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Fatigue Design Concepts

Concepts du dimensionnement à la fatigue

Konzepte des Ermüdungsnachweises

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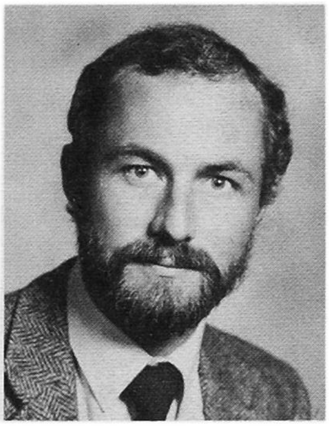

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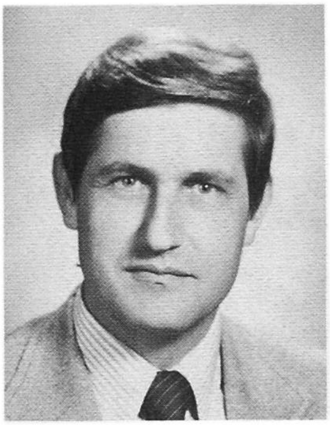

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SUMMARY

The fatigue life of engineering components is determined by a large number of parameters. Consequently, it is difficult to provide simple and sufficiently accurate guidelines for the designer. The influence of welded connections reduces the relative importance of many parameters and thus provides an opportunity for simplified design rules. Several international organizations are co-operating in the development and harmonization of a fatigue design concept for steel structures. New problems, such as a more accurate definition of fatigue loading or the evaluation of the remaining fatigue life of existing structures, are future challenges for international agreement.

RÉSUMÉ

Le comportement à la fatigue d'éléments structurels est régi par un grand nombre de paramètres. Il est par conséquent difficile de fournir aux ingénieurs des règles simples mais néanmoins suffisamment précises. L'influence des assemblages soudés diminue l'importance de nombreux paramètres et offre ainsi la possibilité d'élaborer des règles de dimensionnement simplifiées. Plusieurs organisations internationales coopèrent au développement et à l'harmonisation d'un concept global de dimensionnement à la fatigue. De nombreux problèmes, tels que la définition plus affinée des charges de fatigue ou l'évaluation de la durée de vie restante de structures existantes, sont une vraie gageure pour des conventions internationales.

ZUSAMMENFASSUNG

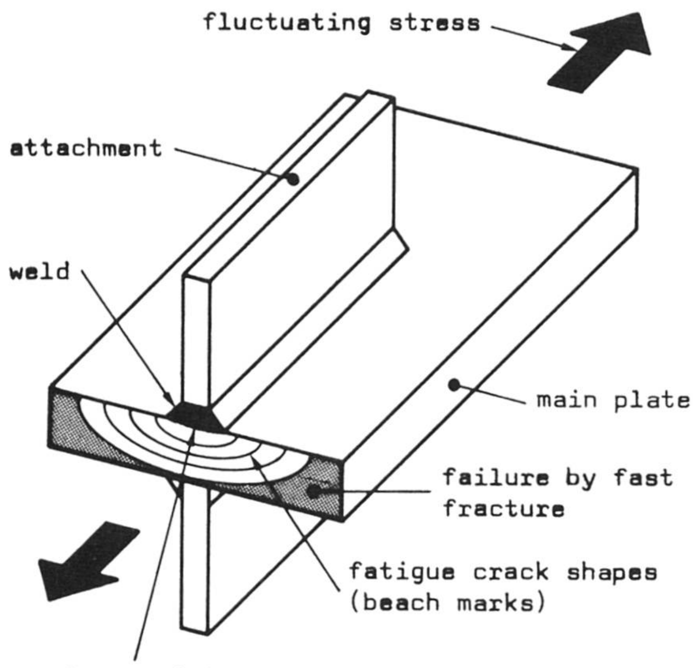
Das Ermüdungsverhalten von Tragelementen wird durch eine grosse Anzahl von Faktoren beeinflusst. Daher ist es schwierig, einfache und genügend genaue Richtlinien für den projektierenden Ingenieur festzulegen. Der Einfluss geschweisster Verbindungen vermindert die Bedeutung einiger Einflussfaktoren und ermöglicht somit vereinfachte Entwurfsregeln. Verschiedene internationale Organisationen arbeiten bei der Entwicklung und Harmonisierung von Konzepten für den Ermüdungsnachweis von Stahlkonstruktionen zusammen. Neue Probleme, wie die genaue Festlegung der Ermüdungsbelastung oder die Bestimmung der Restlebensdauer bestehender Konstruktionen sind zukünftige Herausforderungen an eine internationale Übereinkunft.

1. INTRODUCTION

It is estimated that a majority of all the failures which occur in enginering components can be attributed to fatigue [1]. Fatigue failures may occur in air frames, ships, bridges, cranes, automotive parts, turbines, crane gantry girders, pressure vessels, machinery, pipework, marine platforms, transmission towers, masts and chimneys. Fatigue stresses may be caused by traffic loads or by fluctuating loads due to waves, wind, pressure cycles, vibrations and temperature changes. Fatigue failure begins usually with the slow growth of small fatigue cracks which start from sharp notches or crack-like defects. In machined parts, a large portion of the fatigue life may be expended in microstructural crack formation and growth, known as crack initiation. The fatigue process ends when the crack reaches a length which causes failure of the structure. FIGURE 1 describes a typical fatigue crack process in a welded structural element.

Fatigue is widely researched at many levels. Over 30 academic journals in international circulation are likely to have articles on fatigue; two are devoted exclusively to the subject. Hundreds of trade journals report fatigue test results. The trend toward higher strength materials and lighter construction is increasing the likelihood of damaging fatigue stresses and thus, the research activity. However, in some fields it seems that the gap between researcher and designer is widening. Design approaches proposed by experts are numerous and contradictory. Consequently, the fatigue life calculated for a welded connection in a bridge may be quite different, even by an order of magnitude, when using different recommendations or codes.

Fatigue codes or recommendations exist in almost every industrialised country. Experts meet regularly in an attempt to narrow the gap between academic journals and design calculations. Fortunately, recent research in structural steel has led, not to further complication but to important simplifications. This has resulted in a unprecedented international harmonization of design procedures for fatigue.



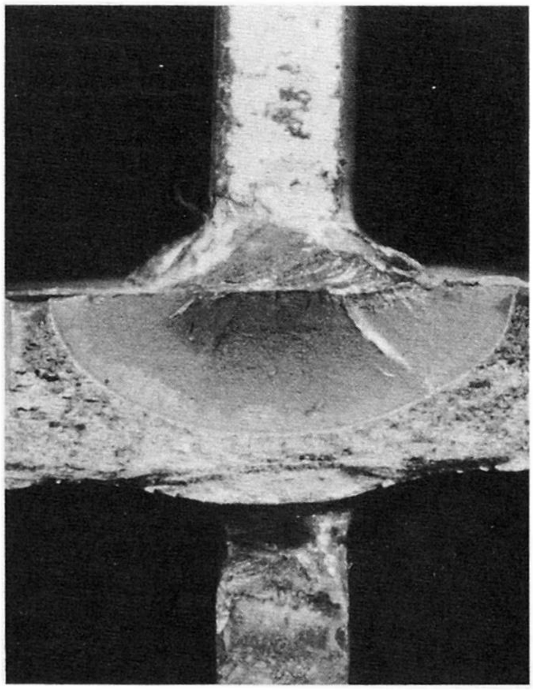


FIGURE 1 : Schematic representation and photograph of a typical fatigue crack process due to the presence of a welded attachment.

This paper outlines the complexities of the fatigue problem in engineering components and describes some special characteristics of welded steel structures. A document which translates these special characteristics into design recommendations is introduced. Finally, the examination of some new developments indicates the direction of future changes in fatigue design concepts.

2. FATIGUE OF ENGINEERING MATERIALS

The factors which influence the fatigue life of an engineering component are grouped together in TABLE 1.

STRESS	GEOMETRY
• stress or strain range • stress sequence • frequency • mean stress • residual stress •	• overall structural design • local stress concentration • small discontinuities : - scratches - grinding marks - surface pitting - cracks - welding process defects • ......
MATERIAL PROPERTIES	**ENVIRONMENT**
• stress-strain behaviour • grain size and shape • hardness • chemical composition • homogeneity • electrical potential • microstructural discontinuities : (dislocations, vacancies, impurities, inclusions, grain boundaries) •	• corrosive liquids or gases • temperature • humidity • hydrogen (embrittlement) • irradiation • ......

TABLE 1 : Factors which may influence the fatigue life of an engineering structure.

2.1 Stress

Although fatigue stresses have a large influence on fatigue life, often their true magnitude is not known. Stress range (FIGURE 2) dominates over all other parameters in this group. If the stress range is not a constant value but changes with time, then the problem should be analysed using variable amplitude concepts and the sequence of the stress ranges may be important.

If the stress range causes large plastic deformations in the component, the fatigue failure is called low-cycle fatigue. Stress ranges are transformed into strain ranges in order to achieve a more uniform relationship with fatigue life.

Additional parameters include the mean value of the stress range and the level of residual stresses. In addition, when the material is affected by time dependent

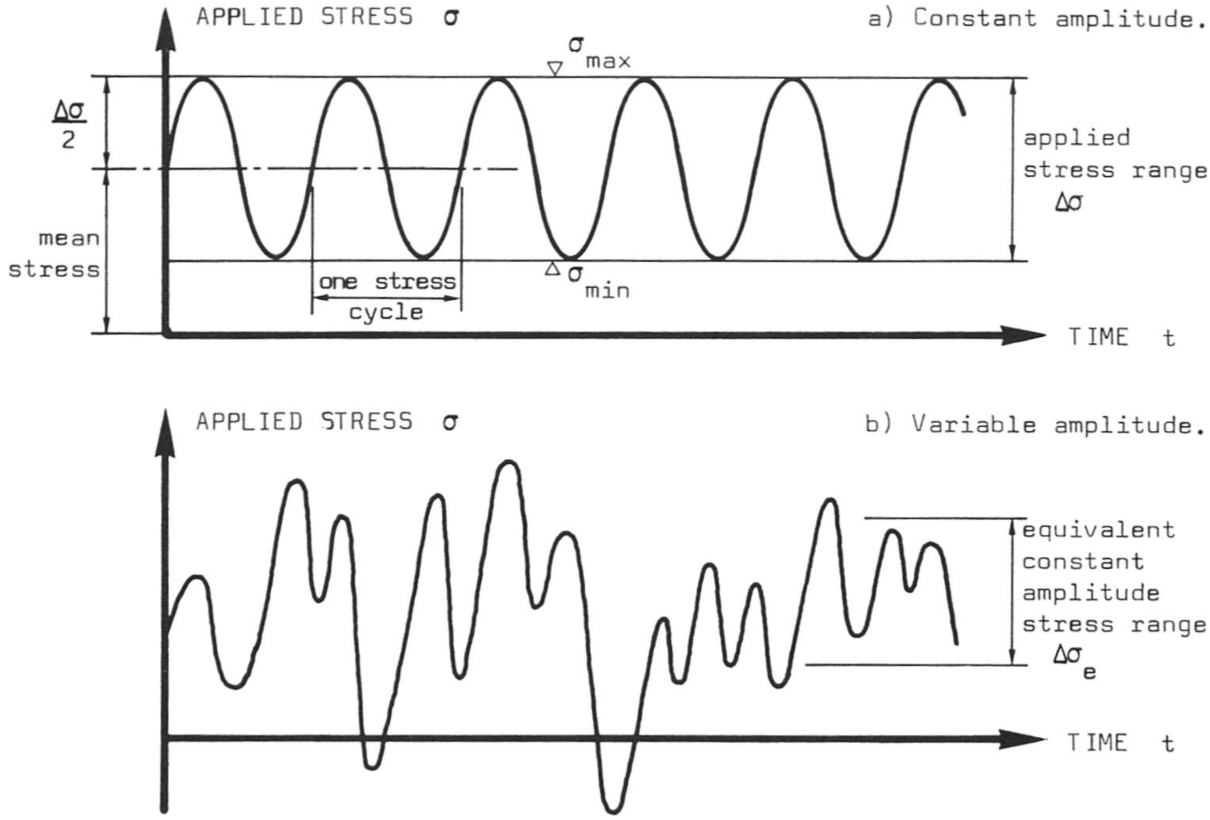


FIGURE 2 : Stress parameters for fatigue.

phenomena, such as creep or corrosion, the frequency of the stress cycles should be considered. The importance of these parameters depends upon the specific fatigue problem. For example, some fatigue situations are completely insensitive to applied mean stresses and residual stresses. In other situations, such as when applied mean stresses are compressive, residual stresses may change the fatigue life by more than a factor of ten.

2.2 Geometry

The geometry of the structure determines where and how quickly the fatigue failure occurs. Geometrical effects have the following three sources : the overall structural design, local stress concentrations and small discontinuities (FIGURE 3). The first two sources are controlled primarily by the designer while the last source, small discontinuities, is determined usually by fabrication and control processes.

The overall structural design includes the sizing of structural shapes, plate thickneses, openings (eg. manholes) and orientation of the structural members. These parameters are similar to those considered in the static strength assessment. The applied stress range is determined using overall structural design parameters.

Local stress concentrators are created by structural details such as welded connections, bolt holes or attachments. These details magnify the effect of the applied stress range because they are an obstacle to smooth stress flow. A simple attachment to support a ladder, welded to a stress carrying member, may reduce the fatigue life of the member by more than ten times. The stress concentration effect is analogous to the case of a large rock on a river bed. The presence of the rock induces higher than average water velocities over the rock just as a bolt hole

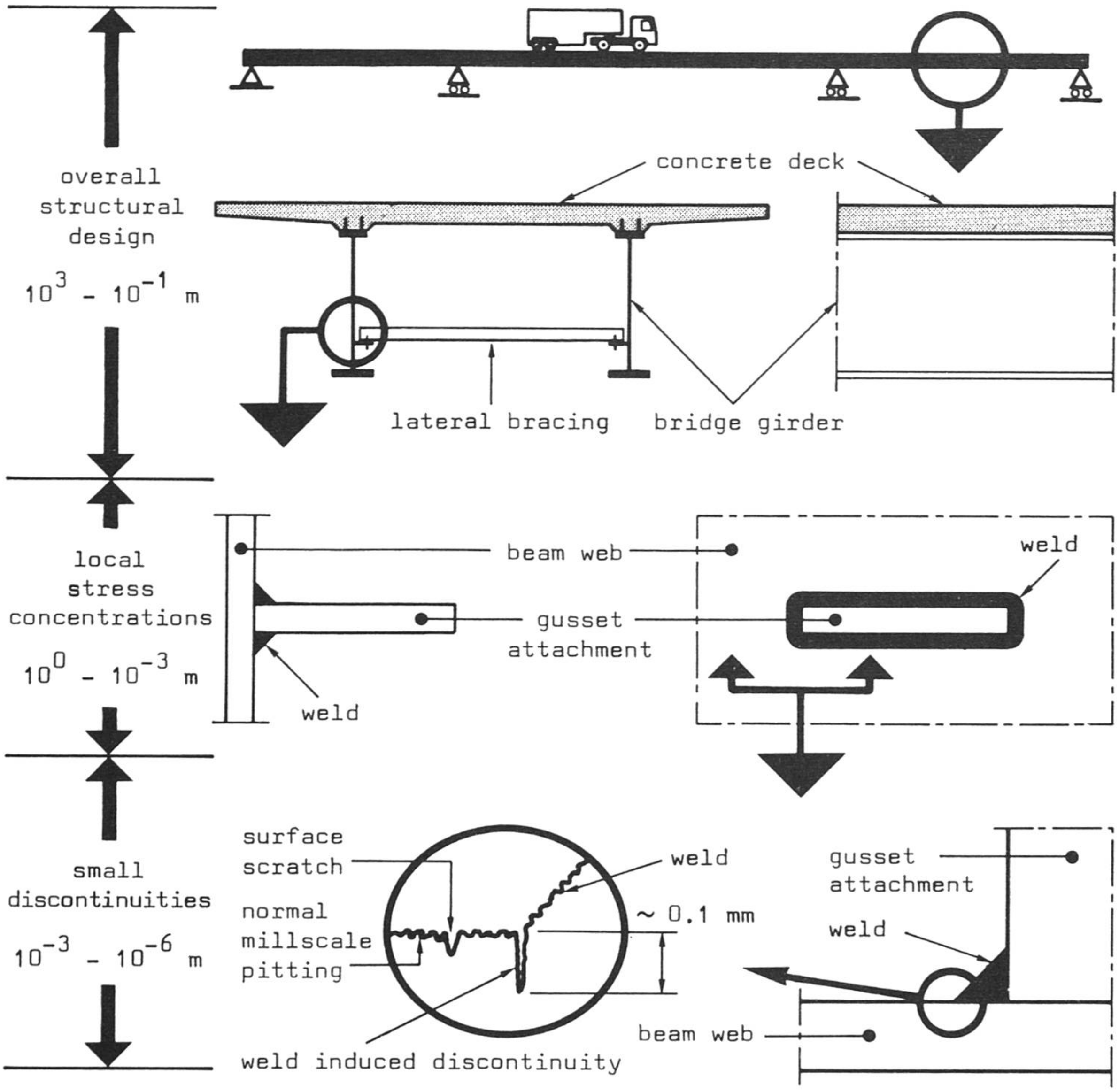


FIGURE 3 : Geometrical effects due to three sources : overall structural design, local stress concentrations and small discontinuities.

induces stresses higher tnan those found in a similar plate without the hole. Note that local stress concentrations may be produced by adding material as well as removing it.

High applied stress ranges and severe stress concentrations cause the material to yield locally even though the majority of the structure behaves elastically. Zones of cyclic plastic deformation are formed. If the fatigue crack is smaller than a surrounding plastic zone, the fatigue crack may grow much faster than it would if it were surrounded by material in an elastic state. A strain based analysis or an energy approach to the problem may be more accurate than elastic theories.

Small discountinuities include corrosion pits, surface scratches, grinding marks, cracks and welding process defects such as porosity, undercut, slag inclusions, lack of penetration and lack of fusion. Small discontinuities are present in nearly every engineering structure. Their presence generally determines the precise location of fatigue failure, and their size and shape may reduce the fatigue life to such a degree that fatigue failure is certain within the life of the structure. Often, small discontinuities are found in locations of local stress concentrations (FIGURE 3). The localized stresses around discontinuities may be more than five times the applied stress value.

2.3 Material properties

Important material properties include chemical composition, stress-strain behaviour, grain size, homogeneity and microstructural discontinuities. TABLE 1 provides a more complete list. Steel and aluminium do not behave in the same manner under fatigue loading because they have very different material properties. Even their crystalline lattice structure is different.

Many material properties are related to the chemical composition. If the chemical compositions of different materials are similar, many other material properties will be similar as well and the overall difference in behaviour may be secondary. This is often the case for medium and low strength structural steels.

2.4 Environment

Examples of environmentally induced effects are corrosion and creep fatigue. This aspect of metal fatigue is complex and largely unknown. Fortunately, the combination of fatigue loading and a severely hostile environment does not occur in many applications. If the combination exists, the problem may be avoided when suitable protection is possible. More research on the fatigue resistance of unprotected material is needed.

TABLE 1 summarizes the fatigue parameters mentioned above. Even if only half of the parameters are relevant to a specific problem, an accurate fatigue assessment may be difficult. An indication of the relative effect of some parameters is found by estimating the percentage of fatigue life expended in the formation and growth of a fatigue crack to a length greater than approximately 5 grain diameters (i.e. 0.05 to 0.25 mm). Generally, material properties and environmental effects influence these shorter cracks to a greater extent than longer cracks. When most of the fatigue life is expended in growing cracks of dimensions larger than 5 grain diameters, the fatigue assessment becomes less complicated. This is often the case for welded steel structures; some important simplifications are outlined in the following section.

3. FATIGUE OF WELDED STEEL STRUCTURES

Welded connections are unavoidable in many modern structures. The economic advantages of a welded connection compared to a riveted detail have been known for over 40 years. Some industries (e.g. those using high pressure reactors) would not even exist without welded connections.

Nevertheless, the introduction of a welded attachment to a structure adds potential complications to the fatigue assessment. FIGURE 4 describes some of the more important factors which require consideration. The high local heat input of the weld process introduces localized residual stresses and a complex metallurgical structure near the weld fusion line. Welding discontinuities are inevitable. Plate distortion, lack of fit and misalignment are difficult to avoid. Also, the weld shape may produce a very severe and rapidly decaying stress concentration. However, the effects of these extra factors enable some convenient simplifications to be made without introducing excessive inaccuracies in the fatigue assessment.

Tensile residual stresses of yield stress magnitude exist near welds and thus, at potential fatigue crack sites in welded steel structures. Residual stresses should be added to the applied mean stress in order to complete the stress analysis. As a result, any applied loading produces a stress range which has a high mean stress

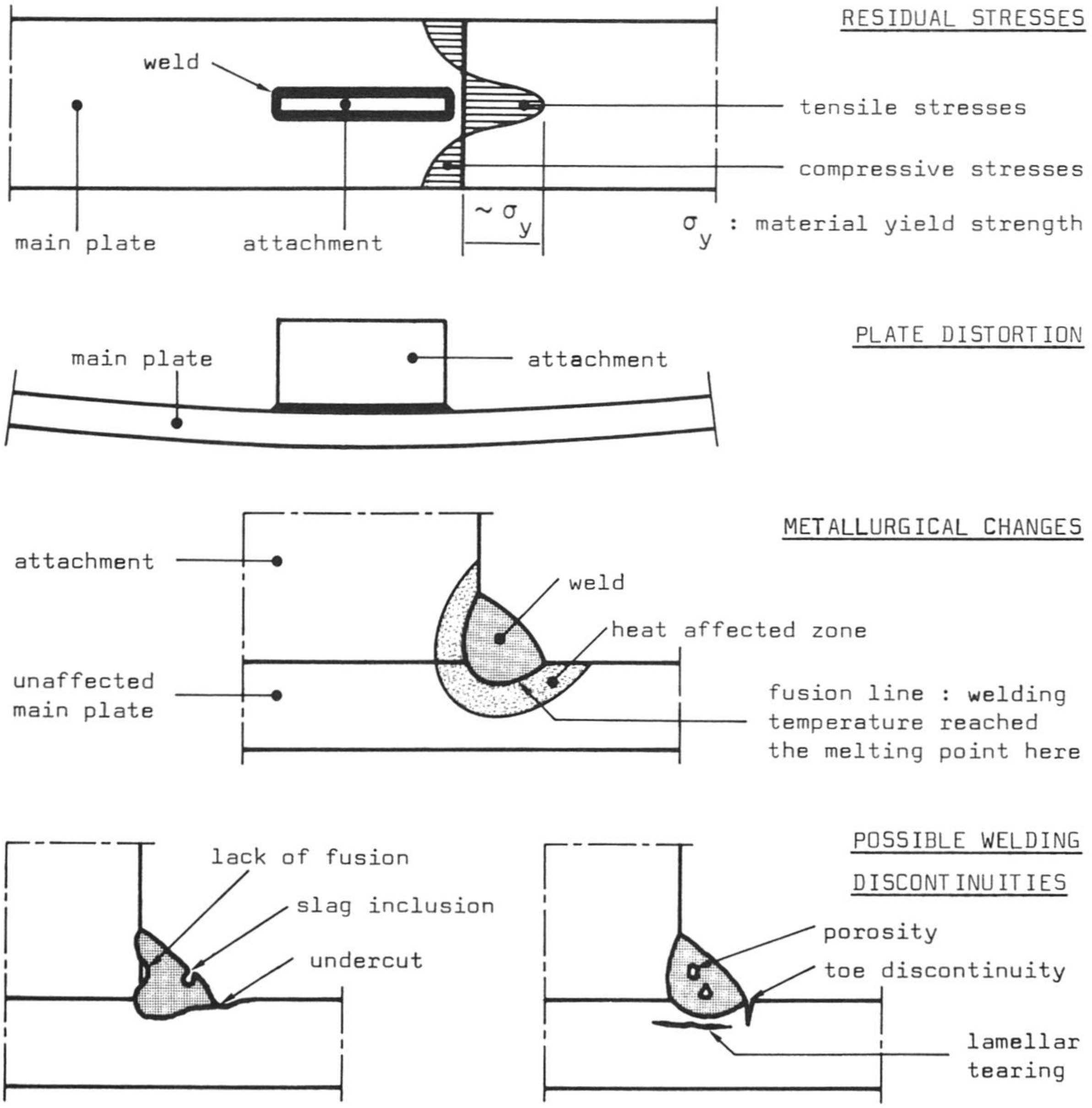


FIGURE 4 : Additional factors to consider for welded joints.

if plastic deformation does not cause relaxation. Even compressive loading results in tensile stress ranges near welds. Moreover, lack of fit and misalignment may introduce additional tensile stresses. The additional stresses near welds are so high that the change in fatigue life due to small changes in the mean value of the applied stress range is unimportant.

The presence of weld discontinuities simplifies the fatigue analysis a great deal. These discontinuities can be very sharp with end radii less than 5 μm. The proportion of total fatigue life expended by the formation of a fatigue crack at the end of such sharp discontinuities is very small. Almost all of the fatigue life is spent in crack propagation.

Critical discontinuities can be much larger than the dimensions of the grains at crack initiation sites. Surface discontinuities also reduce the importance of mildly corrosive environments such as air and rain. These facts diminish the importance of material properties and lead to the conclusion that the influence of variations in the structural steel grade is not important.

The stress state near crack sites provides additional support to the assertions of mean stress and steel grade independence. This stress state is dominated by stress concentrations which have very steep gradients. These gradients help to restrict the size of the plastic zone caused by the stress concentration. In some welded connections the cyclic plastic zone was estimated to be less than 0.1 mm for an applied stress range equivalent to the allowable design static stress of the material [2].

A small plastic zone has two effects. Firstly, high tensile residual stresses are not relaxed. Secondly, a wide range of yield strengths (or steel grades) cannot alter the plastic zone size enough for cyclic plastic deformation to accelerate crack growth. These two conditions are necessary for steel grade and mean stress insensitivity.

Experimental results for welded connections verify these simplifications. A large amount of test data in many countries demonstrates mean stress and steel grade independence [1] [3] [4]. Also, recent studies of welded connections add theoretical support to these simplifications [1] [2] [5] [6].

4. HARMONIZATION OF FATIGUE DESIGN CONCEPTS

Standards, codes and recommendations for fatigue assessment of welded structural steels have been simplified in recent years; these changes were welcomed by design engineers who, for the most part, know little about fatigue behaviour. It has been possible to return to the concept of stress range developed originally by Wöhler in Germany in 1870 [7]. Several national codes began this shift in the 1970's, one hundred years later [4] [8] [9].

Insensitivity of the fatigue strength to the steel grade provides a more global opportunity than the simplification of national codes. Fatigue results using different grades of steel from several countries can be combined into one large international data base which enables the formulation of universal fatigue recommendations. Such recommendations have important advantages, especially for international design contracts. It was in this spirit of rationalization and harmonization that IABSE organized an international colloquium entitled "Fatigue of Steel and Concrete Structures" in Lausanne, Switzerland in 1982 [10].

One of the organizations interested in international harmonization, the European Convention for Constructional Steelwork (ECCS), began its work on a now fatigue design recommendation en 1978. The overall aim of the Recommendations [11] is the preparation of a general concept for the fatigue design of steel structures such as bridges, buildings and other structures using similar structural details. In particular, information is given on the fatigue resistance of structural details, fatigue loads, safety, in-service inspection and maintenance and finally, new developments in reliability, fracture mechanics, improvement methods and the hot spot stress method. The following discussion describes some of these topics further.

4.1 Fatigue strength of structural details

An important part of most recommendations is the section describing the fatigue strength of structural details. In the ECCS recommendations, the details are grouped into : non-welded details, welded structural elements, and bolts and miscellaneous elements. FIGURE 5 shows some examples of typical constructional details. The direction of the applied stresses is indicated by the arrows; the resulting fatigue crack locations are also marked. Often, numerous components exist in a structure and therefore, more than one fatigue category applies. The fatigue assessment should be performed for each case. The fatigue category number is identified by the fatigue strength at $2 \cdot 10^6$ cycles in order to tie in with current practice in many countries.

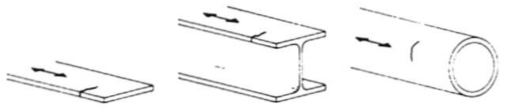
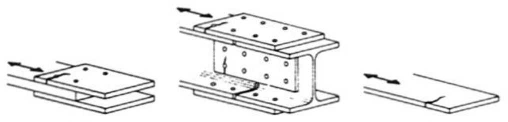
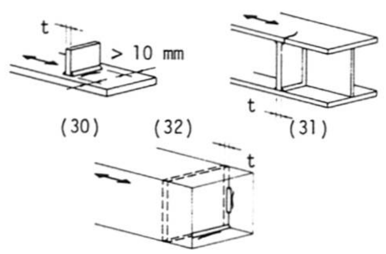
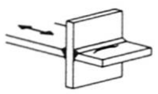
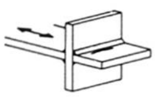
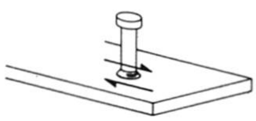
<table>
<tr><th></th><th>CATEGORY</th><th colspan="2">CONSTRUCTIONAL DETAILS</th><th>DESCRIPTION</th></tr>
<tr><td rowspan="2">NON-WELDED DETAILS</td><td>160</td><td colspan="2">
(1) (2) (3)</td><td>Unmachined rolled and extruded products
(unmachined ; sharp edges, surface and rolling flaws removed by grinding)
(1) Plates, flats.
(2) Rolled sections.
(3) Seamless tubes.</td></tr>
<tr><td>140</td><td colspan="2">
(4) (5) (6)</td><td>Bolted connections
(4) + (5) Zones of connections and splices made with bolts or swedge bolts. Stress calculated in the gross section for friction grip connections and in the net section for all other connections. Unsupported one-sided cover plate connections shall be avoided or taken into account in the calculation of stresses. Material with gas cut edges subsequently machined.
(6) Plain plate material with gas cut edges subsequently dressed to remove drag lines.</td></tr>
<tr><td rowspan="5">WELDED DETAILS</td><td>80</td><td>t ≤ 12 mm</td><td rowspan="2">
(30) (32) (31)</td><td rowspan="2">Transverse welds
(30) Transverse fillet welds with the end of the weld > 10 mm from the edge of the plate.
(31) Vertical stiffeners welded to a beam or plate girder flange or web by continuous or intermittent welds. In the case of webs carrying combined bending and shear stresses the strength should be determined using the principal stresses.
(32) Diaphragms of box girders welded to the flange or web by continuous or intermittent welds.</td></tr>
<tr><td>71</td><td>t > 12 mm</td></tr>
<tr><td>71</td><td colspan="2">
(33)</td><td>Cruciform joints with load-carrying welds
(33) Full penetration weld with intermediate plate. Inspected free of discontinuities. Maximum misalignment of plates either side of joint to be < 0.15 x thickness of intermediate plate.</td></tr>
<tr><td>56
(34)</td><td colspan="2" rowspan="2">
(34) and (35)</td><td>(34) Partial penetration or fillet welds, having a strength at the throat greater than at weld toe.</td></tr>
<tr><td>36
(35)</td><td>(35) Welds as (34) but having weld throat strength less than the plate at the weld toe. The stress must be determined in the weld itself. Maximum misalignment of plates either side of the joint to be < 0.15 x thickness of intermediate plate.</td></tr>
<tr><td rowspan="2">BOLTS AND MISCELLANEOUS ELEMENTS</td><td>100</td><td colspan="2">
(41)</td><td>(41) Bearing and swedge type bolts in shear.</td></tr>
<tr><td>80
m = 5</td><td colspan="2">
(42)</td><td>(42) Stud welded shear connectors (failure in the weld) loaded in shear. The shear stress to be calculated on the nominal section.</td></tr>
</table>

FIGURE 5 : Typical constructional details listed in the ECCS Recommendations [11].

If the weld is expected to carry fatigue loads from one member to another, the fatigue life is reduced (compare detail 30 to detail 35). The welded connection in detail 30 does not directly carry an applied stress range. A small amount of stress range enters the attachment only because the main member is subjected to a stress range; no external fatigue loading is applied to the attachment. Conversely, detail 35 transfers the applied stress range directly. Obviously, detail 35 should be avoided when a fatigue assessment is required. The format of this figure directs the designer toward details which have high fatigue strength and thus encourages good detail design.

FIGURE 6 provides the fatigue strength curves if a fatigue life other than $2 \cdot 10^6$ cycles is required. On a log-log scale of stress range against number of cycles, equidistant parallel lines are drawn with a slope of $-1/m$. If the number of stress cycles is less than $5 \cdot 10^6$, the slope constant m is 3. This slope is known to be conservative for the higher categories. However, the fatigue resistance is rarely critical for these details and the design convenience of equal slopes justifies the simplification, especially in cumulative damage calculations.

The constant amplitude fatigue limit is set at $5 \cdot 10^6$ cycles. The fatigue strength which corresponds to this limit represents the stress range for an infinite fatigue life under constant amplitude stresses. If variable amplitude stresses are applied, the fatigue limit has two possible positions. The first position is the constant amplitude fatigue limit which is appropriate only when no stress ranges exceed this limit. The second position, the cut-off limit, applies in all other

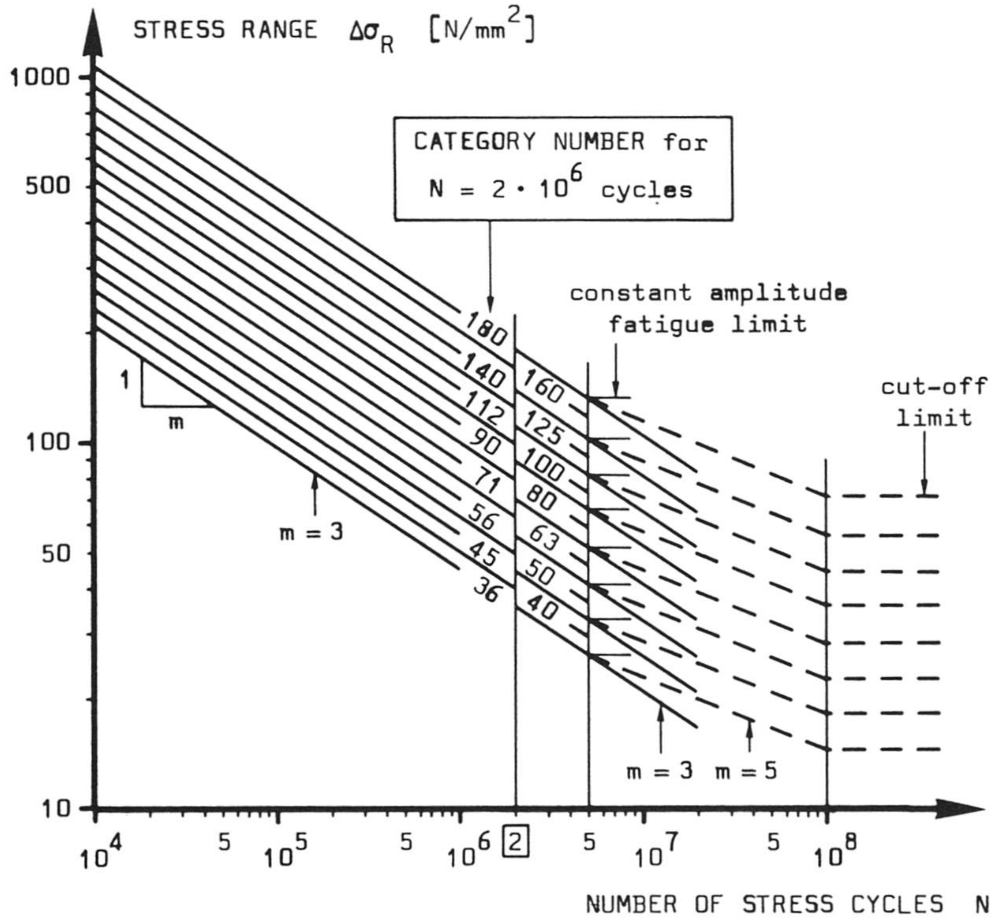


FIGURE 6 : ECCS proposal for "European Fatigue Strength Curves" representing mean minus two standard deviations [11].

cases and is drawn at 10^8 cycles for all details. Between these two limits, the slope constant, m is 3, or optionally, 5.

Some details do not perform exactly as described in FIGURE 6. For example, a cover-plated attachment has a constant amplitude fatigue limit of almost 10^7 cycles. In order to ensure that such non-conservative conditions are avoided, some details are located in detail categories slightly lower than their fatigue strength at $2 \cdot 10^6$ cycles would require.

International agreement was achieved by drawing the set of lines first and only then assigning details to them. This exercice eliminated time consuming disputes between representatives of different countries when their national code differed by only a few percent. This is the reason for the number of curves; no level of accuracy is implied by the proximity of the lines to each other. Most countries should be able to work with half the number of lines.

All relevent parameters discussed in sections 2 and 3 of this paper are included in the three parameters of stress range, cycle life and weld category. Stress level and steel grade need not be considered in the assessment. Nevertheless, some limits are applied. When the maximum applied stress range exceeds 1.5 σ_y, fatigue failure becomes a problem which is treated more accurately by low-cycle fatigue concepts. In addition, the rules are limited to steel grades with yield strengths under 700 N/mm^2, a maximum temperature of 150 °C and details with adequate corrosion protection. Further research is required to investigate possible applications beyond these limits.

4.2 Fatigue loads

The fatigue stength curves are intended to be used with real loads; they should not be adjusted to account for fictitious or idealized loading. Thus, the curves remain valid for specialized applications (such as chimneys) provided that reasonable load estimates are used. Note that the number of stress cycles caused by the fatigue loading depends upon the element under consideration. For example, short elements supporting a bridge deck may suffer 100 times more stress cycles than the main beams. Variations in stress amplitude are accommodated using rainflow counting [12] and Miner's rule [13]. This gives an equivalent applied stress range $\Delta\sigma_e$ as shown schematically in FIGURE 2 and described in [14].

4.3 Safety

The safety concept involves the use of an equation which is similar to other limit state safety concepts :

$$\frac{\Delta\sigma_R}{\gamma_m} \geqslant \gamma_s \, \Delta\sigma_e \, ,$$

where $\Delta\sigma_R$ is the fatigue strength, $\Delta\sigma_e$ is the equivalent applied stress range and γ_m, γ_s are partial safety factors.

The value of $\Delta\sigma_R$ (obtained from FIGURE 6) contains inherently a safety level. The fatigue strength curves are not mean curves; they are drawn at two standard deviations from the mean line. Therefore, if the loads are known exactly and have no statistical distribution, the fatigue assessment will have a 95 % statistical confidence level when the safety factors γ_m and γ_s are set to unity. However, the real level of uncertainty is dependent upon the loading information used. Exact fatigue loads without a statistical variation is a convenience which exists only in the laboratory.

The partial safety factors enable the designer to control more accurately the real safety level. The partial safety factor for material resistance γ_s may be adjusted to the uncertainties in the fatigue load calculation. Fatigue problems require different levels of uncertainty and correspondingly different safety factors. A safety index may be introduced which reflects numerically the required level of uncertainty. Section 5 gives more detail.

4.4 In-service inspection and maintenance

Unlike many other limit states, the reliability of the structure to perform satisfactorily under fatigue loading cannot be fully assured at the construction stage. In-service inspection is recommended for all details requiring a fatigue assessment. Connections which cause general collapse of the entire structure upon failure are not recommended, regardless of inspection provisions. Even when general collapse is not expected, connections where periodic inspection is impracticable or very difficult should be avoided.

Also, some guidance is needed for repair of cracked structures. Welding should not be used to repair fatigue cracks because the repair weld may introduce cracks or defects equally severe as the fatigue crack. Bolted splice plates are often an adequate solution. The remaining life should be calculated using fracture mechanics methods.

4.5 Present state of international recommendations

It is of prime importance that Europe is not flooded with a multitude of different codes, edited by various groups and organizations. The task of design engineers, working at home or abroad, has to be simplified. One way of achieving this goal is to give one and only one set of rules.

In their draft form, the ECCS Recommendations have received general approval from many national and international groups. In additon to the countries represented by committee members and invited guests, close co-operation with international committees is maintained. These are Eurocode (EC3), the International Institute of Welding (IIW) [15], the International Standards Organization (ISO), the European Coal and Steel Community (ECSC) and the Union International des Chemins de fer (UIC). Work is continuing toward harmonization with other national and international groups, including the Fédération Européenne de la Manutention (FEM) and the Comité International des Cheminées Industrielles (CICIND).

5. NEW DEVELOPMENTS

Unusual structural applications and changing design philosophies have introduced several new developments into fatigue assessment procedures over the past 20 years. These developments represent a continuing challenge for those groups interested in international harmonization. Some of the more important topics are fracture mechanics, hot spot stress methods, improvement methods, limit state safety concepts, fatigue loading, fatigue of concrete structures and the evaluation of existing structures.

Fracture mechanics analysis provides a means of evaluating a structure with a crack. The analysis was found to provide useful explanations for brittle fracture in ships and aircraft structures over 40 years ago. In the last twenty years, fracture mechanics principles have been developed to describe fatigue crack propagation. Consequently, the concepts are useful in determining the importance of fabrication defects [16], the length of inspection intervals [6], and the remaining life of a cracked element [17]. Standard structural analyses based on strength of materials procedures cannot evaluate these types of problems.

Fracture mechanics concepts should be used only to complement and not to replace the fatigue design procedures outlined in the previous sections. Additional applications of the concepts include parametric studies of a given detail (effect of plate thickness, attachment length, etc.) or details not covered by the standard fatigue curves. Cautionary notes on the extrapolation to large welded structures and guidelines on the general range of validity of fracture mechanics are given in reference [11].

The hot spot stress method provides a means of analysing complicated structures, such as frames fabricated using large tubular sections. Civil engineering analysis is often not sufficiently accurate for such structures. The hot spot stress defines a geometric stress concentration at the potential crack site (hot spot) based on stresses a certain distance away from the site. These remote stresses are extrapolated to the hot spot, for example to the weld toe, without including the localized concentration due to the weld toe itself. Special techniques such as finite elements, photoelasticity or prototype testing must be used to obtain the geometric stress concentration.

Once the stress concentration is known, the corresponding stress range is calculated (it does not exist at the hot spot in reality), and the designer refers to curve 90 on FIGURE 6. Thus, the advantage of the simple stress range relationship is retained. More details are given in [18] and some cautionary notes are provided in [11] and [19].

Improvement methods give the designer the possibility to use an otherwise unacceptable detail instead of reducing the applied stresses. These methods are appropriate only when more favourable details, such as those in the upper part of FIGURE 5, are not practicable. Other applications include the amelioration of fabrication deficiencies or strengthening of existing structures.

Most improvement methods change either the severity of discontinuities at the potential crack sites or the residual stress distribution or both. Typical improvement methods used to date are stress relieving, grinding or peening. Fatigue lives can be increased by more than 10 times when using appropriate methods but the amount of improvement is not always predictable and depends on the type of detail, steel strength and fabrication conditions [20]. Also, the value of a given method is not only dependent upon its ability to increase fatigue life but also on its cost, its practicability and its ease of quality assurance. Furthermore, the presence of high overloads and corrosion may negate the improvement. Usually, testing is needed in order to justify this design option and its use should be restricted to special applications until more information is available.

Modern safety concepts include the use of a safety index β, which reflects numerically the required level of certainty in the fatigue assessment. Thus a target reliability for a given application may define a safety index and thereby control the minimum values of partial safety factors. Several formulae for the safety index are available. The most appropriate equation depends upon the relationship between loading and strength and upon the type of their statistical distributions. Reference [21] provides an excellent summary of the possbilities and reference [11] contains a simplified proposal for the fatigue design of structures.

Potentially, use of the safety index results in a consistent fatigue assessment for every detail on every member in a structure. However, limited knowledge of applied fatigue loading restricts the use of the safety index to a limited number of well defined fatigue problems. Much research is needed and is continuing in this area [10].

Fatigue loading is a subject which requires a concentrated effort if international harmonization is to be realised. Nearly every country uses a different approach. However, simplified load models, related to the static design live loading through reduction factors, demonstrate remarkable similarities between several countries. Successful harmonization will result in an important clarification of a complicated subject. Already, some modern codes [8,9] contain fatigue design concepts which go beyond the definition of fatigue strength curves; realistic loads are used in the fatigue assessment. Note that a very conservative design may result if ultimate limit state loads are employed in calculations.

Fatigue cracking in concrete structures was identified only recently as an important consideration. Concrete structures may experience fatigue cracking in reinforcing bars, prestressing cables and strands (particularly at the anchor points or joints) and in the concrete itself. Also, the fatigue strength of partially prestressed elements may be much less than fully prestressed elements subject to the same loading. This is particularly true for short elements using very high strength materials.

Little agreement on theoretical models exists and few design alternatives are proven. Historically, concrete structures have not suffered fatigue damage probably because of conservative static design rules. However, changing design philosophies and a much wider range of applications is reducing the inherent safety level in new concrete structures [22]. Future fatigue problems seem inevitable as these new concrete structures age; the suspicion of such difficulties has encouraged increased research activity. Several papers in reference [10] have contributed to further knowledge and understanding of the fatigue of concrete structures.

Methods which evaluate the remaining life of existing structures are required increasingly as the number of structures which exceed their design life grows exponentially each year. This trend corresponds to the bridge construction boom which began over one hundred years ago. Also, few structures need to be replaced when they reach their design life because the design life was never defined scientifically to begin with, and in many cases represented political or economic policies only. Most structures are able to endure fatigue loading well beyond their designated design life.

In general, little is known of previous loading, the actual static and dynamic behaviour of the structure, the effects of structural modifications over the past century and possible fatigue crack locations. Evaluation should begin with simple, conservative assumptions and proceed in steps toward more detailed approaches, until an acceptable decision can be taken regarding the future of the structure [23]. A recent IABSE Symposium in Washington, D.C. concentrated on the evaluation of bridge structures [24].

6. CONCLUDING REMARKS

Fatigue failure in engineering materials is governed by a great number of parameters. However, the effects of a welded connection on the fatigue strength of a structural element can be evaluated without considering the parameters of mean stress and steel grade. These special characteristics of steel structures aided many international groups in the formulation of simplified design rules. The design rules cover the complete design process from the choice of structural details, fatigue loading determination and fabrication requirements to in-service inspection. Further work and harmonization is needed for improvement methods, fracture mechanics procedures, the hot spot stress approach, reliability analysis, fatigue loading, concrete structures and finally for methods which evaluate the remaining life of existing structures.

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