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Railway applications — Strength assessment of rail vehicle structures

Part 3: Fatigue strength assessment based on cumulative damage

National foreword

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European foreword

This document (EN 17149-3:2025) has been prepared by Technical Committee CEN/TC 256 “Railway applications”, the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by July 2025, and conflicting national standards shall be withdrawn at the latest by July 2025.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document is part of the EN 17149 series, *Railway applications — Strength assessment of railway vehicle structures*, which consists of the following parts:

- *Part 1: General;*
- *Part 2: Static strength assessment;*
- *Part 3: Fatigue strength assessment based on cumulative damage.*

Any feedback and questions on this document should be directed to the users’ national standards body. A complete listing of these bodies can be found on the CEN website.

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Introduction

If a fatigue strength assessment is necessary for rail vehicle structures, this assessment may be made with an endurance limit approach or a cumulative damage approach.

An endurance limit approach is based on the assessment of the stress ranges (e.g. derived from the design load cases or from measurements) against an admissible endurance limit. Such an approach is applicable in combination with the loads given in the EN 12663 series or EN 13749.

A fatigue strength assessment based on cumulative damage takes into consideration stress spectra with variable amplitudes and numbers of cycles or stress time histories. This document provides the basic procedure and criteria for a pragmatic method to be applied for fatigue strength assessments based on the cumulative damage approach.

This document does not provide any procedures or criteria for an endurance limit approach. However, the fatigue strength data included in this document can also be applicable for an endurance limit approach.

The main body of the document is based on the nominal stress approach, but the consideration of variable amplitudes and number of cycles using methods described in this standard may equally be applied with the structural stress and the notch stress approach (additional information for these assessment methods is included as informative annexes).

Within this document, the term fatigue strength assessment is always related to the cumulative damage approach unless otherwise noted.

1 Scope

This document describes a procedure for fatigue strength assessment based on cumulative damage of rail vehicle structures that are manufactured, operated and maintained in accordance with standards valid for rail system applications.

This document is applicable for variable amplitude load data with total number of cycles higher than 10 000 cycles.

An endurance limit approach is outside the scope of this document.

The assessment procedure is restricted to ferrous materials and aluminium.

This document does not define design load cases.

This document is not applicable for corrosive conditions or elevated temperature operation in the creep range.

This document is applicable to all kinds of rail vehicles; however, it does not define in which cases a fatigue strength assessment using cumulative damage is to be applied.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 15085-3:2022+A1:2023, *Railway applications — Welding of railway vehicles and components — Part 3: Design requirements*

EN 17149-1:2024, *Railway applications — Strength assessment of rail vehicle structures — Part 1: General*

ISO/TR 25901-1:2016, *Welding and allied processes — Vocabulary — Part 1: General terms*

3 Terms and definitions

For the purposes of this document, the terms, definitions, symbols and abbreviations given in ISO/TR 25901-1:2016 and EN 17149-1:2024 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org>

4 Stress determination

4.1 General

Fatigue loads acting on a component cause fatigue stresses that can be expressed as a stress spectrum. The stress spectrum used to perform the fatigue strength assessment based on cumulative damage approach shall be expressed in terms of stress ranges, mean stresses and number of cycles to represent the design life.

The design stress spectrum shall incorporate any necessary allowance to account for uncertainties in their values (see 6.2).

NOTE The EN 12663 series, EN 15827 and EN 13749 contain information on how to determine design loads for cumulative damage assessment of rail vehicles.

The combination of the individual stress components direct stress and shear stress is considered in 7.5.

4.2 Parent material

The stresses for the parent material shall be determined as described in EN 17149-1:2024, 5.1 and 5.2.

4.3 Welded joints

4.3.1 Modified nominal stresses

The modified nominal stresses for welded joints shall be determined in accordance with EN 17149-1:2024, 5.1 and 5.3.

4.3.2 Structural stresses and notch stresses

For the fatigue strength assessment of welded joints, the structural stress approach and the notch stress approach may be applied. For the application of these approaches, the requirements for the calculation of the relevant stresses and fatigue strength are described in the following informative annexes:

- Annex G for the structural stress approach and
- Annex H for the notch stress approach.

5 Fatigue strength

5.1 Parent material

5.1.1 General

This clause describes the method to derive the fatigue strength of parent material under the following conditions:

- materials used such as construction steel, weldable cast steel, cast iron (GJS and ADI), steel (rolled or forged), cast aluminium, and wrought aluminium;
- application temperature up to 100 °C for aluminium and up to 200 °C for steel;
- plane stress tensor on the components surface (no significant stress component perpendicular to the surface as would occur e.g. with a press fit connection).

The restrictions specified above are met with most applications of parent material for rail vehicles, in which case a simplified assessment method is appropriate. If the scope of the application is exceeded, an assessment method shall be chosen which accounts for the specific application (e.g. high temperatures or 3-dimensional stress states).

Annex C gives an overview of the applicable material factors.

5.1.2 Component fatigue strength $\Delta\sigma_R$ and $\Delta\tau_R$

The fatigue strength is specified by S-N curves, which specify the values of the component fatigue strength expressed as stress range $\Delta\sigma_R$ and $\Delta\tau_R$ (in N/mm², unless stated otherwise) related to:

- $N_C = 10^6$,
- stress ratio $R_\sigma = R_\tau = -1$,
- survival probability of $P_s = 97,5\%$,
- membrane stresses.

The values of the component fatigue strength are determined with Formula (1) and Formula (2):

$$\Delta\sigma_R \left(N_C = 10^6, R_\sigma = -1 \right) = R_m \cdot f_{R,\sigma} \cdot f_{SR,\sigma} \cdot f_{R,C} \quad (1)$$

$$\Delta\tau_R \left(N_C = 10^6, R_\tau = -1 \right) = R_m \cdot f_{R,\tau} \cdot f_{R,\sigma} \cdot f_{SR,\tau} \cdot f_{R,C} \quad (2)$$

5.1.3 Material properties

5.1.3.1 Tensile strength in accordance with material standards $R_{m,N}$

$R_{m,N}$ is the nominal tensile strength in accordance with the material standards considering the actual sheet thickness. For machined components, the thickness of the semi-finished product before machining shall be considered.

For rolled sheets and extrusions an anisotropy factor f_A shall be considered in the direction transverse to the main direction of rolling in accordance with Table 1, unless this is already considered or explicitly excluded in the material standard or component specification. For other material applications $f_A = 1,0$.

$$R_m = f_A \cdot R_{m,N} \quad (3)$$

Table 1 — Anisotropy factor f_A for steel and aluminium

Material	$R_{m,N}$ [N/mm ²]	f_A
Rolled Steel	≤ 600	0,9
	> 600 ≤ 900	0,86
Rolled sheets and extrusions of aluminium	≤ 200	1,0
	> 200 ≤ 400	0,95
	> 400 ≤ 600	0,9
All other material applications	Any value	1,0
Heat-affected zone	Any value	1,0

For heat-affected zones in the vicinity of welded joints the nominal tensile strength for the heat-affected zone $R_{m,HAZ}$ shall be used instead of R_m . The value for $R_{m,HAZ}$ shall be derived from technical literature.

NOTE Examples for such technical literature are [2], [5], [57], [58].

5.1.3.2 Tensile strength specified by drawing or specification $R_{m,S}$

As an alternative to a material standard, the mechanical properties may be specified by the drawing or specification.

$R_{m,S}$ is the tensile strength in accordance with a drawing or component specification. If higher values than those specified in the material standards are specified for $R_{m,S}$ and the values are checked only by random testing, then the specified values are not sufficiently reliable and therefore would be non-conservative to use for the purposes of a fatigue strength assessment. To perform a fatigue strength assessment with a survival probability of $P_S = 97,5\%$ the tensile strength $R_{m,S}$ specified by the drawing or component specification shall be reduced in accordance with Formula (4):

$$R_m = f_{Rm,S} \cdot R_{m,S} \quad (4)$$

If the strength value is checked by three random tests (e.g. hardness test or tensile test) a value of $f_{Rm,S} = 0,94$ is applicable. For other numbers of tests, this value shall be adjusted in accordance with technical literature (e.g. [2]).

If a validated $P_S = 97,5\%$ value within the component is available, $f_{Rm,S}$ may be set to 1,0.

NOTE Strength values verified with 3.1 certificate in accordance with EN 10204 are examples for such validated values.

The $R_{m,N}$ values specified in material standards for a given wall thickness may be used for the purposes of fatigue strength assessment with a survival probability of $P_S = 97,5\%$.

5.1.3.3 Influence of technological size

The assessment method described in this standard does not make any adjustment for the wall thickness of the component. The strength properties used shall consider the appropriate wall thickness.

For components made from semi-finished products the strength properties shall consider the wall thickness of the semi-finished product before machining.

5.1.3.4 Influence of application temperature

If the component operating temperature remains within the scope of applicability specified by this standard, no further adjustment to account for the application temperature is required for the fatigue strength assessment.

5.1.4 Design Parameters

5.1.4.1 Surface roughness factor f_{SR}

The surface roughness factor f_{SR} depends on the material, the nominal tensile strength R_m , the surface roughness R_Z and the manufacturing process and is specified by Formula (5) and Formula (6).

$$f_{SR,\sigma} = f_{SR,edge} \cdot \left(1 - a_{R,\sigma} \cdot \log \frac{R_Z}{[\mu m]} \cdot \log \frac{2 R_m}{b_R} \right) \quad (5)$$

$$f_{SR,\tau} = f_{SR,edge} \cdot \left(1 - f_{R,\tau} \cdot a_{R,\sigma} \cdot \log \frac{R_Z}{[\mu m]} \cdot \log \frac{2 R_m}{b_R} \right) \quad (6)$$

$a_{R,\sigma}$ and b_R are given in Table 2, $f_{SR,edge}$ and R_Z are given in Table 3 and $f_{R,\tau}$ is given in Table 4.

Table 2 — Factors $a_{R,\sigma}$ and b_R for steel and aluminium

Material	$a_{R,\sigma}$	b_R [N/mm ²]
Steel (rolled or forged)	0,22	400
Steel castings	0,20	400
Spheroidal graphite cast iron (GJS)	0,16	400
Ausferritic spheroidal graphite cast iron (ADI)	0,16	400
Wrought aluminium	0,22	133
Cast aluminium	0,20	133

Typical values of the surface roughness R_Z correlating to the average surface roughness R_a are given in Table 3. The factor $f_{SR,edge}$ accounts for the effect of thermal cut edges of steel.

Table 3 — Typical values for R_Z , R_a and $f_{SR,edge}$

R_Z [μm]	R_a [μm]	$f_{SR,edge}$	Example
a	a	1,0	Plate surface or machined edge of steel
80 ^b	25 ^b	1,0	Shot blasted rolled sheet surface; Rolled sheet and extrusions of aluminium
200 ^b	50 ^b	1,0	Rolled sheet surface of steel, not shot blasted; Forged steel; Cast surface
50 ^b	12,5 ^b	0,81	Thermal flame cutting of steel, shot blasted
200 ^b	50 ^b	0,81	Thermal flame cutting of steel, not shot blasted
25 ^b	6,3 ^b	0,94	Plasma or laser cut plate edges of steel, shot blasted
200 ^b	50 ^b	0,94	Plasma or laser cut plate edges of steel, not shot blasted
200	50	1,0	Plasma or laser cut plate edges of aluminium, not shot blasted. (An improvement in the surface roughness factor is only applicable if the affected material (typically 2 mm) is completely removed by machining after cutting.)

^a The values in accordance with the drawing or component specification shall be used. When applied to castings the benefit of machined surfaces is only applicable if the machined surface is free from surface breaking defects.

^b If explicit values for surface roughness are specified in the drawing or component specification those values shall be used for the fatigue strength assessment. When applied to castings the benefit of machined surfaces is only applicable if the machined surface is free from surface breaking defects.

For plate edges of rolled sheets the following requirements shall be applied:

- Sharp corners and surface rolling flaws shall be removed by longitudinal grinding or during subsequent manufacturing processes, for example shot blasting;
- cracks or visible gouges are not permitted;
- weld repairs shall be treated as welded joints;
- notch effects due to shape of edges shall be considered;
- minimum corner radius or chamfer 1 mm;
- all burrs shall be removed.

For plate edges of steel manufactured by plasma and laser cut the surface roughness factor for cut edges $f_{SR,edge}$ shall be applied in accordance with Table 3.

For plate edges of aluminium, manufactured by plasma or laser cut a surface roughness of $R_z = 200 \mu\text{m}$ shall be applied independent of the actual surface roughness to account for the local metallurgical effects. An improvement in the surface roughness factor is only applicable if the affected material (typically 2 mm) is completely removed by machining after cutting.

The values are valid for nominal stress without the consideration of any stress gradients perpendicular to the surface. In the case of a stress gradient perpendicular to the surface (e.g. stress concentration) the influence of the surface roughness may be reduced in accordance with technical literature, e.g. [2].

5.1.4.2 Influence of stress gradient

In the assessment method described in this standard the benefit for the fatigue strength associated with the stress gradient perpendicular to the surface (e.g. due to stress concentration or bending stress) is not included in the fatigue strength values.

The beneficial effects of stress gradients may be considered in accordance with technical literature, e.g. [2].

5.1.4.3 Influence of surface treatment

As a conservative approach in this simplified assessment method the benefit for the fatigue strength associated with the surface treatment (e.g. peening) is not included.

The beneficial effects of the surface treatment may be considered in accordance with technical literature, e.g. [2].

5.1.5 Fatigue strength factors for direct stresses $f_{R,\sigma}$ and for shear stresses $f_{R,\tau}$

For the determination of the component fatigue strength (stress range) for parent material the fatigue strength factors given in Table 4 shall be used. These fatigue strength factors are related to $N_C = 10^6$ cycles and a stress ratio of $R = -1$ and correspond to a survival probability of $P_S = 97,5 \%$.

Table 4 — Fatigue strength factors for direct stresses and shear stresses related to $N_C = 10^6$ cycles

Material	$f_{R,\sigma}$	$f_{R,\tau}^a$
Steel (rolled or forged)	0,75	0,577
Steel castings	0,57	0,577
Spheroidal graphite cast iron (GJS)	$0,42 + \frac{117 \text{ N / mm}^2}{R_m}$	0,65
Ausferritic spheroidal graphite cast iron (ADI)	$\frac{492 \text{ N / mm}^2}{R_m}$	0,7
Wrought aluminium	0,6	0,577
Cast aluminium	0,6	0,75
^a Ratio between the fatigue strength of shear stress and the one of direct stress.		

NOTE For steel castings and spheroidal graphite cast iron, the fatigue strength factors $f_{R,\sigma}$ given in Table 4 are derived in accordance with [2] (fatigue strength factor for alternating direct stresses $f_{w,\sigma}$). The fatigue strength factors represent the fatigue strength ratio with respect to stress range, these factors include a margin of 1,2 as given in [2] to cover uncertainties. For aluminium, the fatigue strength factors given in Table 4 are determined in accordance with test results.

5.1.6 Correction factor for casting $f_{R,C}$

The NDT-level and the corresponding casting quality level applied for castings have an influence on the fatigue strength values for the cast component. The correction factor for casting $f_{R,C}$ accounts for the effects of any remaining defects on the fatigue strength within the casting component. For all non-cast components $f_{R,C} = 1,0$.

In the case of structural castings, it is necessary to specify the quality requirements with respect to the permitted volumetric and surface defect levels to guarantee the mechanical properties to be achieved in regions subjected to high stresses. The relevant mechanical properties and quality requirements shall be verified in accordance with the component specification.

The correction factor for casting $f_{R,C}$ shall be chosen in accordance with the casting quality achieved in the cast component. The values given in Table 5 may be used for castings depending on the NDT-level during production and the verified quality level in accordance with Annex B.

Table 5 — Correction factor for casting $f_{R,C}$

Volumetric inspection by NDT		Inspection of surface conditions		Correction factor for castings $f_{R,C}$
Relevant Standard	Quality level in accordance with ASTM	Relevant standard	Quality class	
The EN 12680 series (UT) The EN 12681 series (RT)	Level 3	EN 1369	LM3, AM3, SM4	0,8
		EN 1370	4S1/5S2, VC3	
		EN 1371-1	LP3, AP3 SP3/CP3	
	Level 2	EN 1369	LM2, AM2 SM2	0,9
		EN 1370	3S1/3S2, VC2	
		EN 1371-1	LP2, AP2 SP2/CP2	

The specification of castings needs to ensure appropriate cast quality to maintain the applicability of the assessment method specified in this document. Informative Annex B gives an example for the casting specification requirements related to volumetric quality levels.

An enhancement of the correction factor $f_{R,C}$ up to 1,0 is applicable, if the fatigue strength values within the component are proven by corresponding tests using test specimens extracted from these regions of the component and corresponding quality assurance measures for the manufacturing process.

A strength assessment method that does not consider the internal casting defects (e.g. voids) in components during the stress determination (e.g. a FEA model representing nominal geometry) should be restricted to castings of quality level 3 or better. For components or parts of components that are not stressed significantly inferior quality levels may also be applied.

For an assessment of such castings, it should be considered that bigger defects can affect significantly the actual stress distributions (e.g. due to locally reduced sections). Therefore, these effects should either be considered for the determination of the stress distribution or the correction factor for castings $f_{R,C}$ should be reduced accordingly.

5.1.7 S-N curves and methods of cumulative damage rule

For S-N curves of parent material all relevant information is given in Table 6 and Table 7.

Table 6 — Parameters for S-N curves

Cumulative damage rule	Exponent beyond knee point N_D	Cut-off limit $\Delta\sigma_L$	Damage sum limit $D_{m,min}$
Modified version of Miner's rule	$2m-1^a$	$0,5 \Delta\sigma_D$	1,0 for spheroidal graphite cast iron, (GJS, ADI), 0,3 for all other materials
Consistent version of Miner's rule	m_2 for austenitic steel and aluminium	-	1,0 for spheroidal graphite cast iron, (GJS, ADI), 0,3 for all other materials
^a No specific symbol is assigned to the exponent beyond the knee point N_D , the slope is specified only by the formula above.			

In Figure 1, the principal representation of S-N curves is given for parent material for direct stress. For S-N-curves of shear stresses the symbol σ is replaced by symbol τ .

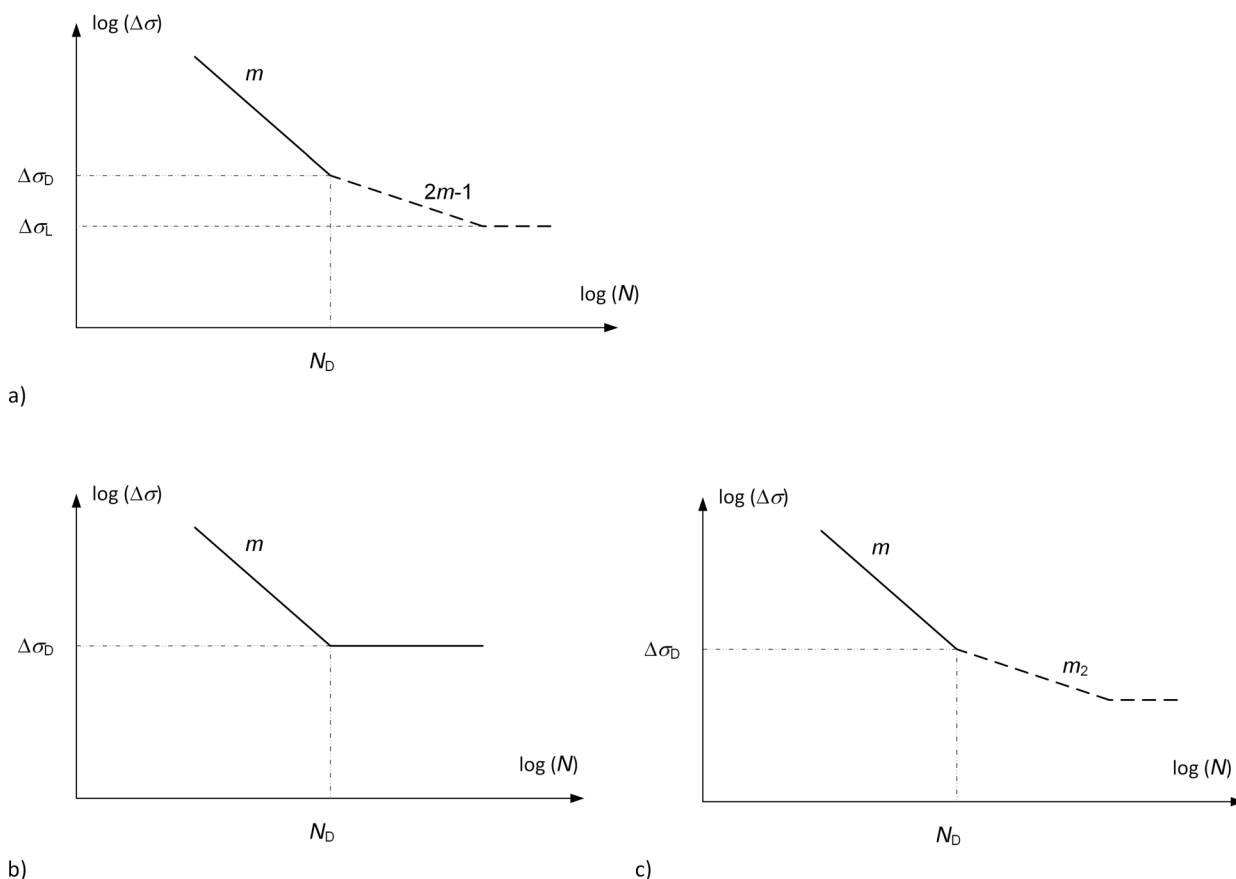


Figure 1 — S-N curves for parent material for direct stresses: a) Miner modified; b) Miner consistent for ferritic steel, steel castings and spheroidal graphite cast iron; c) Miner consistent for austenitic steel and aluminium

For parent material, the knee point position N_D is at 10^6 cycles.

Since $N_D = N_C$ Formula (7) and Formula (8) apply:

$$\Delta\sigma_D (R = -1) = \Delta\sigma_R \quad (7)$$

$$\Delta\tau_D (R = -1) = \Delta\tau_R \quad (8)$$

For parent materials austenitic steel and aluminium, the exponent beyond the knee point until a second knee point at $N_{D,2} = 10^8$ cycles is given in Table 7. This is only necessary for application of the consistent version of Miner's rule.

Table 7 — Material-related values for S-N curve parameters

Material	Stress type	Exponent of S-N curve m	Exponent of S-N curve m_2 for consistent version of Miner's rule	Second knee point $N_{D,2}$ for consistent version of Miner's rule
Ferritic steel	Direct stress	5	-	-
	Shear stress	8	-	-
Austenitic steel	Direct stress	5	15	10^8
	Shear stress	8	25	10^8
Steel castings	Direct stress	7	-	-
	Shear stress	8	-	-
Spheroidal graphite cast iron (GJS, ADI)	Direct stress	7	-	-
	Shear stress	8	-	-
Wrought aluminium and cast aluminium	Direct stress	5	15	10^8
	Shear stress	8	25	10^8

5.2 Welded joints

5.2.1 General

5.2 describes the determination of fatigue strength values related to nominal stress approach. For other stress approaches, the determination of fatigue strength values is described in Annex G for the structural stress approach and Annex H for the notch stress approach.

NOTE Heat-affected zones are assessed in accordance with 5.1.3.1.

5.2.2 Fatigue classes $\Delta\sigma_C$ and $\Delta\tau_C$

The fatigue strength is specified by S-N curves. The fatigue strength S-N curves for welded joints and components are represented by fatigue classes $\Delta\sigma_C$ and $\Delta\tau_C$ (in N/mm², unless stated otherwise) related to:

- $N_C = 2 \times 10^6$ cycles;
- stress ratio $R = 0,5$;
- survival probability of $P_S = 97,5 \%$;
- membrane stresses.

The fatigue classes $\Delta\sigma_C$ and $\Delta\tau_C$ are valid for plate thickness

- $t_{ref} = 25$ mm for welded joints of steel and

— $t_{\text{ref}} = 10 \text{ mm}$ for welded joints of aluminium.

The fatigue classes $\Delta\sigma_C$ and $\Delta\tau_C$ are presented in the tables of Annex D for notch cases representing different weld types and joint details of welded rail vehicle structures of steel and aluminium for quality level C in accordance with EN ISO 5817 or EN ISO 10042. 5.2.7 provides information for the adjustment of the admissible values for other quality levels.

5.2.3 Component fatigue strength $\Delta\sigma_R$ and $\Delta\tau_R$

The values of the component fatigue strength with respect to the stress range $\Delta\sigma_R$ and $\Delta\tau_R$ related to $N_C = 2 \times 10^6$ cycles and to the stress ratio $R_\sigma = -1$ respectively $R_\tau = -1$ are described using Formula (9) and Formula (10):

$$\Delta\sigma_R \left(N_C = 2 \times 10^6, R_\sigma = -1 \right) = \Delta\sigma_C \cdot f_{\text{thick}} \cdot f_{\text{res},\sigma} \cdot f_{\text{post}} \cdot f_{\text{QL}} \cdot f_{\text{CT}} \quad (9)$$

$$\Delta\tau_R \left(N_C = 2 \times 10^6, R_\tau = -1 \right) = \Delta\tau_C \cdot f_{\text{thick}} \cdot f_{\text{res},\tau} \cdot f_{\text{post}} \cdot f_{\text{QL}} \cdot f_{\text{CT}} \quad (10)$$

5.2.4 Influence of thickness f_{thick} and bending

The influence of the thickness is considered by the thickness correction factor f_{thick} . This factor depends on the plate thickness t , the reference thickness t_{ref} and the exponent in correction term for thickness n .

For plate thickness $t \geq t_{\text{ref}}$ the thickness correction factor shall be applied using Formula (11).

$$f_{\text{thick}} = \left(\frac{t_{\text{ref}}}{t} \right)^n \quad \text{for } t \geq t_{\text{ref}} \quad (11)$$

where

- $n = \min(n_{\sigma,\perp}; 0,2)$ for direct stresses transverse to the weld if f_{post} is applied due to grinding, TIG dressing or welds ground flush,
- $n = n_{\sigma,\perp}$ for direct stresses transverse to the weld in all other cases,
- $n = n_{\sigma,\parallel}$ for direct stresses longitudinal to the weld,
- $n = n_\tau$ for shear stresses.

Values for $n_{\sigma,\perp}$, $n_{\sigma,\parallel}$ and n_τ are given in Annex D.

As a conservative approach for plate thickness $t < t_{\text{ref}}$ the thickness correction factor may be applied using Formula (12). A more detailed approach may be applied. Annex E gives an example of such an approach including influences of thickness and effects of bending.

$$f_{\text{thick}} = 1,0 \text{ for } t < t_{\text{ref}} \quad (12)$$

NOTE At potential crack initiation points with a high notch effect (e.g. roots or weld toes with a small weld toe angle) the influence of a reduced plate thickness is different in comparison to those of crack initiation points with a low notch effect (e.g. toes at butt welds or at toes of asymmetric fillet welds with a higher weld toe angle). This is covered by the exponent in correction term for thickness n .

5.2.5 Residual stress factors $f_{\text{res},\sigma}$ and $f_{\text{res},\tau}$

The mean stress sensitivity is considered by the mean stress factors $f_{\text{m},\sigma}$ and $f_{\text{m},\tau}$ as explained and specified in 7.3.4.

For welded joints, the fatigue classes $\Delta\sigma_{\text{C}}$ and $\Delta\tau_{\text{C}}$ as specified in Annex D relate to a stress ratio $R_{\sigma} = 0,5$ and $R_{\tau} = 0,5$, whereas the component fatigue strength values $\Delta\sigma_{\text{R}}$ and $\Delta\tau_{\text{R}}$ derived in accordance with Formula (9) and Formula (10) relate to a stress ratio $R_{\sigma} = -1$ and $R_{\tau} = -1$. The influence on the strength values due to the different stress ratios is considered by the factors $f_{\text{res},\sigma}$ and $f_{\text{res},\tau}$.

The factors $f_{\text{res},\sigma}$ and $f_{\text{res},\tau}$ shall be determined as the inverse values of the mean stress factors $f_{\text{m},\sigma}$ and $f_{\text{m},\tau}$ for the stress ratio $R = 0,5$.

Although no normative requirements for the determination of the mean stress factors $f_{\text{m},\sigma}$ and $f_{\text{m},\tau}$ are specified, it is mandatory to apply the same method for the determination of the mean stress factors $f_{\text{m},\sigma}$ and $f_{\text{m},\tau}$ both in the derivation of the factors $f_{\text{res},\sigma}$ and $f_{\text{res},\tau}$ and in the application of the mean stress adjustment as specified in 7.3.4 and Formula (19).

In welded structures, the manufacturing process and welding process induce residual stresses in the structure. The mean stress sensitivity considers the effects of the residual stress state of the finished structure. A higher mean stress sensitivity resulting in higher values for $f_{\text{res},\sigma}$ and $f_{\text{res},\tau}$ may be assumed in welded structures when stress relief heat treatment is carried out after welding.

New residual stresses can occur if weld repairs or straightening (e.g. to remove distortion) are undertaken after the stress relief heat treatment. In such cases the residual stress factor for the as welded condition shall be applied for the affected region. If, however, it can be demonstrated that the residual stresses have not significantly increased compared to the stress relieved condition, then alternative values for the residual factors may be considered provided they can be justified.

Annex A includes an informative method for the determination of the mean stress factors $f_{\text{m},\sigma}$ and $f_{\text{m},\tau}$. However, other methods in accordance with technical literature may be applied.

5.2.6 Enhancement factor for post-weld improvement f_{post}

Post-weld improvement techniques can increase the fatigue strength at the weld toe transverse to the weld. The increased fatigue strength generally results from an improvement in the weld toe geometry, the removal of the initial flaws at the weld toe or by the introduction of compressive residual stresses at the weld toe.

The enhancement factors for post-weld improvement f_{post} in Table 8 may be applied depending on the improvement technique.

Table 8 — Enhancement factor for post-weld improvement f_{post}

Post-weld improvement technique	Enhancement factor for post-weld improvement f_{post}	
	Direct stresses transverse to the weld	Direct stresses longitudinal to the weld and shear stresses
No improvement technique applied	1,0	1,0
Toe grinding or TIG dressing	1,3	1,15
Butt weld ground flush with the surface of the adjacent plates	1,3	1,15

Other values for enhancement factors may be applied provided evidence is available to justify the enhancement.

The enhancement factor for mechanical impact treatment methods (e.g. hammer peening or needle peening) or other improvement techniques may be determined in accordance with technical literature [26]. For welded joints subjected to post-weld improvement techniques, the range of the enhancement factor is specified in Formula (13) and Formula (14).

$$1,0 \leq f_{\text{post}} \leq \frac{140 \text{ N/mm}^2}{\Delta\sigma_C} \text{ for steel and} \quad (13)$$

$$1,0 \leq f_{\text{post}} \leq \frac{65,3 \text{ N/mm}^2}{\Delta\sigma_C} \text{ for aluminium.} \quad (14)$$

NOTE 1 The upper limit is given by the maximum value of $\Delta\sigma_C$ as specified by this document.

NOTE 2 The lower limit of $f_{\text{post}} \geq 1,0$ applies for cases where values of $\Delta\sigma_C > 140 \text{ N/mm}^2$ for steel and $\Delta\sigma_C > 65,3 \text{ N/mm}^2$ for aluminium are determined based on test data (see 5.3).

The assessment of heat-affected zones shall be performed independently from post-treatment techniques in accordance with 5.1.3.1.

A combination of enhancement factors for different post weld improvements techniques shall not be applied.

In principle, it is possible to use a higher enhancement factor for post weld improvement, provided that the improvement in fatigue performance is validated by appropriate fatigue tests. The evaluation of such fatigue tests is specified in technical literature or international standards or guidelines (e.g. in [1] or [48]).

Further information describing the benefits of post weld improvement techniques related to the fatigue design of welded joints is represented in [1], [6], [26] and [48].

The application of an enhancement factor related to any post weld improvement shall be consistent with manufacturing drawings and component specifications.

5.2.7 Quality level factor f_{QL}

The fatigue classes in Annex D are given for a quality level C in accordance with EN ISO 5817 or EN ISO 10042.

For other quality levels the quality level factor f_{QL} is given in Table 9.

Table 9 — Quality level factor f_{QL}

Weld performance class in accordance with EN 15085-3:2022+A1:2023	Quality level	f_{QL}
CP A, CP B1, CP B2	B	$\sqrt{1,12}$
CP C1, CP C2, CP C3	C	1,0
CP D	D	$\frac{1}{1,2}$

The applicable minimum weld performance class in dependence of a safety category applied in 6.3.2 is specified in EN 15085-3:2022+A1:2023.

5.2.8 Enhancement factor for the weld inspection class f_{CT}

The fatigue classes in Annex D are based on weld inspection classes CT 3 and CT 4 in accordance with EN 15085-3:2022+A1:2023. For crack initiation points which can be inspected during production (see D.1.6) and which are subjected to other weld inspection classes, the enhancement factor $f_{CT} \geq 1$ as given in Table 10 may be applied.

Table 10 — Enhancement factor for the weld inspection class f_{CT}

Weld inspection class in accordance with EN 15085-3:2022+A1:2023	f_{CT}	f_{CT} for joints with weld performance class CP B1, CP B2 or CP C1, which are inaccessible for inspection or repair during maintenance (in accordance with EN 15085-3:2022+A1:2023, 4.5)
CT 1	1,12	$\sqrt{1,12}$
CT 2	$\sqrt{1,12}$	1,0
CT 3	1,0	n/a
CT 4	1,0	n/a

NOTE Quality level factor f_{QL} and Enhancement factor for the weld inspection class f_{CT} are applied independently.

EXAMPLE According to EN 15085-3:2022+A1:2023, a weld performance class CP B1 requires a weld inspection class of CT 2. For CP B1, the quality level factor is $f_{QL} = \sqrt{1,12}$. For CT 2, the enhancement factor for the weld inspection class is $f_{CT} = \sqrt{1,12}$. The combined factor is $f_{QL} \cdot f_{CT} = 1,12$.

5.2.9 S-N curves and methods of cumulative damage rule

Each S-N curve is designated by the fatigue class $\Delta\sigma_C$ and $\Delta\tau_C$ (see Annex D).

The exponent m before the knee point and the position of the knee point N_D for the S-N curves are given in Table 11 for direct stresses, transverse and longitudinal to the weld and for shear stresses in welded joints constructed from steel and aluminium.

Table 11 — Exponent m and number of cycles at knee point N_D of the S-N curve for welded joints

Material	Stress type		Exponent of S-N Curve m	Knee point N_D [10 ⁶]
Steel	Direct stress	Transverse to the weld	Annex D, D.2	Annex D, D.2 in accordance with Formula (15)
		Longitudinal to the weld	4,0	2
	Shear stress		5,0	100
Aluminium	Direct stress	Transverse to the weld	Annex D, D.2	10
		Longitudinal to the weld	6,0	10
	Shear stress		5,0	100

For direct stress transverse to the weld at welded joints constructed from steel, the position of the knee point is depending on the fatigue classes $\Delta\sigma_C$ ($N_C = 2 \times 10^6$):

- If $\Delta\sigma_C \geq 112 \text{ N/mm}^2$ the knee point position is $N_D = 2 \times 10^6$ cycles.
- If $\Delta\sigma_C \leq 50 \text{ N/mm}^2$ the knee point position is $N_D = 10^7$ cycles.
- For $50 \text{ N/mm}^2 < \Delta\sigma_C < 112 \text{ N/mm}^2$ the position of the knee point is given by Formula (15) as:

$$N_D = 10^{\left(4,0895 - 1,9956 \log(\Delta\sigma_C)\right)} \cdot N_C \quad (15)$$

For roots of partial penetration welds with direct stresses perpendicular to the root gap the knee point is independent from the fatigue classes and occurs at $N_D = 10^7$ cycles.

The stress range for the component fatigue strength at the knee point of the S-N curve is given by Formula (16) as:

$$\Delta\sigma_D (R = -1) = \Delta\sigma_R \cdot \left(\frac{N_C}{N_D}\right)^{\frac{1}{m}} \quad (16)$$

For S-N curves of welded joints all relevant information is given in Table 12.

Table 12 — Exponent beyond knee point of S-N curve, cut-off limit and damage sum limit

Cumulative damage rule	Exponent beyond knee point N_D	Cut-off limit $\Delta\sigma_L$	Damage sum limit $D_{m,min}$
Modified version of Miner's rule	$2m-1$ ^a	50 % of strength at N_D	0,5
Consistent version of Miner's rule	-	-	0,5
^a Annex D provides applicable values for m .			

In Figure 2, the principal representations of S-N curves are given for welded joints for direct stress. For S-N curves based on shear stresses the symbol σ is replaced by symbol τ .

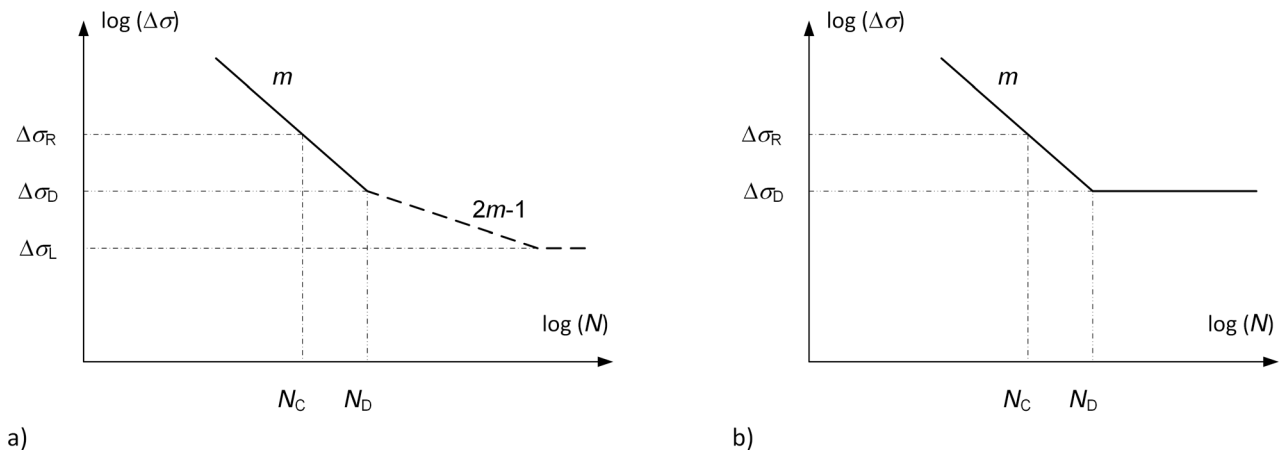


Figure 2 — S-N curve for welded joints based on direct stresses: a) Miner modified; b) Miner consistent

5.3 Determination of the fatigue strength of parent material and welded joints by laboratory tests

Alternative values for S-N curve parameters may be applied for welded joints and parent material provided the fatigue performance is validated by appropriate fatigue tests. The evaluation of such fatigue tests is specified in technical literature and in international and national standards or guidelines (e.g. [1], [48]).

When deriving the fatigue strength from fatigue tests with small scale samples, the statistical conversion factor used to adjust the test data from the 50 % survival probability to a 97,5 % survival probability should be based on technical literature.

NOTE Statistical conversion factors derived from individual test campaigns are most likely non-conservative when compared to statistical conversion factors derived from several independent tests and when compared to statistical variations in real production components.

For the derivation of strength values from fatigue tests, the actual conditions of the test specimen are relevant, not the minimum requirements as specified by drawings or specifications.

At least the following effects shall be considered:

- type of loading (tension-compression, bending, rotating bending, shear);
- stress ratio: the mean stress sensitivity results in different fatigue strength amplitudes at fatigue tests with a stress ratio $R < 0,5$ compared to those of $\Delta\sigma_C$ at $R = 0,5$;
- scattering of test results (determination of strength value with 97,5 % survival probability from mean value of the strength distribution);
- surface conditions;
- casting quality;
- actual manufactured weld quality level of test specimen compared to required quality level;
- actual manufactured weld throat dimension of test specimen;

- residual stress state in the test specimen for welded joints (to ensure a conservative value of $\Delta\sigma_C$ derived from small-scale test specimen, the derivation of $\Delta\sigma_C$ at $R = 0,5$ from tests performed with stress ratios $R < 0,5$ shall consider a high mean stress sensitivity (see A.2.2)).

When determining the S-N curve based on test data, any post weld improvement techniques shall be included in the test and the enhancement factor for post-weld improvement shall be set to $f_{\text{post}} = 1,0$.

6 Partial factors covering uncertainties

6.1 General

Partial factors to cover uncertainties in the fatigue assessment procedure are applied for the derivation of the stress spectrum and with respect to the fatigue strength, taking into account the consequence of failure, the level of inspection applied during maintenance and the extent of the validation process applied.

The application of these partial factors with respect to the fatigue strength assessment given in this standard supersedes the definitions relating to safety category and stress factor given in EN 15085-3:2022+A1:2023.

6.2 Partial factor for loads γ_L

The design load incorporates any necessary allowance to account for uncertainties in its value. It is the representative load multiplied with the partial factor γ_L .

Loads determined in accordance with the EN 12663 series for rail vehicle body structures, EN 13749 and EN 15827 for bogie structures may be regarded as design loads.

If the stress spectrum is derived from physical or virtual on track tests, an appropriate partial factor γ_L shall be specified to cover the uncertainties of these results. Unless otherwise specified in the application standard, a partial factor $\gamma_L = 1,1$ is sufficient to account for all remaining uncertainties of the test and vehicle conditions, provided that the tests are:

- made on representative track and
- made under normal service conditions and
- made with a representative payload and
- made over a sufficient length.

NOTE 1 Representative track is given for a typical track quality. Tests only on new tracks do not cover all uncertainties.

NOTE 2 Normal service conditions are given if speed profile, number of stops, suspension condition, etc. are in accordance with the intended service.

NOTE 3 If the payload condition during the on-track test is the normal design payload (PND) as specified in EN 15663 and referenced in the EN 12663 series and EN 13749, this is regarded as a conservative approach for the payload. This also covers influences of payload changes especially at commuter services. If validated payload spectra are available, combination of tests with different payload levels are regarded as representative if additionally influences of payload changes are considered.

NOTE 4 Sufficient length of tests is given if:

- the total length of the tests is at least 1/10 000 of the lifetime mileage, or

— the entire network of the service in question is measured 3 times, (which would be reasonable for closed networks).

6.3 Partial factor for the component fatigue strength γ_M

6.3.1 General

The partial factor γ_M for the component fatigue strength is

$$\gamma_M = \gamma_{M,S} \cdot \gamma_{M,I} \cdot \gamma_{M,V} \quad (17)$$

where

$\gamma_{M,S}$ partial factor for the consequence of failure (see 6.3.2);

$\gamma_{M,I}$ partial factor for the inspection during maintenance (see 6.3.3);

$\gamma_{M,V}$ partial factor for the degree of the validation process (see 6.3.4).

The partial factor γ_M for the component fatigue strength is limited to a minimum value of 1,0. A value lower than 1,0 is not permissible without additional technical justification.

Table 13 shows the values for the partial factor γ_M derived from Formula (17) rounded to the nearest hundredth.

Table 13 — Partial factor for the fatigue strength γ_M

	Partial factor $\gamma_{M,V}$ for degree of validation process	Partial factor γ_M		
		Safety category "high" $\gamma_{M,S} = 1,2$	Safety category "medium" $\gamma_{M,S} = 1,1$	Safety category "low" $\gamma_{M,S} = 1,0$
Partial factor for the inspection during maintenance $\gamma_{M,I} = 0,9$	1,3	1,40	1,29	1,17
	1,2	1,30	1,19	1,08
	1,1	1,19	1,09	1,00
	1,0	1,08	1,00	1,00
Partial factor for the inspection during maintenance $\gamma_{M,I} = 1,0$	1,3	1,56	1,43	1,30
	1,2	1,44	1,32	1,20
	1,1	1,32	1,21	1,10
	1,0	1,20	1,10	1,00

6.3.2 Partial factor for the consequence of failure $\gamma_{M,S}$

The partial factor $\gamma_{M,S}$ considers the consequence of failure generally following the definition of safety categories in EN 15085-3:2022+A1:2023 (4.4 and Annex G) with adaptations:

a) Safety category 'low'

Failure of the structural detail does not lead to any direct impairment of the overall function. Consequential events with personal injuries are unlikely;

b) Safety category 'medium'

Failure of the structural detail leads to an impairment of the overall function or can lead to consequential events with personal injuries but:

- 1) a warning is given before structure failure or
- 2) the design of the component provides an alternative load path (non-statically determined system or redundant components) or
- 3) the design of the components contains a feature to arrest a propagating crack.

c) Safety category 'high'

Failure of the structural detail leads to consequential events with personal injuries and breakdown of the overall function and none of the criteria for medium safety category apply (see bullets).

NOTE The influence related to the possibility to detect a crack at regular inspection is not considered in the categorization of safety however a separate partial factor $\gamma_{M,I}$ is included in this standard which accounts for this effect.

Depending on the safety category, the partial factor $\gamma_{M,S}$ is given in Table 14. The partial factor $\gamma_{M,S}$ is applicable both for parent material and welded joints.

Table 14 — Partial factor for the consequence of failure $\gamma_{M,S}$

Safety category	Partial factor $\gamma_{M,S}$
Low	1,0
Medium	1,1
High	1,2

6.3.3 Partial factor for the inspection during maintenance $\gamma_{M,I}$

Maintenance practices for rail vehicle products normally ensure that fatigue cracks are detected before they lead to catastrophic structural failure. Therefore, regular inspection may be assumed for the strength assessment except under certain circumstances.

Table 15 shows the applicable partial factor $\gamma_{M,I}$ depending on the applicability of “regular inspection”. The partial factor $\gamma_{M,I}$ is applicable both for welded joints and parent material.

No regular inspection for a structural detail shall be assumed, when the load carrying section is not accessible during inspection.

However, if a welded joint or structural detail is accessible from one side, the inspection of the accessible surface may be assumed to be sufficient to detect local defects before structural failure of the component occurs.

For structures within the scope of this standard that are specified to be inspected in the maintenance program, regular inspection may be assumed if the inspection interval is not higher than one third of the design lifetime.

Table 15 — Partial factor for the inspection during maintenance $\gamma_{M,I}$

	Partial factor for the inspection $\gamma_{M,I}$
Regular inspection	0,9
No regular inspection	1,0

NOTE The limitation for welded joints of weld performance classes CP B1, CP B2 or CP C1 where the structural detail cannot be repaired or replaced in maintenance is considered in the enhancement factor for the weld inspection class f_{CT} (see 5.2.8).

6.3.4 Partial factor for the degree of the validation process $\gamma_{M,V}$

If the structural validation plan consists of the complete validation process as specified by the relevant standard, e.g. in EN 15827, EN 13749, EN 12663-1 and EN 12663-2 the partial factor is $\gamma_{M,V} = 1,0$.

If the validation plan involves a substitution of laboratory tests by increased partial factors, partial factor $\gamma_{M,V}$ shall be determined using Formula (18) with the values for reduced validation process in the applicable line of Table 16:

$$\gamma_{M,V} = \gamma_{M,V,ST} \cdot \gamma_{M,V,FT} \quad (18)$$

The value of $\gamma_{M,V}$ is rounded to the nearest tenth.

Table 16 — Partial factor for the degree of the validation process $\gamma_{M,V}$

	Partial factor for a complete validation process in accordance with the relevant standard	Partial factor in case of a reduced validation process
$\gamma_{M,V,St}^a$	1,0	1,1
$\gamma_{M,V,FT}^b$	1,0	1,2
^a $\gamma_{M,V,ST} = 1,0$ may be applied if the stress determination (e.g. the FEA) is validated by a static laboratory test or for the assessment of measured stress data. ^b $\gamma_{M,V,FT} = 1,0$ may be applied if the calculated fatigue strength assessment is validated by a laboratory fatigue test or if a fatigue test is not mandatory for the feature to be assessed.		

For design features on car bodies where the design load cases given in EN 12663-1 or EN 12663-2 are considered sufficient for the fatigue strength assessment the footnote ^b usually applies and $\gamma_{M,V,FT} = 1,0$ may be applied.

When no laboratory tests are required by the appropriate standards for components attached to bogie frames and car bodies, then for the assessment of these components $\gamma_{M,V,ST} = 1,0$ and $\gamma_{M,V,FT} = 1,0$ may be applied.

Where the design is a development of an earlier product any previous test data, that is still applicable may be used as validation of the revised product and the corresponding partial factor is $\gamma_{M,V} = 1,0$.

7 Procedure of the fatigue strength assessment based on cumulative damage calculation

7.1 General

Clause 7 describes the procedure for undertaking the fatigue strength assessment based on cumulative damage.

In the following assessment procedure, the formulae are specified for direct stress components. In case of shear stresses, these formulae shall be applied by replacing of σ by τ .

The following assessment procedure is based on design stresses, where the partial factor for loads is applied during the determination of the design stress spectra.

The assessment procedure for base material and welded joints consists of the following steps:

- a) Determination of transient stress data (by calculation or measurement);
- b) Data pre-processing for each single stress component:
 - 1) Conditioning (e.g. error correction (spikes), off set correction, etc.);
 - 2) Stress history adjustment in accordance with 7.3.2;
 - 3) Rainflow counting (result: matrix including the design stress ranges, with the corresponding mean stress and cycle counts);
 - 4) Mean stress adjustment in accordance with 7.3.4 (result: design stress spectrum representing stress ranges with constant stress ratio $R = -1$, sorted in descending order, therefore $\Delta\sigma_i > \Delta\sigma_{i+1}$);
 - 5) Application of omission level;
 - 6) Extrapolation to design life (result: design stress spectrum relevant for whole design life).
- c) Damage calculation for each stress component in accordance with 7.4:
 - 1) Determination of stress spectrum shape factor A_{eq} ;
 - 2) Determination of admissible damage sum D_m ;
 - 3) Determination of utilization for single stress component U_c by iterative procedure.
- d) Assessment of fatigue strength for the multi-axial stress state in accordance with 7.5 (combined utilization for multi-axial stress state U_f).

Annex I gives an example for a fatigue strength assessment based on cumulative damage.

7.2 Stress determination

The design stress determination shall be done in accordance with Clause 4 and EN 17149-1:2024, Clause 5.

7.3 Determination of the design stress spectrum

7.3.1 Conditioning

Especially in the case of measured stress data, the raw data shall be checked for plausibility and potential measurement errors. Spikes or mean stress off-sets shall be corrected.

In case of stress data determined by calculation, data conditioning usually is not necessary. However unrealistic stress peaks should be excluded from the assessment.

EXAMPLE stress peaks due to numerical singularities at mesh transitions, contact definitions, concentrated load application, etc.

7.3.2 Stress history adjustment

The stress history used for the assessment can normally be taken directly from the strain gauge measurement or the calculation at the evaluation point. It shall include the applicable partial factor for loads γ_L . In some cases, as described below, an adjustment of the stresses determined for the evaluation point is necessary:

- if the evaluation point for the assessment of parent material does not include all stress concentration effects to determine the applicable stress;
- if the stresses at the evaluation point at welded joints need adjustments to derive applicable stresses for the assessment of the potential crack initiation points, including the effects of plate and effective throat thicknesses, section modulus, eccentricity or bending support of the joint;
- if an enhancement factor considering bending for stress components transverse to the weld line is applied.

Each stress component shall be adjusted using appropriate factors or techniques.

Annex E and Annex F give information about such adjustments for welded joints.

7.3.3 Counting

The transient stress history of each stress component shall be counted using the rainflow method as specified in international standards or technical literature.

NOTE ISO 12110-2 [52] or ASTM E1049 [50] specify methods for rainflow counting.

The residuum occurring from the rainflow counting shall be treated using an appropriate method.

EXAMPLE 1 The residuum can be avoided by placing the beginning and the end of the counting at the global maximum or minimum of the series.

EXAMPLE 2 The open cycle sequence can be treated in accordance with ISO 12110-2 [52].

EXAMPLE 3 The residuum can be counted at half the frequency in accordance with ASTM E1049 [50].

The result of this process is a spectrum of stress ranges $\Delta\sigma_{k,RF}$ related to individual mean stresses $\sigma_{m,k,RF}$ and the number of cycles n_k .

7.3.4 Mean stress adjustment

The mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ consider the mean stress influence on the direct and shear stress range and for welded structures. They also cover the influence of residual stresses due to the manufacturing processes of rail vehicle structures (see 5.2.5).

Within this procedure, the mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ are specified as multiplication factors applied to stress ranges at stress ratio of $R = -1$, consequently for stress ranges at a stress ratio of $R = -1$ the mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ need to have the value of 1,0.

The mean stress factors can vary for each load cycle of a load spectrum depending on the current mean stress and stress range. The mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ are not considered for the determination of the component fatigue strength, which are related to the stress ratio of $R = -1$. Instead the mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ are considered during the determination of the stress spectrum in the fatigue strength assessment process (see 7.2). Therefore, the result of the rain flow counting (stress range cycles with varying mean stresses) are transformed to a stress spectrum with constant stress ratio of $R = -1$ by using mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$.

The adjusted stress ranges are determined using the Formula (19):

$$\Delta\sigma_k = \frac{\Delta\sigma_{k,RF}}{f_{m,\sigma,k}} \quad (19)$$

The index k indicates that the mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ shall be calculated for each element of the rainflow matrix.

The informative Annex A specifies one option for the determination of the mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ in accordance with technical literature.

Other validated methods (e.g. in technical literature or national standards [1], [2], [42] or [43]) to account for the mean stress influence may also be applied.

If the stress ranges are rearranged in accordance with their stress range values after the mean stress adjustment index k becomes index i ($\Delta\sigma_k \rightarrow \Delta\sigma_i$).

A simplified conservative assessment may be undertaken without the need to calculate the mean stress factor for each stress cycle by using the assumption that all stress cycles are high fluctuating stresses.

NOTE When applying Annex A, this is the case assuming all stress cycles fall into field IV.

7.3.5 Omission

After counting and mean stress adjustment of the stress spectrum all cycles with a stress range $\Delta\sigma_i < \Delta\sigma_{OM}$ are omitted. The omission level $\Delta\sigma_{OM}$ is specified by Formula (20):

$$\Delta\sigma_{OM} = 0,1 \Delta\sigma_D \quad (20)$$

NOTE These cycles with small stress ranges do not contribute significantly to the damage.

The data pre-processing results in a stress spectrum with constant stress ratio which can be visualized in a representation shown in Figure 3.

All stresses below the omission level need not be considered for further calculations and iterations. For stress spectra where the maximum stress range is lower than the omission level, the following procedure cannot be applied. In this case a utilization for single stress component $U_c = 0$ shall be used.

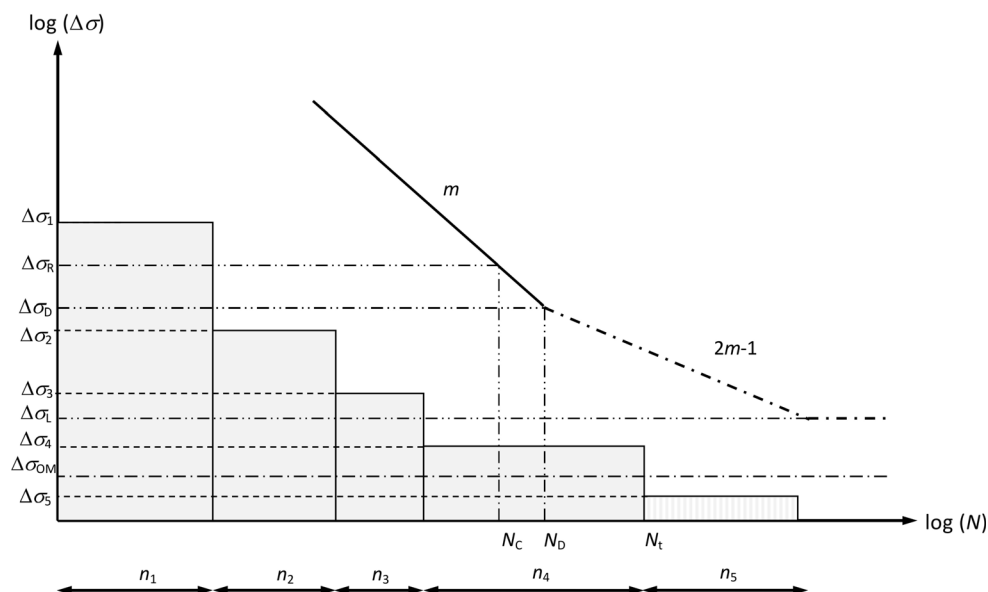


Figure 3 — Example of stress spectrum for the assessment of the fatigue strength and S-N curve related to modified version of Miner's rule

7.4 Damage calculation for each single stress component

7.4.1 General

For the fatigue strength assessment one of the following cumulative damage rules (damage accumulation hypotheses or Miner's rules) shall be applied using the parameters specified in 5.1.7 and 5.2.9:

- modified version of Miner's rule;
- consistent version of Miner's rule.

The use of other methods is permissible under the precondition of a valid justification.

NOTE 1 A comparison of the damage accumulation with the consistent version of Miner's rule is an example of a valid justification.

The formulae in 7.4 specify the damage calculation for the modified version of Miner's rule.

NOTE 2 The modified version of Miner's rule is an approximation of the consistent version of Miner's rule.

For the application of the consistent version of Miner's rule the formulae for the damage calculation are given in technical literature.

EXAMPLE 1 [2] gives a procedure for the application of the consistent version of Miner's rule.

The procedure specified in 7.4.2 and 7.4.3 may be simplified by the conservative approach of setting the admissible damage sum D_m to $D_{m,min}$ (see Table 6 and Table 12) without calculating the stress spectrum shape factor A_{eq} .

7.4.2 Determination of stress spectrum shape factor A_{eq}

The stress spectrum shape factor A_{eq} considers that the stress spectrum is not a constant amplitude stress spectrum. It is used for the determination of the admissible damage sum.

The stress spectrum shape factor is a function of the stress ranges and the number of cycles of each stress range block in relation to the maximum stress range $\Delta\sigma_1$ and the total number of cycles in the given stress spectrum (see Formula (21)). Therefore, it is independent from the absolute values of the stress spectrum.

NOTE According to 7.3.5, load cycles with a stress level below the omission level $\Delta\sigma_{OM}$ are not considered here. According to 7.3.4, the stress ranges $\Delta\sigma_i$ are recalculated to a ratio of $R = -1$.

$$A_{eq} = \frac{1}{\sum_{i=1}^j \left(\frac{\Delta\sigma_i}{\Delta\sigma_1} \right)^m \cdot \frac{n_i}{N_t}} \quad (21)$$

7.4.3 Determination of admissible damage sum D_m

The admissible damage sum D_m as specified here with the upper limit of 1 and the lower limit of $D_{m,min}$ is only applicable in combination with the subsequent determination of the cumulative damage sum D_{it} as specified in 7.4.4.

The admissible damage sum D_m is specified using Formula (22), Formula (23) and Formula (24):

$$D_m = \frac{2}{\sqrt[4]{A_{eq}}} \text{ for } D_{m,min} \leq \frac{2}{\sqrt[4]{A_{eq}}} \leq 1 \quad (22)$$

$$D_m = D_{m,min} \text{ for } \frac{2}{\sqrt[4]{A_{eq}}} < D_{m,min} \quad (23)$$

$$D_m = 1 \text{ for } \frac{2}{\sqrt[4]{A_{eq}}} > 1 \quad (24)$$

7.4.4 Determination of the utilization for a single stress component U_c

The cumulative damage sum D_{it} for a stress spectrum is determined in accordance with Formula (25).

To evaluate the utilization related to the stress spectrum for a single stress component the following iterative procedure shall be applied to determine the stress spectrum scaling factor which when applied to the stress spectrum results in a cumulative damage of $D_{it} - D_m = 0$:

- The stress ranges $\Delta\sigma_i$ of the stress spectrum are scaled by the scaling factor x_{it} (see Figure 4).
- The cumulative damage sum D_{it} is determined with the scaled stress ranges $x_{it} \cdot \Delta\sigma_i$.
- By variation of the scaling factor x_{it} the cumulative damage sum D_{it} shall be converged to the admissible damage sum D_m . So, the difference of $(D_{it} - D_m)$ shall converge to zero under the condition $D_{it} \leq D_m$ (x_{it} approaches x_{Dm}).

Due to the nonlinear behaviour of the method in some cases no exact solution exists, since $D_{it}(x_{it})$ is a discontinuous function. In such cases x_{Dm} shall be calculated by finding the minimum value of x_{it} for $D_{it} - D_m \leq 0$.

$$D_{it} = \sum_{i=1}^{\delta-1} \left(\frac{x_{it} \cdot \Delta\sigma_i}{\Delta\sigma_D} \right)^m \cdot \frac{n_i}{N_D} + \sum_{i=\delta}^{j_{it}} \left(\frac{x_{it} \cdot \Delta\sigma_i}{\Delta\sigma_D} \right)^{2m-1} \cdot \frac{n_i}{N_D} \quad (25)$$

NOTE 1 With a scaling factor $x_{it} = 1$ Formula (25) results in the cumulative damage sum of the given spectrum.

The utilization for single stress component U_c corresponds to the reciprocal value of the converged scaling factor (x_{it} approaches x_{Dm}) for the analysed stress component under the consideration of the partial factor γ_M :

$$U_c = \gamma_M \cdot \frac{1}{x_{Dm}} \quad (26)$$

The utilization for single stress component U_c shall be determined for each stress component.

EXAMPLE 1 For parent material this procedure results in Formula (27) to Formula (29).

$$U_{c,\sigma_x} = \gamma_M \cdot \frac{1}{x_{Dm,\sigma_x}} \quad (27)$$

$$U_{c,\sigma_y} = \gamma_M \cdot \frac{1}{x_{Dm,\sigma_y}} \quad (28)$$

$$U_{c,\tau_{xy}} = \gamma_M \cdot \frac{1}{x_{Dm,\tau_{xy}}} \quad (29)$$

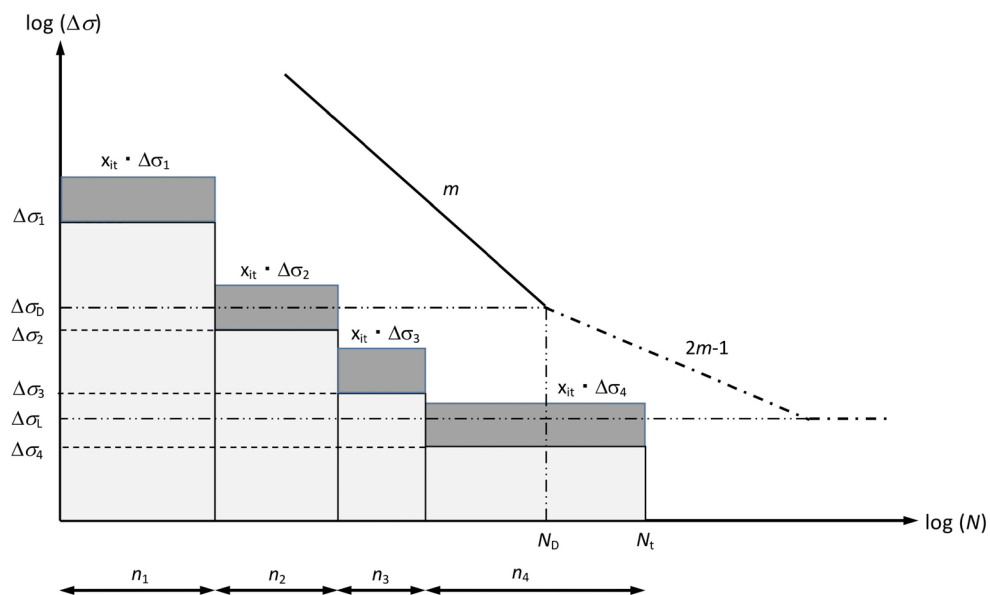


Figure 4 — Example of original and scaled state of stress spectrum for the assessment of the fatigue strength and S-N curve related to modified version of Miner's rule

This iterative procedure shall be applied to all stress components to determine the respective scaling factors x_{Dm} for each stress component.

NOTE 2 Damage-equivalent stress ranges for the number of cycles N_D and N_C can be determined using the Formula (30) and Formula (31).

$$\Delta\sigma_{eq, N_D} = \frac{\Delta\sigma_D}{x_{Dm}}; \quad \Delta\tau_{eq, N_D} = \frac{\Delta\tau_D}{x_{Dm}} \quad (30)$$

$$\Delta\sigma_{eq, N_C} = \frac{\Delta\sigma_D}{x_{Dm}} \cdot \left(\frac{N_D}{N_C} \right)^{\frac{1}{m}}; \quad \Delta\tau_{eq, N_C} = \frac{\Delta\tau_D}{x_{Dm}} \cdot \left(\frac{N_D}{N_C} \right)^{\frac{1}{m}} \quad (31)$$

7.5 Assessment of fatigue strength

For all versions of Miner's rule, the fatigue strength of structural details shall be assessed by the combined utilization for a multi-axial stress state U_f . Demonstration of fatigue strength is given if $U_f \leq 1$ under consideration of the partial factor γ_M as given in Clause 6.

For the assessment of parent material, a fixed assessment orientation cannot be specified independently from the stress data.

For the assessment of welded joints, the orientation is fixed and geometrically specified with respect to the orientation of the weld. Therefore, the critical plane approach (see 7.6) shall not be applied for welds.

For parent material, Formula (32) gives the general procedure for calculating the combined utilization.

$$U_f = \sqrt{\left(U_{c, \sigma_x} \right)^2 + \left(U_{c, \sigma_y} \right)^2 + \left(U_{c, \sigma_x} \right) \left(U_{c, \sigma_y} \right) + \left(U_{c, \tau_{xy}} \right)^2} \quad (32)$$

Formula (33) may be applied for parent material if one of the following criteria is fulfilled:

- proportional stress state with direct stress components of same sign; or
- if the whole assessment procedure is subjected to a critical plane approach in accordance with 7.6.

$$U_f = \sqrt{\left(U_{c, \sigma_x} \right)^2 + \left(U_{c, \sigma_y} \right)^2 - \left(U_{c, \sigma_x} \right) \left(U_{c, \sigma_y} \right) + \left(U_{c, \tau_{xy}} \right)^2} \quad (33)$$

For welded joints, Formula (34) gives the procedure for calculating the combined utilization.

$$U_f = \sqrt{\left(\max \left(U_{c, \sigma_{\perp}}; U_{c, \sigma_{\parallel}} \right) \right)^2 + \left(U_{c, \tau} \right)^2} \quad (34)$$

NOTE Where the stress state is regarded as a uniaxial stress, the other components are set to zero (see 7.3.5 and EN 17149-1:2024, 5.1).

7.6 Critical plane approach

The critical plane approach offers one option to consider the effect of varying stress history results depending on the orientation of the stresses used for the assessment (assessment orientation). The application of the critical plane approach is intended to identify the orientation on which the acting stress components create the maximum utilization.

NOTE 1 In general, the orientation of the principal stresses are not constant over the stress history. When applying the critical plane approach the fatigue strength assessment is done based on stress data determined in a fixed coordinate system tangential to the component surface constant over the full stress history. The result of the combined utilization is dependent on the assessment orientation.

With a given history of stress tensors one specific assessment orientation will result in a maximum combined utilization. The orientation leading to this maximum result is called critical plane.

The critical plane approach specified as follows is a simplified method to approximate an orientation close to the critical plane, but the critical plane itself is not identified exactly.

The critical plane approach procedure consists of the following steps:

- Determination of stress components $\sigma_{x,0}(t)$, $\sigma_{y,0}(t)$, $\tau_{xy,0}(t)$ in an arbitrary initial assessment orientation.
- Assessment of fatigue strength with these stress components following the full procedure as specified in 7.3, 7.4 and 7.5, resulting in a combined utilization $U_{f,0}$.
- The assessment orientation is rotated incrementally by an angle $\Delta\psi$. The stress components $\sigma_{x,1}(t)$, $\sigma_{y,1}(t)$, $\tau_{xy,1}(t)$ are determined by a rotational transformation of all stress tensors of the stress data history.
- The fatigue assessment is repeated with the altered stress components $\sigma_{x,1}(t)$, $\sigma_{y,1}(t)$, $\tau_{xy,1}(t)$, restarted at the procedure step “counting” (see 7.3.3), resulting in the combined utilization $U_{f,1}$.
- The assessment with altering orientation angles is repeated to cover the complete range of assessment orientations.
- The final combined utilization U_f is determined as the maximum of all combined utilizations $U_{f,i}$ from each increment.

The accuracy of the approximation of the critical plane is dependent on increment $\Delta\psi$ between the orientations investigated. A step interval of $\Delta\psi \leq 10^\circ$ is recommended.

NOTE 2 In general it is sufficient to use the stress data that is the result of the first procedure steps conditioning (7.3.1) and stress history adjustment (7.3.2) as an input for the critical plane approach.

NOTE 3 It is sufficient to vary the assessment orientation in a range from $0^\circ \leq \psi < 90^\circ$, since a transformation of 90° will result in identical combined utilization U_f with stress component results swapped between the x- and y-component.

Annex A (informative)

Procedure for determination of mean stress factors for parent material and welded joints

A.1 General

This annex specifies the determination of the mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ using a Haigh Diagram.

The mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ are used for:

- consideration of the actual stress ratio of single stress ranges in the given stress spectrum to be assessed. The mean stress factors are used to convert a spectrum of stress ranges with varying mean stress into a spectrum of stress ranges with constant stress ratio of $R = -1$ (see 7.3.4, Mean stress adjustment).
- consideration of residual stress state of welded structures. The mean stress factors are used to determine the residual stress factors $f_{res,\sigma}$ and $f_{res,\tau}$ in accordance with 5.2.5.

The mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ are functions of:

- the mean stress sensitivities M_σ and M_τ . For parent material the mean stress sensitivity is dependent on the material (see A.2.1). For welded joints the mean stress sensitivity is dependent on the residual stress state (see A.2.2).
- the stress ratio of the given stress range expressed by the mean stress σ_m and the stress amplitude σ_a .

The mean stress factors $f_{m,\sigma}$ and $f_{m,\tau}$ are related to the stress ratios $R_\sigma = -1$ and $R_\tau = -1$. Therefore, the mean stress factors are $f_{m,\sigma} = 1,0$ for the stress ratio $R_\sigma = -1$ and $f_{m,\tau} = 1,0$ for $R_\tau = -1$.

The mean stress factors are determined based on the assumption of constant stress ratios.

NOTE Formula (A.5) to Formula (A.11) determine the intersection of the definition line displayed in Figure A.1 and Figure A.2 (represented by four straight lines, one for each field of the diagram) and a straight line representing the stress ratio specified by the origin of the diagram and the mean stress σ_m and the stress amplitude σ_a .

A.2 Mean stress sensitivity

A.2.1 Parent material

For parent material the mean stress sensitivities for direct stress M_σ and for shear stress M_τ , are dependent on the nominal tensile strength R_m of the material and the material parameters a_m and b_m . They are calculated by Formula (A.1) and Formula (A.2). For these formulae, the material parameters a_m and b_m are given in Table A.1.

$$M_\sigma = \frac{a_m}{1000} R_m + b_m \quad (A.1)$$