TALAT Lecture 2402

Design Recommendations for Fatigue Loaded Structures

60 pages, 36 figures

Advanced Level

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Objectives:

- Calculation of design stresses for variable stress ratios in practice, explanation on the background of design recommendations
- To teach the concept of partial safety factors and supply appropriate background information for aluminium
- To enable the designer to evaluate service behaviour of structural details on a more sophisticated level applying the same principles as in current design recommendations
- To provide understanding of the fatigue design procedure according to current recommendations

Prerequisites:

- Background knowledge in engineering, materials and fatigue as well as some knowledge in statistics required

Date of Issue: 1994

2402 Design Recommendations for Fatigue Loaded Structures

Table of Contents

2402.01 The R-Ratio Effect

- Data background
- Data evaluations
- Drafting a proposal for the factor f(R)
- Final ERAAS design proposal for f(R)
- Residual stress effects

Assumptions and statements made in the following are based on information and experimental test data available in connection with the ECCS-EAA Fatigue Workshops in Munich and Zurich in February and March 1990, respectively. These intermediate results helped to formulate the outline of R-ratio effects presented. Due to the succeeding discussions in the ECCS Committee 2 concerning the drafting of the European Recommendations for Aluminium Alloy Structures in Fatigue Design (ERAAS Fatigue) in meetings in the following summer and winter, as well as due to further intensive evaluations and the enforcement of general principles governing the format of fatigue design procedures, the final R-ratio dependency of fatigue strength design values is not always identical to the first actual results.

There is, unfortunately, incomplete experimental information to allow a quantitative statement on the effect of R-ratio on the fatigue strength of aluminium structural elements. Accordingly the treatment of this effect has varied in the past with the data available or reflecting the viewpoint of those drafting the respective recommendation, see **Figure 2402.01.01**.

Aluminium Fatigue Design

Recommendations

R-independent	R-dependent
	DVS 1608 (1969)
	"LDV" (1970)
	ALCAN Handbook
	UNI 8634 (12/1985)
	Austrian Recommendations (3/1988)
	Assoc. American RR Freight Cars (3/1980)
Ontario Highway Bridge Code (1979/1983)	
Recommended Specifications Aluminium Association (10/1985)	
BS 8118: (1985)	
light/heavy struct. el. (1989)	
ERAAS Fatigue Design up to Draft 8:1985	ERAAS Fatigue Design, Doc. 68, 1992

Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | R-Dependencies in Fatigue Design Recommendations | 2402.01.01

Roughly, earlier recommendations accept R-dependent fatigue strength values, since they seem to be based either on small specimen test results, or on rather simple structural elements or even only on base material with no significant residual stresses. More recent fatigue design rules, in steel as well as in aluminium, attempt to place the emphasis on the behaviour of larger, full-size components and welded constructions and thus assume the presence of more or less significant residual stresses. Consequently, the latter are based on a R-ratio-free design concept and do not always make use of any possible beneficial effect for R values near or below zero. Although not explicitly stated, it can be derived from respective experimental evidence that fatigue strength values at approximately R = + 0.5 or higher have formed the basis of the proposed design values. The fact that the ERAAS-Fatigue Design values are given both as R-independent and R-dependent reflects the growing knowledge level during the drafting period of the re-commendations and the desire to cover possible beneficial structural cases.

Data Background

The first comprehensive data evaluation attempt in 1985-1986 was confined to analysis of fatigue tests with small specimens only, the so-called CAFDEE test data.

During the second data evaluation stage interest focused on larger components, the welded and base material beam fatigue tests performed by the TUM and earlier respective tests made available by the aluminium industry. Again comparative analysis of fatigue tests at two different R-values were possible with the beam test results from TUM only. A set of small specimen data at different R levels was analysed in parallel, though, allowing for a comparison along the lines of this homogeneous data a comparison with earlier assumptions in analyses and recommendations. The decision was taken at this stage to refrain from attempting a quantification of the R-ratio effect on fatigue strength and operate along the assumption of larger structural elements with respective significant residual stresses and consequently adopt an R-independent design procedure.

Discussions that followed on the next ECCS TC2 meeting in Grenoble in November 1989 and different reactions to the above proposal prior to and during the third comprehensive data evaluations at the EAA-ECCS Fatigue Workshops in Munich, February 1990, and Zurich, March 1990, now encompassing the more recent test results of the second TUM beam fatigue test program and a new large contingent of further test data on small specimens made available by the aluminium industry**,** expressed the wish for a better differentiation of cases possible in practice. Information on R-dependency was summarised once more, opening the possibility to the design engineer to distinguish between more cases in practice and utilise beneficial effects where this would seem appropriate.

Data Evaluations

Information on the data analysed on the three mentioned evaluation stages is summarised:

Stage I: Due to the non-homogenous character and the unreliability in the documentation of earlier test data it was decided not to use the old material for purposes of the European recommendations.

Stage II: (a) Type: ALS (Alusuisse/Zurich resp. Neuhausen) small speci-
mens,
6005A alloy base metal, transverse butt weld
Sample size: 424 and 407 respectively typical data set sample size:
41
Life range: 10^4 to $2 \cdot 10^6$ cycles
R-ratio: values between -3 and +0.7
Information: see Fig. 4 and Fig. 5 EAA-Report March 1989

(b) Type: TUM beams, 7020 alloy
transverse butt weld, longitudinal and transverse fillet
weld attachment on beam flange
Sample size: total/at R=0.1/at R=-1

butt weld	43/23/15
long. fillet attach.	53/19/34
transv. fill./cover plate	43/15/28

Life range: $6 \cdot 10^4$ to $2 \cdot 10^6$ cycles
R-ratio: values for -1 and +0.1
Information: EAA Report 3/89

Stage III: (c) Type: TUM beams in 7020 and 6005A alloys, due to the still
running tests of the 1987-1990 test series at the time of
these evaluations and the resulting small sample sizes
only a limited number of cases give valid statements
Sample size: web-to-flange fillet welds 87
cover plate 26
Life range: 10^4 to $5 \cdot 10^6$ cycles
R-ratio: -1, +0.1, +0.6
Information: Fatigue Workshop Munich,1990

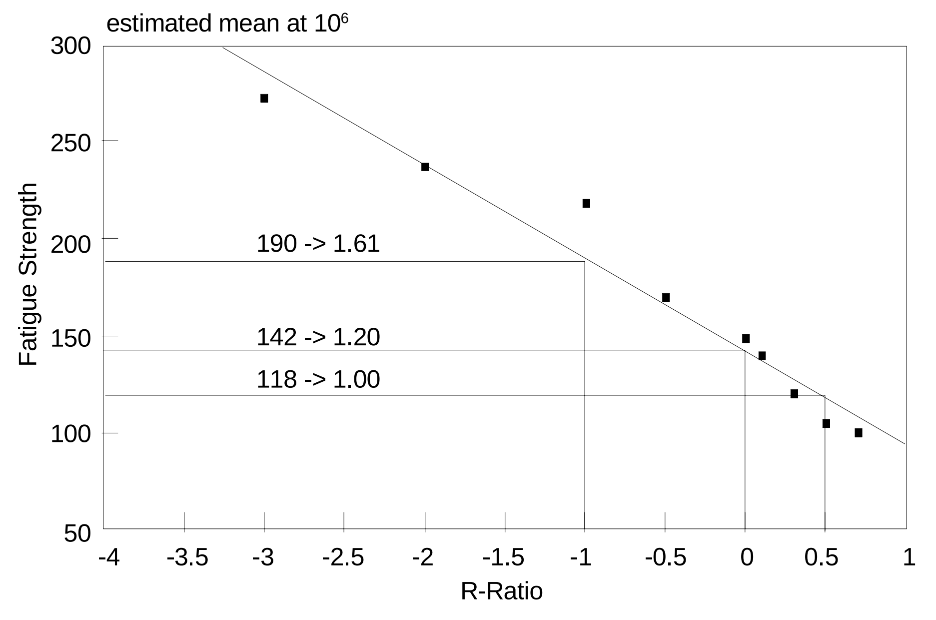
(d) Type: small specimens, different structural details and alloys
of the 5000/6000/7000 series
Sample size: base metal 7020 : 2209
5000 : 1719
6000 : 5035
notches, holes : 851
butt weld : 6027
web stiffener or non-load-carr. transv. fillet : 1586
cruciform or load-carrying transv. fillet : 1262
Life range: 10^4 to 10^7 cycles
R-ratio: -1 and +0.1
Information: Fatigue Workshop Documents, 1990
Alusuisse Zurich data

Stage II Evaluation

The relationship in **Figure 2402.01.02** is based on mean fatigue strength values at one million cycles estimated by linear regression analysis, excluding run-outs.

During the Munich Workshop though, a second relationship, with somewhat different values, was established, this one based on lower boundary curves for the test data at two million cycles:

R	-3	-2	-1	-0,5	0/0,1	+0,3	+0,5	+0,7
S_R [MPa]	166	166	166	129	113	96	86	79
$S_R/S_{0.5}$	1,93	1,93	1,93	1,50	1,31	1,12	1,00	0,92

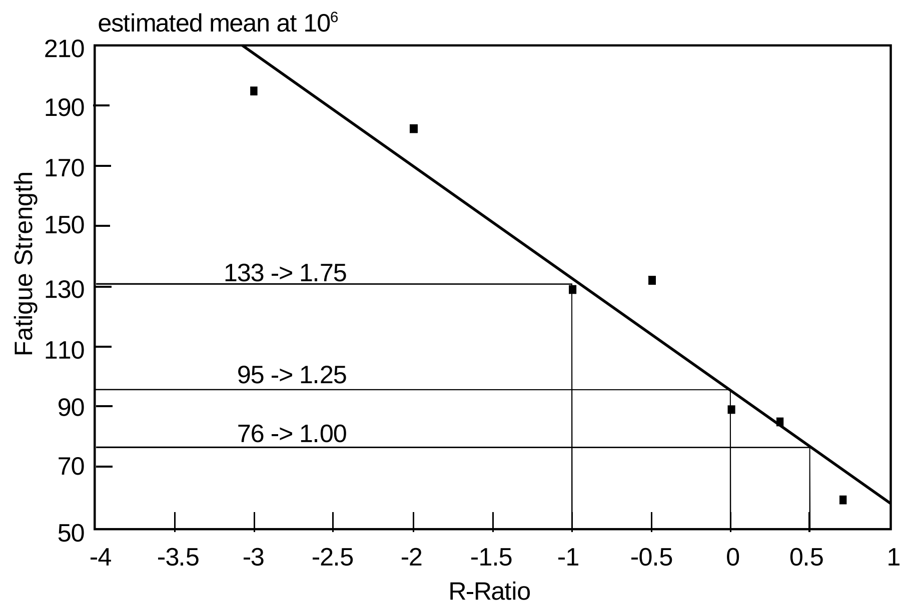


R-Ratio vs. Fatigue Strength for Base Metal Small Specimen Test Data 2402.01.02

This was considered more representative and was used (at this stage of development) to establish the fatigue strength enhancement factor f(R) in the case of base material, see further on **Figure 2402.01.04**.

It is mentioned at this point already that the respective value stated on the first column of **Figure 2402.01.06** has been derived directly from the figures of the above table.

Concerning information on the transverse butt weld specimens again as mean stress values at one million cycles the relationship of **Figure 2402.01.03** is established.



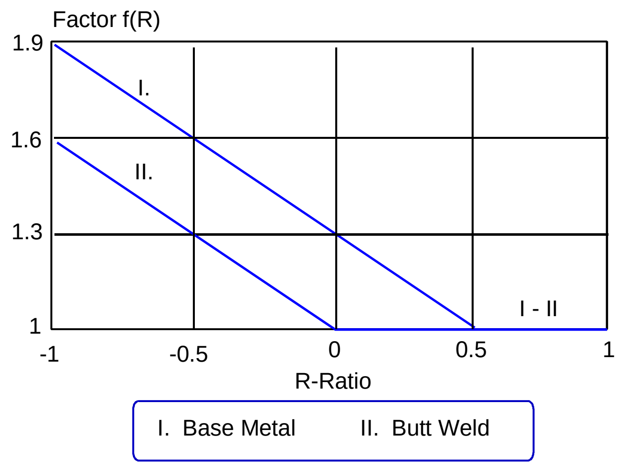
R-Ratio vs. Fatigue Strength
for Transverse Butt Weld Small Specimen Fatigue Data
2402.01.03

Or, again, the following relationship if strength values at two million cycles are used:

R	-3	-2	-1	-0,5	0/0,1	+0,3	+0,5	+0,7
S_R [MPa]	131	131	76	(95)	54	54	50	46
S-1/S+0,5 = 1.52								
S-1/S_0 = 1.41								

Initially it was thought that both, base material and (butt) welded joints, could be treated by a common assumption due to the factors originating from **Figure 2402.01.02** and **Figure 2402.01.03** with data from small specimen tests. Comparison of different data exhibited different fatigue strength ratios at respective R values and there was no clear overall picture. Some of this information will be given in the following.

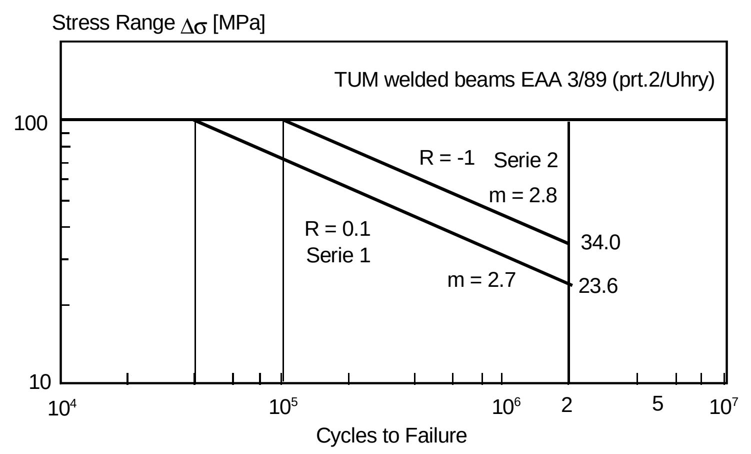
The proposal thus for welded details, according to **Figure 2402.01.04**, assumes a relationship parallel to the one for base material but on a lower level. The characteristic f(R) value at R = -1 equals 1.6 and reaches 1 for R = 0, being thus on the safe side.



Source:D. Kosteas, TUM

TALAT	Factor f(R) from Source II for Base Metal and Transverse Butt Weld	2402.01.04

The above mentioned result of S_{-1}/S_0 = 1.41, established on the basis of a rather large and homogeneous sample of small specimens, together with the almost identical value of
S_{-1}/S_0 = 34.0/23.6 = 1.44 as calculated for the large welded components of the TUM aluminium beams, **Figure 2402.01.05**, lie in accordance with further minimum values as will be shown, and indicate thus the limit to be attained with some degree of reliability for welded details.



TALAT	Effect of R-Ratio on TUM Beam Tests of the 1982-1986 Research Program	2402.01.05

Stage III Evaluation

Additional support in the case of welded beams came from test results of the current TUM beam test program 1987-1991. Valid statements based on a reliable number of test points for 7020 beams were possible in the case of longitudinal non-load-carrying fillet welds (web-to-flange welds with start and stop positions or tack welds) giving at $2 \cdot 10^6$ cycles

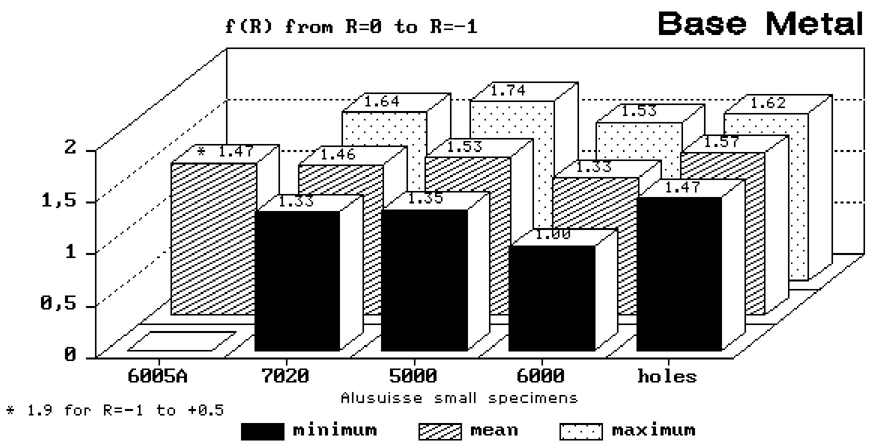
f(R)=1.14 for R=+0.1 to -1 and
f(R) = 1.57 for R = +0.6 to -1

and similarly in the case of transverse load-carrying fillet welds of flange attachments, i.e. cover plates

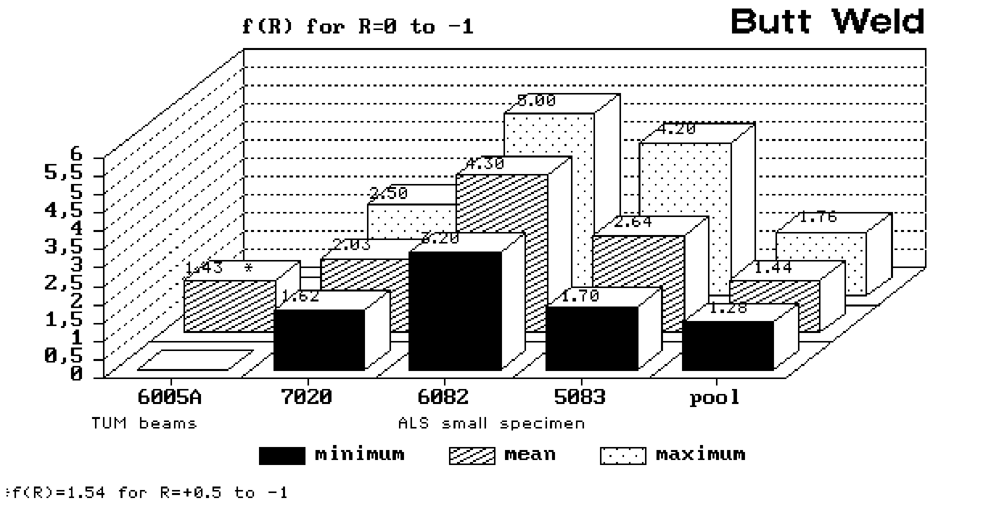
f(R) = 1.24 for R = +0.1 to -1 and
f(R) = 1.60 for R = +0.6 to -1.

The fourth information source added significant weight to the evaluations by the considerable amount of small specimen data, almost 19000 data points, on base material and various weldments in the standard 5000, 6000 and 7000 alloy series.

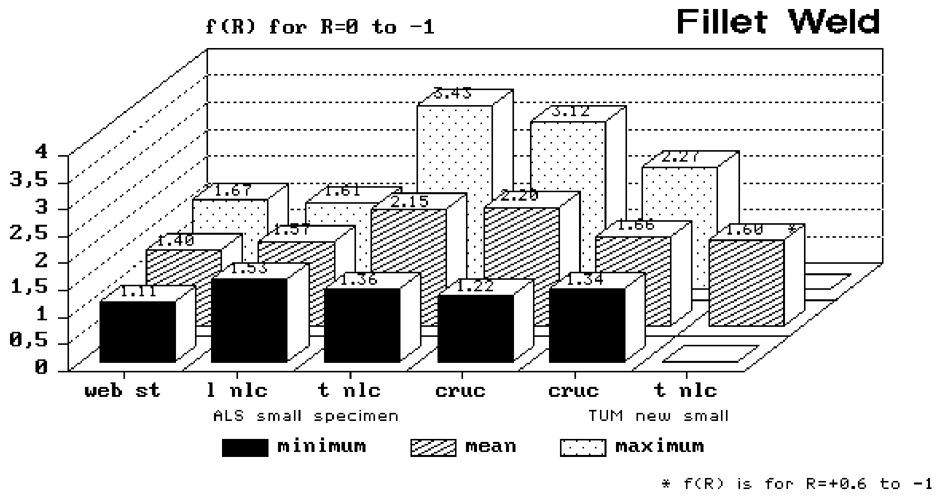
The following **Figure 2402.01.06, Figure 2402.01.07** and **Figure 2402.01.08** summarise minimum/mean/maximum enhancement factors f(R) at $2 \cdot 10^6$ cycles and between the R values 0 and -1. Especially for welded details, i.e. joints with assumed significant residual stresses, it was decided to accept an enhancement factor only in the range between 0 and -1. For values R > 0 the factor should be equal to one.



TALAT Training in Aluminium Application Technologies	Enhancement Factor f(R) at 2*10⁶ Cycles for Base Material	2402.01.06

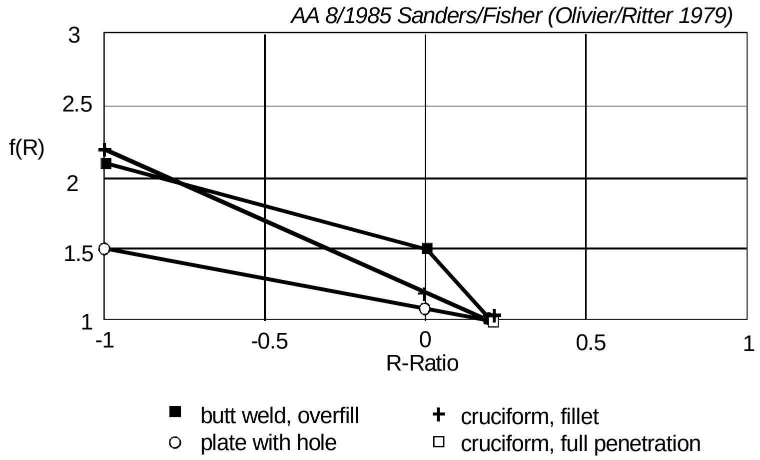


TALAT	Enhancement Factor f(R) at 2*10^6 Cycles for Transverse Butt Weld	2402.01.07

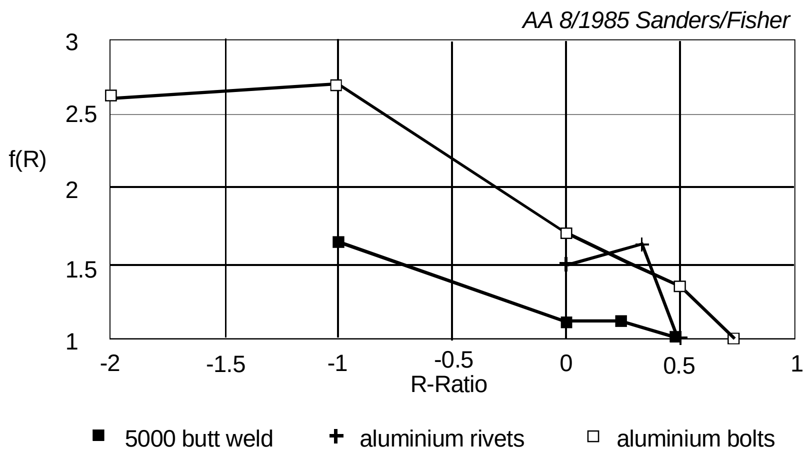


TALAT	Factor f(R) at 2*10^6 Cycles for Longitudinal or Transverse, Load-Carrying or Non-Load-Carrying Fillet Weld	2402.01.08

The Fatigue Workshop evaluations were completed by information on the treatment of the R-ratio effect on fatigue strength as these had been included in a recommendation and a standard for the design of aluminium structures. **Figure 2402.01.09** and **Figure 2402.01.10** give information from the proposal for the Aluminum Association in the U.S..

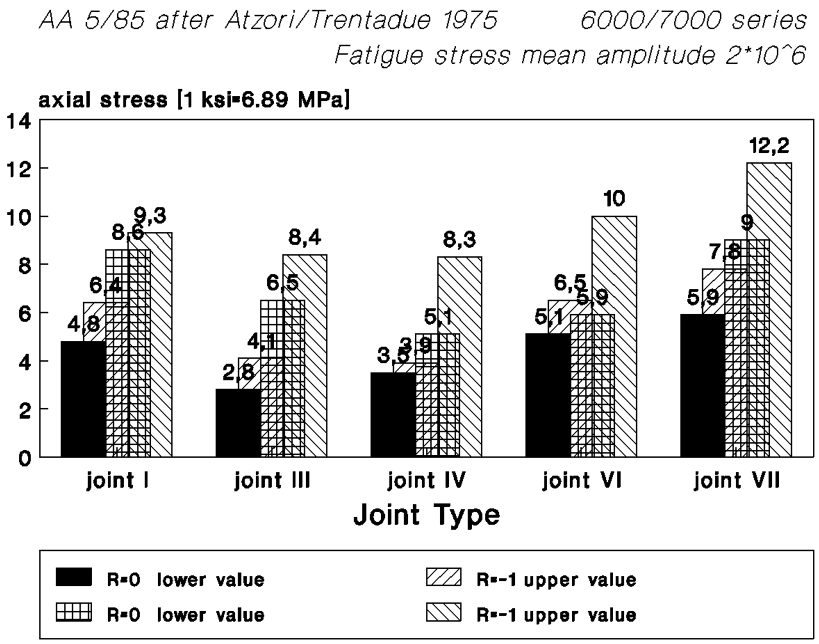


TALAT	Enhancement Factor f(R) in Design Recommendations Draft of the Aluminum Association - (a)	2402.01.09

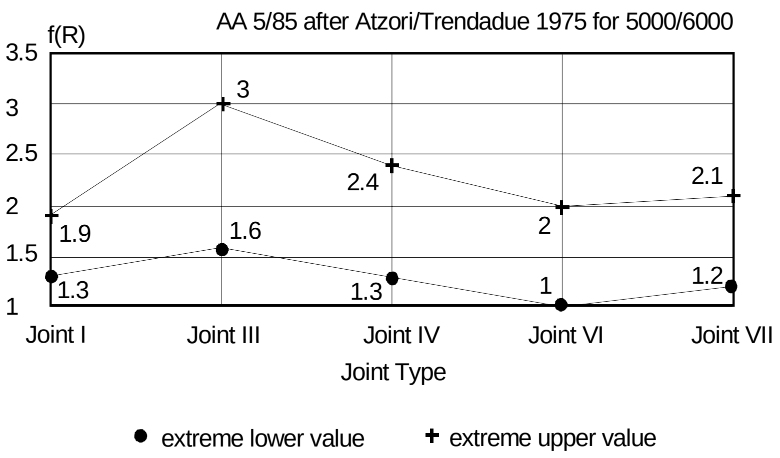


TALAT	Enhancement Factor f(R) in Design Recommendations Draft of the Aluminum Association - (b)	2402.01.10

Figure 2402.01.11 and **Figure 2402.01.12** attempt to reconstruct from rather limited information the scatter band of the factor f(R) for several welded details analysed and providing a background for the Italian standard on aluminium design.



TALAT Training in Aluminium Application Technologies | Mean Stress Amplitude Values at 2*10^6 Cycles for Several Welded Joint Types in 6000 and 7000 Alloys | 2402.01.11

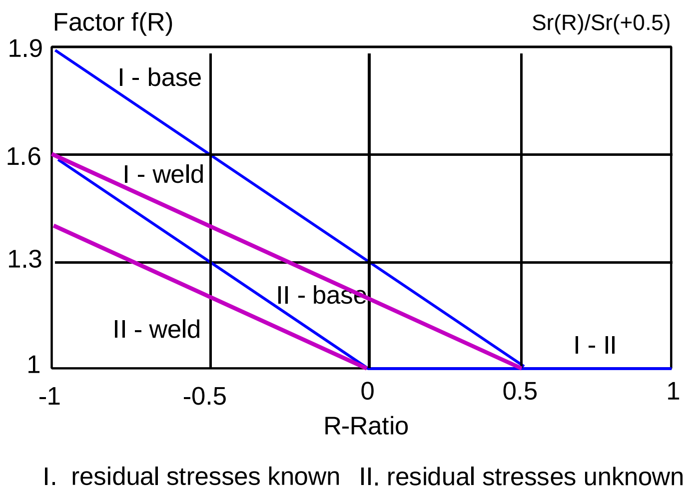


D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | Extreme Limit Values for the Enhancement Factor f(R) for Several Welded Joint Types in 6000 and 7000 Alloys | 2402.01.12

Drafting a Proposal for the Factor f(R)

Using in general the mean values observed for the enhancement factor f(R) in all the cases outlined above a design proposal was drafted for the European Recommendations following the evaluations of the Workshops. The original proposal, as first suggested in **Figure 2402.01.04**, was now extended to include two practical cases for both base material elements and weldments, **Figure 2402.01.13**. In the one case knowledge of residual stresses in the structural element is available and if taken into account in the design procedure allows for higher design stresses. Should no information on the stress situation be available or not considered in design then a lower line gives the respective values of f(R) vs. R for base material and weldments. The concept consists thus of two pairs of parallel lines each. The line for base material and residual stresses not known is not covered by actual data but based on an assumption following discussion on the Fatigue Workshop and a respective proposal by Dr. M. Ogle, The Welding Institute.



Source:D. Kosteas, TUM

TALAT	Proposed Design Values for the Enhancement Factor after ERAAS Draft 8.6	2402.01.13

In order to give a full picture of the final proposal and its rules as it was included in the ERAAS document the respective clauses are given in the Appendix.

This may seem as a rather severe set of rules, departing also from the original position of the first evaluations. The introductory statements on residual stress measurement results should be considered very carefully, though. The existence and behaviour of residual stresses on larger elements under fluctuating loads is by no means quantifiable at the moment and an extrapolation of these results to every possible case in practice does not seem prudent.

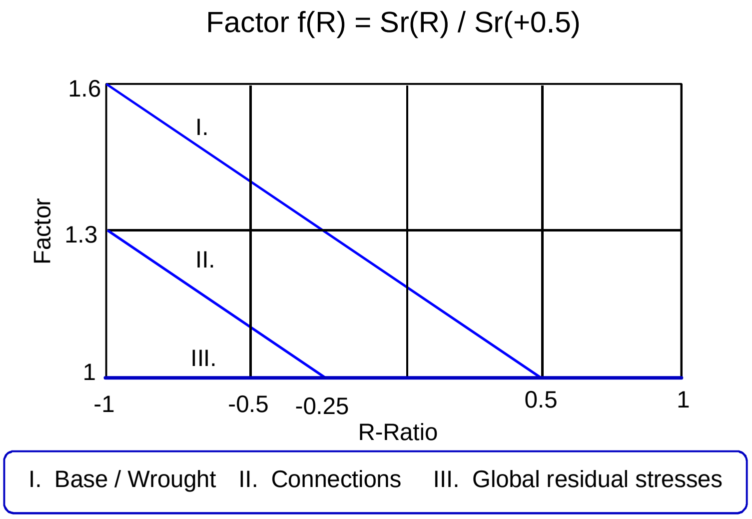
It must be born in mind that in the case of base material there was satisfactory experimental evidence available only in the form of small specimen tests, i.e. cases with "known" residual stress or equal to zero.

The similar magnitude of strength ratios at a certain R value between larger components and small specimens seem to indicate that a fair amount of residual stresses may still be locked in the latter (this has also been shown by test results by Maddox and Webber a few years ago). Information about the specimen sizes, welding procedures and parameters would be necessary to clarify this matter, but were not available at the time of the above evaluations.

To correctly read and apply values of the factor f(R) it should be mentioned once more that the diagram states only values relative to the fatigue strength at R = +0.5, the latter being the basic design value at $2 \cdot 10^6$ cycles of a specific structural detail relating to the classification or design curve value given in the data sheet of the Recommendations.

Final ERAAS Design Proposal for f(R)

The above proposal was discussed intensively, arguments concentrating on variability and scatter of enhancement factors f(R), the reliability of data sources, also their comparability, but above all on how accurate and realistic a definition of residual stress patterns can be in practice. Trying to cover these uncertainties it was decided to lower further the design proposal for the f(R) relationship, practically assuming now values justified by the majority of lower limits in the analysed data (as depicted for instance, but not exclusively, in **Figure 2402.01.08, Figure 2402.01.09** and **Figure 2402.01.10**). Thus the proposal after **Figure 2402.01.14** was adopted as the final design proposal for the European Recommendations.



Source: Figure B1.1 ECCS ERAAS, 1992

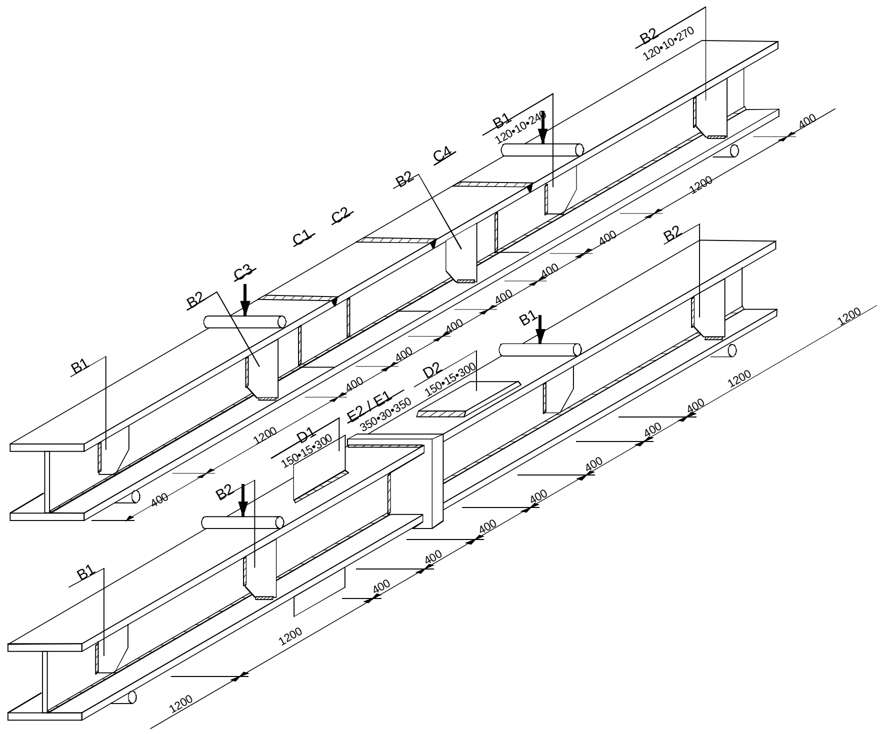
TALAT	R-Ratio Dependency and Residual Stresses (ERAAS)	2402.01.14

Line I is applicable only to base material and wrought products where there are no residual stresses acting on the structural elements or where such stresses can be fully taken into consideration in the design concept. Line II is to be used generally for all connections, also welded ones, where knowledge on the residual stress situation is available and is being considered. Line III covers those cases where significant global residual stresses are present but cannot be considered in the design analysis. This last case with no allowance for an enhancement factor includes thus all welded details in general practice.

Residual Stress Effects

We have already mentioned the difficulties in detecting, measuring or in any way quantifying the residual stress situation of a structural component. Indirectly this situation has been reflected in the proposal for the f(R) factor.

Currently there are again some efforts undertaken to quantify the residual stress pattern of welded aluminium constructions. During the course of drafting the ERAAS information from the comprehensive welded beam fatigue testing programs at the Technical University of Munich it was possible to undertake initial residual stress measurements on full-size welded components of 7020 and 5083 alloys, **Figure 2402.01.15.**

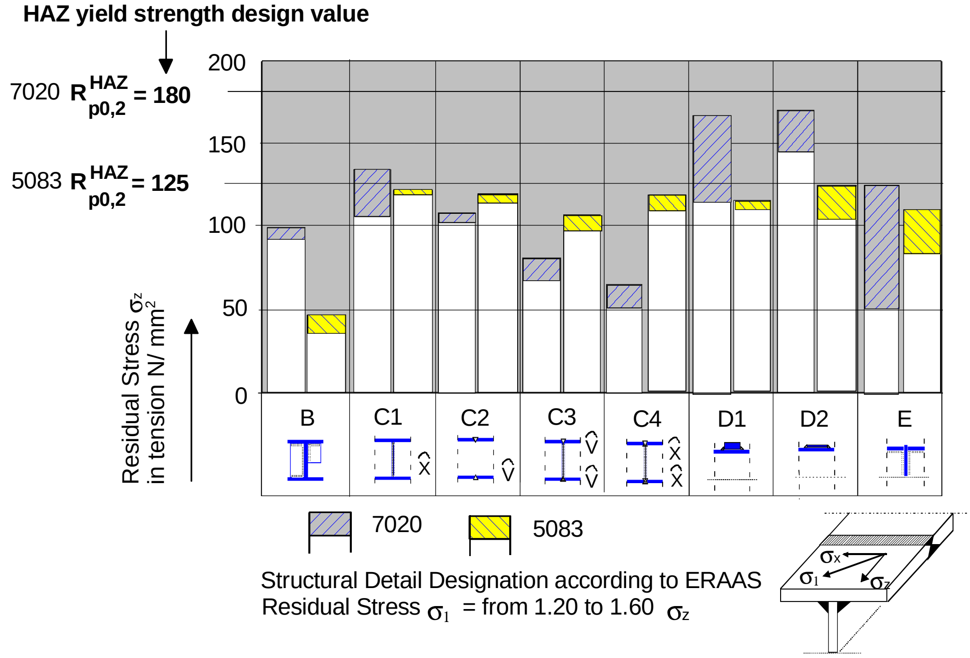


Source: D. Kosteas, Technical University Munich

TALAT Training in Aluminium Application Technologies	Welded Aluminium Beams for Fatigue Tests	2402.01.15

The measurements themselves and the difficulties associated with the interpretation of these limited results or the sometimes somewhat contradictory information have been described elsewhere and allow presently only the following general conclusions:

- residual stresses in welded components of considerable magnitude, reaching values up to the 0.2-yield-limit of the HAZ, was registered, **Figure 2402.01.16**
- scatter is an inherent feature in measurements made by the hole-drilling method. Efforts were undertaken to make measurements sufficiently close to the welds, approximately 1 mm off the weld toe, by using rosettes with the strain gages arranged on one side only
- there were some but no significant differences in residual stresses in the structural details of the 7020 and 5083 alloy.



Source: D. Kosteas, Technical University Munich

TALAT Training in Aluminium Application Technologies | Residual Stresses Measured in Fatigue Test Beams | 2402.01.16

As seen in **Figure 2402.01.16** the highest values of residual stresses were recorded at fillet welded longitudinal or transverse attachments on beam flanges. Residual stresses in these details attained values of over 180 MPa. Residual stress measurements at butt welded splices and cruciform joints made with butt-like full penetration welds attained values between 120 and 140 MPa.

No answer can be offered for the time being to the question of whether initially measured residual stresses are maintained, and at what magnitude, during subsequent load cycling of the components. Indirect measurements at strain gauge monitored crack initiation sites showed values up to 120 MPa. these gauges may not have been sufficiently close to the maximum residual stress site, though. Residual stresses, therefore, may have been higher.

The general lower location and steeper slope of S-N curves giving the behaviour of components vs. small specimen data agree with similar findings in steel weldments (see DIN 15018 and Eurocode 3 or ECCS TC6).

There are still difficulties in interpreting differences between S-N curves with stress ratios of R = -1 and R = +0.1. The first show at times approximately 40% higher fatigue strength values of stress range plotted in a log-log diagram at $2 \cdot 10^6$ cycles. The effect is more pronounced in the case of 7020 alloy details. It does not seem prudent, though, to allow for a bonus in design values in such cases of large components, since sufficiently reliable data is still missing.

Appendix

The following clauses from the ERAAS Fatigue Design, final version, December 1990, cover:

B.3 Influence of R-Ratio

For stress ratio values less than R=+0.5 a fatigue strength enhancement factor f(R) may be considered and is given in Fig. 16. (see **Figure 2402.01.14**) This factor is stated for a fatigue life $N=2 \cdot 10^6$ cycles. For other fatigue life values see Clause B.3.2.

B3.1 The following cases shall be distinguished (see Fig. 16):

I Base material and wrought products in structural elements, assuming that any residual stresses can be neglected for such elements

f(R) = 1.6	for R < -1
$f(R) = -0.4 \cdot R + 1.2$	for $-1 \leq R \leq +0.5$
f(R) = 1	for R > +0.5

II Connections (welds or fasteners) in simple structural elements.

f(R) = 1.3	for R < -1
$f(R) = -0.4 \cdot R + 0.9$	for $-1 \leq R \leq -0.25$
f(R) = 1	for R > -0.25

III For complex two- or three-dimensional structures with residual stresses a constant factor shall be used

f(R)=1

For connections in structures which have been adequately stress-relieved curve I shall be used

B3.2 For the calculation of fatigue strength at values R other than +0.5 and N between $1 \cdot 10^4$ and $5 \cdot 10^6$ cycles the following procedure is given, assuming that the basic design line as given in the Data Sheets is rotated around its value at $1 \cdot 10^4$ cycles.

The resulting slope is:

$$m(R) = \frac{-2.301}{\log f(R) + \log \Delta\sigma_{2 \cdot 10^6} - \log \Delta\sigma_{10^4}}$$

where

f(R): from Fig. 16
$\Delta\sigma_{2 \cdot 10^6}$: the corresponding fatigue stress range of the basic design curve at $2 \cdot 10^6$ cycles (for R=+0.5).
$\Delta\sigma_{10^4}$: the corresponding fatigue stress range of the basic design curve at $1 \cdot 10^4$ cycles (for R=+0.5).

For fatigue life values $N > 5 \cdot 10^6$ cycles the fatigue strength values of design classes for welded details B, C, D, E, and F are defined assuming that the slope of the design curve is m'(R)=m(R)+2. For base material design class A use m'(R)=m(R).

2402.02 Safety and Reliability

- Reliability concept
- Partial safety factor concept
- Concept of fatigue design curves

Values used in fatigue life predictions should be chosen so that they lead to a conservative life. There are many different uncertainties which can influence fatigue life predictions decisively. These may be associated for instance with

- load estimation
- stress calculation
- S-N data
- fabrication
- damage accumulation theories

For practical reasons the above influences will be expressed as safety margins within the design procedure expressing their inherent uncertainties.

A fatigue design concept is based on an assessment of required life, cycles to failure, for the given environmental conditions and structural configuration. The assessment may be based on

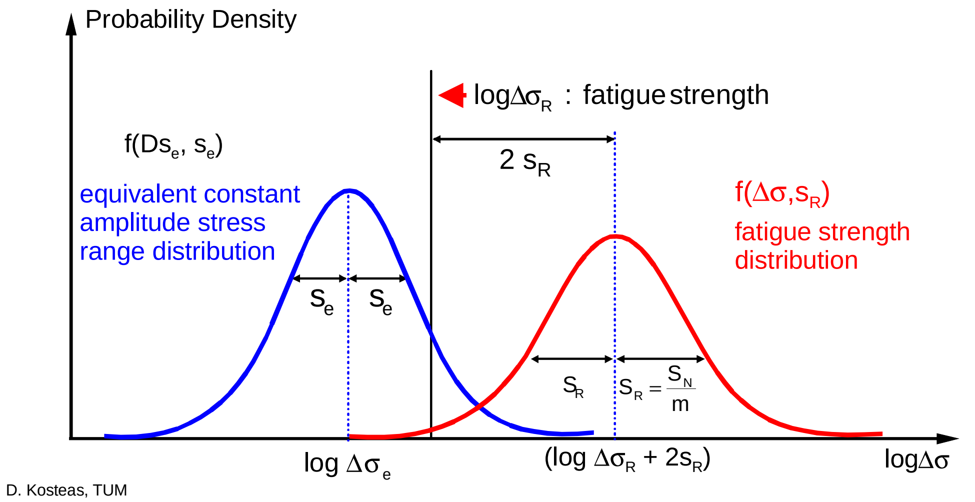
- reliability analysis
- partial safety factors for loading and material related to respective S-N curve
- fatigue design curves or 'allowable S-N curves'

Reliability Concept

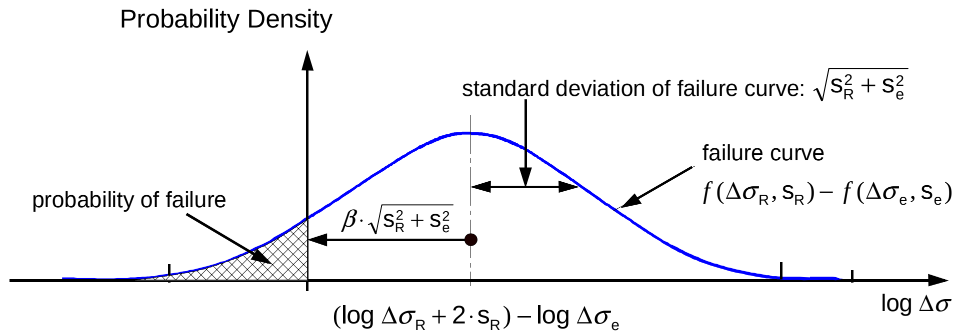
The probability of failure of a structure can be determined through a suitable reliability theory, when the variability of the parameters governing fatigue life are known. So far as due to a certain load distribution S and a material or component strength distribution R a load-strength combination of the type R<S can occur a structure will fail (see **Figure 2402.02.01**). The probability distribution of the quantity R-S is then by definition the probability of failure (see **Figure 2402.02.02**). The safety factor is defined as the ratio of corresponding statistical values of the two original distributions. In **Figure 2402.02.01** the definition of the partial safety factor for loading γ_S and the partial safety factor for resistance or material γ_R are given. The safety index β is related to the partial safety factors by the relation

$$\beta = \frac{\log \gamma_S + \log \gamma_R}{\sqrt{\left(s_S^2 + s_R^2\right)}} \qquad (1)$$

Load and Resistance Distribution



TALAT Training in Aluminium Application Technologies | Load and Resistance Distribution | 2402.02.01

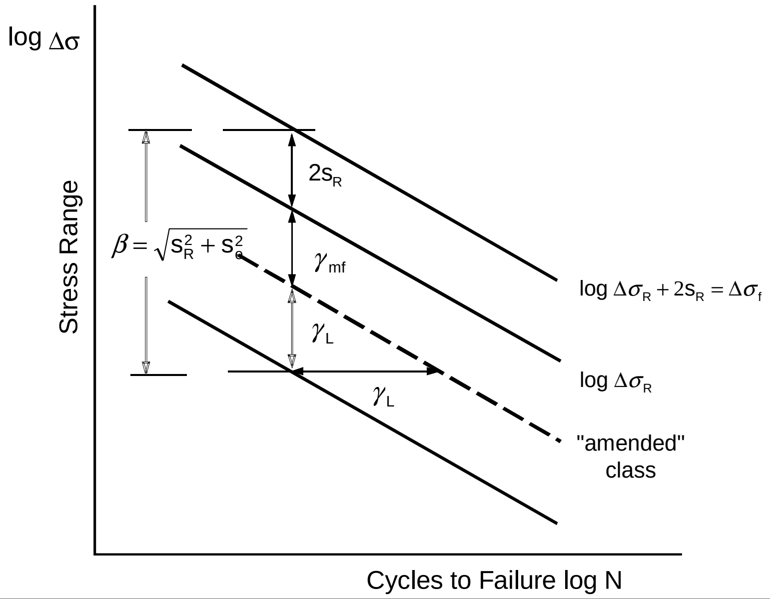


TALAT Training in Aluminium Application Technologies | Probability of Failure Distribution | 2402.02.02

Assuming that the S-N relationship is expressed by a straight line of slope m in log-log co-ordinates for a given life N we usually distinguish between

- a the allowable loading for this life (see **Figure 2402.02.03**) line referring to the mean of fatigue strength $\Delta\sigma$
- a line referring to limit value of fatigue strength $\Delta\sigma_R$ and a distance of two standard deviations $2s_R$ from the mean value as above - identical to the design classification value for a structural detail in the design recommendations
- an 'amended' line in γ_m-fold distance and, lastly,
- a line in a γ_l-fold distance from the last one representing.

Schematic Definition of Safety Factors



TALAT Training in Aluminium Application Technologies | Schematic Definition of Safety Factors | 2402.02.03

Following the usual definition of design lines in Recommendations as fatigue strength limits with 97.5% probability of survival and with respective partial safety factors equation (1) can be written for the purposes of a fatigue assessment as follows

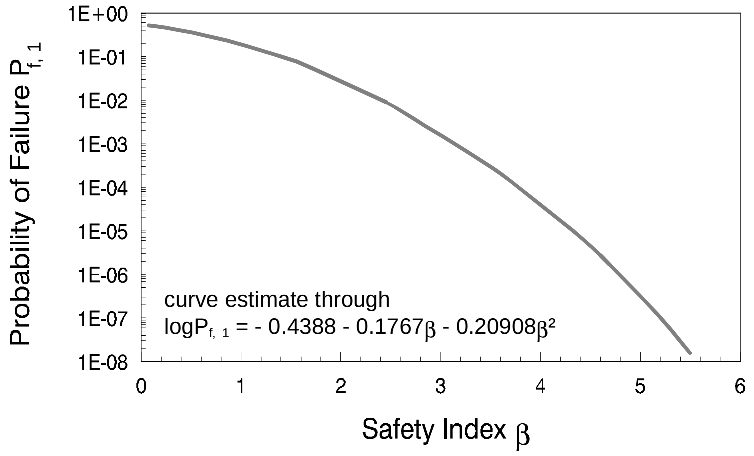
$$\beta = \frac{\log \gamma_S + \log \gamma_R + 2s_R}{\sqrt{\left(s_S^2 + s_R^2\right)}} \qquad (2)$$

This equation indicates the safety level, i.e. the probability of failure at the end of the design life. Taking as a basis a proposal of the Nordic committee the value of the index ß is in functional relationship with the annual probability of failure $p_{f,1}$ (see **Figure 2402.02.04**)

$$\log(p_{f,1}) = -0.4388 - 0.1767*\beta - 0.20908*\beta^2 \qquad (3)$$

This relation gives us the possibility to calculate recommended β-values for different applications and design lives of structures. As an example, BS8118: 1991, Part 1 indicates the following values (see also **Figure 2404.02.05**)

Highway bridges	120 years	Buildings, cladding	30 years
Flood protection works	100	Boats	30
Buildings, primary structures	100	Cranes	20
Breakwaters	60	Containers	15
Lattice towers and masts	50	Vehicle bodies	10
Tall towers	50	Scaffolding	10
Railway vehicles	35		



$$\beta = \frac{k_S s_S + \log \gamma_F + \log \gamma_M + k_R s_R}{\sqrt{s_S^2 + s_R^2}}$$

TALAT — Training in Aluminium Application Technologies | Safety Index β | 2402.02.04

Design Lives

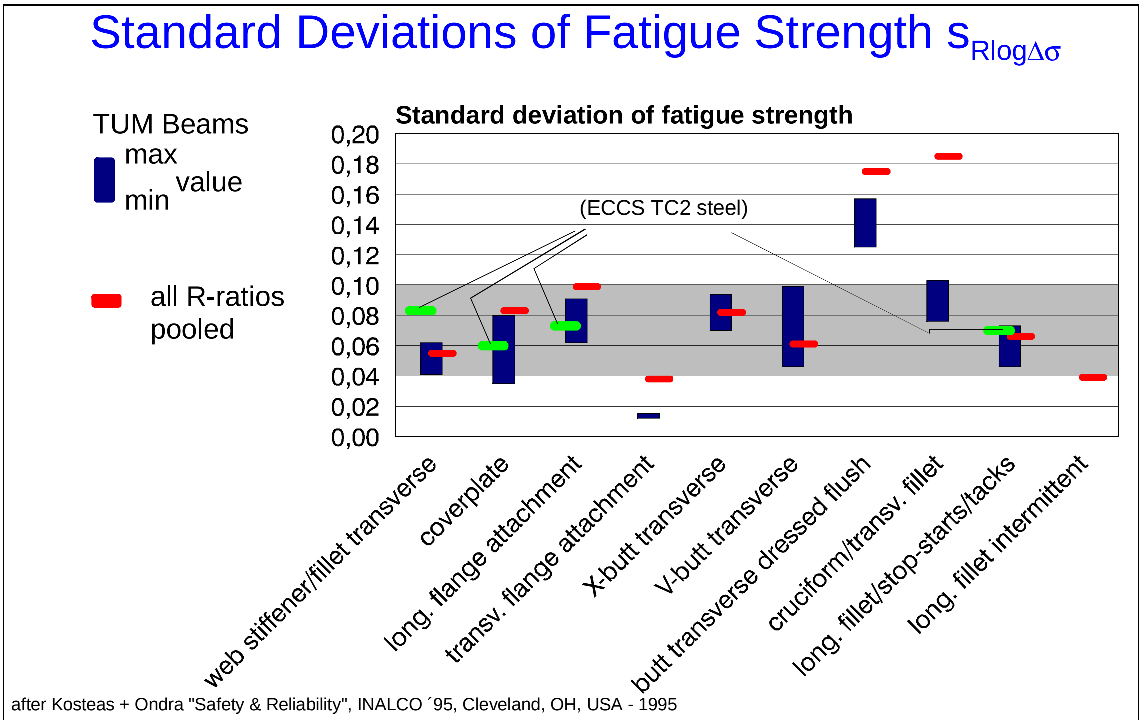
after BS 8118: 1991, Part 1

Type of Structure	Design Lives in Years
Highway Bridges	120
Flood protection works	100
Buildings, primary structures	100
Breakwaters	60
Lattice towers and masts	50
Tall towers	50
Railway vehicles	35
Buildings, cladding	30
Boats	30
Cranes	20
Containers	15
Vehicle bodies	10
Scaffolding	10

D. Kosteas, TUM

TALAT — Training in Aluminium Application Technologies | Design Lives | 2402.02.05

Equation (2) can be solved if the load and the fatigue strength distributions with respective scatter values are known. There is only scant information about load distributions and an additional problem arises due to the fact of specific load histories and stress spectra in various applications. Recent comprehensive fatigue test analysis has provided several values for different aluminium alloys and their welded joints also in the case of large components, **Figure 2402.02.06.** The values in the diagram are logarithms of the standard deviation of the fatigue strength. For design purposes a transformation to respective values in terms of fatigue life can be derived $S_{R,(\log N)} = m^* S_{R,(\log\Delta\sigma)}$. Accordingly the relationship between the safety factors in the strength scale and the life scale would be $\log\gamma_{(\log\Delta\sigma)} = m^*\log\gamma_{(\log N)}$.



TALAT Training in Aluminium Application Technologies	Safety and Reliability - Standard Deviations of Fatigue Strengths	2402.02.06

As a result of the above difficulties in defining parameters for the described reliability assessment procedure, especially the definition of an appropriate probability of failure and respective β-value, this procedure is not yet a part of recommendations. We mention here the attempt to present certain definitions and values in the ECCS 6 'Fatigue Design of Steel Structures Recommendations' where a proposal of an appropriate value for $\beta = 3.5$ has been stated.

Partial Safety Factor Concept

It is obvious that a direct definition of recommended partial safety factor values presents the least difficulties for the engineer in practice. But even such a procedure has not been incorporated into recommendations in the case of fatigue design. It is already though a part of the static design assessment procedure, for instance Eurocode 3 Steel, ECCS 6 Recommendations for fatigue design in steel, ECCS 2 Recommendations for Aluminium Alloy Structures, BS 8118: 1991.

In drafting the recent recommendations for aluminium design in fatigue values for the partial safety factors have been discussed in estimating design curves. As an indication for recommended values in this area the following is stated.

For the fatigue material safety factor γ_R and depending on the consequences of failure or the redundancy of a structure the values of 1.2 (statically determinate structure) and 1.0 (statically indeterminate structure) in case of easy inspectability of the component for fatigue cracks is proposed. In case that components cannot be inspected the respective values are 1.4 and 1.2.

The condition in the fatigue assessment procedure is that estimated life should not be shorter than the factored design life. Here the fatigue life safety factor $\gamma_{S,(logN)}$ expresses the quality and confidence of the loading history. If records of loading are kept, or frequency of loading is well established $\gamma_{S(logN)}$ = 1.25, but in the case that no records are kept or frequency is unknown a substantial increase of $\gamma_{S,(logN)}$ = 10 is to be assumed. These values correspond to $\gamma_{S,(log\Delta\sigma)}$ values of 1.08 and 2.15 respectively for a representative slope value of m = 3.75 as recorded in several details of the ERAAS Fatigue Design. Especially in reassessments of a structure in mid-life this factor should also be reassessed.

Defining the product of the two partial safety factors as a nominal safety

$$\gamma = \gamma_{R,(log\Delta\sigma)} * \gamma_{S,(log\Delta\sigma)}$$

the following values result from the above proposals in the case of the ERAAS Fatigue Design and for an S-N curve slope of m = 3.75.

Structure is statically	Inspectability	Loading	
		known	unknown
indeterminate	good	1.06	1.85
	poor	1.27	1.85
determinate	good	1.27	2.22
	poor	1.48	2.59

In comparison to these the respective values of Eurocode 3 for steel structures and especially a 'non-fail-safe' structure (i.e. in the case that component failure results in a an overall failure are given:

Inspect/Repair of component is	Design Concept fail safe	Design Concept non fail safe
easy	1.00	1.25
difficult	1.15	1.35

It must be pointed out that the Eurocode postulates a defined pattern of maintenance and that in the case of difficulties with inspection and repair the owner should be notified.

Concept of Fatigue Design Curves

Current recommendations for fatigue design in aluminium alloy structures use the concept of design curves almost unanimously and do not make use of any further safety factors. This is for instance the case with the 'ECCS-European Recommendations for Aluminium Alloys Fatigue Design' (1992) and the 'British Standard 8118: 1991 Structural Use of Aluminium'. The latter leave the possibility open for the designer to introduce additional partial safety factors for both loading and fatigue strength.

The overall load factor γ_S should be taken to be unity provided that the loading and the evaluated fatigue strength data comply with certain conditions pertaining to loading. All sources of fluctuating stress in the structure should be identified and obtained as an upper bound estimate of the service loading sequence for the structures design life. Realistic assessment of the fatigue loading is crucial to the calculation of the life of a structure.

In both recommendations (ERAAS-Fatigue Design and BS 8118) the value of the partial safety factor on fatigue strength γ_R is assumed to be unity as well. The design curve through which the fatigue assessment is performed is defined at a „mean minus 2 standard deviation level" below the mean line through experimental data.

In certain circumstances the designer may wish to increase the nominal design life by multiplying by a factor (the fatigue life factor $\gamma_{S,(\log N)} > 1$). The choice of the value of this factor could be influenced by the following conditions:

- the possibility of increasing crack growth during the later stages of the life of the detail
- the accuracy of the assumed loading spectrum
- whether records of loading will be kept during the life of the detail
- the possibility of a change of use of the structure in mid-life

The designer may also wish to apply a fatigue material factor $\chi_{R,(\log\Delta\sigma)}$ to the design stress range as given by the design curves in the recommendations. The design stress range would be divided by $\chi_R > 1$ and the choice of the appropriate value could be influenced by the following considerations:

- the need for the detail to exist in a very hostile environment
- whether failure of the detail will result in failure of the entire structure, or whether alternative load paths exist.

The assumptions of the previous paragraph indicate recommended values.

2402.03 Background on Current Design Recommendations

- European Recommendations ERAAS Fatigue Design 1992
  - Full-size component testing and analysis
  - Detail classification and design curves
  - The S-N slope proposal
  - Comparison to steel codes
- The British Standard 8118:1991
  - Data sources
  - Data analysis and detail classification
  - Design curves
  - Classification of details
- Comparison between BS 8118 and ERAAS

Given the fact that currently the two most complete and extensive documents covering fatigue design of aluminium structures are the European Recommendations for Aluminium Alloy Structures Fatigue Design and the British Standard BS 8118 an outline of the drafting stages, the data analysis and evaluation and the ensuing design format is presented. This background information provides the necessary knowledge for adaptation of procedures in design problems with special environmental conditions or manufacturing parameters and possible utilisation of other specific experimental data. In the following paragraphs on the ERAAS description concentrates more on the data background and its analysis. The description on BS 8118 presents some basic considerations about fatigue specifications. The two documents show many similarities in the data evaluation and classification, a comparison is given in a third section. Finally the BS document gives also full details on quality assurance, but this is handled underTALAT Lecture 2404.

European Recommendations ERAAS Fatigue Design 1992

Bearing in mind that in preparing the recommendations one of the most important items to be resolved was the definition of design values respective to specific structural details considerable consultations took place trying to pinpoint the type of details reliably supported by experimental evidence or the number of different ones to be considered in the document. Out of a total of over 45 different details mentioned in various specifications of the time it was recognised that information was available for only 14 of them. If one demanded statistically reliable data the number had to be reduced to a "nucleus" of 6 details.

Full-Size Component Testing and Analysis

The above elements were determinative of the actions to follow. Considering previous work of ECCS TC2 and corresponding to the interests of several national bodies the European Aluminium Association (EAA) decided in June 1988 to provide within the framework of the COST 506 Program of the Commission of European Communities a widely accepted information base for a standard on advanced structural design of aluminium components exposed to fatigue loading. The information base would include fatigue data related to full-scale components available in Europe by this date. Within the EAA a study was performed on "the data harmonisation and establishment of principles for a fatigue design code for welded aluminium structural elements" at the Technical University of Munich together with the Centre de Recherches Pechiney in Voreppe, France. The work plan, as outlined initially by the author, included: (1) establishment of a common data base, (2) establishment of analysis methodology, (3) establishment of cases to investigated, (4) statistical/regression analysis of individual data sets or "families"/groups of data sets, (5) definition of characteristic values, and (6) proposal for P-S-N curves for design along established concepts. This "COST 506 - EAA Study" provided the first comprehensive outline for the fatigue behaviour of structural components, especially beams, in aluminium.

Later efforts concentrated on enlarging this data base through additions of further fatigue test results (TUM Beam Fatigue Project B), numerous additional attempts to compare sets of data, to analyse variations, to define influence of geometrical parameters, possible influence of alloy effect or residual stresses and R-ratio upon fatigue behaviour, to define structural detail classifications and to estimate design values. **Figure 2402.03.01** outlines the range of materials and structural details covered by the various analyses and included in the final document of the ERAAS.

THE COST 506 - EAA DATA PACKAGE

Beams

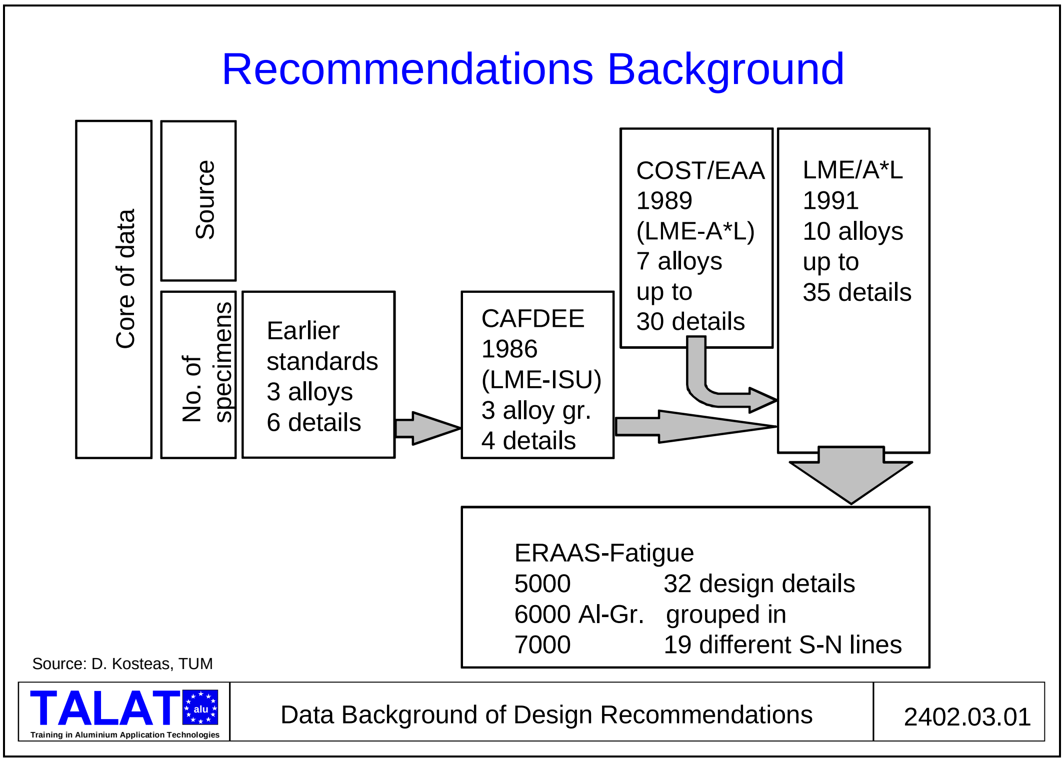
Source	No. of Struct. Details	No. of Data Sets	No. of Data Points
ALS	25	110	983
TUM	11	38	174
AMAG	8	11	90

Total Number of Data Points: 1247 including 142 run-outs
Base Metal: 105 Data Points
Weldments: 1142 Data Points

Small Specimens ALS

Structural Detail	No. of Data Sets	No. of Data Points
Base Metal	11	423
Drilled Holes	3	123
Butt Weld Trans.	10	407

Total Number of Data Points: 953
ALS alloy 6005A tests only



Taking into account the views expressed above on the reliability of existing data packages and the respective analyses it was decided to take into account fatigue test data on aluminium components, beams, as base material and welded details. Only a few data were available in riveted connections or as notches in the form of drilled holes. Three institutions contributed to the respective data packages, as outlined in the above table. Because of the high degree of uniformity in a further data package concerning tests on small specimens with alloy 6005A and the comprehensive information on parameters such as plate thickness and stress ratio it was felt that these data would contribute decisively to the formulation of respective influences on fatigue and they were added to the analysis.

Two parallel analysis procedures were undertaken, see boxes below, with corresponding statistical-regression models. The first used the initially "unidentified" data sets - i.e. distinguished only by their data set number but not described as to their corresponding structural detail type or other characteristics - in an attempt to prove the statistical compatibility of certain groupings of data or the fact that individual data sets could be reliably related to a common group leading thus to the "detail class" for design purposes. The second used the model to predict individual S-N relationships of both original data sets and "families" of data sets, deciding about the possible groupings primarily through engineering judgement - i.e. taking into account knowledge about structural detail type, failure location and type, initial imperfection, workmanship, alloy, joining procedure, etc.

It should be pointed out that there was a very satisfactory correspondence between the end results of the two parallel analysis procedures - especially when considering the desired subsequent classification of design cases in a limited number of classes.

Especially in the first analysis internal coherence of each group was carried out: characteristic values of data sets of each group were compared (scatters, slopes, logcycle means for a given stress level); within the groups data sets exhibit the same slope and scatter values; the significant differences between logcycle means of data sets are not "physically" too important, compared to data set scatter.

THE COST 506 -EAA ANALYSIS PROCEDURE

Analysis Uhry/CRV (purely statistical)	Analysis Kosteas/TUM (engineering assumption)
Individual Data Sets	
maximum likelyhood censored data = run-outs test for outliers standard linear regression	with or without run-outs maximum likelyhood with run-outs test for outliers
Data Sets Grouped	
grouping on the basis of common individual slope, intercept and scatter; significantly different from respective group parameters (graphical verification)	grouping on the basis of same structural detail
statistical analysis of each group = "family"	

For several reasons such as conservative analysis in view of limited or inexact information, difficulties in establishing run-outs from current reports or test procedures, further analysis options - beyond the maximum-likelyhood method exercised by both CRV and TUM - were carried out by TUM such as a linear regression excluding run-outs altogether and a linear regression assuming identified run-outs as failed specimens.

THE COST 506 -EAA ANALYSIS MODELS

Model (1)	**logN = a + b*logS** double-log linear model for the analysis of individual data sets
Model (2)	**logN = a(i) + b*logS** assuming that one certain feature has no effect on scatter or slope but only on the intercept of the lines
Model (3)	**logN = a(i) + g(j) + b*logS** assuming that two features have no effect on scatter or slope but only an additive effect on the intercept of parallel lines

The effects of alloy, R-ratio, plate thickness and data source were also investigated on subgroups of "balanced data" extracted from the global file of data sets in order to avoid confusions or bias.

The alloy effect was studied on Alusuisse data only, since these comprised a comprehensive set of data, approximately equal numbers of observations for each alloy and involved a greater number of alloys (see boxes below). The study was carried out according to the following steps:

a) a subfile was set-up containing those common details present for the different alloys,
b) for each alloy the common slope and scatter values for the data sets of this alloy were estimated using the statistical model no. 2 (see box above) and supposing that here the data set had no effect on scatter or slope but only on the location of the parallel straight regression lines,
c) scatters of different alloys were compared by the Hartley test,
d) slopes were compared by the studentized range test,
e) alloys were gathered and the alloy effect on logcycle mean was estimated using the statistical model no. 3 (see box above) and supposing that the alloy as well as the detail have no effect on slope or scatter and that their effects on the location of the regression lines are simply additive, i.e. they have no interaction.

Three similar analyses were performed for the listed alloy groups. Summarising the results: no alloy effect was observed for the welded details, whereas in the case of parent material alloy 7020 exhibited higher values than the 5000 or 6000 series alloys with an estimated difference of d = 0.8 + or - 0.2 in logcycle mean for a stress level of 100 MPa.

Alloy Effect

Flange Edge	6082		
Attachment with or without transition Radius			
Coverplate			
Flange Attachment, vertical, longitudinal		5086	
Web Stiffener		6082	
Web Attachment	6005A	7020	
Butt Weld, transverse			5083, 5454 6005A, 6082 6082, 7020
Base Metal, Extrusions, Built-up Beams			

Thickness Effect

Source	Flanges	Attachments
ALS	10	8 to 10
TUM	15	110 or 15
AMAG	15	15

R-Ratio Effect

Source	0,15	0,10	0,06-0,08	-1
ALS	X	X	X	
TUM		X		X
AMAG		X		

The R-ratio effect was studied with the same methodology as above, but solely on TUM beam data since we had here consistent and sufficient data on 3 details: all data for alloy 7020 and in the two R-ratio values +0.1 and -1. The three details - longitudinal vertical attachment with fillet welds on beam flange, coverplate on built-up beam flange, full beam connection with butt weld with overfill as welded - showed non-significant differences in slope/scatter (-2.7/0.15 and -2.8/0.18 for the R-values +0.1 and -1, respectively), but exhibited a significant difference for the logcycle mean value at a stress of 100 MPa; here the value for R = +0.1 was 4.61 ± 0.07 and the value for R = -1 was 5.01 ± 0.07, i.e. a difference as correction between the two R-ratios of 0.4 ± 0.1. The effect of R-ratio has been studied later on in considerable depth, utilising further test results, and, especially the extensive contingent of small specimens of the Fatigue Workshop Zurich - see following chapters.

Variations in the thickness of cross section elements of the beams and their attachments was not sufficiently significant so as to be quantitatively stated. Taking into account the above mentioned small specimen test results and bearing in mind the well established experience from earlier investigations of no significant thickness effects, at least for the range between 6 and 15 mm, the issue was not followed more closely.

Finally, a possible effect of the data source was studied graphically. For six structural details no consistent pattern emerged for the relation of the three data sources. The same was valid when comparing logcycle mean values for a given stress value for details from the respective source. For the structural detail of transversely butt-welded beams results available from all three sources were compared as to significant differences in their scatter, slope or logcycle mean values. Differences were not significant. The overall conclusion was that results from the three sources were considered homogeneous enough to be analysed simultaneously as one data set.

Detail Classification and Design Curves

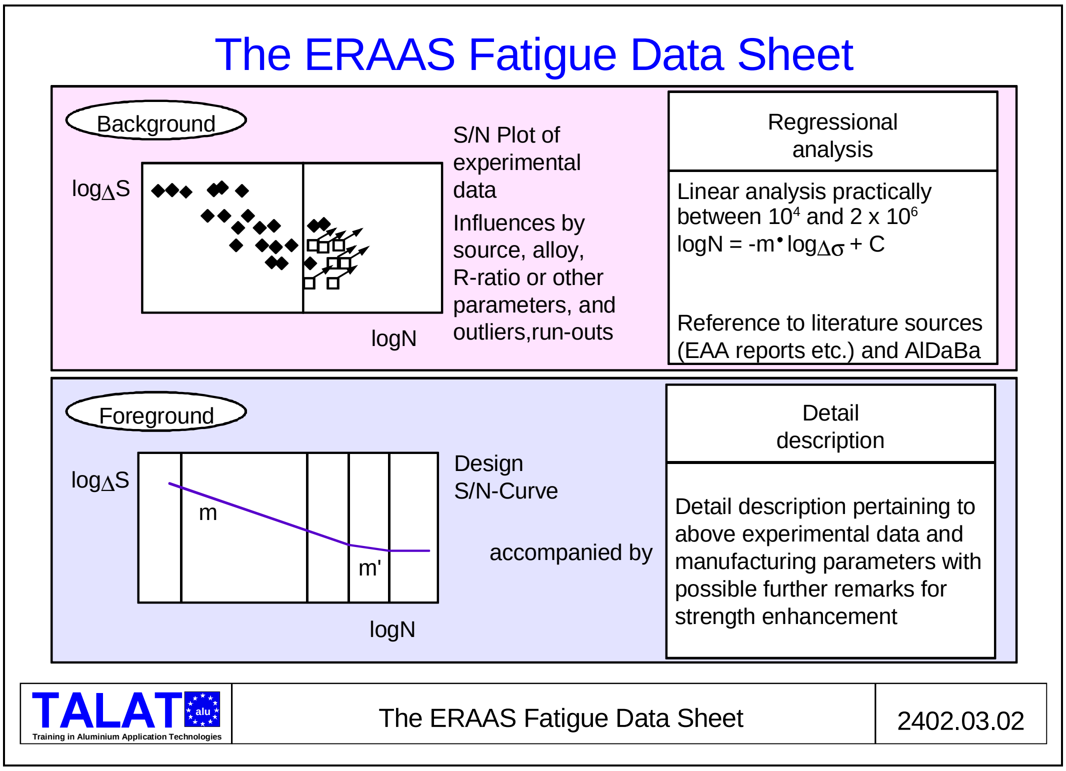
Following several in-between proposals the format of the recommendations was finalised and the concept discussed called for:

- a set of S-N curves as representative design lines, limited in number,
- lower limit curves, i.e. strictly "mean minus two standard deviations", thus covering most unknown variables in detail type, manufacturing, quality and loading parameters,
- straight line regression, often extrapolated down to regions around $2*10^6$ cycles, on the safe side, often rather conservative though, for a wide spectrum of applications of the recommendations,
- a clause in the recommendations to enable more sophisticated design and manufacturing with considerably higher quality and ensuing fatigue strength.

A second concept emerging was demanding for:

- a more rigid design procedure with a greater number of structural details defined in more detail in the recommendations,
- a larger number of variations of these details according to manufacturing characteristics (especially for weldments) with respective strength levels, demonstrating thus in a better way capabilities of the material, and
- as a result this meant a larger number of detail classification cases and design lines.

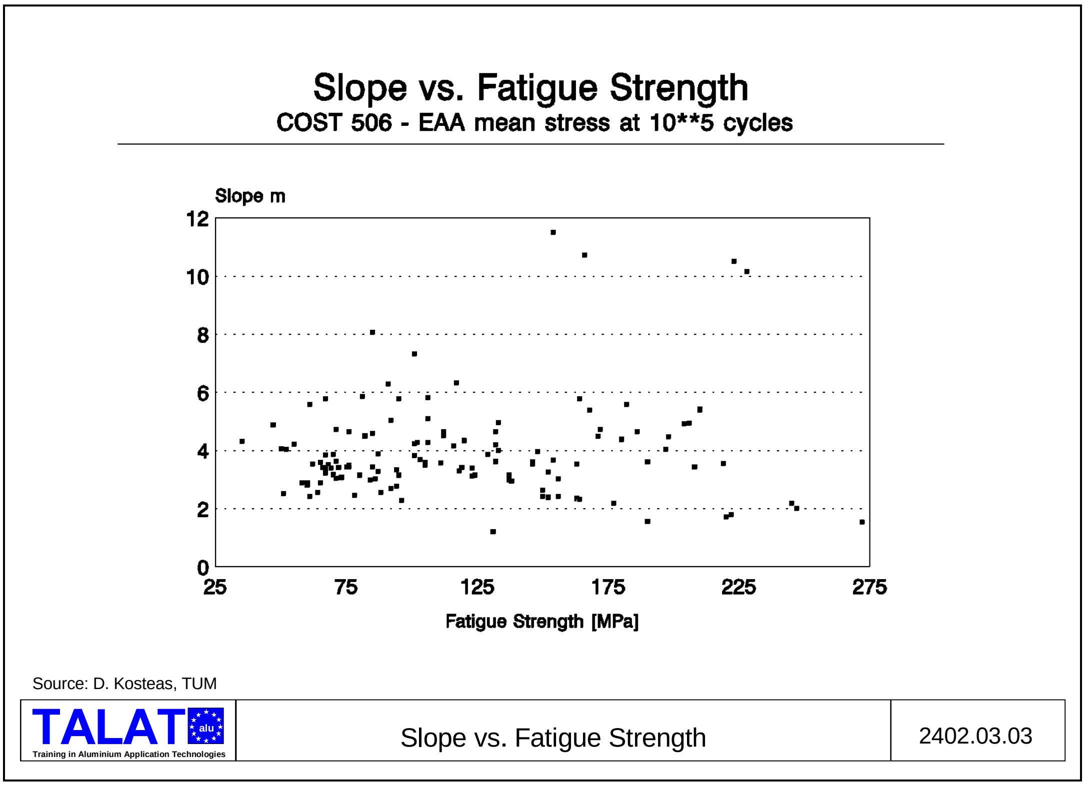
The above led to the decisions for the fatigue stress range value at $2 \cdot 10^6$ cycles of the basic design curve (R = +0.5). Information on the initial test values, R-influence factors and residual stress effects (TUM test reports, EAA evaluations, Workshop results) was integrated into proposals for the Recommendations. The "Data Sheet", **Figure 2402.03.02**, provides the link between the design curve and detail description in the Recommendations and the background information analyzed. It represents also a key-element for the implementation of the Aluminium Data Bank and the development of the ALFABET design procedure system, see **Lecture 2404.01**. A need for a more detailed and diversified classification of butt welds, depending on manufacturing quality was reached by enlarging the number of classes to and by re-analysing all available data in small specimens, extruded or built-up components.

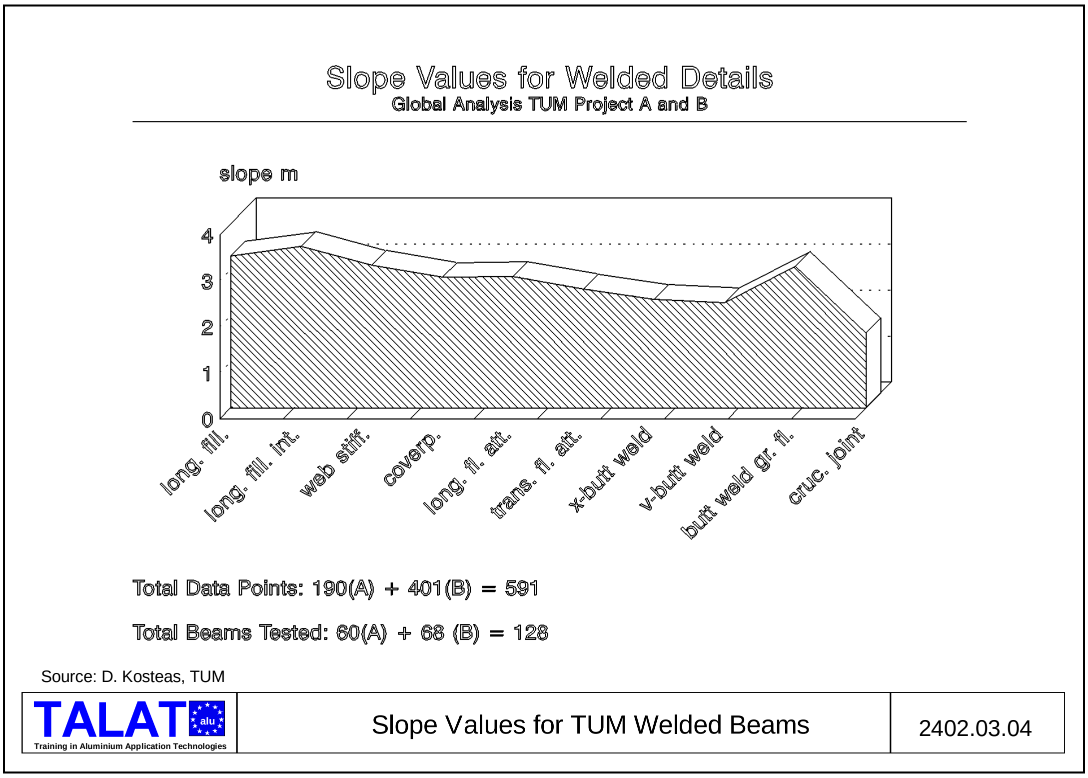


The S-N Slope Proposal

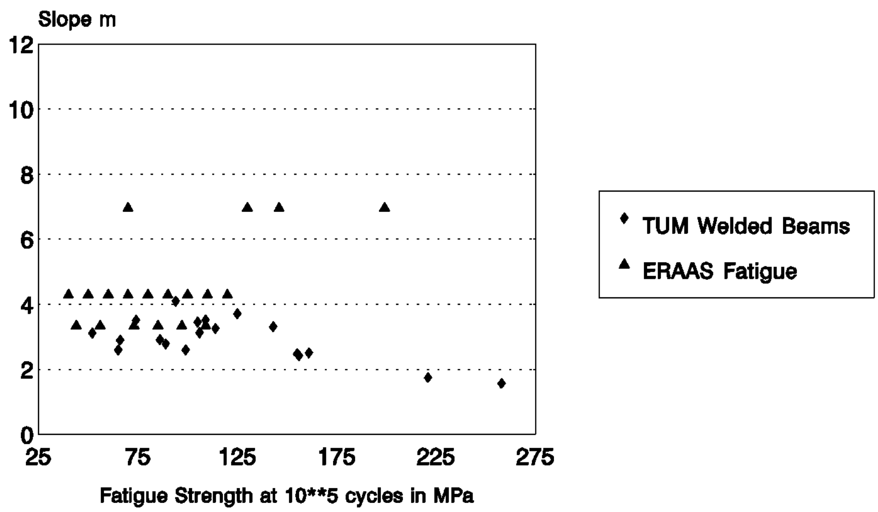
Other than mere statistical aspects had to be considered for the definition of the design S-N lines. The degree of uniformity and harmonisation regarded as optimum under the implied or specified conditions has been attained mainly through best fit at the desired probability of survival level of fatigue strength at the critical life region, most times at $2 \cdot 10^6$ cycles, and an assumed slope value, common for a group of structural details. That these values lie within the range of experimentally established values is demonstrated with **Figure 2402.03.03** showing the data point field of slope values m vs. fatigue strength for the data file of the COST 506 - EAA Study; with **Figure 2402.03.04** showing the values for welded details for the TUM beam programs; and finally through **Figure 2402.03.05** which gives the TUM welded beam slope values vs. their respective fatigue strength values at 10^5 cycles (since it is at this life region approximately that we have the centre of gravity of the data point field) against the assumed slope values at the three levels of m = 7.00 for parent material and m = 3.37 or 4.32 for the welded details. It should be mentioned perhaps that the above assumed slope values are in reality "calculated" values for two characteristic stress-life pairs from the respective S-N plots.

This concept was checked against some other options, common in other specifications. The first option was to use instead of the fixed strength values (best-fit at critical lives) an equi-distant parallel design S-N line band with three possible, i.e. lying within the experimentally established values, slopes of m = 3.4 / 3.8 / 4.3. The second possibility was given by a parallel line band with m = 3.8 through the original ERAAS strength values at $2 \cdot 10^6$ cycles. The result of these comparisons showed clearly the advantages of the adopted ERAAS proposal.





Slope vs. Fatigue Strength



TUM Data: mean values

Source: D. Kosteas, TUM

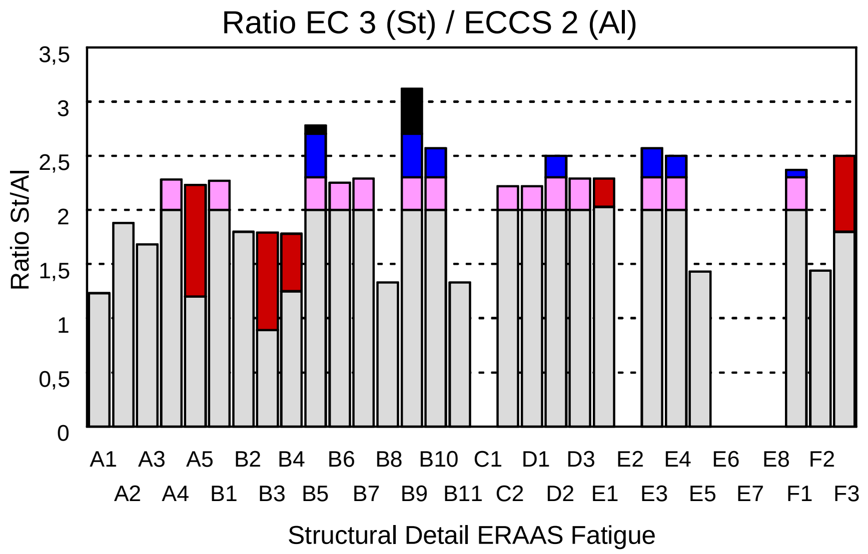
TALAT Training in Aluminium Application Technologies	Slope Values ERAAS vs. TUM Welded Beams	2402.03.05

Comparison to Steel Codes

In design practice the relative strengths of different materials take a special meaning in the very first steps of material and structural configuration selection decisions. Such rough estimations should be considered very carefully though, even with scepticism. Nevertheless they are in use and in the case of the fatigue strength behaviour of different details between the two materials steel and aluminium, even if other manufacturing and structural parameters have to be taken into account as well, they offer a picture of the existing interrelations.

A comparison of fatigue values at $2 \cdot 10^6$ cycles between aluminium and steel is demonstrated in **Figure 2402.03.06.** It is interesting to notice that even between different existing specifications in steel there are significant differences in the absolute values proposed. Another fact is the different relation of various structural details to each other in the case of steel and in the case of aluminium. Finally the last column of the table shows the ratio of steel to aluminium when comparing the European specifications in steel (EuroCode 3 or ECCS 6) to the ERAAS Fatigue Design 1992 document. Out of 27 details where the ratio could be established only 1 exhibited a value higher than 3.00. There are 4 cases with values higher than 2.50; frequently, in 11 cases, we find values even lower than 2,00.

Fatigue Strength Comparison at 2 x 10^6 Cycles



Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Fatigue Strength Comparison Steel/Aluminium	2402.03.06

COMPARISON BETWEEN STEEL AND ALUMINIUM FATIGUE STRENGTHS

TUM Kosteas 05.02.1991
A Comparison of Fatigue Values in MPa at $2*10^6$ cycles
Between Aluminium and Steel for 32 Structural Details

Steel: DIN 15018, DIN 4132, DS 804, DASt Ri 011, EC 3, ECCS TC6
Aluminium: ERAAS vFatigue Design Final Document

	Aluminium	Steel		Ratio Steel/Aluminium	
Detail		range of recomm.	EC3 ECCS TC6	range	EC 3 ECCS TC6
A1	130	116-194	160	0,89-1,49	1,23
A2	85	116-194	160	1,39-2,28	1,88
A3	95	116-194	160	1,22-2,04	1,68
A4	70	116-194	160	1,66-2,77	2,28
A5	0,9*A	87-143	0,88*A	,74-2,27	1,20-2,23
B1	55	93-194	125	1,69-3,52	2,27
B2	50	(77-90)	(90)	(1,54-1,80)	(1,80)
B3	45	76-90	80-40(?)	1,69-2,00	1,79-0,89
B4	40	52-64	71-50	1,30-1,60	1,78-1,25
B5	45	93-194	125	2,07-4,31	2,78
B6	40	(77-90)	(90)	(1,93-2.25)	(2,25)
B7	35	76-90	80	2,17-2,57	2,29
B8	30	52-64	40	1,73-2,13	1,33
B9	40	93-194	125	2,32-4,85	3,12
B10	35	69-90	90	1,97-2,57	2,57
B11	30	52-64	40	1,73-2,13	1,33
C1	60	93	---	1,55	---
C2	45	86-107	100	1,91-2,38	2,22
D1	45	77-100	100	1,71-2,22	2,22
D2	40	77-100	100	1,92-2,50	2,50
D3	35	58-80	80	1,66-2,29	2,29
E1	35	50-80	80-71	1,43-2,29	2,29-2,03
E2	23	39-64(?)	---	1,70-2,78	---
E3	35	52-90	90	1,49-2,57	2,57
E4	18	39-51	45	2,17-2,83	2,50
E5	35	50-76	50(?)	1,43-2,17	1,43
E6	23	39-51	(?)	1,70-2,22	---
E7	18	(?)	(?)	---	---
E8	23	(?)	(?)	---	---
F1	30	59-90	71	1,97-3,00	2,37
F2	25	36-39	36	1,44-1,56	1,44
F3	20	39-58	50-36	1,95-2,90	2,50-1,80

(?): questionable or problematic classification
(-): no special classification for extruded shapes in steel

The British Standard 8118: 1991

The BS 8118 is a major revision to its predecessor CP 118 the Code of Practice for the Structural Use of Aluminium. In 1979 it was decided that design of aluminium structures should follow in the footsteps of the codes for other leading structural materials such as concrete and steel, and become limit state. A new British Standard Committee was set up to tackle this task, with a sub-panel to draft the revised fatigue rules. The main objectives are summarised in the following sections.

The Main Committee agreed that, wherever possible, the aluminium code should continue to be drafted in a format familiar to designers using other current limit state codes. This applied especially to the steel codes where physical laws of structural behaviour were so similar to those of aluminium.

This was particularly important, as had been shown in the case of CP 118, since most structural aluminium designers have their college and in-practice training primarily in steel. If a designer is tempted to consider aluminium as an alternative to steel he is much more likely to make the decision to do so if the learning curve is as short as possible and he feels he is on familiar ground. This is becoming an increasingly important factor as the lead time for design and development becomes shorter in today's increasingly competitive world.

The first step in drawing up the new fatigue rules was to see if the assumptions used for BS 5500 and PD 6493 could be used for structural details. The results of a survey of published S-N data for aluminium in 1980 showed that a reasonable fit resulted if the BS 5400 fatigue strengths were divided by a factor of 3. This approach was accepted by the Committee and it was incorporated into the BS 8118-Draft for public comment published in 1985. It had also received little adverse comment internationally during the five intervening years. There were comparatively few public comments on the fatigue clauses, except from the transportation sector of the UK aluminium industry. The concern was about the substantial lowering of the S-N curve for the short welded attachment detail at long endurances, which is a particularly governing detail in the design of transport vehicles.

In 1988 the European Aluminium Association (EAA) sponsored work to collect and analyse an important collection of mainly unpublished S-N data which had been made available to their committee.

At the same time, The Welding Institute was commissioned by the UK Aluminium Federation and the Department of the Environment to collect and analyse any additional published data which had not been included in the analyses used for the Draft for Public Comment. Important sections of the EAA database were also made available to the BS 8118 Committee for analysis. The content of these data are described in more detail below.

In 1980 the European Convention for Structural Steelwork (ECCS) Technical Committee 2 Task Group 4 started to draft the ECCS Fatigue Rules. The authors and other members of the BS 8118 committee were active on that committee and it provided a valuable opportunity for a two-way sharing of views on the problems of interpretation and analysis of S-N data for fatigue purposes. The work carried out since the 1985 draft for Public Comment has resulted in some important changes to the fatigue section.

Although the rules have been primarily drafted for UK use, nevertheless the collaboration work on the European scene described above has had considerable influence on the final character of the rules.

Firstly, some relaxations have been possible to some of the more onerous S-N (or $\Delta\sigma$-N) curves. These have been developed specifically from the aluminium data and the middle and upper curves are generally higher than the "steel divided by 3" curves originally proposed, particularly at high endurances.

The detail classification tables have also been modified to take into account more commonly used aluminium details whilst still retaining the BS 5400 general format.

Data Sources

Summarising the main sources of S-N data considered during the course of preparation of the various British Standard documents, it will be seen that between the time of CP 118 and BS 8118 the number of sources of data considered had trebled.

It can be seen that the bulk of the earlier data was on thin plate (much of it on butt welds). The most important source as far as CP 118 was concerned was the program carried out by Gunn and McLester, which was mainly responsible for the detail classification system in that document. Whilst the subsequent data up to 1982 (which was used for the derivation of the Draft for Public Comment) extended the thickness range and doubled the data base size, it was not until after that time that a significant database of larger specimens was available.

The most comprehensive source was a commercially confidential database which was made available through the European Aluminium Association. The data were predominantly from one source and consisted of over 50 test series on 220 mm deep I-beams with a variety of welded details, 10 of which came into category of short transverse attachments. In addition, the early results of the large beam tests being conducted at the Technical University of Munich were included. Overall, the 9 main sources provided 160 fatigue test series, containing over 1300 test results mainly lying between $5 \cdot 10^4$ and $5 \cdot 10^6$ cycles.

Unpublished CAFDEE data base were also available. However the computer summaries did not contain sufficient information on details to enable accurate interpretation to be carried out. Initial inspection did not show evidence that any of the BS 8118 design curves were unsafe. Time and resources did not allow further inquiries into the source data to be undertaken.

Following the public comments on the draft version of BS 8118, a study was initiated to examine sources of fatigue test data not in existence or taken into account when producing the draft. The aim was to assess whether any changes should be made to the S-N curves or the detail classifications. Particular emphasis was placed on the fatigue strength of members with short (in direction of stressing) welded attachments or stiffeners, as their apparently over-conservative treatment in BS 8118 was of such practical significance. Such details were widely used and the proposed BS 8118 design curve was considered to be potentially penalising to many designs in welded aluminium.

Another important consideration was the scale effect and the problem of relating fatigue data obtained from small-scale specimens to real structures. The main issue was the influence of high tensile residual stresses. These are inevitable in real structures but often absent in small-scale specimens, particularly those incorporating transverse fillet weld attachments. The importance of this issue was confirmed in a special investigation of the influence of residual stresses in such specimens. High tensile residual stresses were induced by taking special precautions, like depositing a longitudinal weld bead, or simulated by cycling from a high tensile maximum stress. The results tended to confirm that the proposed S-N curve in BS 8118 was realistic in terms of slope and position for situations when high tensile residual stresses are present.

The other important aspect of a scale effect was the influence of the thickness of the stressed member and the size of any attachment. Limited test data together with fracture mechanics analysis related to steel weldments had indicated that these dimensions could influence fatigue strength and hence should be included in the descriptions of joints in the classification system. Indeed, specification of such dimensions offered the possibility of breaking down widely scattered test results into smaller groups and hence providing more precise fatigue design recommendations.

Hence, in the subsequent review of available data the concentration was on fatigue data obtained from structural components (mainly beams) or large test specimens. Furthermore, attention was confined to results obtained from specimens tested in axial tension or from beams in bending, to represent the most severe fatigue loading conditions. Data obtained under both constant and variable amplitude loading were considered, with particular reference to the applicability of the constant amplitude S-N curve in the very high cycle regime when performing cumulative damage calculations. In the event, few data obtained under variable amplitude loading were located and eventually a special fracture mechanics analysis was performed to establish the most appropriate form of the constant amplitude S-N curve in the high cycle regime for cumulative damage calculations.

SOURCES OF CONSTANT AMPLITUDE S-N DATA				
Document		**CP 118**	**Draft BS 8118**	**BS 8118**
Date of Publication		1969	1984	1992
Approximate Number of Main Data Sources	Newly Considered	5	17	10
	Total	5	22	32
Approximate Total Number of Test Series		78	111	265
Alloys	5+++	44	44	4
	6+++	44	44	44
	7+++		4	4
Specimens	plate	44	44	4
	beams		4	44
Main thickness range	majority	5-6	6-12	6-15
	others	9	25	

Notes:
1. 'Source' refers to a written record of S-N test summarising a test program. Some sources are from the same laboratory, but at different dates.
2. A 'test series' is a set of data points for identical specimens, used for the purpose of deriving an S-N curve. Typically 6-10 data points per series.

Key: 44 major content 4 minor content

Data Analysis and Detail Classification

The following principles were observed:

1. Select large specimen constant amplitude data covering full range of fatigue strengths.
2. Perform regression analysis of individual data sets, excluding run-outs.
3. Determine best fit slopes according to fatigue strength. Choose 'convenient' m values.
4. Choose a convenient set of fatigue strength intervals to cover the full range of details. These together with the slopes define the design 'line'.
5. For each detail type for which good data exist, select the nearest design line to give a lower bound to the data making due allowance for any quality assurance problems which may exist in practice.
6. Where data are poor or non-existent for detail types needed in practice make recourse to steel database and/or fracture mechanics.
7. Resolve high endurance spectrum loading effects by fracture mechanics.

Design Curves

A major issue in the review of the Draft BS 8118 proposals was the slopes of the $\Delta\sigma_R$-N design curves. For most classes the slope was mainly m = 3, but increasing to 3.5 and 4 for high class details, where the equation of the $\Delta\sigma_R$-N curve is $\Delta\sigma_R{}^m \cdot N = A$ (i.e. an increase in m leads to a shallower curve). The fatigue curves in CP 118 were generally shallower and proposals were being made to adopt shallower curves in other design codes (e.g. ECCS, USA and Canada).

Following the principles described above, the relationship between m and $\Delta\sigma_R$ was established using the large beam database. The fatigue strength $\Delta\sigma_R$ at the 'reference' life of $2 \cdot 10^6$ cycles was taken as a convenient basis for comparison. There a clear trend towards higher m values with increasing fatigue strength can be obtained. The scatter band is wide and there are many test series (or 'data sets) where m was below 3 for the lower strength details.

The results showed that a value of 3 was a reasonable fit for the lower class details and if anything resulted in a slight conservatism for low cycle conditions (the 'pivot' being at $2 \cdot 10^6$ cycles). This confirms the trend towards a slope just above 3 for the mean minus 2 standard deviation confidence limits for the lower and middle fatigue strengths. The value of having the same slope for the most commonly used joint details is considerable, in that once a damage summation has been done for one class the effect of increasing or reducing the magnitude of applied stress range can be rapidly assessed.

Classification of Details

The closing remarks here are quite similar to the procedure followed for the ERAAS document, underlining once more the relation between the two recommendations. It was anticipated that it would be possible to combine fatigue data sets for a range of joint dimensions of a particular detail, or even different details if the failure mode and fatigue lives were similar. Therefor, an attempt was made to do this using statistics. However, problems arose because of the large number of variables involved. In particular, uncontrolled differences between specimens tended to mask the effects that variables such as size, thickness and relative joint proportions were having on fatigue life. Thus, it proved necessary to rely heavily on engineering judgement when creating the classification system. In this respect, existing fatigue rules for steel were helpful as a guide to initial classifications.

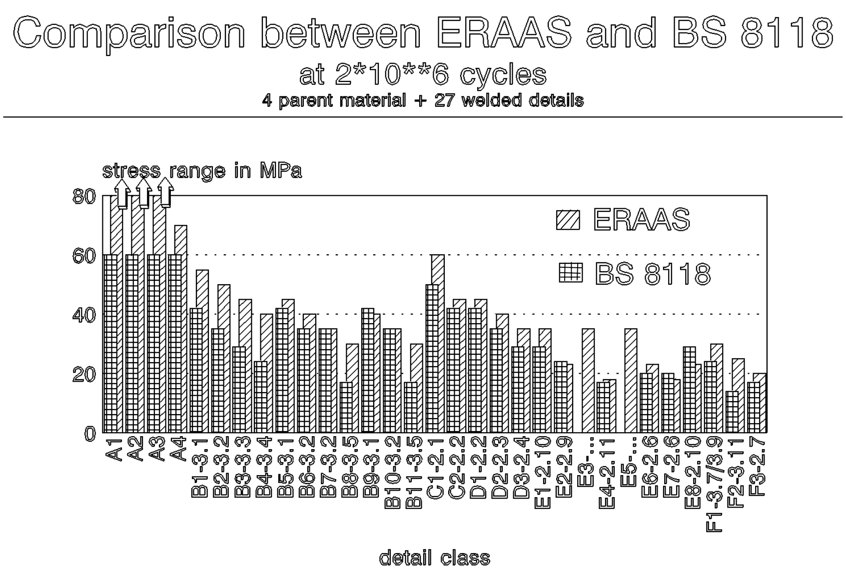
Neither the BS 8118 nor ECCS rules make any distinction on the basis of alloy for welded joints. Useful confirmation of this was provided in the EAA report by Technical University of Munich and Voreppe Research Centre.

The method of validating the classifications so deduced was first to check that the proposed design $\Delta\sigma_R$-N curve represented a safe lower bound to the appropriate fatigue data. The main emphasis was on the results obtained from large-scale specimens and in those cases the comparison could be safely made over the full range of the fatigue data. However, in the case of data obtained from small specimens the comparison was made only in the low endurance range, when residual stress effects are at their least.

Where isolated outliers in the data for a particular detail were present, a judgement had to be made as to whether low lives were due to poor quality control in manufacturing or testing. In such cases the risk of neglecting them might be eliminated by means of the quality control requirements in Part 2. This principle was applied in the case of the transverse full penetration butt welds. Alternatively, where it was known that quality assurance of a detail could be unreliable in practice, due to inadequate NDT technology, a more generous margin would be left between the data and the design limit. This applied particularly to all partial penetration welds and full penetration butts made from one side or between complex shapes.

Comparison between ERAAS and BS 8118

Reference has been frequent within this paper to the respective development of the BS 8118 as far as provisions for the fatigue assessment procedure are considered. Detailed presentation of this document is undertaken in three other papers of this conference. At this place we wish to give a comparison of the design lines for the respective structural details only, **Figure 2402.03.07, Figure 2402.03.08** and **Figure 2402.03.09**.



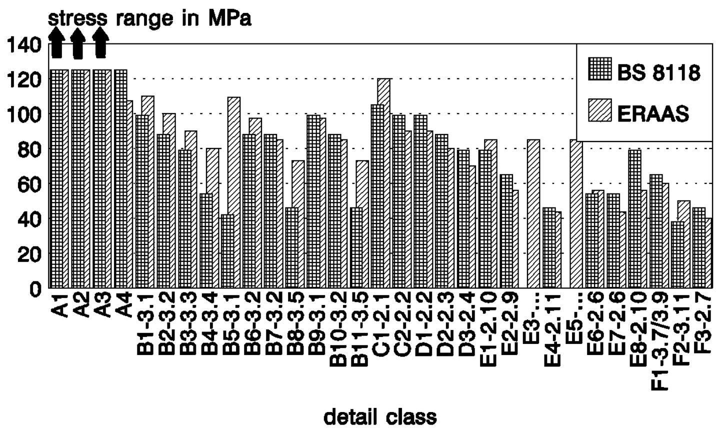
Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Comparison of ERAAS and BS 8118 Design Strength Values at $2*10^6$ Cycles	2402.03.07

Comparison between ERAAS and BS 8118

at 10**5 cycles

4 parent material + 27 welded details



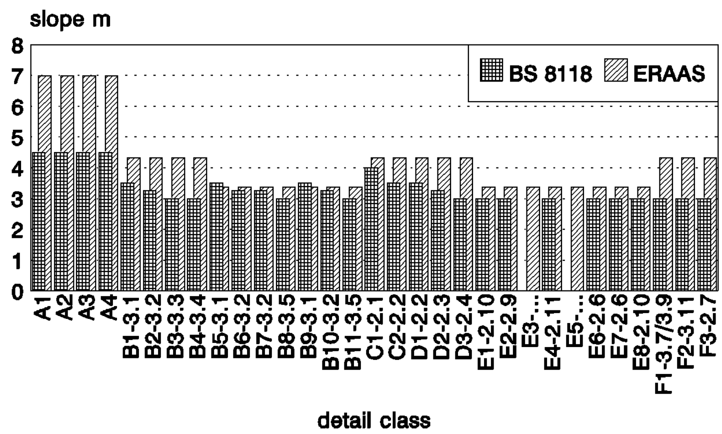
Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Comparison of ERAAS and BS 8118 Design Strength Values at 10^5 Cycles	2402.03.08

Comparison between ERAAS and BS 8118

Slope m

4 parent material + 27 welded details



Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Comparison of ERAAS and BS 8118 S-N Design Line Slope Values	2402.03.09

The overall impression is the following:

For parent material the BS shows much lower values and does not distinguish between the alloys. The ERAAS bases its assumptions on respective available experimental information and evaluations.

In the case of welded details there is a rather good to excellent agreement in a significant number of classes, thus especially for cases B5 to B7, B9 and B10, and practically all cases from C1 to F8, **Figure 2402.03.07**. The agreement is more pronounced at shorter lives, as is demonstrated by **Figure 2402.03.08** which gives the values at 10^5 cycles. As already explained elsewhere, there have been different approaches to the problem of harmonisation of the overall design line format with the actual experimental evidence. this is also obvious from the diagrams showing the comparison in slope values, **Figure 2402.03.09**.

A few remarks relative to the attempted comparison of structural details between the ERAAS and BS 8118 documents. Often matching problems between the detail definitions may arise. So in the case of detail ERAAS-B3 compared to BS-3.3, the former may be a weld from one or even both sides. The ERAAS document often distinguishes between welds in extruded or in built-up elements, the former generally offering a more favourable situation, i.e. the latter are classified at a lower level because of the influence of higher residual stresses. This is demonstrated when comparing the detail classes B5 and B9, ERAAS gives two different values of 45 and 40 MPa respectively, whereas BS states a common value of 42 MPa. Here we also have a difficulty in matching the respective details, following the classification diagram of the BS we may have classified these details under class 3.6, whereby there is no clear distinction between V- or X-type welds; since we had ample experimental evidence for higher strength values in the case of ERAAS data we finally chose the comparison with BS case 3.1. There are rather significant differences in the classifications for the details B8 and B11 between the two documents. A satisfactory explanation has to be worked out for this, it is interesting to note though that both are matched to class 3.5, which gives considerably lower design strength, but that for B11 - the lower of the two in ERAAS since it relates to built-up elements with higher residual stresses - there is rather good experimental evidence available. This is true also in the case of details D1, D2 and D3, but here the difference are not significant between the two documents in the first place. The question is still open why the ERAAS value is so much higher in case C1. E1 was related to 2.10 since the weld length is below 25mm, the TUM beams have shown a rather good behaviour, higher values than in the BS, and they also show good agreement to respective structural details of the recent Lehigh beam test results (compare to 5th INALCO paper by Fisher and Menzemer). Detail E2 may have also been compared to class 2.10, but here class 2.9 was chosen as more likely because of the overall dimensions of the attachment. Details E7 and E8 represent the rather seldom case where the BS document states higher values than ERAAS; E8 relates to class 2.10 with a rather high value, this can be explained perhaps by the fact that ERAAS covers a built-up beam with the more unfavourable residual stress conditions. Concerning the cases F1 and F2, which relate in the case of the TUM beam connection to class 3.7 or 3.8, experimentally there was no significant evidence for a distinction between butt or fillet weld connection and the values recorded are higher than the ones in the BS document in spite of the fact that again they relate to built-up components. Lastly, we may mention that the definition of a "partial penetration butt weld" was banished from the ERAAS document as a contradiction in itself ,since a butt weld should represent an intentionally full penetration weld. We acknowledge the fact, though, that the situation has arisen in practice.

2402.04 Fatigue Design Calculation Example: Gusset Plate Welded on Edge of Tubular Element

- Design procedure
- Calculation example after ERAAS
- Utilising the TUM-ALFABET software
- Calculation example after BS 8118
- Literature References for Lecture 2402.04

Currently, two recommendations treat the fatigue design of aluminium structures in a comprehensive manner, the recently published "ERAAS Fatigue Design" and the "BS 8118" [1, 2]. Detailed description of their contents and background have been published [3, 4, 5, 6] and parts of this information have been used in other chapters of this course. Further national and international activities concerning recommendations have also been reported [7, 8, 9] and a very detailed comparative analysis has been carried out during the drafting stage of "ERAAS Fatigue Design" [3, 10].

The purpose of this chapter is to give an outline of the fatigue analysis concept, following rather closely "ERAAS Fatigue Design", and demonstrate the procedure with a calculation design example.

Design Procedure

The fatigue limit state assessment of structural elements in aluminium alloys is carried out in respective recommendations by formulating rules for the estimation of the safe life of commonly used details. $\Delta\sigma$-N design curves for various details have been calculated from standard strength data.

In particular cases the design can be justified by special, more sophisticated analysis or by acceptance testing involving fatigue experts and/or experienced laboratory.

The type of details covered by the respective recommendations, the pertaining environmental conditions, the alloys and the product forms and joining methods to be used, any strength improvement methods, shall be followed. The fatigue assessment verifies that the resistance of a structure $\Delta\sigma_R$ (the fatigue strength value depending on the structural detail considered and the total number of stress cycles during the required life) is sufficient to withstand the damaging effect of the loading $\Delta\sigma$ expected within the design life of the structure, i.e. $\Delta\sigma \leq \Delta\sigma_R$.

In the case of variable amplitude loading defined by a design spectrum the fatigue assessment is based on the Palmgren-Miner rule of cumulative damage. One of the following calculation procedures may arise:

- if the maximum stress range due to the variable amplitude loading is less than the constant amplitude fatigue limit no fatigue assessment is required (**refer to Figure 2402.04.01**),

- if the maximum stress range due to the variable amplitude loading is higher than the constant amplitude fatigue limit either a cumulative damage calculation after the Palmgren-Miner rule expressed through

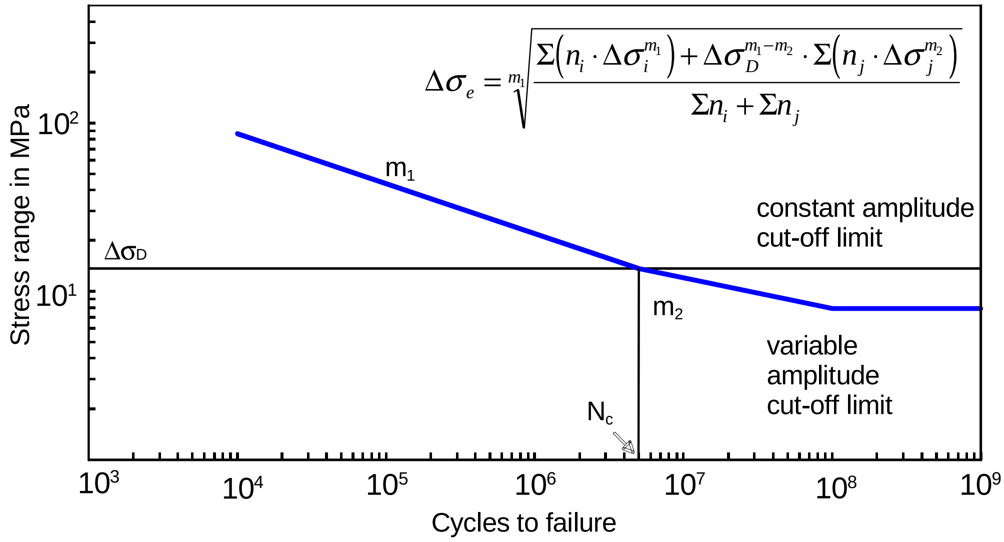
$$\sum \frac{n_i}{N_i} < 1$$

or an equivalent constant amplitude stress range

$$\Delta\sigma_e = \sqrt[m_1]{\frac{\sum\left(n_i \cdot \Delta\sigma_i^{m_1}\right) + \Delta\sigma_D^{m_1 - m_2} \cdot \sum\left(n_j \cdot \Delta\sigma_j^{m_2}\right)}{\sum n_i + \sum n_j}}$$

calculation (again based on the Palmgren-Miner assumption) may be used - see also ERAAS Fatigue 3.04.

Schematic Fatigue Strength Curve



Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Schematic Fatigue Strength Curve	2402.04.01

Realistic assessment of the fatigue loading is critical to the calculation of the design stresses and respective rules on loading, the calculation of stresses and the definition of design stress spectra have to be followed.

Data sheets, as for instance in "ERAAS Fatigue Design", give the design fatigue strength values and the classification of structural details [1, 3]. Information on further influencing parameters like plate thickness or R-ratio may also be utilised.

Quality assurance requirements along with inspection techniques are of major importance and are either included to a certain extent in the description of detail classification [1] or are stated explicitly in further accompanying documents [2].

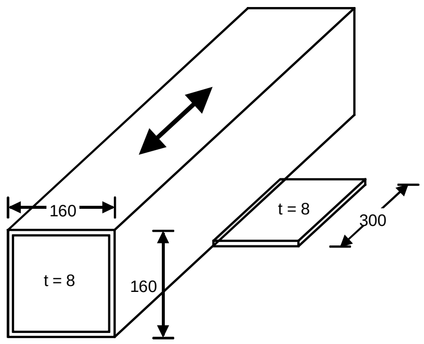
Calculation Example after ERAAS

The fatigue assessment is performed according to ERAAS - Fatigue Design, ECCS document N^{o} 68, 1992.

The component to be assessed consists of a tubular element with a gusset plate attachment welded on its edge, see **Figure 2402.04.02**. The dimensions are 160/160 mm and a wall thickness of 8 mm. The gusset plate is rectangular in shape, with no transition radius, and a thickness of 8 mm and a length of 300 mm.

The tube is extruded in alloy 6082-T6 (AlMgSi1). The alloy designation is irrelevant though for the following fatigue assessment, since design curves for a specific welded detail are the same irrespective of the alloy.

Structural Detail



Alloy: 6082-T6

Loading History

Stress level No.	No of cycles	Stress range MPa
1	25	60
2	45	40
3	55	36
4	95	32
5	130	28
6	200	24
7	350	20
8	800	16
9	2600	12
10	3700	8
11	6400	4

$\Sigma n_1 = 14400$

Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | Fatigue Design Calculation Example | 2402.04.02

Loading

A loading history had been established through measurement during a certain period of operation. This results in a respective stress history at the detail location and through appropriate cycle counting methods like the reservoir method, a respective stress spectrum as given below. This stress spectrum will be repeated 400 times during the design life, see **Figure 2402.04.02**

Classification of Structural Detail

According to ERAAS - Fatigue Appendix B the detail is classified as case E4 with a reference design strength of 18 MPa at $2 \cdot 10^6$ cycles. The value at $5 \cdot 10^6$ cycles (knee-point of the S-N curve) is $\Delta\sigma_D$ 13.7 MPa. The slope of the S-N curve for stress levels $\Delta\sigma$ above $\Delta\sigma_D$ is $m_1 = 3.37$ and for values below $\Delta\sigma_D$ the slope is $m_2 = 5.37$. The corresponding variable amplitude cut-off limit at 10^8 cycles is 7.9 MPa, i.e. stress level no. 11 does not contribute to the damage accumulation.

Fatigue Assessment

According to ERAAS - Fatigue, Chapter 3 the fatigue assessment is performed by comparison of the equivalent stress range $\Delta\sigma_e$ for the given stress spectrum to the design fatigue strength $\Delta\sigma_R$, calculated from the S-N curve at the design life of the structure.

The equivalent stress range is calculated by

$$\Delta\sigma_e = \sqrt[m_1]{\frac{\sum\left(n_i \cdot \Delta\sigma_i^{m_1}\right) + \Delta\sigma_D^{m_1 - m_2} \cdot \sum\left(n_j \cdot \Delta\sigma_j^{m_2}\right)}{\sum n_i + \sum n_j}}$$

n_i	$\Delta\sigma_i$ MPa	$n_i \cdot \Delta\sigma_i^{m1}$
5000	60	9825840584
18000	40	4510396026
22000	36	3865112226
38000	32	4488890624
52000	28	3916750516
80000	24	3584279527
140000	20	3393119235
320000	16	3656236837

$\Sigma n_i \cdot \Delta\sigma_i^{m1} =$ 37240625573

n_j	$\Delta\sigma_j$ MPa	$n_j \cdot \Delta\sigma_j^{m2}$
1040000	12	648987946124
1480000	8	104677886527
(2560000)	4	--------

$\Sigma n_j \cdot \Delta\sigma_j^{m2} =$ 753665832651

Design life $\Sigma n_i + \Sigma n_j$ = 3 200 000 cycles

$$\Delta\sigma_D^{(m1-m2)} = 13.7^{-2} = 0.0053$$

$$\Rightarrow \Delta\sigma_e = 16.6 \text{ MPa}$$

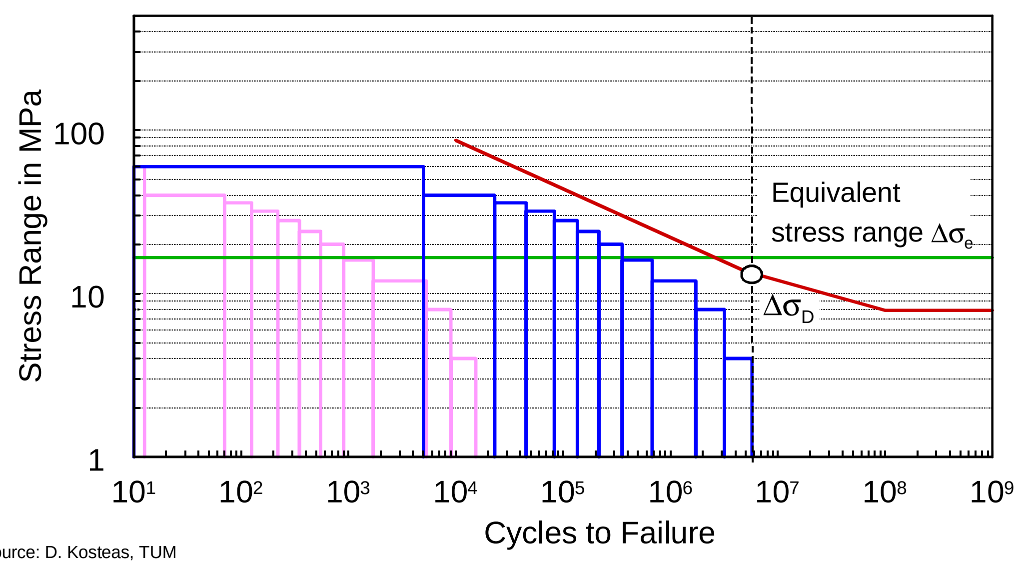
The respective value $\Delta\sigma_R$ for the structural detail out of the S-N line for a design life of $3.2 \cdot 10^6$ cycles is

$$\Rightarrow \Delta\sigma_R = 15.7 \text{ MPa}$$

$$\Rightarrow \Delta\sigma_e \geq \Delta\sigma_R$$

The structural detail is not safe for the projected design life (see **Figure 2402.04.03**).

Load-Spectrum, Equivalent Stress Range according to ERAAS-Fatigue Design



Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies	Load-Spectrum, Equivalent Stress Range according to ERAAS-Fatigue Design	2402.04.03

Concluding Remarks

As an alternative a similar structural detail but with a transition radius of R>50 mm may be introduced. This detail can now be classified as detail class **E3** in ERAAS - Fatigue Design. The reference design strength is now 35 MPa at $2 \cdot 10^6$ cycles. The value $\Delta\sigma_D$ at $5 \cdot 10^6$ cycles is 26.7 MPa. The slope of the S-N curve for stress levels $\Delta\sigma$ above $\Delta\sigma_D$ is $m_1 = 3.37$ and for values below $\Delta\sigma_D$ the slope is $m_2 = 5.37$. The corresponding variable amplitude cut-off limit at 10^8 cycles is 15.3 MPa, i.e. stress levels nos. 9, 10 and 11 do not contribute to the damage accumulation.

n_i	$\Delta\sigma_i$ MPa	$n_i \cdot \Delta\sigma_i^{m1}$
5000	60	9825840584
18000	40	4510396026
22000	36	3865112226
38000	32	4488890624
52000	28	3916750516
80000	24	3584279527
140000	20	3393119235
320000	16	3656236837
	$\Sigma n_i \cdot \Delta\sigma_i^{m1}$	37240625573

n_j	$\Delta\sigma_j$ MPa	$n_j \cdot \Delta\sigma_j^{m2}$
(1040000)	12	--------
(1480000)	8	--------
(2560000)	4	--------
	$\Sigma n_j \cdot \Delta\sigma_j^{m2}$	--------

Design life $\Sigma n_i + \Sigma n_j = 680000$ cycles

$\Delta\sigma_D^{(m1-m2)} = 26.7^{-2} = 0.0014$

$\Rightarrow \Delta\sigma_e = 25.5$ MPa

The respective value for the structural detail out of the S-N line for a design life of 680000 cycles is

$\Rightarrow \Delta\sigma_R = 48.2$ MPa

$\Rightarrow \Delta\sigma_e \leq \Delta\sigma_R$
This structural detail E3 shows sufficient fatigue strength resistance.

Another alternative would be to manufacture a gusset plate welded underneath the tube by a transverse fillet weld. This would result to a detail classification similar to class E8: vertical transverse attachment on built-up beam with $\Delta\sigma$ = 23 MPa at $2 \cdot 10^6$ cycles or class F3: Cover plate with transverse fillet welds with $\Delta\sigma$ = 20 MPa at $2 \cdot 10^6$ cycles. Neither of these resembles exactly the case investigated or brings an enhancement in fatigue strength as large as the smooth transition radius of case E3. The advantage of these latter options is in the more simple manufacturing procedure.

Utilising the TUM-ALFABET Software

The Aluminium Data Bank is a joint project of the Technical University of Munich, Germany, and the Iowa State University, Ames, Iowa, USA [11]. It provides the harmonized documentation of material data, especially in the area of fatigue. Data from small aluminium specimens, but especially of major importance full-scale fatigue test data as well as substantial fracture mechanics and crack propagation data is included. In a further step, recommendations and codes are being added to enable the user to perform an assessment in a dialogue with the computer. These programmes are linked together to one system, the so-called expert system "ALFABET".

A first item has been produced by the Technical University of Munich, the "Classification and Design of Fatigue Loaded Aluminium Constructions" as a computerised version of the "ERAAS Fatigue Design" rules. It comprises of a complete manual of the recommendations, quick cross-references, a structural detail unit with full descriptions, a survey menu for the selection of details and a complete design menu featuring all significant spectrum input and performing the final fatigue assessment.

For more details on the use and availability of the data bank contact the author.

Calculation Example after BS 8118

The fatigue assessment is performed according to BS 8118: Structural Use of Aluminium, Part 1: Code of Practice for Design, 1991.

The component to be assessed consists of a tubular element with a gusset plate attachment welded on its edge, see **Figure 2402.04.02**. The dimensions are 160/160 mm and a wall thickness of 8 mm. The gusset plate is rectangular in shape, with no transition radius, and a thickness of 8 mm and a length of 300 mm.

The tube is extruded in alloy 6082-T6 (AlMgSi1). This alloy designation is irrelevant though for the following fatigue assessment.

Loading

A loading history had been established through measurement during a certain period of operation, see example in **Figure 2402.04.02**. This results, through appropriate cycle counting methods like the reservoir method, in a respective stress history at the detail location and a respective stress spectrum as given below. This stress spectrum will be repeated 400 times during the design life.

Classification of Structural Detail

According to BS 8118, Section 7, Table 7.2 the detail to be assessed is classified as detail 2.11 with a maximum permitted class of 17 N/mm^2. From Table 7.4 the values m: slope and K_2: constant of the f_r-N curve

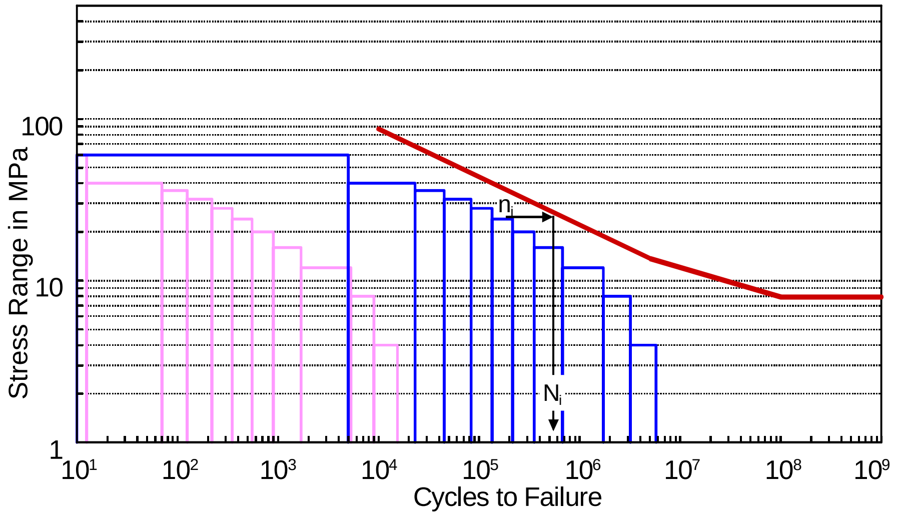
$$(f_r)^m \cdot N \leq K_2$$

for the detail 2.11 are given as follows:

$$m = 3.0$$
$$K_2 = 9.83 \cdot 10^9$$

The variable amplitude cut-off stress occurring at 10^8 cycles is f_{ov} = 6.9 N/mm^2, see **Figure 2402.04.04.**

Load-Spectrum according to BS 8118



Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | Load-Spectrum according to BS 8118 | 2402.04.04

Fatigue Assessment

According to BS 8118: Part 1: 7.3 the fatigue assessment procedure is as shown in **Figure 2402.04.05**. It follows that the chosen detail is not safe for the projected design life.

Fatigue Assessment according to BS 8118

n_i	f_i	N_i	n_i/N_i	Σ ni/Ni
5 000	60	45 509	0.109 868 4	0.109 868 4
18 000	40	153 594	0.117 192 1	0.227 060 5
22 000	36	210 691	0.104 418 3	0.331 478 8
38 000	32	299 988	0.126 671 7	0.458 150 5
52 000	28	447 795	0.116 124 6	0.574 275 1
80 000	24	711 082	0.112 504 6	0.686 779 7
140 000	20	1 228 750	0.113 936 9	0.800 716 6
320 000	16	2 399 902	0.133 338 8	0.934 055 4
1 040 000	12	5 688 657	0.182 82	1.116 875
1 480 000	8	19 199 219	0.077 086 4	1.193 962
2 560 000	4			

Note: Σ ni/Ni is > than 1; therefore the detail is not safe!

Source: D. Kosteas, TUM

TALAT Training in Aluminium Application Technologies | Fatigue Assessment according to BS 8118 | 2402.04.05

Concluding Remarks

A new structural detail with higher fatigue resistance should be chosen. BS 8118 does not include a similar gusset plate with a transition radius in the list of typical details. Under certain conditions of manufacturing and loading it may be assumed, though, that such a structural option would produce a detail which could be classified between the two cases of Detail 2.9/2.10, as an upper boundary, and Detail 2.7, as a lower boundary.

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2402.06 List of Figures