Available online at www.sciencedirect.com
ScienceDirect
Journal of Constructional Steel Research 62 (2006) 1199–1209
JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH
www.elsevier.com/locate/jcsr

Fatigue reliability of welded steel structures

M.K. Chryssanthopoulos*, T.D. Righiniotis

School of Engineering, University of Surrey, Guildford, Surrey, UK

Abstract

In general, two different approaches to the formulation of the fatigue limit state are considered, the first based on *S–N* lines in combination with Miner's damage accumulation rule, and the second based on fracture mechanics crack growth models and failure criteria. Often, the two approaches are used sequentially, with *S–N* being used at the design or preliminary assessment stage and fracture mechanics for more refined remaining life or inspection and repair estimates. However, it is essential to link the results, and the decisions made, at the design and assessment stages, and it is therefore important to develop compatible methodologies for using these two approaches in tandem. In doing so, it is essential to understand and quantify different uncertainty sources and how they might affect the robustness of the results obtained, and the subsequent decisions made about the structure. The objective of this paper is to highlight parts of recent research at the University of Surrey on the fatigue assessment of steel bridges. The work includes the development of a probabilistic fracture mechanics methodology for the prediction of fatigue reliability, using up-to-date crack growth and fracture assessment criteria and incorporating information on inspection and subsequent management actions.

Keywords: Crack growth; Fatigue; Fracture mechanics; Inspection; Steel bridges; Structural reliability

1. Introduction

Over the last twenty years or so, probabilistic methods for the assessment of fatigue reliability have attracted significant attention. In the civil engineering field, much of the research, from the mid-80s onwards, was directed towards applications in offshore structures, in particular tubular joints subject to stochastic loading. This effort was aided considerably by progress in experimental techniques associated with the measurement of crack growth data under laboratory conditions, and the development of technology aimed at measuring cracks in actual structures.

At the same time, advances in probabilistic methods, especially the concerted effort in developing structural reliability methods for damage accumulation problems under time-varying loads, made it possible to cast fatigue assessment problems in a reliability format. As a result, by the late 80s, not only had a large number of publications appeared addressing particular resistance and load modelling issues but also the first papers dealing with a complete methodology for fatigue reliability evaluation were being produced, including updating following inspection and repair [1–5]. In the following years, this approach was adopted by offshore operators for estimating remaining fatigue life, and for determining inspection plans, of ageing structures [6–8].

In the past decade, considerable interest has arisen in adapting and implementing these techniques for applications in metallic bridges, thus focusing on fatigue details found in girders and plated structures subjected to traffic loading [9–13]. The characteristics of bridge live loading being substantially different from wave loading on offshore structures, led to revised formulations for the reliability problem. In parallel with these developments, improved methods for fatigue and fracture assessment were actively being pursued for other structures, e.g. nuclear plants [14] and ships [15].

An additional factor, contributing to an increased interest in fatigue design and assessment, has been the flurry of activity associated with the development of a new generation of structural codes, both at national and international level; for example, a new European standard for fatigue design [16] has been prepared, whilst other documents have been updated

* Corresponding address: Department of Civil Engineering, School of Engineering, University of Surrey, GU2 7XH, Guildford, Surrey, UK. Tel.: +44 1483 686 632; fax: +44 1483 450 984.
E-mail address: mkchry@surrey.ac.uk (M.K. Chryssanthopoulos).

0143-974X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jcsr.2006.06.007

and extended in order to incorporate recent developments in fracture mechanics assessment methods [17]. The underlying philosophy in these regulatory bodies, as well as amongst owners and operators, is increasingly focusing on the need to introduce probabilistic concepts for fatigue life prediction. Thus, the development of probabilistic fatigue models, and their testing and validation through examples and case studies, could considerably enhance available guidance documents. In this respect, the effort of the Joint Committee of Structural Safety in developing the Probabilistic Model Code [18] is of particular note.

In general, two different approaches to the formulation of the fatigue limit state may be considered, the first based on *S–N* curves in combination with Miner's damage accumulation rule, and the second based on fracture mechanics crack growth models and associated failure criteria. Often, as can be seen in some of the references cited above, the two approaches are used sequentially, with *S–N* being used at the 'design' stage and fracture mechanics at the 'assessment' stage, in other words for new and existing structures respectively. In the former case, the purpose of a fatigue analysis is to determine a design life, associated with a target reliability, whereas in the latter the objective is to determine inspection intervals or time to repair, once more linked to target reliabilities.

It is often desirable to link the results, and hence the decisions, at the 'design' and 'assessment' stages. Thus, it is important to develop compatible methodologies for using these two approaches in tandem. Although the majority of engineers working in the above mentioned industries are more familiar with the *S–N*, rather than the fracture mechanics, approach for fatigue analysis, the latter is increasingly gaining ground as fitness-for-purpose criteria are becoming popular with owners and regulators.

The fatigue process may be regarded as comprising three stages; crack initiation, crack propagation and final failure. A fatigue analysis based on *S–N* curves, the latter being derived from standard fatigue tests, typically lumps all three stages into one, though the definition of failure within this context is not always clear. On the other hand, a fatigue analysis based on fracture mechanics is concerned primarily with the second stage, though it can be extended to include final failure through the introduction of appropriate limit state criteria related to fracture resistance (which could be expressed in terms of a critical crack size). The extent to which a fracture mechanics approach can provide comparable information on fatigue life with that derived from *S–N* curves will depend, in part, on the number of load cycles expended during the initiation stage. A common assumption in fatigue analysis of welded joints is that the initiation stage is negligibly small compared to the propagation stage. This is because fatigue cracks develop from small defects introduced right from the outset in areas of stress concentration. The weld toe is considered as a critical area in which such cracks are often to be found. Clearly, this assumption needs to be evaluated for the specific prevailing conditions.

The objective of this paper is to highlight the key factors that need to be considered in fatigue reliability analysis, and to present a case study, pertaining to welded bridge details, in which the proposed procedures are implemented and utilised in support of decision making. As will become evident, much work has been, and is still being, carried out in this area stemming from different industrial sectors and applications. Thus, it is considered essential to sift through and process information from experiments and field observations, as well as to integrate and consolidate the procedures to be followed in fatigue reliability analysis.

2. *S–N* approach

An *S–N* curve is a relation between the stress range under constant amplitude loading and the number of stress cycles to failure. The standard *S–N* curve can be expressed in the form of:

$$NS^m = A \tag{1}$$

where N is the number of stress cycles to failure at a constant amplitude stress range S, A and m are the material parameters. Sometimes a model with two segments is used, having parameters A_1 and m_1, A_2 and m_2. The stress range level at which the two curves intersect is defined by $A_1 S_0^{m_1} = A_2 S_0^{m_2}$.

Many steels subjected to pure constant amplitude loading in inert environments exhibit a fatigue limit, i.e. a stress level below which fatigue failure appears to never occur. However, it is generally accepted that even infrequent overloads (i.e. stress cycles that exceed the fatigue limit value) may lead to fatigue damage even though the vast majority of stress cycles are below the fatigue limit. In essence, a fatigue limit no longer exists and every stress cycle is treated as damaging, as determined from the *S–N* curve(s) [19].

There are many sources of uncertainty in the fatigue process and its analysis. Wirsching [20] has produced an itemised list, which includes the fatigue process itself, the extrapolation from laboratory test specimens and procedures to details in real structures, the loading conditions, the local environment (temperature, presence of water/humidity etc.), the dynamic effects, as well as the stress analysis methods used to obtain estimates of local stress ranges from globally applied forces and displacements.

The uncertainty associated with *S–N* curves is typically assessed from laboratory tests on nominally identical specimens under constant amplitude loading. In a typical fatigue test, the stress level (i.e. the independent variable) is specified and the cycles to failure (i.e. the dependent variable) are recorded. Under these conditions, it has been observed that the distribution of $\ln N$ for a fixed value of S exhibits a variation which is independent of S (at least until test results at very low stress levels are considered), whereas the mean value of $\ln N$ varies linearly with $\ln S$. In general, the lognormal distribution provides a better fit to N than other candidate distributions such as the Weibull distribution, though there is no apparent physical or mathematical reason for this [20]. Assuming then that in Eq. (1) the parameter m is deterministic and that the uncertainty is lumped into the second parameter A, it is easily shown that if