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A probabilistic fatigue approach for riveted joints using Monte Carlo simulation

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ABSTRACT

The availability of probabilistic fatigue strength S–N data for riveted connections is essential to carry out reliability analysis of ancient riveted bridges. This paper proposes a procedure to derive probabilistic S–N fields for riveted connections, using material fatigue data and detailed finite element modeling of the joints. Strain-life fatigue data of the plain material as well as fatigue crack growth data are used to compute the total fatigue life of a riveted connection, integrating both the local and Fracture Mechanics approaches to fatigue. The basic fatigue data is inputted in the probabilistic form as well as some relevant parameters of the model which are subjected to higher uncertainty. Three dimensional finite element modeling of the riveted joint is carried out to assess the local stresses/strains at the critical location, as well as the stress intensity factor history, for an expected growing fatigue crack. The proposed approach allows the assessment of the effects of both clamping stresses on rivets and friction coefficient, on local stress/strain values and stress intensity factors. The clamping stresses on rivets and friction coefficient are assumed random variables. The inputs, in the probabilistic form, are accounted in the fatigue strength assessment procedure using the Monte Carlo sampling technique. Resulting p–S–N_f field computed for a simple riveted joint is compared with experimental data, illustrating a very satisfactory performance of the model. In addition, the sensibility of the p–S–N_f field to some input parameters is discussed.

1. Introduction

All across the world there are a very significant number of old riveted highway and railway bridges in operation, which may show important fatigue damage levels. The long operational period of these structures, typically characterized by increasing traffic intensity, both in terms of vehicle gross weights/axle loads as well as truck/train crossing frequencies, contributes to the reduction of the current structural reliability of these structures, mainly due to fatigue damaging progress. Many of the old riveted bridges were not originally designed taking into account the fatigue process, since fatigue design procedures only appeared in design codes some decades after their construction. This issue raises concerns about the likely poor original bridge fatigue detailing.

A number of fatigue assessment methodologies for riveted railway bridges have been proposed in the past [1,2], some being of probabilistic form [3–5]. The proposed probabilistic approaches seek the probability of failure or the reliability index, being inherent the comparison of the probabilistic fatigue strength data with the probabilistic fatigue loading. Some of the proposed methodologies for fatigue assessment of riveted bridges aimed the estimation of the remaining fatigue life of the primary members of the bridge (main girders, stringers, cross-girders) [1–5] and are supported by simplified global models of the bridge. However, most of the fatigue-damage related cases that have been reported for the riveted bridges were observed on riveted connections between the primary members and the fatigue damage has been attributed to secondary effects (e.g. out of plane deformation) [6,7]. Very few fatigue assessments of riveted connections have been based on detailed stress analysis such as that provided by finite element models [8–10].

Current design codes of practice propose the use of global S–N approaches to assess the fatigue resistance of riveted joints. In many cases, a unique S–N curve is proposed independently of the joint geometric configuration, which may be inappropriate for all kinds of riveted joints [11]. Also, code based S–N curves are usually presented in deterministic form which is difficult in their application for reliability analysis. Design code S–N curves are developed based on a statistical analysis of a significant database of fatigue tests performed on riveted details covering distinct steels and riveted joint configurations. All the data is correlated together and statistical analysis (e.g. linear regression analysis) is used to specify the mean S–N curve and convenient safety margins. This is the case of AREMA, BS5400 and EC3 procedures.

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These code approaches are global ones incorporating significant safety margins in order to be applicable to the diversity of riveted joint geometries and materials.

Local approaches to fatigue allow the effects of the actual geometry and material properties to be properly accounted in the fatigue behavior of the joint [12]. Also, for the particular case of the riveted joints, the use of local approaches allows the clamping stress on rivets and friction effects to be conveniently accounted [13].

This paper presents a procedure to generate probabilistic stress-life data for riveted shear splices, integrating both the local strain and Fracture Mechanics based fatigue approaches. Strain-life and fatigue crack propagation data from the plain material are provided in the probabilistic form. A detailed 3D finite element (FE) model of the riveted joint is proposed to assess the elastoplastic strains at the critical locations as well as the stress intensity factor histories for a feasible propagating crack. These outputs of the FE model are expressed as a function of the clamping stresses on rivets and friction coefficient. Both clamping stresses and friction coefficient are assumed random inputs of the proposed procedure to estimate the probabilistic S–N field, following assumed probability density functions. The elastoplastic strains are required for computation of crack initiation within the framework of the local strain approaches to fatigue. The stress intensity factors are used to compute the crack propagation until failure. The initial defect assumed in the crack propagation process is also assumed a random variable of the procedure.

The probabilistic stress-life field is derived for a riveted joint using the Monte Carlo simulation method. The inputs of a base deterministic model are previously converted into statistical distributions. The output of the model – the total fatigue life – is evaluated from random inputs, selected with respect to their statistical distributions. This process is carried out over a high number of simulations to result the probability density distribution of the total number of cycles to failure. This process is demonstrated for a simple riveted connection made of puddle iron from the Fão road bridge.

The procedure presented in this paper can be actually used as an alternative to the global approaches foreseen in design codes. It is more time consuming since it requires fatigue properties of base materials and accurate finite element models of the joint. However it allows a clear understanding of the influent parameters on fatigue behavior as well as to specify appropriate safety margins from a probabilistic model framework.

2. Proposed probabilistic modeling approach

In this paper, a model for the fatigue behavior prediction of riveted joints is proposed, based on the assumption that fatigue damage is regarded as a process of macroscopic crack initiation followed by a process of macroscopic crack propagation. Therefore, the total fatigue life may be evaluated according to the following relation:

$$N_f = N_i + N_p \tag{1}$$

where N_f is the total number of cycles to failure, N_i is the number of cycles to initiate a macroscopic crack and N_p is the number of cycles to propagate the crack until failure. To compute the number of cycles to initiate the crack, the local approaches to fatigue, based on the strain-life data from smooth specimens are used. For this purpose and since a probabilistic model is aimed, the probabilistic strain-life field, as originally proposed by Castillo and Fernández-Canteli, based on the Weibull distribution, is adopted to compute the crack initiation [14,12]:

$$N_i = \exp\left[B + \frac{\lambda + \delta(-\log(1-p))^{1/\beta}}{\log(\varepsilon_a) - C}\right] \tag{2}$$

where p is the probability of failure, ε_a is the strain amplitude, λ, δ and β are the Weibull constants and B and C are the additional model parameters. Parameters B and C may be estimated using a constrained least squares method; parameters λ, β and δ may be computed using the maximum likelihood method [14].

Concerning the simulation of the fatigue crack propagation, the Linear Elastic Fracture Mechanics based Paris law is adopted [15]:

$$\frac{da}{dN} = C\Delta K^m \tag{3}$$

where C and m are the material constants, ΔK is the stress intensity factor range and da/dN is the fatigue crack propagation rate. The number of cycles to propagate the crack, N_p, results from the integration of the Paris law, between an initial defect, a_i, and a final defect a_f:

$$N_p = \frac{1}{C}\int_{a_i}^{a_f} \frac{1}{\Delta K^m}\, da \tag{4}$$

The previous integral may be solved numerically, using the following incremental form for the number of cycles:

$$N_p = \sum_{i=1}^{n_{inc}} \Delta N_i; \quad \Delta N_i = \frac{\Delta a_i}{C\Delta K_i^m}. \tag{5}$$

The crack is propagated according to the predefined crack increments, assuming constant the stress intensity factor, during each increment. This approximation yields very satisfactory results if the crack increments are kept small.

Several sources of uncertainty may arise when computing the number of cycles to propagate a crack. One source of uncertainty is introduced by the estimation of the parameters of the propagation law. Additionally, the crack initiation criterion may play an important influence on the final result of the integral of Eq. (5). In the literature, the local approaches to fatigue have been used to model a macroscopic crack initiation, but distinct definitions have been adopted. Several initial crack size criteria have been proposed in the literature in the range 0.1–1.0 mm [16–22], the value of 0.5 mm being a very common definition. In the proposed procedure, the macroscopic crack initiation size is assumed a source of uncertainty of the model itself and therefore a_i is assumed a random variable, following a proposed probabilistic distribution. The critical crack size, a_f, is estimated based on the material toughness which was assumed a deterministic property. Any possible variability in the material toughness will show a very low influence in the fatigue crack propagation life prediction results, since the crack propagation rates for cracks approaching the critical size are very high, resulting in a negligible variation in the total number of cycles to failure.

Two additional sources of uncertainty were accounted in the prediction procedure: the clamping stresses on rivets and the friction coefficient. These two parameters show very high uncertainty in the riveted joints; consequently they were accounted as random variables in the fatigue modeling process. These parameters were assumed inputs of the finite element models proposed for the riveted joint under investigation and have an influence on relations between the applied stress range and the local strain histories, as well as the stress intensity factor histories.

Fig. 1 illustrates the procedure proposed to compute the fatigue life, N_f, for riveted connections, given the applied net stress range, $\Delta\sigma_{net}$. The inputs of the model that are defined in probabilistic form (random variables) are pointed out in the figure, namely: the clamping stresses on rivets, the friction coefficient, the crack initiation size, a_i, and the C coefficient of the Paris law. In addition, the strain-life model is also proposed in the probabilistic form. The number of cycles to crack initiation is assumed a random variable for a given strain amplitude.