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Design Considerations for Welded Hollow Section Joints

Remarques au sujet des assemblages soudés de profils creux

Bemessung geschweisster Verbindungen von Hohlprofilen

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SUMMARY

After some general considerations in fatigue design, a review of the design curves for tubular joints is given. Curves for both nominal and hot spot stress ranges are shown. The method of determining the hot spot stress range is described. In addition, design curves for square hollow section joints are given. Finally, the fracture mechanics approach is outlined.

RESUME

Après quelques considérations générales sur le calcul à la fatigue on donne un aperçu des courbes de dimensionnement pour les assemblages de profils tubulaires. On montre les courbes pour les différences de contraintes aussi bien nominales qu'extrêmes. On décrit la méthode pour déterminer la différence de contraintes extrêmes. On donne en outre des courbes de dimensionnement pour les assemblages de profils creux à section carrée. Finalement, l'approche par la mécanique de rupture est esquissée.

ZUSAMMENFASSUNG

Nach einigen allgemeinen Betrachtungen über die Ermüdungsbemessung gibt der Beitrag eine Übersicht über die Bemessungskurven für Hohlprofilverbindungen. Es werden sowohl Kurven für nominelle als auch für extreme Spannungsdifferenzen vorgestellt. Die Methode zur Bestimmung extremer Spannungsdifferenzen wird beschrieben. Zusätzlich werden Bemessungskurven für Verbindungen von Rechteckrohren gegeben. Anschliessend wird die bruchmechanische Behandlung des Problems skizziert.



1. INTRODUCTION

Recently the results of an extensive ECSC research programme concerning the corrosion fatigue behaviour of steels in offshore structures have been reported [1]. Besides tests on welded flat steel specimens nearly 300 tubular joints were tested. The results of these tubular joint tests showed that the previously used AWS-X design curve was too optimistic for large sized joints. In the new editions of the AWS [2] and API [3] codes additional lower design curves are introduced for joints without an improved weld profile. In the U.K. a draft for "New fatigue design rules" [4], based on the results of the European offshore research programme, has been published. Last years also a by ECSC and Cidect funded research programme was carried out regarding the fatigue behaviour of joints in square hollow sections. This paper reviews the existing design curves for joints in circular and rectangular hollow sections.

2. GENERAL CONSIDERATIONS IN FATIGUE DESIGN

For the determination of the fatigue life of a hollow section joint information is needed regarding:

- the loading in the members of the joint
- the S-N curve(s) to be used
- the stress distribution in the joint
- the influence of the environment
- a cumulative damage calculation procedure.

Generally the stress range S_r of the loading is taken into account whereas the stress ratio R is neglected, however for small sized joints it is shown that the influence of the R -ratio can be considerably [5,6]. The S_r - N curves can be given for the nominal stress range in the members or for the hot spot stress range in the joints. In the last method the S_r - N curves are generally valid but the stress distribution in the joint has to be known to calculate the maximum (hot spot) stress range. In both cases the stress ranges determined in design should be consistent with those used in the analysis of the test results (e.g. the determination of the stress concentration factors). Further the criterion of failure on which the S_r - N curves are based should be known (e.g. crack through the wall or complete failure).

Test in a corrosive environment (seawater) [1] have shown that the fatigue life of welded joints decreases by a factor of 2 to 3 and that no fatigue limit exists in the high cycle range.

For the calculation of the damaging effect of random loading the Palmgren-Miner rule is generally accepted. To prevent a fatigue failure (or a particular probability of failure) it is necessary to satisfy the condition.

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \dots = \sum \frac{n_i}{N_i} \leq D$$

where:

- n_i is number of load cycles occurring with stress range S_i
- N_i is number of load cycles, with stress range S_i , at which failure (or a certain probability of failure) occurs
- D is cumulative damage ratio being unity or smaller

3. FATIGUE DESIGN

3.1 General

In 3.2 and 3.3 the design curves taken from three codes are given. For a good comparison the following additional clauses in the codes have to be known.

- AWS-code [2]

The curves are valid for redundant structures in atmospheric service. For critical members whose sole failure mode would be catastrophic, D shall be limited to a fractional value of 1/3.

- API-code [3]

In general the design fatigue life of each joint and member should be twice the intended service life of the structure. For the design fatigue life, D should not exceed unity. For critical elements whose sole failure could be catastrophic, use of an additional margin of safety should be considered.

The S_r -N curves are based on an effective cathodic protection.

- DoE-code [4]

The design S_r -N curves are based on the mean minus-two-standard-deviation curves for relevant experimental data. For a critical member, e.g. one whose sole failure would be catastrophic, an additional factor on life should be considered. For unprotected joints exposed to sea water the basic S_r -N curve is reduced by a factor of 2 on life. The basic S_r -N curve is given for 32 mm wall thickness. For wall thicknesses from 22 to 100 mm a correction on stress range has to be used being:

$$S_r = S_B \left(\frac{t_0}{t} \right)^{\frac{1}{4}}$$

Where:

t is the wall thickness of the detail under consideration

t_0 is the wall thickness relevant to the basic S_r -N curve (wall thickness 32 mm)

S_B is the basic fatigue strength (wall thickness 32 mm)

S_r is the fatigue strength of the detail under consideration

For joints with wall thicknesses smaller than 22 mm no modification for the fatigue strength is given.

3.2 Nominal stress design curves for circular hollow section joints.

In fig. 1 the nominal stress design curves from the AWS- and API-code are given for circular hollow section joints. Table I shows the joints and stresses to which the curves apply. This together with the requirement that the design life has to be twice the service life according to the API, leads to a more conservative design using the API-code instead of the AWS code. Use of the curves is simple, however it does not give a real impression of the safety because the curves are lower bounds for test results in the common range of application. Especially for relatively thick walled small sized joints these curves may be very conservative, whereas for large sized joints the thickness effect should be included. Better design procedures based on nominal stress and more consistent with those described in 3.3 are still in study.

3.3 Hot spot strain design curves

It is generally known that the fatigue strength of hollow section joints depends mainly on the hot spot stress- or strain range in a joint. The hot



spot stress-or strain range is the maximum stress-or strain range at the weld toe and is influenced by: the global geometry of the joint, the global geometry of the weld and the condition of the weld toe. In the various codes and in the literature there are different definitions for the hot spot strain range [7]. In the Working Group III of the European offshore research programme the hot spot strain is defined as the extrapolated strain at the weld toe through the strain measuring points A and B as shown in fig. 2. In this way the influence of the geometry is included whereas the effect of the weld toe is excluded. This definition has also been adopted in the DoE-code [4]. For geometries with pronounced three dimensional effects e.g. joints with a diameter ratio of one, the distance between the measuring point B and the weld toe should be $0.4 t$. The stress-or strain concentration factor used in design should be consistent with the definition used in the analysis of the test results. Information regarding stress concentration factors can be found in [8, 9 and 10]. In fig. 3 the hot spot strain design curves from the AWS-, API- and DoE-code are given. The API-X, and AWS-X curves, are applicable for the so called controlled and improved weld profile. The same remarks as made for the curves for nominal stresses are valid for the difference between the API and AWS curves. The DoE-T line is steeper and has been based on the test results of the ECSC programme and gives the mean minus-two-standard-deviation curves for joints with wall thicknesses of 32 mm. As failure criterion is taken crack through the wall which is roughly 80 % of the total life. For wall thicknesses $22 \leq t \leq 100$ mm the influence of the wall thickness is incorporated by the function given in 3.1

For joints with wall thicknesses $t < 22$ mm no correction factors are given. An analysis of the test results shows that for $4 \leq t \leq 22$ mm the same correction factor is applicable for $N = 10^7$ cycles, however the slope of the curves change in such a way that the stress range at $N = 10^4$ remains nearly constant.

3.4 Classification method

For joints in rectangular hollow sections not sufficient information is available for the determination of parametrical formulae for stress concentration factors. Therefore S_r -N curves based on nominal stress range are given but the main influencing geometrical parameters are taken into account. The joints are classified in three basic types:

- K- and N-joints with gap
- K-joints with overlap
- N-joints with overlap

Within this classification and within the range of validity given (table II) the wall thickness ratio is the main influencing parameter whereas the influence of the other geometrical parameters is not significant. Fig. 4 shows the S_r -N curves which are based on lower bounds minus two standard deviations for each group. This figure shows the checking procedure for design which is based on the nominal stress range in the members due to axial load and bending moment. The connection between brace and chord is checked by using the curves A, B or C respectively whereas the chord beside the joint is additionally checked with curve D. The curves have been based on tests on joints with chord dimensions up to 200 mm. For larger sections a preliminary scale function ($f(S)$) is included which may be modified in future to bring it in line with that for circular hollow section joints. The S_r -N curves given under 3.2 and 3.3 are safe for all R-ratios. It is shown however that especially for joints with small wall thicknesses the R ratio can have a considerable influence. This is the reason that these curves may only be used up to $R = +0.2$. For higher R-ratios the S_r values have to be reduced. To prevent visual cracks under serviceability condition a load factor of 1.2 is advised (about a factor 2 in life). More detailed information is given in [5, 6].



4. FRACTURE MECHANICS

The service life of welded connections with regard to fatigue can, in principle, be predicted with the aid of fracture mechanics. The governing parameter for fatigue is here the "stress intensity factor range" (ΔK).

$$\Delta K = f \Delta \sigma \sqrt{\pi a}$$

where: a = dimension of the defect (crack)

$\Delta \sigma$ = stress range

f = geometric correction factor

The relation between ΔK and the crack growth is given in its simple form by the relationship of Paris and Erdogan:

$$da/dN = C \Delta K^m$$

where: da/dN = crack growth per cycle

C and m are material constants, determined by simple fracture mechanics fatigue tests.

The service life can be calculated by:

$$N = \frac{1}{C} \int_{a_1}^{a_c} \Delta K^{-m} \cdot da$$

where: a_1 = initial defect size

a_c = critical defect size

ΔK can be determined by finite element calculations. For complex geometries, like tubular joints, these calculations are very difficult and time consuming. The disadvantage of fracture mechanics is the lack of experience with this approach. However, the advantages are a more general applicability and the possibility of calculating the remaining lifetime of a cracked node.

5. CONCLUSIONS AND REMARKS

Considering the fatigue behaviour of tubular joints shows that a design method based on hot spot stress is the most uniform design procedure. Comparison of the design curves of the existing codes with the test results shows that for joints with wall thicknesses $t > 22$ mm the DoE recommendations give the best approach. For joints with smaller wall thicknesses some modifications are possible to take the better fatigue performance into account however the approaches should be consistent for joints with $t = 22$ mm.

Information regarding stress concentration factors is available although this should be used with caution especially for complicated joints [4].

For joints in square hollow sections the classification method can be used although in future after obtaining more test evidence the methods given for circular- and square hollow section joints should be consistent with each other.

Although fracture mechanics provides a basis for understanding the importance of various parameters, at this stage not sufficient data is available to use this method in general.



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Table I Nominal stress design curves for simple T, Y- or K connections.

type of weld	checked member	kinds of stress	design curves	
			API	AWS
full penetration welds	brace	nominal brace stress range	D'	DT
partial penetration or fillet welds	brace	nominal brace stress range	E'	ET
controled/improved profile	chord	punching shear stress range*	K	K ₁
no controled/improved profile	chord	punching shear stress range*	K'	K ₂

* punching shear stress range v_p

$$v_p = \tau \sin \theta \left[\alpha f_a + \sqrt{(2/3 f_{by})^2 + (3/2 f_{bz})^2} \right]$$

τ = thickness ratio t/T

θ = brace angle

α = 1 for K connections; 2 for T- and Y-connections

f_a = axial load stress range

f_{by} = in-plane bending stress range

f_{bz} = out-of-plane bending stress range

Table II Validity ranges of the various parameters

Parameter	
θ_i	$40^\circ - 90^\circ$
b_i, h_i	$b_i = h_i$
b_o	$\leq 450 \text{ mm}$
b_o/t_o	≤ 25
b_1, b_2	$b_1 \approx b_2$
$\beta = b_i/b_o$	$0.5 \leq \beta \leq 1.0$
$R = \frac{S_{r \min}}{S_{r \max}}$	$-1 \leq R \leq +0.2$
Fe	Fe 360 Fe 510 St E 47 St E 70
gap	$0.5(b_o - b_i) \leq \text{gap} \leq 1.1(b_o - b_i)$
overlap	$50\% \leq \text{overlap} \leq 100\%$

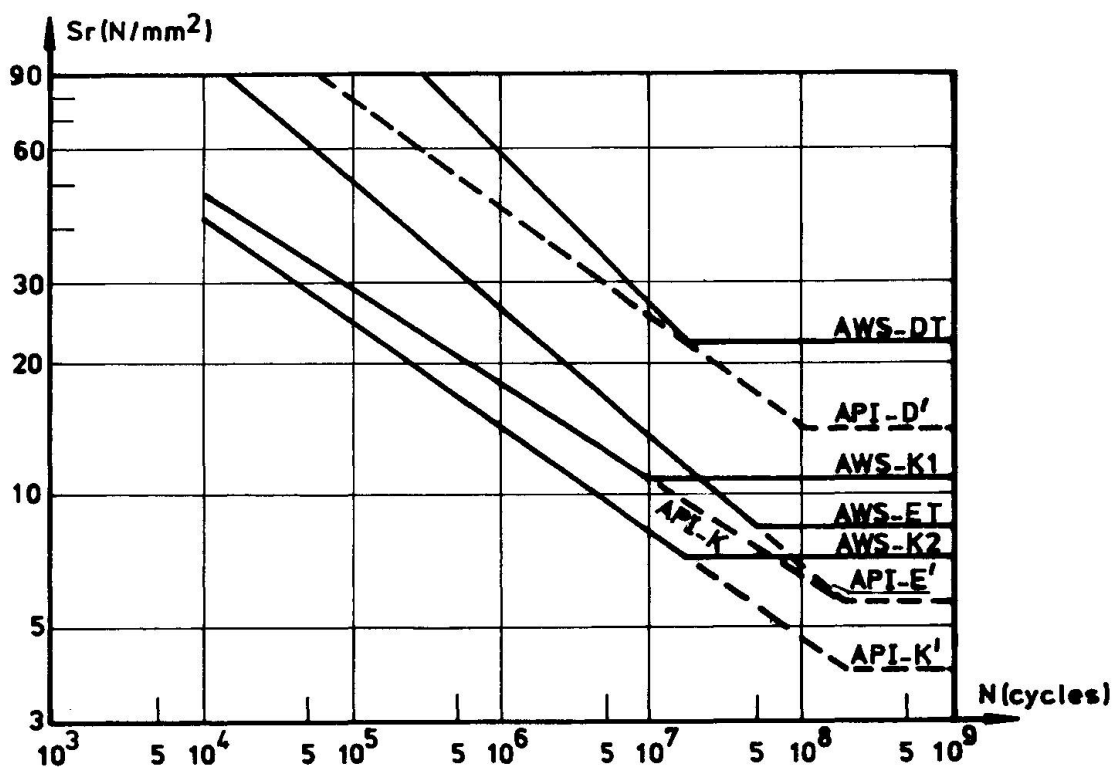


Fig. 1. Nominal stress curves taken from various design codes

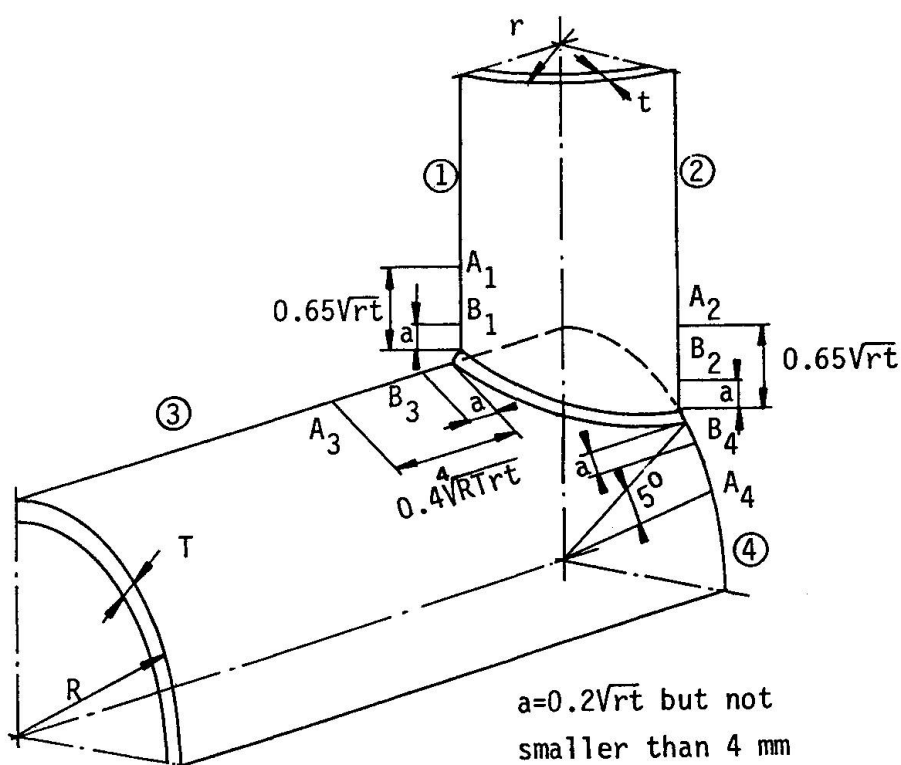


Fig. 2. Location of the points of the SNCF curve which has to be used for the extrapolation to the weld toe

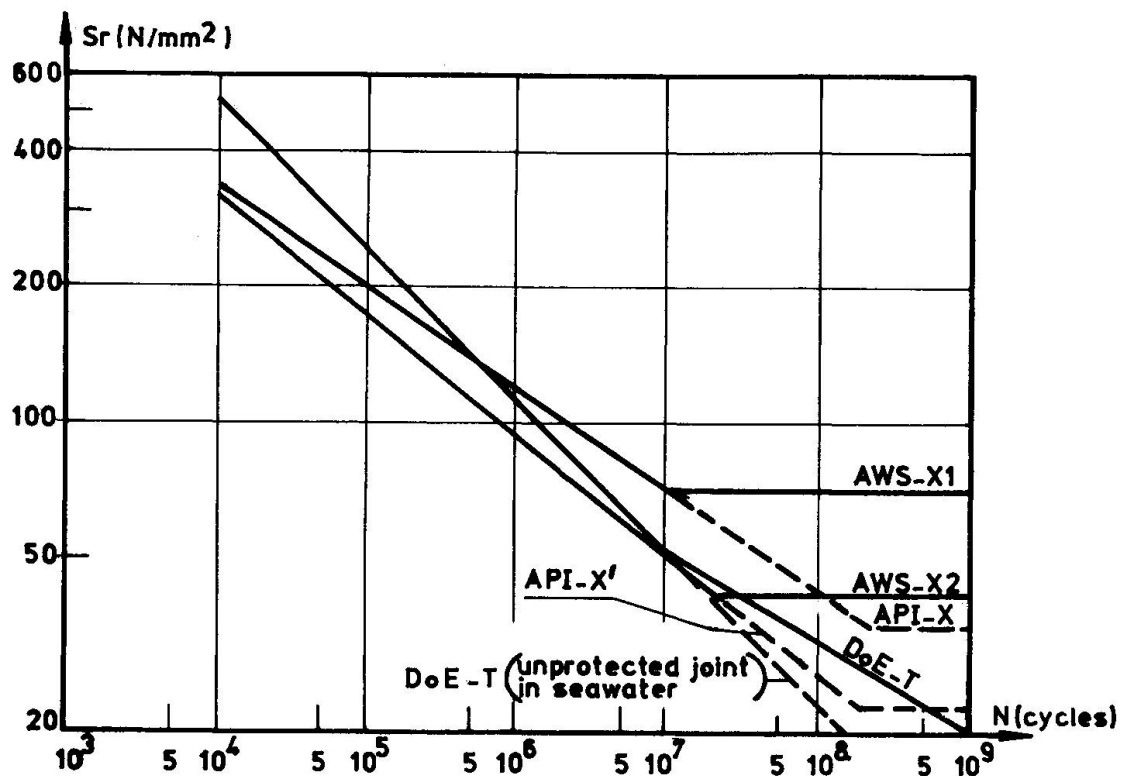


Fig.3. Hot spot stress curves taken from various design codes

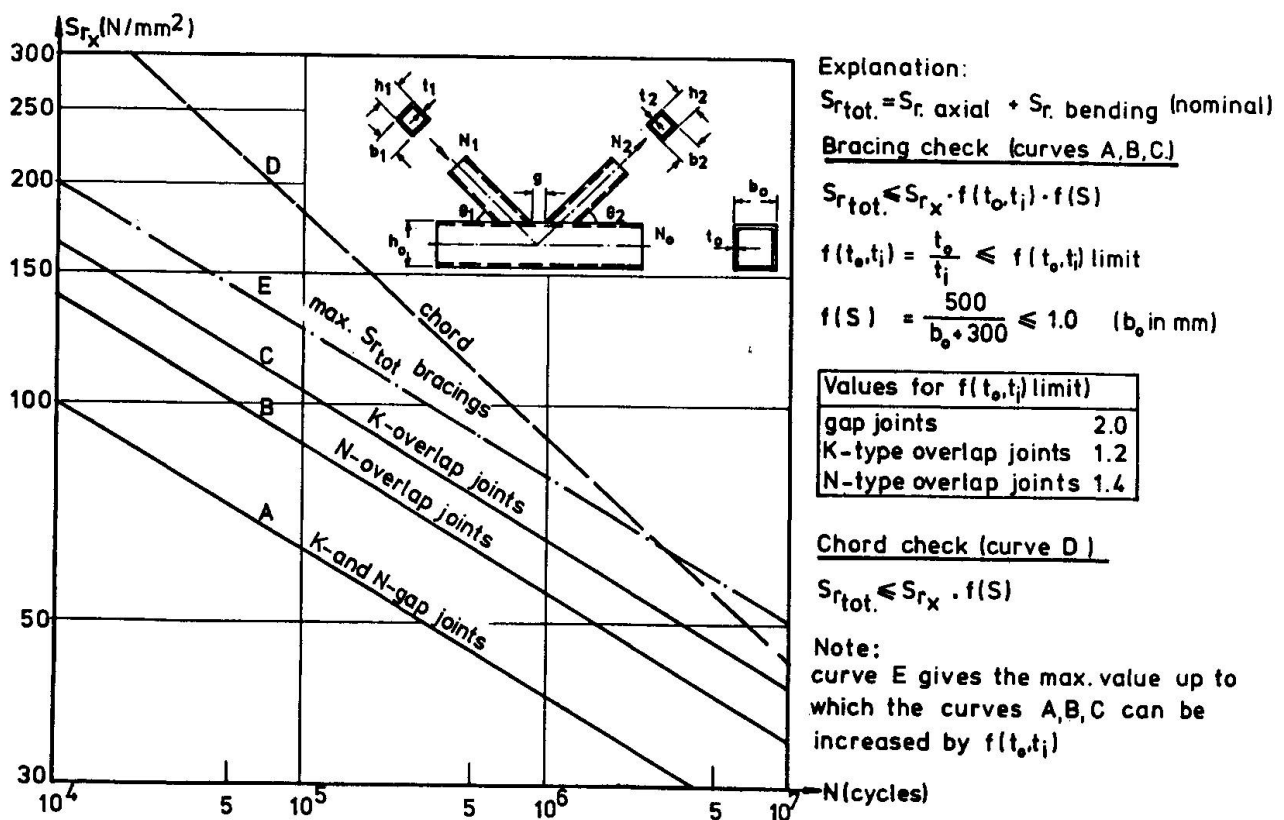


Fig.4 Recommended 95% survival S_r -N curves for K- and N-type joints made of square hollow sections