Journal of Constructional Steel Research 139 (2017) 466–472

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

New framework for calibration of partial safety factors for fatigue design

Luca D'Angelo [a,*], Alain Nussbaumer [b]

[a] European Organization for Nuclear Research (CERN), Switzerland
[b] Resilient Steel Structures Laboratory (RESSLab), Swiss Federal Institute of Technology Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 1 March 2017
Received in revised form 15 September 2017
Accepted 8 October 2017
Available online xxxx

Keywords:
Fatigue design
Partial safety factors
Variable amplitude loadings
Welded joints
Fatigue life

ABSTRACT

In Eurocode standards, three verification schemes are proposed for fatigue design under variable amplitude loadings: 1) Based on constant amplitude fatigue limit; 2) Based on constant amplitude equivalent stress range at $2 \cdot 10^6$ cycles; 3) Based on accumulated damage. Characteristic values of fatigue resistance and load effects as well as partial safety factors are introduced in design equations in order to achieve a target reliability level. In this paper a new framework for calibration of fatigue partial safety factors is presented. Three different fatigue limit state functions are formulated for direct comparison with the three verification schemes proposed in Eurocodes. The variable amplitude S-N curves used in this framework are defined using an original probabilistic approach. The presented framework is then applied to two typical bridge fatigue sensitive welded joints. The comparison of results with partial safety factors values recommended in Eurocodes shows that the Eurocode-based partial safety factors should be revised by considering different fatigue sensitive details and by further differentiating between the three verification schemes.

1. Introduction

The safety and serviceability issues in structural design are addressed in structural codes by defining design equations which compare load and resistance effects. Due to the inherent uncertainty in load and resistance terms, these are modeled as random variables. Characteristic values of random variables and partial safety factors are introduced in order to ensure a certain level of reliability for the designed structural component.

The typical design equation for verification of a structural component (see Eurocode 1990 [1]) is:

$$G = \frac{zR_c}{\gamma_M} - (\gamma_{F1}E_{c1} + \ldots + \gamma_{Fn}E_{cn}) = 0 \quad (1)$$

where: R_c is the characteristic value of resistance; z is the design factor; γ_M is the partial safety factor for resistance; E_{ci} is the characteristic value of the ith action effect; and γ_{Fi} is the partial safety factor for the ith action effect.

According to the design Eq. (1) a reliability analysis can be made with the following limit state equation:

$$g = zR - (E_1 + \ldots + E_n) = 0 \quad (2)$$

The calibration of partial safety factors is a decision problem, in which partial safety factors are decision variables which are calibrated by minimizing an objective function. Faber et al. [2] proposed a practical approach for calibration of partial safety factors, in which the objective function is formulated as follows:

$$W(\gamma) = \sum_{j=1}^{L} w_j \cdot [\beta_j(\gamma) - \beta_t]^2 \quad (3)$$

where: L is the number of load cases; w_j are the importance factors of different design load cases; and β_t is the target reliability index. Partial safety factors γ are computed by minimizing the objective function in Eq. (3), in which the reliability index is computed by solving the limit state equation (see Eq. (2)), having determined the optimal design factor $\hat{z}$ from the design equation (see Eq. (1)). It is noted that when partial safety factors are calibrated from Eq. (3) they are not independent and in the case with one resistance factor and one loading factor only the product of them can be calculated.

In this paper a new framework for calibration of partial safety factors for fatigue design is presented. The general limit state Eq. (2)

* Corresponding author.
E-mail addresses: luca.dangelo@cern.ch (L. D'Angelo), alain.nussbaumer@epfl.ch (A. Nussbaumer).

https://doi.org/10.1016/j.jcsr.2017.10.006
0143-974X/

and the general design Eq. (1) are adapted to the three verification schemes cases proposed in Eurocode 1993-1-9 [3] for fatigue design under variable amplitude loadings: 1) Based on constant amplitude fatigue limit; 2) Based on constant amplitude equivalent stress range at $2 \cdot 10^6$ cycles; 3) Based on accumulated damage.

Fatigue resistance terms in design and limit state equations are characterized by using ML-MCS method [4], which allows to increase the confidence in characteristic and design values of fatigue resistance with respect to current standards.[1] The target reliability indexes for fatigue limit state functions are based on the recommendations of JCSS [5].

The paper is structured as follows:

- In Section 2 the three design verification schemes proposed in Eurocode 1993-1-9 for fatigue design under VA loadings are recalled and shortcomings of Eurocode-based partial safety factors are highlighted.
- In Section 3 the new framework for calibration of fatigue partial safety factors using ML-MCS S-N model is presented.
- In Section 4 an application of the framework to two typical bridge fatigue sensitive welded joints is considered.
- In Section 5 results of analyses of the two considered study cases are presented.
- In Section 6 results are discussed and comparison with partial safety factor values recommended in Eurocode 1993-1-9 is made.

The developed framework has general applicability and can be used with different refinement degrees: differentiating between detail categories and design methodologies, to set for example different partial safety factors in function of the methodology, or serve as basis to re-calibrate fatigue partial safety factors valid for all details and methodologies for a given target reliability level.

2. Fatigue design under VA loadings in Eurocode standards

In Eurocode standards, three verification schemes are proposed for fatigue design under VA loadings: 1) Verification scheme based on CAFL (see EN-1991-2 [6]); 2) Verification scheme based on CA equivalent stress range at $2 \cdot 10^6$ cycles (see A.6 of EN-1993-1-9 [3]); and 3) Verification scheme based on accumulated damage (see A.6 of EN-1993-1-9 [3]).

2.1. Verification scheme 1: based on CAFL

The fatigue design based on CAFL exceedance has to meet the following criterion:

$$\gamma_{Ff} \cdot S_{\max_c} \leq \frac{\text{CAFL}}{\gamma_{Mf}} \tag{4}$$

where: CAFL is the characteristic value of the fatigue limit; $S_{\max_c}$ is the characteristic value of maximum loading stress range; γ_{Ff} is the loading partial safety factor, which is set to 1.0; and γ_{Mf} is the resistance partial safety factor.

[1] In [4] the authors presented new probabilistic method which allows to improve accuracy in the estimation of CA and VA fatigue S-N curves of welded steel connection, using combination of Maximum Likelihood Method and Monte-Carlo Simulations Method. The new probabilistic method is referred to as ML-MCS approach. Improvement of accuracy in the estimation of the high cycle fatigue region of S-N curves is of primary importance when assessing remaining fatigue life of existing structures. Nevertheless, use of accurate S-N curves is a primary requirement also when fatigue design partial safety factors have to be calibrated

Table 1
Recommended values for partial factors for fatigue strength (Table 3.1 of [3]).

Design method	Consequence of failure	
	Low consequence	High consequence
Damage tolerant	1.00	1.15
Safe life	1.15	1.35

2.2. Verification scheme 2: based on CA equivalent stress range

The fatigue design based on CA equivalent stress range has to meet the following criterion:

$$\gamma_{Ff} \cdot S_{E,2} \leq \frac{S_c}{\gamma_{Mf}} \tag{5}$$

where: $S_{E,2}$ is the equivalent stress range, at $2 \cdot 10^6$ cycles, which is computed by using Fatigue Load Model (FLM) 3 and λ damage equivalent factors; and S_c is the characteristic fatigue strength at $2 \cdot 10^6$ cycles (FAT).

2.3. Verification scheme 3: based on damage accumulation

The fatigue design based on damage accumulation has to meet the following criterion:

$$D_d = \sum_{i}^{N_{tot}} \frac{n_i}{N_i} \leq 1.0 \tag{6}$$

where: n_i is the number of cycles corresponding to the design loading stress range $\gamma_{Ff} \cdot S_i$; N_i is the endurance to failure obtained from the factored $\frac{S_c}{\gamma_{Mf}} - N$ curve.

The definition of the partial resistance factor γ_{Mf} in Eurocode 1993-1-9 (Section 1.4, pp. 9, [3]) is ambiguous because γ_{Mf} is strictly defined for fatigue strength at $2 \cdot 10^6$ cycles (therefore relevant only for verification scheme 2), but it is applied by extension for fatigue strengths at any number of cycles (verification schemes 1 and 3).

Recommended values of partial factor γ_{Mf} are presented in Table 1. Sedlacek et al. address the issue of calibration of fatigue design partial safety factors in [7]. Nevertheless, a proof of rigorous calibration of the values recommended in Table 1 is not available and the real reliability level, β, corresponding to these values is still under debate.

3. New framework for partial safety factor calibration

In this section a new framework for calibration of fatigue partial safety factors using ML-MCS approach-based S-N curves is presented. The framework includes the three verification schemes which have been presented in Section 2. One different limit state function is formulated for each of verification schemes. Partial safety factors are calibrated by using the following general objective function, which is valid for all three verifications:

$$W(\gamma_{Ff}, \gamma_{Mf}) = \sum_{j=1}^{L} w_j \cdot [\beta_j(\gamma_{Ff}, \gamma_{Mf}) - \beta_t]^2 \tag{7}$$

where: γ_{Ff} is the partial safety factor for fatigue loading; γ_{Mf} is the partial safety factor for fatigue resistance; L is the number of load cases; w_j are the load case importance factors; β_j are the computed reliability indexes, for $j = 1, \ldots, L$; $\beta_t = -\Phi^{-1}([\Phi(4.2)]^{100}) =$