ALUMINIUM STRUCTURES
FATIGUE DESIGN – CONCEPTS AND TOOLS

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The recently compiled European Codes for design and execution in aluminium structures are presented and discussed. Within the framework of material characteristics, consequences of failure and execution classes for structural components design principles and concepts for parts and their joints of the comprehensive and in several aspects innovative approach to fatigue design rules of EN 1999-1-3 is discussed. The following introductory text is accompanied by a series of figures illuminating characteristic procedures – links to these figures are mentioned where necessary in the text.

Specifications for the design and execution of structures will follow certain universal concepts of safety and reliability, as well as design principles and methods, irrespective of the specific field of application. The area of application of Eurocodes for the design of aluminium structures is the "design of buildings" as well as "structural engineering works" covering - by merit of the supporting experimental data background – related fields of application like transportation, e.g. marine structures, rail-bound vehicles, etc. Eurocode 9: EN 1999-1 on design and EN 1090-3 on execution provide to the engineering community a comprehensive tool to deal with a variety of structural shapes, joints, and loading cases. The presentation indicates also differences in material characteristics between aluminum and steel leading to different procedures in respective codes and outlines several innovative approaches that have been integrated in the aluminum design code.

STRUCTURAL INTEGRITY CONCEPT

The design of aluminium structures is in accordance with the general rules in EN 1990 setting the principles for characteristic and design values for actions and resistance, and respective partial safety factors within the reliability framework, Fig. 3. The reliability management for design and execution work according to EN 1990: Basis of structural design – Annex B introduces a classification system with subsequent requirements to execution and inspection of work, which is adjusted to the importance of the structure with the intention to optimize costs in providing for a safe and reliable structure. The consequences of structural failure are the main classification feature, Fig. 4 to 6.

The selection of the execution class is also influenced by the stress situation and the design criteria, and defines the necessary requirements for execution work. The latter are influenced by the testing method and the extent of inspection, as well as the structural detail and the limits of its imperfections or the quality level QL, as defined for instance in EN ISO 10042 for welded details. The execution class may apply to the whole or a part of the structure, to one or more components or to specific details. It is a condition for aluminium structures that their execution shall follow the rules given in EN 1090-3. The execution class should be defined in the project specification.

GENERAL DESIGN

The new Eurocode 9 for design of parts presents a broad range of wrought and cast alloys for structural components, along with characteristic values for the material properties, and for connecting devices (bolts, rivets) in both aluminium and steel. Respective information is included, in detail especially for welded joints, and adhesively bonded joints. This alloy list may have to be adapted for applications in shipbuilding and specific alloys should be controlled in respect to durability requirements or when in contact with other materials recommendations in EN 1999-1-1 Annex D and EN 1090-3 should be observed. Rules for fatigue design in EN 1999-1-3 cover all the above options.

FATIGUE DESIGN

The elaboration of fatigue design rules for aluminium structures has been a comprehensive task on national and especially European level in the last 25 years. The basis for the drafting procedure has been a comprehensive and reliable data bank, including a significant amount of full-size component tests, Fig. 8. Ensuing multiple data analyses and evaluation workshops refined the statistical input parameters, thus allowing for the fulfilment of basic safety and reliability rules on the one hand, but also for practicable engineering solutions on the other. A representative compilation of results has been published which together with an earlier outline of the code draft provide links to numerous background references.

THE CODE FORMAT

Repeated discussions within the drafting body, not only on issues of experimental data interpretation, but also on the overall format of the code, the importance and extent of analysis and verification methods, the inclusion of specific structural details and joining methods, even on details of visual presentation, manifest the special significance that fatigue design has for light-weight aluminium structures under repeated loading - at a lower ratio of dead to live load.

A general adaptation to the format of respective codes for steel structures has been undertaken, although differences do persist. As a consequence of the sound data basis with large components and their comprehensive statistical analysis, both for conventional stress vs. life as well as for crack propagation vs. stress intensity relationships, the Eurocode for aluminium was first to introduce some new issues or changes over earlier codes.

Three separate fatigue design procedures are distinguished:

a) Traditional safe-life design, based on evaluation of S-N curves
b) Damage tolerant design, and
c) Design assisted by testing.

In safe-life design it was decided to group the different structural details in three slope value groups (m=7 or 4,3 or 3,4 in the main cycle range from 10^5 to $5 \cdot 10^6$ cycles), the first covering practically parent material, the other two all welded details. Together with assuming a higher cycle range as the reference point for estimation of design S-N curves this approach allows for a closer fit to actual test data in the cycle range of primary interest for aluminium applications and thus more economical design. The mean stress effect was also taken into account in design by introducing a bonus factor, Fig. 10.

Rules for aluminium in damage tolerant design bear in our view a clearly formulated concept and procedure. The method is introduced as a complementary design option to safe-life design, in case that the latter with the linear damage accumulation leads to values larger than unity. Damage tolerant design is based on the estimation of crack propagation on the basis of fracture mechanics criteria and procedures. Of special importance is the fact that in the case of aluminium complete information about the crack propagation behavior of the material and its welded joints is available, allowing for respective quantitative establishment of inspection intervals.

In the following specific issues in the Eurocode for fatigue design are highlighted and further background data is provided.

ESTABLISHMENT OF DESIGN S-N CURVES

In addition to the above mentioned points we may add that an equidistant mesh of characteristic values for the design curves, i.e. the value $\Delta\sigma_C$ [N/mm²] at $2 \cdot 10^6$ cycles, has been conceived, introducing a logical pattern in case of necessary reductions due to corrosion or thickness effects, Fig. 11.

To demonstrate the situation during the data analysis of earlier small specimen data together with large component test results from different laboratories and the life cycle range a representative diagram is given in Fig. 12 for the cruciform joint, i.e. transverse load-carrying fillet welds. Additional comparisons between design curve proposals in different recommendations were also performed.

The format of the design curves is given in Fig. 13 for the main life cycle range between 10^5 and 10^8. The code defines also a design curve for the range between 10^3 and 10^5, but only for some alloys and R-ratios where test data has been available.

Bearing in mind the current state of development of fatigue design documents in metal structures an interesting fact is demonstrated in Fig. 15 between recommended fatigue strength values of aluminium vs. steel structural details (parent material and several welded joint configurations) with the ratio of Al:St being for most details higher than 1:2,5.

SAFETY FACTORS AND RELIABILITY

The Eurocode defines a partial safety factor on loading γ_{Ff} which may vary between 1,0 and 1,5 depending on the confidence limits for the intensity and the number of cycles of the fatigue design load spectrum. In both safe-life and damage tolerant design a partial safety factor γ_{Mf} for fatigue strength is taken as unity (excluding adhesive bonded joints for which a higher value is introduced) as far as no other values are given in a National Annex.

The definition of the fatigue strength design values involves a statistical evaluation, based on estimates of mean and standard deviation, assuming a normal distribution, of observed logarithmic life cycles (dependent variable) for given logarithmic stress values (independent variable) or respectively a linear $\log\Delta\sigma$-$\log N$ regression analysis for the different life ranges, Fig. 17. A mean regression line for a specific probability of survival (usually ca. 97,7% or at 2 standard deviations from the mean) will be established. For design purposes the latter is assumed parallel to the first and defines the design limit values.

The fatigue assessment in EN 1999-1-3 practically requires that

$$\gamma_F \Delta\sigma_e < \frac{\Delta\sigma_R}{\gamma_M}$$

The following evaluations of the reliability index β and the relation to the partial safety factors γ_{Ff} and γ_{Mf} as well as the relationship to parameters of the loading and resistance distributions (referring to the manufacturing characteristics and quality classification of a structural detail) demonstrate the actual situation for aluminium structural components and offers guidance towards appropriate values in design practice.

The relationship between the reliability index and the scatter of loading and strength can be expressed through

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

which leads by following Fig. 17 to the relationship demonstrated in Fig. 18.

Assuming recommended values for the statistical parameters, the load scatter, and the partial safety factors the reliability (or safety) index β curve for varying scatter in test data is calculated. It reaches its maximum of β=2,24 for medium or larger values of the standard deviation of fatigue strength.

Sufficient data on the scatter of various welded structural details has been collected, Fig. 19, and can be utilized for estimations of reliability in practice.

The joints analyzed are given in Fig. 21 and the results for the four details with varying parameters of scatter in loading s_S, product of partial safety factors in loading and resistance, and k_N the multiple of standard deviations from the mean value of fatigue strength in Fig. 22 may be summarized as follows:

- For practical values of loading scatter s_S=0,02 to 0,06 the safety index β reaches ist maximum value,
- In case of $\gamma_F=\gamma_M$=1,0 / k_R=2,0 / k_S=1,0 and mean s_R=0,07 the maximum β-value is 2,236 (for arbitrary loading and resistance minβ=1,6),
- a demand for very low scatter in fatigue strength is not per se a guarantee for higher β-values, in several cases depending on the interrelation with the other parameters it may even lead again to somewhat lower values,
- It is much more effective to have reliable information about the loading distribution and a not so high scatter value,
- In the case of test results for aluminium welded joints (which is the case for the steel as well) practical values of resistance scatter between 0,03 and 0,18 or loading between 0,02 and 0,06 lead to values β not beyond ≈2.2,
- Only in cases with partial safety factors $\gamma_{Ff}\cdot\gamma_{Mf}>1.35$ values of β≈3,5 may be reached, and

this only at rather low load distribution scatter,

- The β -value may be enhanced significantly by lowering the fractile of fatigue strength or assuming a lower design value, as demonstrated by values for k_R=3 (this corresponds to a fractile of approximately 99% probability of survival for a sample size of 10 and a confidence level of 0,75)
- In practice it does not appear appropriate though to try to attain higher β-values through magnification of k_R, i.e. lower fractiles of strength or lower design values.

Attention is drawn to the safety index β values for practical cases, which are generally lower than recommended values of 3,8 for ultimate limit state assessment. This issue needs further clarification.

DESIGN BY TESTING

For acceptance of a safe life design, the life to failure determined by test, adjusted to take account of the number of test results available, should be

$$T_m \geq F \cdot T_L$$

with T_L: design life (in cycles), T_m: the mean life to failure determined by test (in cycles), and F: factor dependent upon the effective number of test results available – to be defined, Fig. 24.

In practice only estimates for the mean and standard deviation of the population, i.e. x_m and s respectively, may be calculated for a sample size n, Fig. 25. Accordingly correction factors expressing the confidence intervals of both the mean and the variance (or standard deviation) have to be applied. The multiplier K (infinite sample size) thus becomes k (limited sample size) and includes a theoretical value k_1 of the distribution belonging to a specific probability of survival, a correction for the confidence interval of the standard deviation k_2 and the mean k_3 respectively. These depend on the standard deviation s, sample size n and, naturally, on the desired level of confidence α. The factors k_1, k_2 and k_3 can be expressed by the normal, chi-square (standard deviation) and t-Student (mean) distributions respectively for a given probability of survival and confidence level, Fig. 26.

In most practical applications the assumptions can be made that: (1) the standard deviation value is known from previous experience, i.e. based on a sufficiently large sample size – this allows k_2 to be set to unity, (2) sufficient knowledge of the underlying distribution is available or no significant deviation from the normal distribution exists and (3) in the correction for the confidence interval for the mean the t-distribution may be replaced by the normal distribution. Thus in the general case of *more specimens all tested to failure* we get the factor k

$$k = k_1 + k_3 = z_{(1-\alpha/2)} + \frac{z_{(1-\alpha/2)}}{\sqrt{n}}$$

In the case of *more specimens simultaneously tested until failure of first specimen* and in order to estimate k, we may assume that the resulting life of the first specimen – relating to T_L from the expression above - will lie on the upper boundary of the respective distribution, and the required or design life – relating to T_m from the expression above - will be at the lower boundary of the distribution.

The lower boundary will be derived from $x_m – k_1 \cdot s$, with k_1 according to Fig. 26. The upper boundary will be derived correspondingly from the expression $x_m + k_4 \cdot s$. The appropriate value of k_4 is calculated from the assumption that if the probability of survival of one specimen, failing at the corresponding life, is P, then the probability of survival of n specimens at the same level will be P^n. To be on the safe side a sufficiently low value for P^n=c will be defined, and k_4 is calculated from the normal distribution at $c^{1/n}$ probability for corresponding values n. The factor k is calculated from

$$k = k_1 + k_2 = z_{(1-\alpha/2)} + z_p$$

The expression may be transformed to

$$\log T_{\mathrm{L}} = \log T_m - \log F$$

and by comparison to the expressions in Fig. 25 we get

$$\log F = k\,\mathrm{s} \quad \text{or} \quad F = 10^{ks}$$

The factor F can be obtained from Fig. 27 for the two options of testing. The value of the standard deviation has to be estimated. Previous experience with similar structural cases provides more reliable values. Data available for various aluminium welded structural details give a range of different standard deviation values $s_{\log\Delta\sigma}$. These may be transformed by the respective average regression line slope of m = 4 to values $s_{\log N}$ for the life range up to the constant amplitude fatigue limit of $N = 5x10^6$.

The values F for the testing option of more specimens simultaneously tested until failure of first specimen are based on a probability of survival of 95% and a confidence level of 0,95 for the normal distribution and a standard deviation value of $s_{\log N}=0{,}18$. In the case of first sample to fail a probability of survival value of $P^n=5\%$ is assumed.

GEOMETRIC STRESS ANALYSIS

The geometric or hot spot stresses, as defined originally with steel structures, cannot be determined in welded aluminium structures, as the stress-strain relationship in the heat affected zone is not known generally, and is different from the parent material. Matters are further complicated as there is one decisive disadvantage of the structural stress concept, e.g. on gusset plates or in detailed modeling of weld seams in the weld toe, numerical singularities and peak stresses are calculated which in reality do not arise or are reduced in magnitude due to local plastic deformation. The size of these singular stresses depends mainly on the chosen mesh density, the degree of modeling and the type of finite elements employed.

In any case the originally proposed method of stress analysis and fatigue design based on the “hot-spot stress” concept had to be changed and now follows practically the “reference detail” method of the IIW Recommendations (IIW (2003)), again combined with the structural detail categories of the safe-life design.

Initially it was intended to introduce in the code a new concept for a reliable and user-friendly derivation of stresses in fatigue design, a calculation based on finite element analysis and the definition of the “simplified geometric stress” at a specific reference point, characteristic for estimations at fillet weld toe configurations avoiding the above mentioned disadvantages at the vicinity of the toe and the HAZ in aluminium, Fig. 29. The implementation of such an approach, Fig. 30, had to be postponed though until sufficient evidence of its reliability has been gathered. A procedure similar to other application fields has been introduced for the hot-spot concept in the fatigue design rules, Fig. 31.

EXECUTION

Structural details and corresponding design fatigue strengths in EN 1999-1-3 are linked to specific execution and inspection requirements in EN 1090-3, Fig. 33 and 34. Through the weld quality level of EN ISO 10042 the correspondence is established in EN 1090-3 to production weld inspection provisions. Again the utilization factor provides a link to the NDE method and extent of inspection, and is defined in fatigue as

$$U = \frac{\Delta\sigma_{F,k}\gamma_F}{\Delta\sigma_{R,k}/\gamma_M}$$

In case of stress situation SS3, i.e. fatigue, the same three execution classes apply, Table 3, though with different quality requirements for the three utilization factor ranges U<0,3, 0,3 to 0,7, and 0,7 to 1. However additional requirements have to be given for special notch cases and for welds of quality level B.

As the present document EN ISO 10042 does not adequately cover all cases especially in fatigue it has been necessary to provide additional requirements for respective weld cases in EN 1090-3.

FURTHER REMARKS

The issue of different load components in axially fatigue loaded bolted connectors in respective joints of steel or aluminium plates, also as additionally adhesively bonded joints, is pointed out in Fig. 36.

As already mentioned there is a fair amount of crack propagation data on parent material of aluminium alloys as well as for the HAZ and the weld metal zone in welded joints, Fig. 38. Following initial analyses, Fig. 39, a more comprehensive evaluation would make these data more readily available in general use.

As indicated in Fig. 8 the still not adequately solved issue of harmonization of critical values of imperfections and the quantification and correlation and the classification and actual fatigue behaviour of structural details in service is of importance. The current significant discrepancies between the classifications of a specific detail for different national standards are unacceptable, Fig. 41 and 42. The issue has been addressed above partly where the additional provisions in EN 1090-3 have been introduced in the case of welds loaded in fatigue parallel to the link between the execution standard, the design standard and EN 10042.

The engineering community would benefit from the issuance of a software package for general design and for fatigue design in special. Initial attempts for earlier versions of the code may stimulate further developments here, Fig. 44 to 48.

With the completion of the new ISO code, Fig. 51, for friction stir welding in aluminium this innovative joining method with significant advantages in strength and manufacturing options for aluminium may find its way eventually in respective design rules for structures.

CONCLUSIONS

The three fatigue design procedures, safe life design, damage tolerant design and design assisted by testing, provide the new code with all necessary tools for industrial applications. A quantitative correlation and harmonization of quality characteristics (imperfection size limits) of structural details with fatigue service behavior will be a significant task of the future.

Damage tolerant design is based appropriately on fracture mechanics and crack propagation evaluations provides respective data and support inspection procedures. The powerful tool of quantitative fractography of fatigue fracture surfaces should also be considered in further developments.

The consequence class and the stress situation govern criteria for the selection of the execution class in aluminium structures primarily. This approach is different to steel where production technology and service conditions categories define the execution class too. The stress situation in aluminium defines additional NDT extent, as in steel, but is also a criterion for additional requirements to the quality level. The requirements for inspection and acceptance are more complicated in the case of aluminium. A simplification by integration of the stress situation or utilization factor criterion into the execution class may be feasible.