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Environment-assisted fatigue of steel bridges: A conceptual framework for life assessment

Environment-assisted fatigue of steel bridges: A conceptual framework for life assessment

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Abstract. This paper presents a framework based on a recently proposed fatigue strength curve of corroded steel to assess the life of an existing steel bridge exposed to environment-assisted fatigue. Environment-assisted cracking (EAC) and how it affects the structural integrity of steel bridges are introduced by the framework. Determination of both corroded and uncorroded details in a corrosive environment are also included in this framework. To conform the applicability and significance, a fatigue life of a railway bridge was assessed by methods given in the framework. The obtained fatigue lives were compared. The difference of the estimated fatigue lives emphasizes the importance of having this framework to consider the interaction of corrosion and fatigue mechanisms.

1. Introduction

Bridge authorities are paying significant attention to the ageing issues of bridges, as bulk of bridges are subjected environment-assisted damages and replacement of all these is not economical. Environment-assisted cracking (EAC) is one of the main deterioration processes that affect the integrity of bridges. Steel bridges exposed to an aggressive environment are subjected to loss of protective coating, thus a loss of material due to corrosion [1-4]. These bridges suffer a change of stiffness and structural behaviour, causing a reduction of the remaining fatigue life.

Detailed provisions and frameworks are not available for assessing structural integrity due to EAC [1,5]. Bridge assessment guidelines to detect loss of material and stress concentration due to corrosion are specified by codes and standards and are only provided in some nations. A simplified assessment procedure for existing bridges was proposed based on past studies [7,8]. This assessment procedure is mainly based on visual inspections and non-destructive testing. Internal damages such as cracking and defects due to EAC cannot be detected by these techniques, which is an essential concept that should be included in the guidelines [5,6].

A guideline for assessing structural integrity due to EAC and the need of generalized S-N curves for structural details exposed to corrosive environments have been covered in a study by Adasooriya et al [5,6] by proposing a generalized formula of S-N curve for corroded structural details. The applicability and significance of the proposed curve are to be confirmed by performing case studies. A clear guideline of using the formula is also highly required for practicing engineers.

Therefore, the main objective of this paper is to propose a conceptual framework for fatigue life assessment of steel bridge details which are corroded and/or exposed to corrosive environment. The applicability and significance of the framework is confirmed by estimating fatigue life a railway bridge. The results are compared with the conventional approaches.

2. Conceptual framework for life assessment of steel bridge details

A conceptual framework for fatigue life estimation is presented in Figure 1. Determination of fatigue life of both corroded and uncorroded is included in the framework. The methods are based on damage accumulation from the Eurocode [9] and newly proposed method for estimating life of members subjected to corrosion and EAC [5,6]. The framework can be applied to existing steel bridges in an urban or marine environment.

The framework consists of a few major steps. First, a structural analysis is performed to simulate the currents state of the bridge, hence identify the critical elements. Stress spectrum of identified critical elements are determined in the next step. These stress ranges are then utilized for the remaining life calculation using both conventional approach and the newly proposed method. Current state of the bridge should be identified by suitable approach which were published by authors recently [1]. Hence, structural details are categorised as uncorroded, corroded and/or exposed to corrosive environments. The conventional method, which consists of Eurocode detail category-based S-N curves and Miner's rule, are used for remaining fatigue life estimation of uncorroded details as shown in Figure 10. The recently proposed formula of S-N curve for corroded structural details [5,6] and Miner's rule are utilized to calculate the remaining fatigue life of corroded details and/or details which are exposed to corrosive environment as shown in Figure 1. The fatigue strength range of structural details in corrosive environments, $\Delta\sigma_{cor}$, and corresponding number of cycles to fatigue failure, has been presented as [5],
If $\Delta\sigma_{cor} \geq \Delta\sigma_{D,cor}$,

$$\Delta\sigma_{cor} = \Delta\sigma_D \left[N_{f,LCF}^{c} N_{f,CAFL}^{1/m}\right] N_R^{(-c-1/m)}$$
$$where\ c = \log\left[\frac{\Delta\sigma_D}{\Delta\sigma_{D,cor}}\right] \Big/ \log\left[\frac{N_{f,CAFL}}{N_{f,LCF}}\right] \qquad (1)$$

The constant amplitude fatigue limit of uncorroded detail, $\Delta\sigma_D$ is the stress range at the fatigue curve slope changing point, corresponding to the $N_{f,CAFL}$ cycles. The $-1/m$ is the slope of the fatigue strength curve uncorroded details, where m is equal to 3 when $\Delta\sigma \geq \Delta\sigma_D$, equal to 5 when $\Delta\sigma_D \geq \Delta\sigma > \Delta\sigma_L$ and infinite when $\Delta\sigma \leq \Delta\sigma_L$, where $\Delta\sigma_L$ is the fatigue endurance limit of the detail corresponding to $N_{f,VAFL}$. $N_{f,LCF}$ is the number of cycles to fatigue failure of uncorroded details when stress range transits from high cycle fatigue to low cycle fatigue region. $\Delta\sigma_{D,cor}$ is the stress range at intersecting points of two slopes of the uncorroded fatigue curve of the details, exposed to corrosive environments, corresponding to $N_{f,CAFL}$ cycles. The $\Delta\sigma_{L,cor}$ is the stress range corresponding to $N_{f,VAFL}$ cycles of the bridge details, exposed to corrosive environments and/or corroded details.
If $\Delta\sigma_{cor} \leq \Delta\sigma_{D,cor}$

$$\Delta\sigma_{cor} = \Delta\sigma_{D,cor}\left[N_{f,CAFL}^{-\acute{c}}\right] N_R^{\acute{c}}$$
$$where\ \acute{c} = \log\left[\frac{\Delta\sigma_{D,cor}}{\Delta\sigma_{L,cor}}\right] \Big/ \log\left[\frac{N_{f,CAFL}}{N_{f,VAFL}}\right] \qquad (2)$$

The numerical values of parameters used in Eq. (1) and (2) are clearly presented in the Table 2 of authors' previously published article [5]. Hence total fatigue lives or remaining fatigue lives can be calculated for corroded, uncorroded details and/or details which exposed to corrosive environments as shown in last step of the Figure 10.

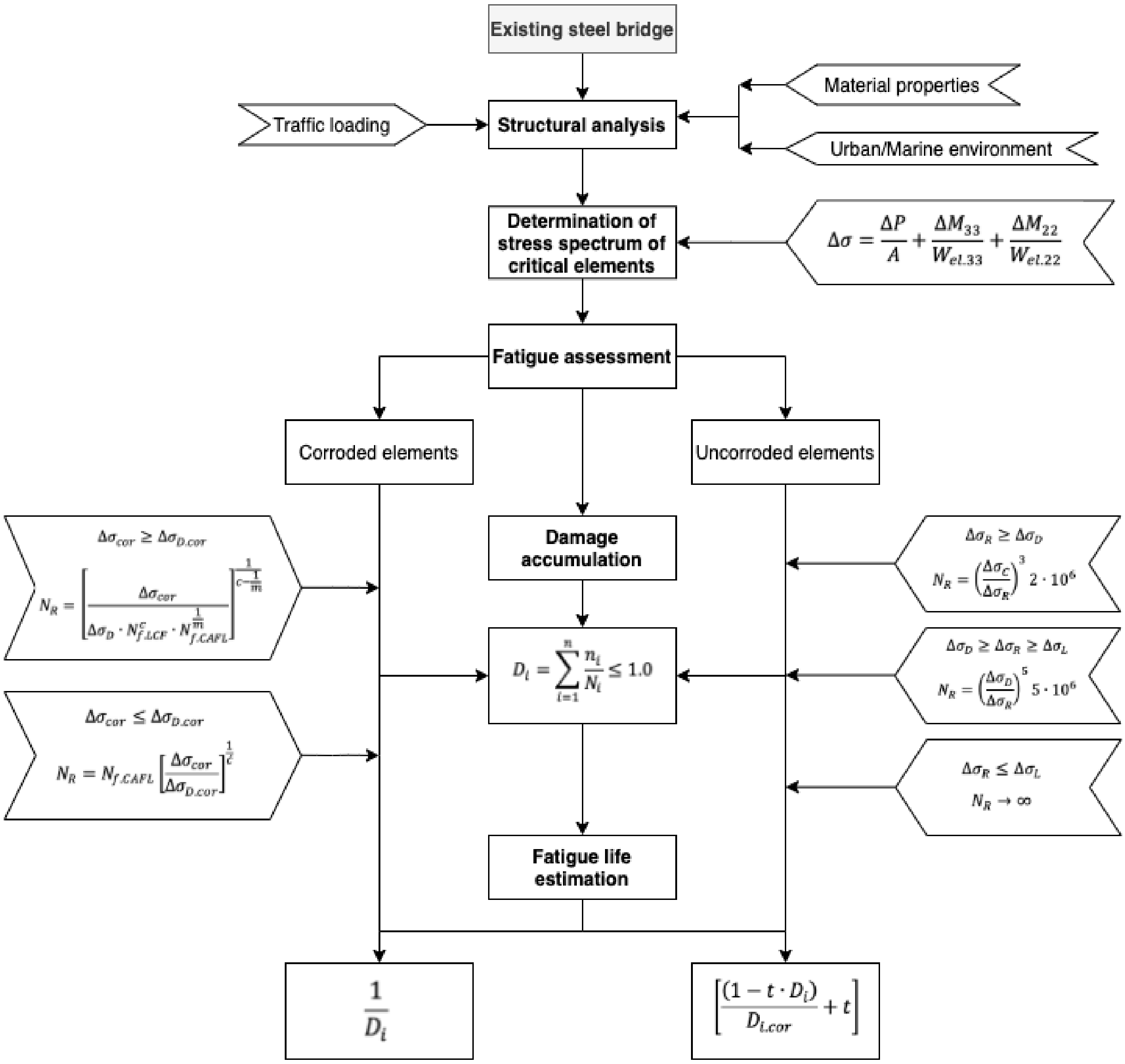

Figure 1. Conceptual framework for estimating fatigue life of corroded structural members.

3. Case study: Fatigue assessment of steel bridge in corrosive environment

The methodology presented in conceptual framework in the previous section was applied to a steel bridge in a corrosive environment. Firstly, the environmental conditions, current state and critical details of the bridge were identified. A structural analysis to simulate the current state of the bridge was the be done to check for design limit state, hence evaluating the state of stress histories. Lastly a fatigue assessment will be carried out to calculate remaining life of critical detail using the framework shown in Figure 1.

3.1. Considered bridge and its current status

A railway bridge in a marine corrosive environment is to be considered for fatigue life estimation. The considered bridge shown in Figure 2 is a Warren truss girder bridge and constructed in 2007. Length and width of the bridge are 38.5m and 5m respectively. The bridge consists of ten different cross-sections, which will be considered in the fatigue assessment. Some of the joints and details have already corroded due to loss of coating after 10 years of life. Photos of the bridge reveals surface corrosion on the bottom and top chord, as well as the diagonals of the bridge. Since the bridge is located in a marine environment, it is likely that it is subjected to pitting and crevice corrosion due to presence of chloride and salt ions. It is known that the bridge has been constructed according to the Eurocode and grade of steel is S355.

Figure 2. Considered railway bridge

3.2. Structural analysis

The bridge has been modelled in general purpose package SAP2000 [10] based on provided structural details and drawings. Primary structural elements was only included in the model (i.e. rails and rail sleepers/rail road ties were not considered). The structure has fixed bearings in one end, and longitudinal free bearings in the other end according to the drawing. The connection is assumed to be rigid joints. The three-dimensional (3D) model, shown in Figure 3 (a), is analyzed under fatigue loading to determine the stress histories of fatigue critical members/joints. The loading relevant to fatigue analysis were taken according to Eurocode EN 1993-1-2[11]. The fatigue loads on slender elements due to wind excitations were taken from EN 1991-1-4. Traffic mix representing the different trains is provided in Annex D.3 in EN 1991-2. For this case study, "Standard traffic mix with axles ≤ 22,5 t (225 kN)", is chosen. This traffic mix covers train type 1-8, and is reproduced Annual traffic tonnage of 25 000 000 tonnes passing over the bridge on each track [11].

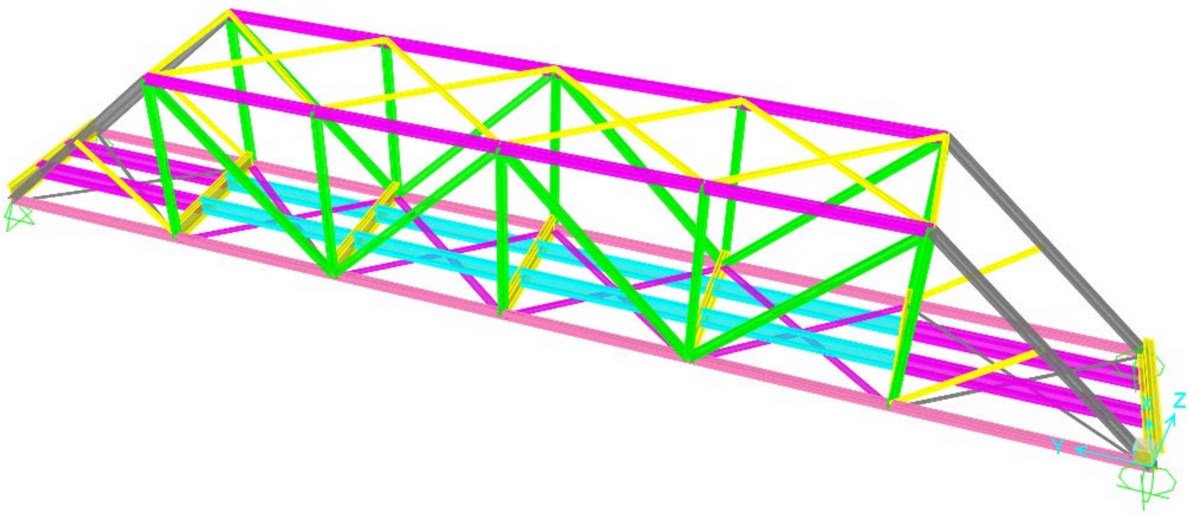

Figure 3. Structural model of considered bridge in SAP2000.

3.3. Design limit state and stress evaluation

Failure due to fatigue is associated with cumulative damage caused by a repeated application of stress and fatigue design therefore requires to be checked by Fatigue Limit State (FLS). The stresses need to be based on an elastic stress analysis for the FLS, with no plastic redistribution, and to consider shear lag and geometrical configurations leading to stress concentrations. The FLS is therefore more suitable, as fatigue life depends on the stresses at positions where connections/attachments are made or where the shape of the members changes [12].

The described traffic loading establishes a spectrum of stress ranges $\Delta\sigma$, consisting of a series of stresses generated of each train model, $\Delta\sigma_{VEH1} - \Delta\sigma_{VEH8}$ for each member. Element forces, i.e. maximum and minimum bending moments of both strong and weak axis, as well as the axial force of each members are obtained from the output structural analysis in SAP 2000. The moment range about major and minor axis of the members ΔM_{33} and ΔM_{22} are divided by associated section modulus $W_{el.33}$ and $W_{el.22}$. The axial force range ΔP are divided by the area A. As a result, the nominal stress range can be found from superposition for each member from the following formula,

$$\Delta\sigma = \frac{\Delta P}{A} + \frac{\Delta M_{33}}{W_{el.33}} + \frac{\Delta M_{22}}{W_{el.22}} \tag{3}$$

Calculations of the nominal stress ranges of the critical members of each cross-sectionals are done and the stress ranges has been calculated at the end points (i.e. at the cross-section just before the joint) of each member, where the maximum nominal stress range are selected and will be used in the fatigue assessment. Members of each cross-sectional group, which gives the maximum nominal stress range and therefore lowest fatigue life, are selected from each cross-sectional group. These members are termed as "fatigue critical members" and shown in Figure 4.

3.4. Fatigue life estimation of critical members

Fatigue lives were performed for the fatigue critical members using the safe life method according to the proposed conceptual framework shown in Figure 1. The safe life method is to be applied for critical elements where local formation of cracks could rapidly lead to failure of either the structural component or the whole structure. As follows, the method provides an acceptable level of reliability that the structure will perform satisfactorily for its design life without requirement of regular in-service inspection for fatigue damage. The joint details of the fatigue critical members 1-9 and 10 were categorized/identified as detail category 90 and 160 respectively [9]. The corresponding S-N curves were used with the conceptual framework to calculate corresponding fatigue lives and results are shown in Table 1.

4. Comparison of results and discussion

The applicability and significance of the proposed framework will be discussed in this chapter by comparing fatigue lives obtained by conventional approach and the proposed framework.

4.1. Comparison of fatigue lives

The fatigue life estimation of an existing steel bridge in a marine environment has now been performed by using both conventional approach (method 1) and proposed framework (method 2). The results are presented in Table 1 and there is a significant difference between the fatigue live by two methods. This reduction of fatigue lives emphasizes the importance of identifying current states of critical joints and using of accurate S-N curves of joints which are already corroded and/or exposed to corrosive environment due to loss of coating or etc.

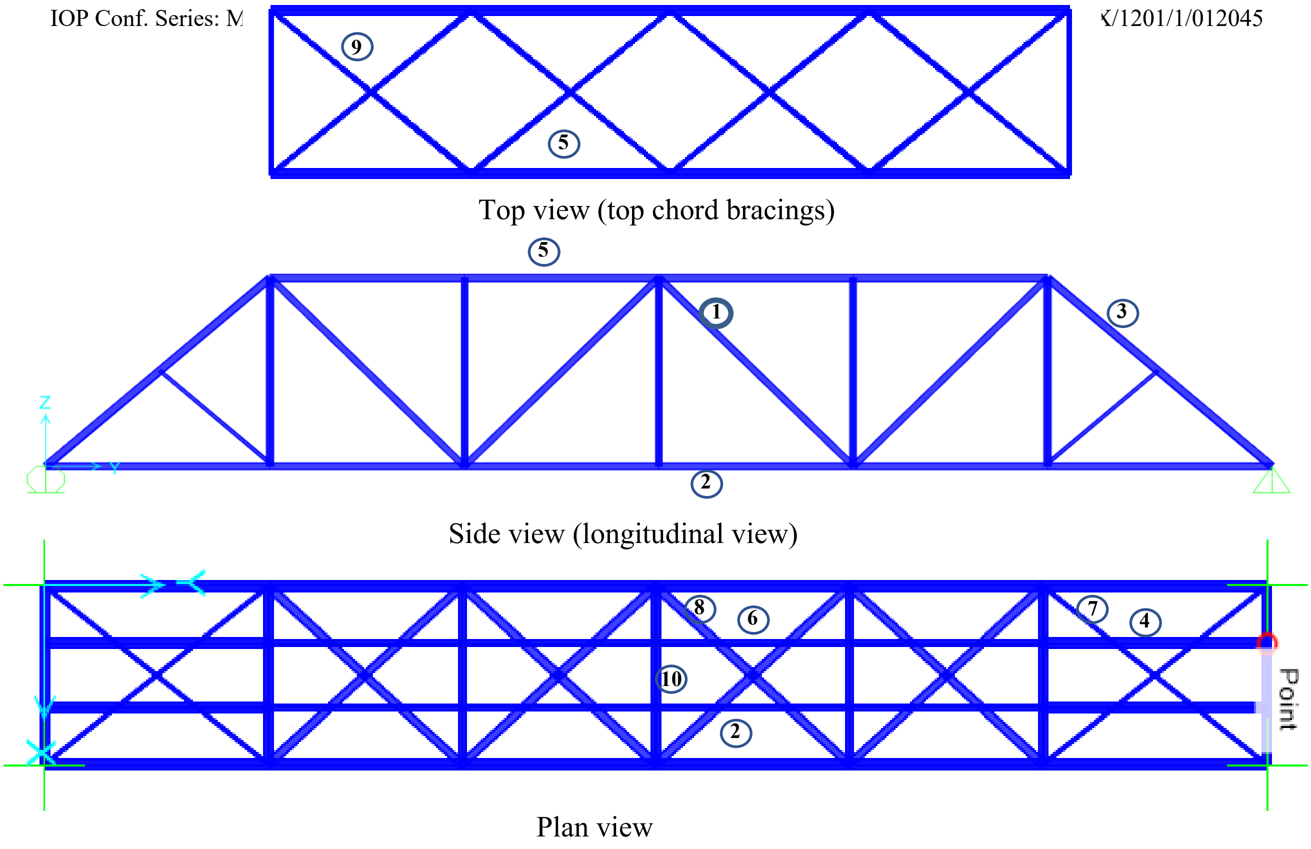

Figure 4. Fatigue critical members and the designations.

Table 1. Comparison of the calculated fatigue lives of cross-sectional groups

Fatigue critical members	Cross sectional group (type of member)	Method 1: Conventional approach [20]	Method 2: Proposed conceptual framework
1	HEA220	50.2 years	22.2 years
2	HEA240	45.2 years	21.4 years
3	HEA260	37 years	19 years
4	HEA550	103.2 years	33.2 years
5	HEB260	96.9 years	32.3 years
6	IPE550	52.8 years	23.2 years
7	Plate 80x8	684.1 years	75.6 years
8	Plate 220x8	660.6 years	74.8 years
9	HEAA120	infinite	infinite
10	UB686/284/125	31.5 years	18.8 years

4.2. Applicability and significance of the proposed method

The reduction in estimated fatigue life emphasizes the importance and significance of the proposed framework. The procedure of fatigue assessment is rather uncomplicated as the proposed framework together with Eurocode provide necessary formulas and associated parameters in form of S-N curves for the different detail categories. The newly added formulas do not require any material properties other than those provided by S-N curves in codes. Therefore, proposed conceptual framework is quite applicable for assessing structural integrity of steel bridges due to EAC.

5. Conclusions

A framework was proposed to determine the fatigue life of bridge details in corrosive environments. The framework is applicable for fatigue assessment of corroded elements as the structural analysis and determination of stresses are the same as conventional approaches. Furthermore, fatigue strength formulas of structural details in corrosive environments, which were newly introduced in the framework resulted in a significant reduction of the fatigue life of critical members evaluated in the case study compared to conventional fatigue estimations. This emphasizes the importance of using the precise framework which take account the effect of EAC for maintenance of corroded steel bridges to avoid critical damage. The fatigue verification shows satisfactory results, however, due to the noticeable fatigue life reduction, a sufficient corrosion protection of the steel should be determined. Even though the calculated fatigue lives are conservative, an extensive evaluation of the present state of the bridge could be taken into consideration to suggest life extension strategy and maintenance of the bridge. Furthermore, measurements of the actual traffic loading can be performed to give more precise bridge response in form of stress ranges, and these are recommended for future research.

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