table IC 3220-1 Table IC 3220-2
immediate plastic instability	Elastic Inelastic	IC 4212.1 IC 4212.2	Table IC 3220-1 Table IC 3220-2
immediate local fracture, exhaustion of ductility	Elastic Inelastic	IC 4213.1 IC 4213.2	Table IC 3220-1 Table IC 3220-2
fast fracture		IC 4214	(later)

* Not required for level D.

As in level A, either the limits based on elastic analysis or the limits based on elasto-plastic analysis need to be satisfied. The applicable safety factors and load factors for elastic analysis rules and elasto-plastic analysis rules are given in tables IC 3220-1 and IC 3220-2, respectively.

IC 4300 RULES FOR THE PREVENTION OF C-TYPE DAMAGE (LEVELS A AND C)

The rules of this article are aimed at providing sufficient safety margins with regard to C-type damages (IC 2120) and are applicable only if the rules for the prevention of M-type damage have been satisfied.

These rules apply to all loadings for which level A or level C criteria are specified. They do not apply to loadings corresponding to level D criteria, as such loadings are presumed to be extremely unlikely and the cycles few in number.

The complete time history of combined loadings for which the levels A and C criteria are specified must be taken into account in the analysis of C-type damage. After subjecting the structure to the history of loadings, the following criteria must be satisfied at all points of the structure.

- progressive deformation or ratcheting (IC 4310)
- time-independent fatigue (IC 4320)

To simplify the analysis, the complete time history may be subdivided into separate operating periods, each of which may include one or more types of cycles. The way in which the operating periods are combined depends on the specific limits being evaluated, as described in the following sections.

IC 4310 Progressive deformation or ratcheting

Either the rule for elastic analysis (IC 4311) or the rule for elasto-plastic analysis (IC 4312) must be applied.

IC 4311 Elastic analysis (Progressive deformation or ratcheting)

The elastic analysis rules for progressive deformation depend on the range of the stress or strain during a cycle but not the number of cycles and must be satisfied for each individual operating period. It may be shown that the limits are satisfied by considering only bounding cases.

To apply the rules of this paragraph, the maximum values of the following five quantities over the time for each operating period need to be determined for each layer first:

- maximum thickness-averaged temperature: Max $T_{m,k}$,
- maximum local primary membrane plus bending stress intensity (excluding plasma disruption loadings): Max $\left(\overline{P_L + P_b}\right)_k$,
- maximum range of stress intensity due to disruption loadings: $\overline{\Delta P_k}$
- maximum in the thickness secondary stress intensity range: $\overline{\Delta Q_k}$.
- maximum in the thickness stress intensity range: $\Delta\left[\overline{P} + \overline{Q}\right]_k = \overline{\Delta P_k} + \overline{\Delta Q_k}$.

It is important that the stress state be identical at the beginning and at the end of the operating period concerned.

To prevent the occurrence of progressive deformation on the basis of elastic analysis, the 3 S_m rule (IC 4311.1) may be used.

IC 4311.1 $3S_m$ rule

For each operating period, the following criteria must be satisfied at all points of all the layers in the structure:

$$\boxed{\text{Max}\left(\overline{P_L + P_b}\right)_k + \Delta\left[\overline{P} + \overline{Q}\right]_k \leq 3S_{m,k}} \quad (1)$$

where

$S_{m,k}$ = allowable stress, defined in IC 2723 and given in A.MAT.5.1, for the thickness-averaged temperature and neutron fluence of the kth layer.

IC 4312 Elasto-plastic analysis (Progressive deformation or ratcheting)

The rules for progressive deformation using elasto-plastic analysis are based on the total plastic strain accumulated over the complete loading history for which level A or level C criteria are specified. To calculate the accumulated strain, an incremental cyclic elasto-plastic analysis should be conducted until cyclic stabilization, giving either the exact value or an upper bound to the strains resulting from all the cycles envisaged.

Two forms of limits are given on the accumulated plastic strain, depending on the ductility of the material. For a material with high ductility, the limit is expressed simply as a maximum allowable strain. For a material with reduced ductility, the limit is expressed in incremental form to account for the effect of time-varying ductility. This gives the designer the option to take credit for the fact that incremental strains that occur while the material is ductile are less damaging than incremental strains that occur while the ductility is reduced.

In the incremental form of the rule, the complete operating history is divided into N time-blocks. Each block may include several loading and stress-strain cycles. The length of a block is determined by the time period in which the ductility can be assumed constant. Within each block, the strain limits are defined as the lowest values that may occur during that time interval. Optionally, the analyst may elect to use only one block, in which case the strain limit shall correspond to the lowest value during the entire loading history. For each block i, the following definitions are used:

$\varepsilon_{tr,ki}$ = minimum true strain to rupture of the kth layer, defined in IC 2732 and given in A.MAT.3.6 of Appendix A, for the temperature T_{ki} and neutron fluence Φt_{ki} at the point under consideration with T_{ki} and Φt_{ki} defined such that $\varepsilon_{tr,ki}$ has the lowest value during the interval i,

$\left(\varepsilon_{tr,k}\right)_{min}$ = minimum value of $\varepsilon_{tr,ki}$ of the kth layer at any time during the total operating period,

$\varepsilon_{u,ki}$ = minimum uniform elongation of the kth layer, defined in IC 2731 and given in A.MAT.3.4 of Appendix A, for the thickness-averaged temperature T_{mki} and neutron fluence ϕt_{mki} with T_{mki} and Φt_{mki} defined such that $\varepsilon_{u,ki}$ has the lowest value during the interval i,

$\varepsilon^*_{u,i}$ = effective uniform elongation, defined in IC 2731.1, during interval i

$$= \frac{1}{h}\sum_{k=1}^{k=n}\left[h_k \varepsilon_{u,ki}(T_{mki}, \phi t_{mki})\right]$$

$\left(\varepsilon^*_u\right)_{min}$ = minimum value of $\varepsilon^*_{u,i}$ at any time during the total operating period,

$T_{\kappa i}$ = temperature at the point under consideration of the kth layer during interval i,

Φt_{ki} = neutron fluence at the point under consideration of the kth layer during interval i,

$T_{m\kappa i}$ = thickness-averaged temperature of the kth layer during interval i,

Φt_{mki} = thickness-averaged neutron fluence of the kth layer during interval i,

t_i	=	duration of interval i
TF_{ki}	=	maximum triaxiality factor (IC 2543) of kth layer during interval i.
Δ	=	symbol preceding a strain quantity that refers to the increment in that strain quantity during the interval i, noting that interval i may include several stress-strain cycles.

IC 4312.1 Effective significant mean plastic strain (Elasto-plastic, ratcheting)

The effective significant mean plastic strain at all times must satisfy one of the following two limits, Eq. (1) or (2). First, check if the following more conservative limit is satisfied:

$$\boxed{\left(\bar{\varepsilon}^*_m\right)_{pl} \le 0.5\,\lambda_1 \left(\varepsilon^*_u\right)_{min}} \qquad (1)$$

where

λ_1	=	a safety factor dependent on the criteria level (Table IC 3312-1)
$\left(\bar{\varepsilon}^*_m\right)_{pl}$	=	effective significant mean plastic strain (IC 2623).

If Eq. 1 above cannot be satisfied, the time history may be subdivided into blocks, and the effective significant mean plastic strain increments at all times must satisfy the following summation limit:

$$\boxed{\sum_{\substack{i=1 \\ \text{blocks}}}^{N} \frac{\left(\Delta\bar{\varepsilon}^*_m\right)_{pl,i}}{\varepsilon^*_{u,i}} \le 0.5\,\lambda_1} \qquad (2)$$

where

$\left(\Delta\bar{\varepsilon}^*_m\right)_{pl,i}$	=	effective significant mean plastic strain increment (IC 2623) during interval i

IC 4312.2 Significant local plastic strain (Elasto-plastic, ratcheting)

The significant local plastic strain of the kth layer at all times must satisfy one of the following two limits, Eq. (3) or (4). First, check if the following more conservative limit is satisfied:

$$\boxed{\left(\bar{\varepsilon}_k\right)_{pl} \le \min\left[5\%, \lambda_2 \left(\varepsilon_{tr,k}\right)_{min}\right]} \qquad (3)$$

where

λ_2 = a safety factor dependent on the criteria level (Table IC 3312-1)

$\left(\bar{\varepsilon}_k\right)_{pl}$ = significant local plastic strain (IC 2616) of the kth layer

If Eq. 3 above cannot be satisfied, the time history may be subdivided into blocks, and the significant local plastic strain increments in each of the kth layer (k =1 to n) at all times must satisfy the following summation limit:

$$\boxed{\sum_{\substack{i=1 \\ \text{blocks}}}^{N} \frac{\left(\Delta\bar{\varepsilon}_k\right)_{pl,i}}{\varepsilon_{tr,ki} \;/\, TF_{ki}} \le \lambda_2} \qquad (4)$$

where

$\left(\Delta\bar{\varepsilon}_k\right)_{pl,i}$ = the increment of significant local plastic strain (IC 2616) in the kth layer during interval i.

IC 4320 Time-independent fatigue

The rules for time-independent fatigue of a single layer structure are given in IC 3320. The same rules should be satisfied by all the layers in a multilayer structure.

Note: The current method of fatigue design does not address the potential for failure by delamination initiating at the junction of an interface with a free surface where an elastic stress singularity exists. The ability of such interfaces to withstand cyclic thermal and mechanical loadings should be established by experiments.

IC 4400 BUCKLING RULES (LEVELS A, C, AND D)

The rules for buckling of a multilayer structure are the same as those of a single layer structure given in IC 3400.

IC 4500 HIGH-TEMPERATURE RULES FOR MULTILAYER HETEROGENEOUS STRUCTURES

(Will be issued at a later date.)