Analysis of Fatigue Recommendations Considering New Data

Analyse des recommandations à la fatigue compte tenu de nouveaux résultats

Analyse der Empfehlung über Ermüdung unter Berücksichtigung neuer Daten

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SUMMARY

At long lives, a shortage of large-scale test data contributes to uncertainty associated with the accuracy of guidelines for fatigue assessments. This paper compares fatigue recommendations proposed by the European Convention for Constructional Steelwork (ECCS) with recent test results. Several areas require more testing and theoretical work. Certain aspects of the ECCS Recommendations, such as constant-amplitude fatigue limits, options for variable-amplitude loading and detail classifications, could be adapted to this new information.

RÉSUMÉ

Pour les longues durées de vie, le manque de résultats concernant des essais en vraie grandeur mettent en doute la précision des recommandations à la fatigue. Cet article compare les recommandations à la fatigue proposées par la Convention Européenne de la Construction Métallique (CECM) avec des résultats d'essais récents. Plusieurs domaines nécessitent encore des essais et des développements théoriques. Certains paragraphes des recommandations de la CECM, comme les limites de fatigue sous amplitude constante, les choix pour le chargement sous amplitude variable et la classification des détails pourraient être adaptés en fonction de ces nouvelles informations.

ZUSAMMENFASSUNG

Das Fehlen von Versuchen im Massstab 1:1 stellt die Genauigkeit der Empfehlungen über Ermüdung in Frage. Dieser Artikel vergleicht die durch die Europäische Konvention für Stahlbau (EKS) vorgeschlagenen Empfehlungen über Ermüdung mit den neuesten Resultaten. Verschiedene Themenkreise verlangen mehr Versuche und theoretische Kenntnisse. Gewisse Aspekte der EKS-Empfehlungen wie die Dauerfestigkeit bei konstanter Amplitude, Möglichkeiten für Belastungen mit variabler Amplitude und die Definition der Konstruktionsdetails könnten in dieser neuen Information enthalten sein.

1. INTRODUCTION

Over the past ten years, much activity has concentrated on the development and international harmonization of recommendations for the fatigue design of steel structures. For example, the International Standards Organization (ISO) is studing a draft proposal. Background development work for some parts of this document was performed by Technical Committee 6 "Fatigue" of the ECCS which published recommendations in 1985 [1]. The European Community is considering a Eurocode draft for steel design (EC3). Much of Chapter 9, "Fatigue" of this draft is also based on the ECCS Recommendations. In addition, revisions of guidelines and codes are taking place on a national scale, for example in Australia, Italy and the USA.

Such developments represent considerable progress towards simplification and harmonization. There are many benefits, such as a greater understanding of the most important factors (secondary factors tend to confuse non-experts), reduced chances of misinterpretation, use of enlarged data bases, and easier participation in international projects. This last benefit is important since, increasingly, structures are not designed and fabricated in the same country as where they are erected.

However, there are still some areas of disagreement. A lack of test data obliges those committees developing design recommendations to estimate behaviour in some areas. This is particularly true for long fatigue lives ($> 2 \times 10^6$ cycles). Also, some recommendations are formulated using data obtained mostly from tests of small specimens. Examination of the relevance of these recommendations to large structures is not possible since there are few results from large-scale tests. As a result, disagreements originate from different estimates of long-life fatigue strength and how these estimates should be represented within design recommendations.

In order to resolve these disagreements, testing activity has increased, particularly long-life tests of large-scale elements. Recently, new fatigue test results have been collected and evaluated for proposed revisions to design recommendations in the USA [2]. Also, testing is planned and in progress in several locations, for example [3-5]. Differences between results from small-specimen testing and large-scale beam testing have been observed for both constant and variable-amplitude loading. Small-specimen test data can give unconservative estimates of fatigue strength, even for detail types which traditionally, have been thought [6] to require no correction [2].

This paper reviews present knowledge of high-cycle fatigue strength as well as recommendations proposed for evaluations of structures requiring long service lives. New test data are compared with the ECCS recommendations. More specifically, constant-amplitude fatigue limits, some detail classifications and the shape of the fatigue-strength curve in the long-life regime are evaluated. Finally, areas where further study would be beneficial are identified.

2. LONG-LIFE FATIGUE BEHAVIOUR OF WELDED STEEL DETAILS

Even at long lives, initial discontinuities and severe stress concentrations create conditions where fatigue cracks grow upon the first cycle of fatigue loading. Such growth can be modelled with sufficient accuracy using linear-elastic fracture mechanics, e.g. [7]. Therefore, under constant amplitude stresses, design documents model fatigue strength versus cycle life to be a straight line when plotted using logarithmic axes. Typically, this line breaks and becomes horizontal at the crack-growth threshold stress range, also called the constant-amplitude fatigue limit (CAFL). Although this effect is well documented for small components, the majority of data for large-scale structures are taken from tests at stress ranges which are not near the CAFL [2].

Threshold stress ranges are governed by initial defect sizes, geometry and stress range. Average applied stresses can also influence the value of the threshold stress range under certain conditions. Variations in crack opening, from one average stress to another, is the principal source of such effects. However, in welded joints, residual stresses are usually high, thereby creating conditions where the crack remains open, regardless of the average applied stress. Therefore for welded structures in non-corrosive environments, the CAFL depends primarily upon the initial defect size and geometrical conditions. Fatigue categories in modern codes reflect the relative influence of these factors, e.g. [1].

Most structures are subject to variable-amplitude loading. Above the CAFL, Miner's summation, rainflow analysis and the fatigue-strength relationship lead to a definition of the effective constant-amplitude stress range, $\Delta\sigma_e$ [1]. Such a definition allows use of constant-amplitude relationships for variable-amplitude load conditions. Although there is some disagreement on the accuracy of this approach for specimens [8], tests of beams, containing large zones of tensile residual stresses near yield strength, have shown that this definition is satisfactory, e.g. [9].

Interest in variable-amplitude fatigue strength has recently shifted to fatigue lives most representative of the expectations of civil engineering structures. For example, bridges are often expected to withstand stress cycles of one hundred million or more at low stress ranges (10-40 N/mm^2). Stress ranges below the CAFL influence fatigue life if there is at least one cycle in the variable-amplitude spectrum above the CAFL. This influence is due to a gradual exceedence of the threshold stress range by smaller cycles as crack length, driven by those cycles above the CAFL, increases. Therefore, values of the equivalent stress range, $\Delta\sigma_e$ below the CAFL may bring about fatigue failure. Test programs have verified this effect, even for stress spectrums where 0.1 % of the stress ranges exceed the CAFL [10]. Therefore two factors, $\Delta\sigma_e$ and $\Delta\sigma_{max}$, are important for fatigue assessments of welded steel details.

Figure 1 illustrates three cases of variable-amplitude stress spectra. Case 1 occurs when all cycles in the spectrum are above the constant-amplitude fatigue limit. Stress spectra of this type were used to study the equivalent constant-amplitude approach. When some, but not all, stress ranges are below the CAFL, the stress spectrum is Case 2. Since fatigue lives corresponding to stresses described by Case 2 are often necessary design values, Case 2 spectra have been the subject of recent research projects. The results of these projects are examined in the next section. Case 3 spectra are those spectra that have no stress range above the CAFL. If very long lives (> 10^8 cycles) are required, designs should ensure that all stress spectra are in Case 3. No fatigue crack growth is expected to result from Case 3 spectra since no stress range exceeds the CAFL.

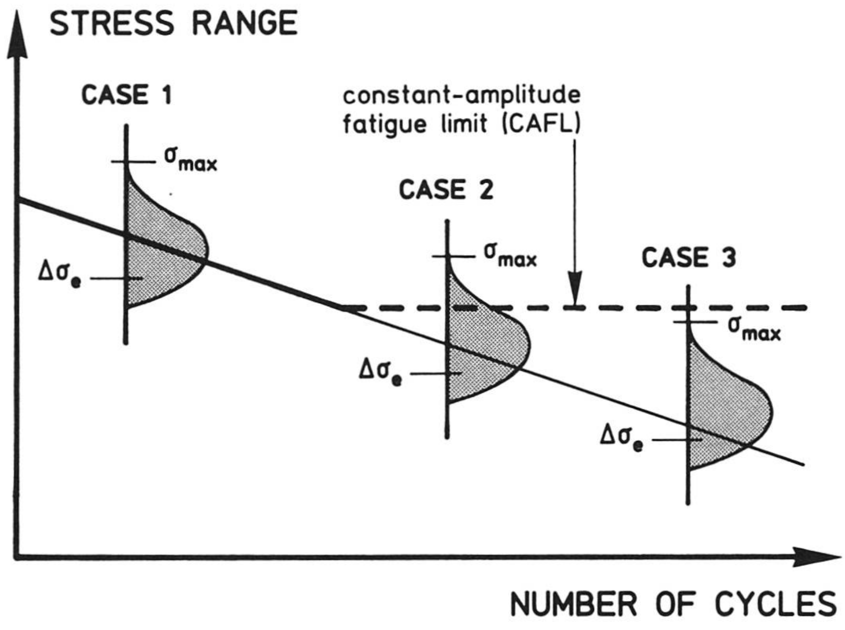


Figure 1. Three cases of variable amplitude stress spectra

3. RECOMMENDATIONS FOR LONG-LIFE FATIGUE DESIGN OF STEEL STRUCTURES

Recent design documents have provided fatigue-strength relationships for structural elements subjected to Case 2 spectra. Since the calculation of the equivalent constant-amplitude stress range employs these relationships, they influence methods used to analyse stress spectra. Various relationships have been proposed; this paper compares the following fatigue-strength curves with test data (see also Figure 2) :

Curve 1 : slope constant of three below CAFL; no cut-off limit.

Curve 2 : slope constant of five below CAFL; cut-off limit at stress range corresponding to the fatigue strength indicated by this curve at 10^8 cycles.

Curve 3 : slope constant of three below CAFL; cut-off limit at same stress range determined in Method 2.

Curve 4 : slope constant of three below CAFL; cut-off limit at stress range corresponding to the fatigue strength indicated by this curve at 10^8 cycles.

Curve 1 is the simplest approach; it considers that all cycles are damaging from the beginning of the fatigue life. In other terms, a threshold stress range of zero is assumed if one cycle in the spectrum exceeds the CAFL. Method 1 is a conservative, lower-bound estimate and therefore, it is suggested by some researchers as a reasonable design approach, e.g. [10].

Curve 2 is more complicated. The double slope was proposed after specimen testing [11]; there is very little experimental work which supports this relationship. However, Curve 2 is attractive theoretically because it attempts to account for the gradual exceedence of the threshold stress range by initially non-damaging cycles as a fatigue crack increases in length. The cut-off limit is a lower bound where stress ranges smaller than this value are assumed not to affect fatigue life.

Curve 3 and 4 are equivalent to Curve 1 plus a cut-off limit. Cut-off limits are useful because small stress cycles caused by vibration and other effects can be omitted from stress spectrums. The importance of the cut-off limit is increasing with improvements in stress-measurement technology. Small cycles can now be measured precisely and included in the stress spectrum using equipment such as stress-histogram recorders, for example see Figure 3. Since the number of these small cycles may be very large, they may influence the accuracy of the fatigue assessment. Currently, cut-off limits are fixed arbitrarily in design documents.

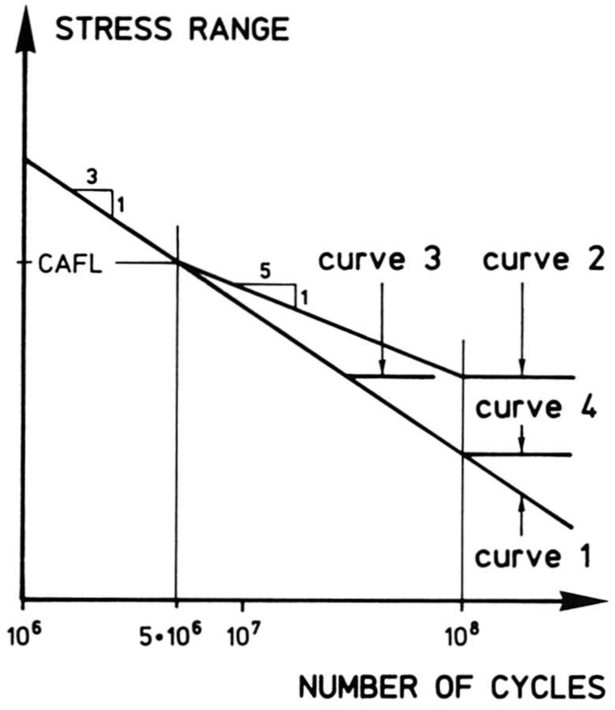


Figure 2.
Fatigue-strength Curves examined. Each Curve corresponds to an analysis Method of the same number.

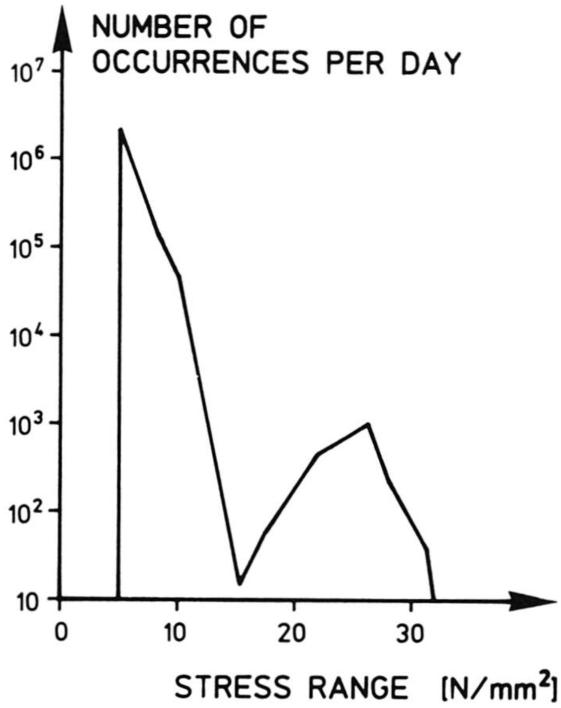


Figure 3.
Stress-range histogram taken from strain measurements of a dynamically loaded structure. Very conservative fatigue assessments result if no cut-off limit is employed.

Each Curve described above defines a method for stress-spectrum analysis. In Figure 2, each Curve is assigned the same number as the Method used in the next Section for data reduction. Table 1 is a list of equations corresponding to each Method for the determination of equivalent constant-amplitude stress ranges and number of stress cycles. Methods 1, 2 and 3 are options proposed by the ECCS Recommendations [1]. Method 4 is a more conservative variant of Method 3.

Table 1. Analysis of spectra according to four Methods.

METHOD	EQUIVALENT CONSTANT-AMPLITUDE STRESS RANGE, $\Delta\sigma_e$	NUMBER OF CYCLES
1	$[(\Sigma n_i \, \Delta\sigma_i^3) \, / \, N_1]^{1/3}$	$N_1 \times N_s$
2	$[(\Sigma n_k \, \Delta\sigma_k^3 + \Sigma n_j^* \, \Delta\sigma_j^{5*} \, / \, CAFL^2) \, / \, N_2]^{1/3}$ if above equation < CAFL, then use $[(\Sigma n_k \, \Delta\sigma_k^3 \, CAFL^2 + \Sigma n_j^* \, \Delta\sigma_j^{5*}) \, / \, N_2]^{1/5}$	$N_2 \times N_s$
3	$[(\Sigma n_i^* \, \Delta\sigma_i^{3*}) \, / \, N_2]^{1/3}$	$N_2 \times N_s$
4	$[(\Sigma n_i^* \, \Delta\sigma_i^{3*}) \, / \, N_3]^{1/3}$	$N_3 \times N_s$

* include only those stress-range magnitudes which are greater than the cut-off limit definied by the Method.

CAFL : constant-amplitude fatigue limit
n_i : the number of cycles in spectrum at stress range, $\Delta\sigma_i$
n_j : the number of cycles in spectrum at stress range, $\Delta\sigma_j$
n_k : the number of cycles in spectrum at stress range, $\Delta\sigma_k$
N_1 : total number of cycles in spectrum
N_2 : total number of cycles in spectrum less those cycles at stress ranges lower than stress range corresponding to one hundred million cycles on the fatigue-strength curve which has slope constant of five below the CAFL
N_3 : total number of cycles in spectrum less those cycles at stress ranges lower than stress range corresponding to one hundred million cycles on the fatigue strength curve with a single slope
N_s : number of times spectrum is repeated
$\Delta\sigma_i$: a stress range in the spectrum
$\Delta\sigma_j$: a stress range in the spectrum having a magnitude less than the CAFL
$\Delta\sigma_k$: a stress range in the spectrum having a magnitude greater than the CAFL

4. COMPARISON OF RECOMMENDATIONS WITH NEW DATA

This section discusses two topics : the magnitude of the CAFL and the shape of the fatigue strength curve below the CAFL. Test results are compared with the values of CAFL for three details classified in the ECCS Recommendations. Next, the four Methods described in Section 3 are compared with test results of several details using their ECCS classifications.

Data is analysed in the same way a design engineer would analyse a structure subject to the same loading spectra as the test beams - assuming that the designer would refer to the ECCS classifications. The ECCS classifications correspond to mean experimental values minus two standard deviations. Therefore, these comparisions are not intended to lead to the development of new models. Clearly, such development would require comparison of test data with those curves which correspond to mean experimental values.

4.1. Constant-amplitude fatigue limit

The magnitude of CAFL is important since this value determines the appropriate case of variable amplitude loading, as indicated in Figure 1, and thus the complexity of the assessment. For designers, the CAFL is probably most useful for distinguishing Case 2 from Case 3 since this distinction determines whether or not a fatigue assessment is necessary. Also, some methods of stress spectra analysis include calculations which employ the CAFL, as set forth in Table 1.

There is much variation in recommendations for the CAFL. For example, Swiss [12] and American codes [13] prescribe CAFL's at stress ranges corresponding to fatigue lives which vary from two to twenty million cycles, depending upon the detail category. This variation probably reflects test results most accurately. Italian recommendations place the CAFL at fatigue strengths which intersect with fatigue lives of five and ten million cycles for high and low detail categories, respectively [14]. The British standard [15] simplifies this approach by specifying a CAFL corresponding to a fatigue life of ten million cycles for all detail categories. The ECCS recommendations [1] suggest a CAFL at five million cycles for all detail categories. Differences in design recommendations are largely due to lack of test data and varying attitudes relating to how fatigue guidelines should reflect fatigue behaviour. Each code is a compromise between accuracy and simplicity, and since these compromises are often fixed arbitrarily, they are common sources of disagreement.

ECCS recommendations are compared to three details having low fatigue strengths : coverplated beams with coverplate or flange thickness greater than 20 mm (Detail Category - ECCS 36) in Figure 4a, coverplated beams with coverplate and flange thickness less than 20 mm (ECCS 50) in Figure 4b, and welded attachments longer than 150 mm (ECCS 50) in Figure 5. Comparisons are made in terms of stress range on histograms of beam failures over two million cycles. The bars in these histograms are divided into the following three bands of fatigue lives : between two and five million cycles, between five and ten million cycles and over ten million cycles. Fatigue lives refer to beam failure, not first detection of cracking. Beam failure is normally defined to be the number of cycles when a certain increase in midspan deflection is observed. This increase is predetermined to indicate the presence of a crack which is propagating so quickly that the additional number of cycles to complete failure is small compared with the number of cycles already applied [2].

Results for beam failures at thin coverplate details, from refs. [9] [16-18], are shown on Figure 4a. This detail is probably the only in which has more than twenty test results for beam failures above two million cycles. Also, at stress ranges near the lower bound of the beam-failure data, several tests were continued until 10^8 cycles without cracking (these results are not shown in Figure 4b). There is much scatter in the results; beam failures at lives of two to five million cycles were subjected to stress ranges of 41 to 105 N/mm^2. At lives of five to ten million cycles, beams experienced stress ranges of 34 to 55 N/mm^2, and lastly, over ten million cycles, stress ranges varied between 32 to 55 N/mm^2. The CAFL limit corresponding to the ECCS classification for this detail is 37 N/mm^2. The results indicate that this limit does not represent the lower bound of all test data; a more conservative limit would be 32 N/mm^2.

Results of beams with thick coverplated details [19-20], shown in Figure 4b, indicate that the ECCS Classification gives a CAFL which is below all stress ranges where fatigue failure has been observed. However, the amount of data is limited. Data is also not very abundant for beam failures due to longitudinal attachments, as shown in Figure 5 [18] [21-23]. Again, there is much scatter and the CAFL corresponding to the appropriate ECCS classification does not represent the lower bound of all test data.

Figures 4 and 5 include fatigue lives above the fatigue life (5 x 10^6 cycles) corresponding to the CAFL in the ECCS Recommendations. Therefore, if researchers refer to such recommendations for help relating to the number of cycles when constant-amplitude fatigue tests may be stopped, they will not obtain satisfactory advice. Guidelines are made for designs; they should warn against being used for testing. Further work is necessary to determine appropriate recommendations for testing.

The CAFL is an important parameter in fatigue assessments of civil-engineering structures. However, the quantity of test data presently available does not reflect this importance. The three details examined in this paper are those which have been studied most thoroughly. Currently, it is not possible to fix the level

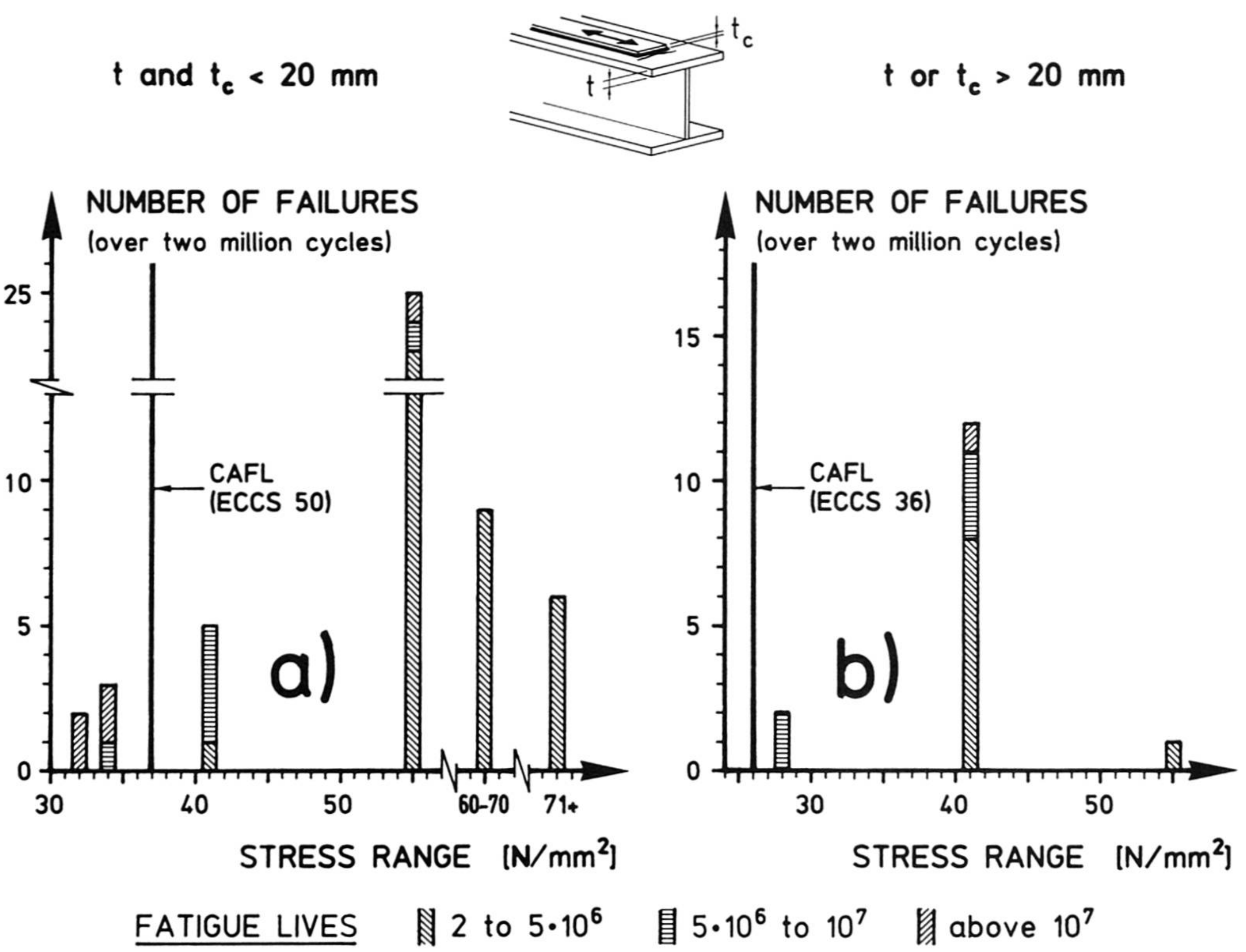


Figure 4. Constant-amplitude fatigue failures of coverplated beams [9] [16-20].

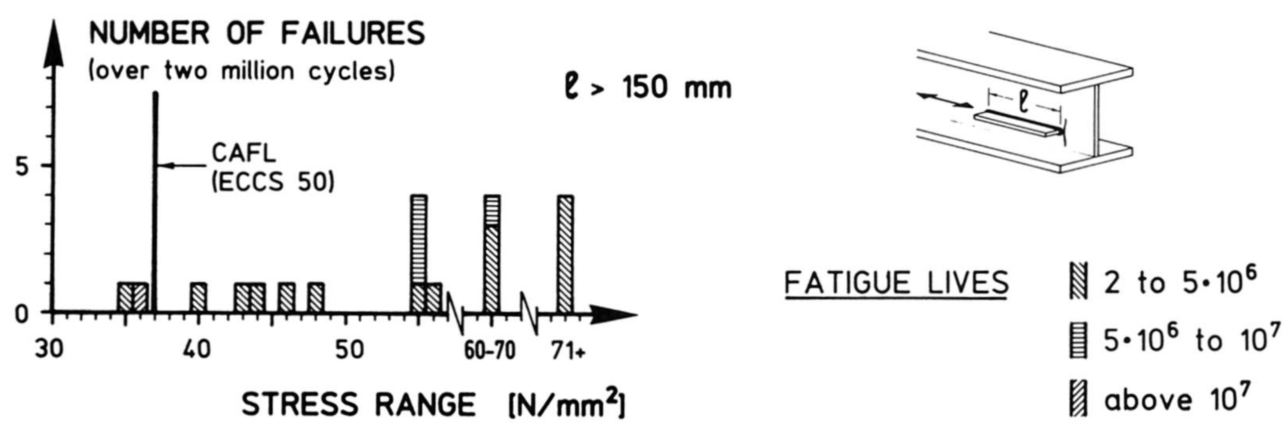


Figure 5. Constant-amplitude fatigue failures of beams with longitudinal attachments [18] [20] [22-24].

of the CAFL with acceptable accuracy for most details. Much more work, both experimental and theoretical, is needed.

4.2 Variable-amplitude fatigue behaviour

An attempt was made to collect all existing data according to the following two criteria : fillet-welded details on beams only, and fatigue lives of more than ten million cycles (number of blocks x total number

Table 2. An example of stress-spectra analysis. a) A spectrum applied to a longitudinal-attachment detail. b) The four Methods used to analyse the spectrum. For notation, see Table 1.

a)

NUMBER OF CYCLES, n_i	STRESS RANGE, $\Delta\sigma_i$ [ksi]	STRESS RANGE, $\Delta\sigma_i$ [N/mm^2]
1	6.0	41
1	5.5	38
3	5.0	34
6	4.5	31
24	4.0	28
69	3.5	24
152	3.0	21
255	2.5	17
301	2.0	14
212	1.5	10

1 block, N_1 = 1024 cycles

Number of blocks to failure : N_s = 39551

b)

Classification ECCS 40 : CAFL = 29 N/mm^2. Cut-off limits : 16 and 11 N/mm^2.

n_i	METHOD 1 $n_i\,\Delta\sigma_i^3$	METHOD 2 $n_k\,\Delta\sigma_k^3$	METHOD 2 $n_j^*\,\Delta\sigma_j^{5\,*}$	METHOD 3 $n_i^*\,\Delta\sigma_i^{3\,*}$	METHOD 4 $n_i^*\,\Delta\sigma_i^{3\,*}$
1	7E+04	7E+04		7E+04	7E+04
1	5E+04	5E+04		5E+04	5E+04
3	1E+05	1E+05		1E+05	1E+05
6	2E+05	2E+05		2E+05	2E+05
24	5E+05		4E+08	5E+05	5E+05
69	1E+06		6E+08	1E+06	1E+06
152	1E+06		6E+08	1E+06	1E+06
255	1E+06		4E+08	1E+06	1E+06
301	8E+05				8E+05
212	2E+05				
1024	5.58E+06	4.27E+05	1.91E+09	4.55E+06	5.34E+06

$\Delta\sigma_e$ [N/mm^2]	17.6	21.4	20.7	18.7
NUMBER OF CYCLES	4.05E+07	2.02E+07	2.02E+07	3.21E+07

of cycles in a block). Also, details without fatigue cracking were not considered, and fatigue life was taken as beam failure - not first detection of cracking. A literature search resulted in six details subjected to eleven spectrum shapes from five different sources [4-5] [9-10] [24].

As described in Section 3, four Methods are used to determine $\Delta\sigma_e$ and number of cycles corresponding to the four fatigue-strength relationships shown in Figure 3. Typical calculations employed by each Method are listed in Table 2. Methods 3 and 4 are investigated only when necessary since these Methods can be described as intermediate analyses between two boundaries, Method 1 and Method 2.

Results for fatigue cracks growing from coverplate details, with both flange and coverplate less than 20 mm, are given in Figure 6a. When stress spectra are analysed according to Method 2, a better agreement with the corresponding Curve is possible. This Curve provides a conservative lower bound for all test data. Better agreement using Method 2 is also observed for coverplate details with flange or coverplates greater than 20 mm, Figure 6b. Again, this Curve provides a lower bound for the data and furthermore in comparison with Curve 1, the decrease in stress range with increasing life is modelled more accurately.

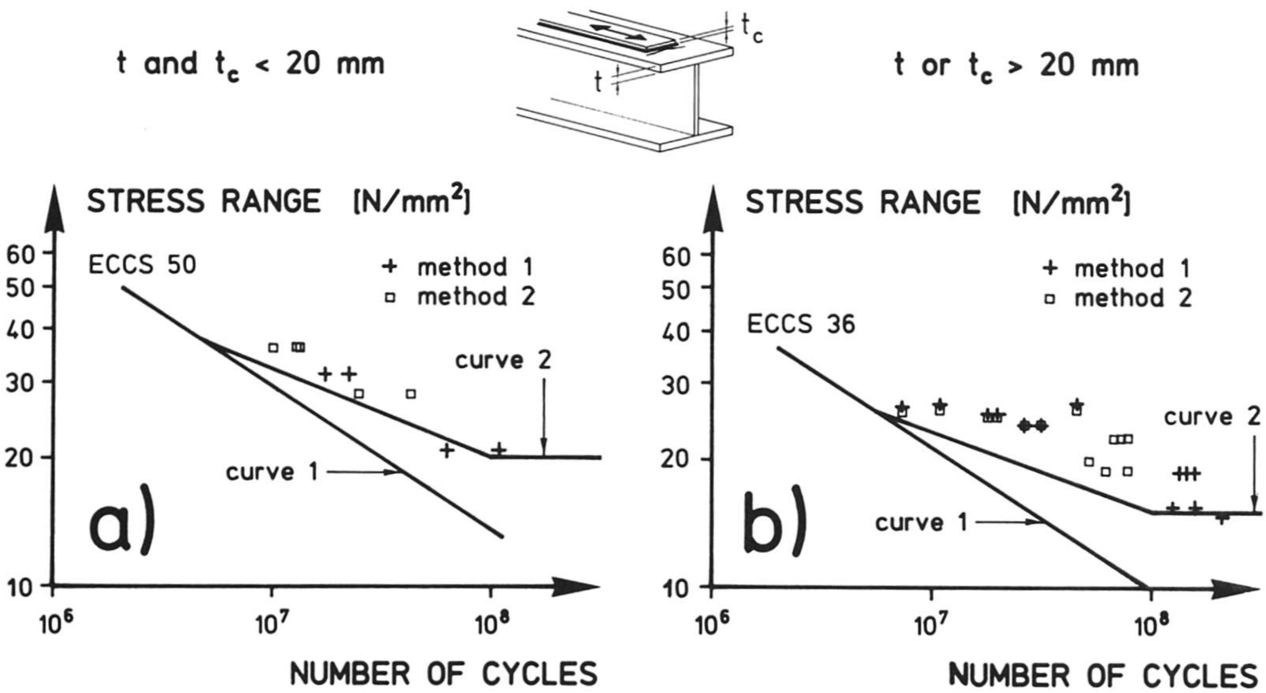


Figure 6. Variable-amplitude fatigue failures of coverplated beams [9-10].

The ECCS classification for longitudinal attachments (ECCS 50) is not conservative even for Method 1, as shown in Figure 7a. This is also confirmed by constant-amplitude test results [21]. Therefore, for the purposes of this study, a classification of ECCS 40 is assumed. For this detail, spectra analysed according to Method 2 do not provide a satisfatory agreement with the fatigue strength Curve, see Figure 7b. Also, two other attempts to analyse this data using a double-slope fatigue strength curve, firstly, according to British recommendations [15] and, secondly, using ECCS Classification 36 did not provide a lower bound. Therefore, Method 2 may not always result in conservative fatigue assessments.

Method 3 succeeds in providing a lower bound for all data points except one, as indicated in Figure 7c. This last point is finally brought above the fatigue strength curve when Method 4 is employed as shown in Figure 7d. Very few beams have been tested at stress ranges where the difference between Method 3 and

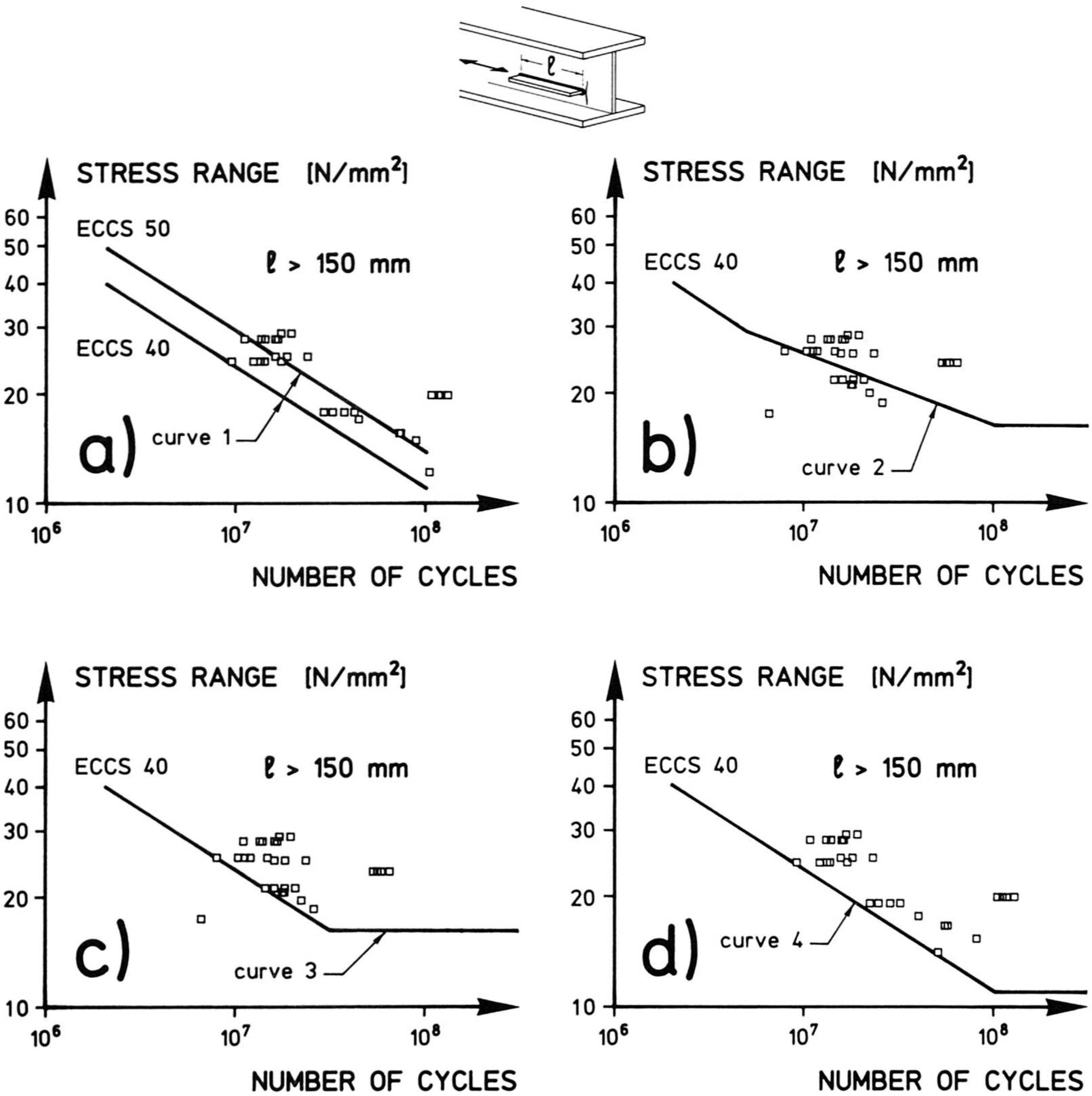


Figure 7. Variable-amplitude fatigue failures of beams with longitudinal attachments longer than 150 mm [5] [10].

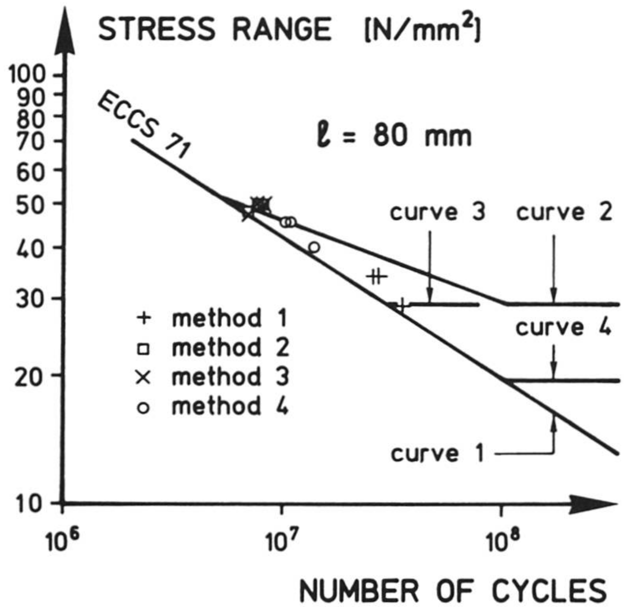
Method 4 can be examined; more testing of several types of details at various stress spectra is needed to define cut-off limits.

A study in progress of flange attachments on large beams [4] indicates that all Methods are equally reasonable, see Figure 8. Nevertheless, Method 2 is slightly unconservative for one result. Note that these curves should represent mean fatigue strengths less two standard deviations; the incidence of test results falling below these curves should be relatively rare. Methods 1 and 4 probably provide the best agreement. Even though Method 2 is satisfactory, nothing is gained by the increase in complexity over the other Methods.

All remaining data, fitting the criteria set for this study, are presented in Figure 9. Clearly, much more long-life testing of constructional details is required. Although the amount of data in Figure 9 is small, Method 2 appears to provide a better relationship for three cases of transverse attachments, transverse stiffeners and longitudinal attachments.

Considering all cases, Method 2 was most successful for details on small beams and least successful on larger beams (depths of 450 mm and greater). This may be due to a more severe residual stress distribution in larger beams. When welded, larger elements cool less uniformily, thereby creating higher residual stresses over larger areas. Therefore, larger elements may be more sensitive to small stress ranges in the stress-range spectrum. Consequently, an analysis more conservative than Method 2 may be necessary for large structures.

Finally, the shape of the loading spectrum may influence the success of Method 2. If a certain percentage of stress ranges in a spectrum are near its maximum stress range, Method 2 is likely to be satisfactory. However if nearly all of the stress ranges are less than half of the maximum stress range, other Methods



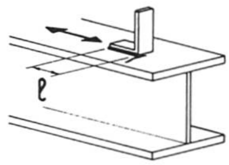
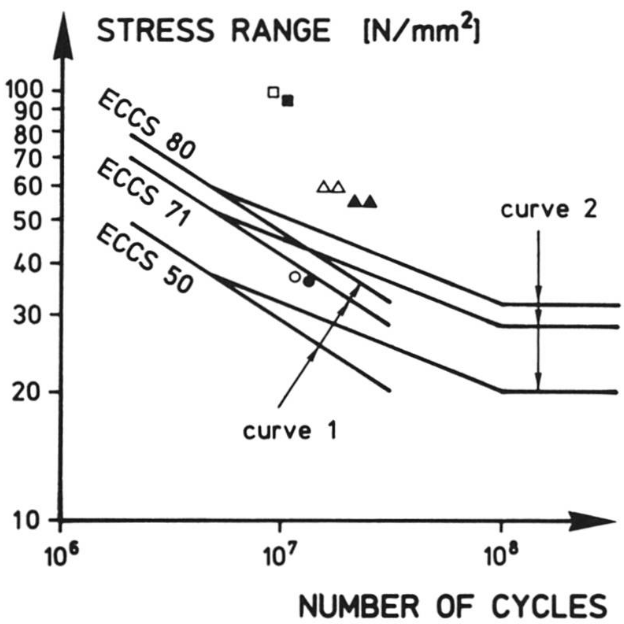


Figure 8.
Variable-amplitude fatigue failures of beams with longitudinal attachments, 80 mm long [4].



DETAIL	METHOD 1	METHOD 2	ECCS category
transverse attachment	■	□	71
transverse stiffener	▲	△	80
longitudinal attachment	●	○	50

Figure 9.
All remaining data of variable-amplitude beam tests having a duration greater than ten million cycles [24].

may be more appropriate. Further work is needed to better quantify the influence of spectrum shape and to associate spectrum types with parameters such as service conditions and structural characteristics.

5. CONCLUSIONS

1. The quantity of test data presently available at stress ranges near constant-amplitude fatigue limits does not correspond to their importance to fatigue assessments. More work, both experimental and theoretical, is needed to define constant-amplitude fatigue limits. More work is also needed to examine more thoroughly variable-amplitude behaviour of steel structures at long fatigue lives.

2. Since constant-amplitude fatigue limits proposed by the ECCS Recommendations do not provide a lower bound of all available test data for some detail categories, further study may be needed to propose and evaluate revisions.

3. When compared to a single-slope fatigue-strength curve, the double-slope curve proposed by the ECCS Recommendations may improve the accuracy of fatigue assessments. However, this improvement can not be expected for all types of structural elements and all stress spectra. In some cases, the double-slope proposal is not conservative while in other situations, increases in complexity of the analysis - brought about by the double slope - cannot be justified. Element size as well as spectrum shape may have an influence upon the most appropriate method for fatigue assessment of structures subjected to variable-amplitude loading.

4. The ECCS classifications for some details may need to be revised.

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