Received: 19 December 2019 | Revised: 25 December 2019 | Accepted: 27 December 2019
DOI: 10.1111/ffe.13193

ORIGINAL CONTRIBUTION

FFEMS Fatigue & Fracture of Engineering Materials & Structures

WILEY

S-N curve for riveted details in corrosive environment and its application to a bridge

N.D. Adasooriya | **T. Hemmingsen** | **D. Pavlou**

Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Stavanger, Norway

Correspondence
N. D. Adasooriya, Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Stavanger, Norway
Email: mudiyan.n.adasooriya@uis.no

Abstract

A formula for stress-life curve is proposed to predict the fatigue life of riveted bridges located in corrosive environments. The corrosive environment-dependent parameters of the S-N curve are determined based on the corrosion fatigue testing results of different types of steel specimens in air, fresh water, and seawater. Eurocode detail category 71 and UK WI-rivet detail category represent the fatigue strength of riveted members. The proposed S-N curve formula is compared with full-scale fatigue test results of riveted joints, plate girders, and truss girders, which were tested in a corrosive environment. Thus, the validity of the formula is confirmed. The formula does not require any material parameter other than the code-given fatigue curve of riveted details. The fatigue life of a riveted railway bridge is estimated by using the proposed formula, and the results are compared with conventional approaches. The applicability and significance of the proposed curve are confirmed.

KEYWORDS

corrosion fatigue, riveted joints, S-N curve, steel bridges

1 | INTRODUCTION

Bridge authorities are paying significant attention to the ageing issues of bridges, as most railway bridges in the world are reaching their design life.[1-5] Replacement of all of these is practically impossible, due to both the decommissioning and new building costs, as there are many ageing bridges. Most of the structural members of these bridges were constructed by riveted members (i.e. built up by riveting the plates). Riveting was widely used to assemble metal structures before 1940.[5,6] Drilling, punching, and reaming are major processes used for making rivet holes. Then hot rivets drive through the holes of the two plates and hammer the shank to form the second rivet head.[5] The clamping force develops in between plates when cooling the rivets. The release of clamping force increases the bearing, and this may have a significant effect in reducing the fatigue strength.[5] Some degree of corrosion has always been present in these old bridges, due to the difficulty of maintaining the coating/corrosion protection system in between layered parts/plates of riveted built-up sections.[5-7] Some of these bridges are located in urban industrial and moderate marine environments, which have been classified as severely corrosive environments.[7,8] Although many bridges are located onshore, deicing salt may simulate a marine environment for bridges in snowy regions.[7] The combined influence of the severe corrosive environment and the cyclic stresses due to variable traffic loads initiate cracks in both corroded and uncorroded regions (i.e. corrosion-free areas and/or coating-lost areas) of the riveted members and joints.[9-12] Fractures due to the cyclic stress in corrosive media are designated as corrosion fatigue (CF), which is a type of environmentally assisted cracking; hence, fatigue strength degradation (i.e. degradation of the S-N curve) can be observed. The fatigue performance of riveted joints and members depends on the type of material, production methods of rivet holes, clamping force, degree of coating, state of deterioration due to corrosion, and the corrosive environment. A significant amount of full-scale fatigue testing has been carried out for riveted details.[5,7,8] It is difficult to compare the degree/severity of the effect of CF for the above tests, without studying the distinction of mechanisms between corroded members tested in air, corroded members tested in a corrosive environment and uncorroded members tested in corrosive environments. The contradictory conclusions reported in the literature motivate more accurate simulation of the CF strength of riveted structural details in different corrosive environments.[7,13,14]

Detailed provisions and models/formulas are not available in codes of practices to predict the fatigue strength of the riveted details of land-based structures, which are exposed to corrosive environments.[4,7,8] As bolted and/or welded joints are popular for modern bridge applications, new fatigue standards have not paid major attention regarding S-N curves for riveted details. A few past studies recommend neglecting the endurance limit (i.e. the S-N curve should be used without a cut-off limit) to take into account the fatigue strength degradation due to the effect of a corrosive environment.[4,11,12,15] The modified S-N curves do not match the available fatigue test results of riveted details exposed to corrosive environments.

To overcome the previously mentioned problems, the main objective of this paper is to propose a formula for an S-N curve for riveted joints and members exposed to corrosive environments. The parameters used in the formula are mainly dependent on a corrosive urban environment and the riveted detail categories of both steel and wrought iron. The urban environment-dependent parameters of the S-N curve formula are conservatively determined, based on the CF testing results of different types of steel presented in a previous publications.[3,16] The proposed S-N curve formula is verified by comparing the full-scale fatigue test results of uncorroded (i.e. corrosion-free), weathered, and deteriorated riveted girders (i.e. both plate and truss girders) tested in an urban environment. The fatigue life of a riveted bridge is estimated by using the proposed S-N formula, and the results are compared with conventional approaches.

2 | PROPOSED S-N CURVE FOR RIVETED BRIDGES EXPOSED TO A CORROSIVE ENVIRONMENT

The fatigue strength curve for specimens in a corrosive environment, which was proposed by authors' previous studies,[3,16] is further developed to obtain an *S-N* curve for riveted joints and members, which are exposed to corrosive environments. The fatigue design standards, currently used in Europe, have defined only two detail categories for riveted structural details. Those are detail category 71, which is given in Eurocode,[17] and WI-rivet detail category, which is given in the UK railway assessment code.[4,18,19] The curve has been obtained by modifying the design S-N curves of both detail category 71[17] and WI-rivet detail category, which is given in the UK railway assessment code,[4,18,19] respectively. The environmentally assisted CF behaviour of the tested laboratory specimens was utilized for this modification.

2.1 | The concept used for the proposed curve

The stress range and peak stress level are the governing parameters of CF crack initiation and propagation. The CF crack initiation may occur without the presence of pits, and the CF cracks are expanded by the post reaction of corrosion for carbon steel. [20] Gliding can be seen in some of the grains due to cyclic stresses. When dislocations reach a grain boundary, gliding is ceased.[21] When the stress is reversed, the movement of the grains retraces along the slip plane. Slight irregularities restrict the movement and develop another parallel slip plane. Finally, these disorganized bands of material cause separation between slip planes while initiating the cracks at high stress ranges. Due to the interaction of a corrosive environment, disorganized atoms are moving along slip planes with less activation energy unlike with corrosion. This behaviour may be observed even in lower stress ranges (i.e. bellow the fatigue endurance limit),[3,16] and hence, there is no safe stress level at which the fatigue life is infinite. The environmental, metallurgical, and structural factors are the governing parameters of the CF strength.[4,22] Negligible differences between low-cycle fatigue (LCF) lives in corrosive and noncorrosive environments were found in almost all the fatigue test results of steel specimens, and a significantly larger difference is found in the very high cycle fatigue (VHCF) region.[3,7,21,23,24]

2.2 | Derivation of fatigue strength curve for the riveted details in corrosive environments

The fatigue strength curve is presented in Figure 1 for riveted details, which are not exposed to a corrosive environment[17-19] (i.e. design S-N curves given in fatigue codes), and the corresponding formula can be presented in general for both detail category 71[17] and WI-rivet detail category[4,18,19] as shown in Equation (1).

$$\Delta\sigma = \left(\Delta\sigma_D N_{f,CAFL}^{1/m}\right) N_R^{(-1/m)} \tag{1}$$

The $\Delta\sigma$ is the stress range, and N_R is the corresponding number of cycles to fatigue failure. The $\Delta\sigma_D$ is the stress range at the fatigue curve slope changing point, which corresponds to the $N_{f,CAFL}$ cycles. The $\Delta\sigma_D$ is defined as the constant amplitude fatigue limit.[17] The slope of the fatigue strength curve is $-1/m$. According to the Eurocode,[17] 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, which corresponds to $N_{f,VAFL}$. This is also defined as the fatigue cut-off limit or variable amplitude fatigue limit in Eurocode given detail category 71.[17] These fatigue curves are generally referred to as trilinear S-N curves. The fatigue curves of the WI-rivet detail category, which is given in the UK railway assessment code,[4,18,19] do not have such a cut-off limit and are commonly named bilinear S-N curves. The curve parameters, slopes, and details of knee points (i.e. $N_{f,CAFL}$, $N_{f,VAFL}$, $\Delta\sigma_D$, and $\Delta\sigma_L$) are listed in Table 1 for both detail categories by referring to the relevant standards.[4,17-19]

According to the CF mechanism and the concept of fatigue endurance of laboratory specimens mentioned

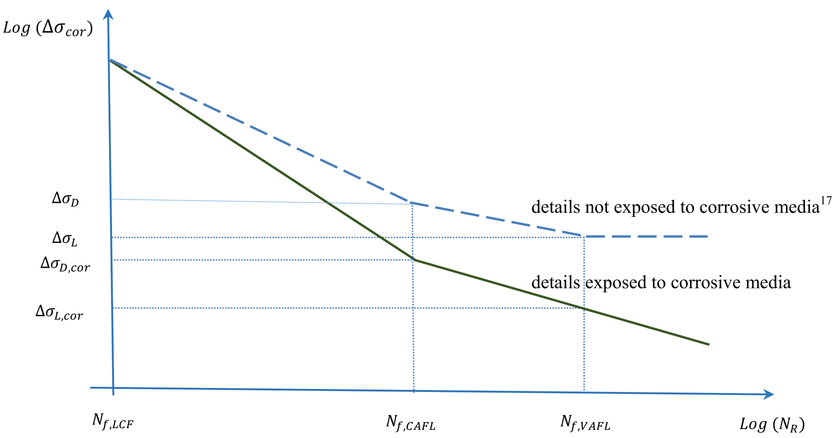


FIGURE 1 Schematic representation of fatigue strength curve of riveted details exposed to corrosive environments [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Parameters used in the proposed fatigue strength curve of riveted details in corrosive environments

Parameter	Eurocode Detail Category 71		WI-Rivet Detail Category	
$N_{f,LCF}$	10^4		10^4	
$N_{f,CAFL}$	5×10^6		10^7	
$N_{f,VAFL}$	10^8		10^8	
m, m	3, 5		4, 6	
$\Delta\sigma_D$ (MPa)	52.3		44.0	
$\Delta\sigma_L$ (MPa)	28.7		30.0	
Corrosion parameters	Urban environment		Urban environment	
	Mean value	Conservative value	Mean value	Conservative value
$\Delta\sigma_{D,cor}$, MPa	33.5	28.0	26.8	22.0
$\Delta\sigma_{L,cor}$,MPa	14.9	11.5	15.5	12.0
c	0.072	0.100	0.072	0.100
ć	−0.271	−0.298	−0.238	−0.263

in Section 2.1, the linear variation in the difference between the fatigue strengths of riveted details, which are not exposed to corrosive environments, has been observed, as shown in Figure 1. The previously published CF test results of steel specimens,[3,16] which were tested in corrosive environments, show a nonlinear behaviour of the S-N curve. This can be conservatively assumed as a bilinear S-N curve. For most of the steel specimens, the intersecting points of the two slopes of the assumed bilinear S-N curves were found between 10^6 to 10^7 cycles. This range coincides with the number of cycles at the first intersecting points of the two slopes of S-N curves of specimens tested in non-corrosive environment, i.e. $N_{f,CAFL}$. Therefore, the $N_{f,CAFL}$ is considered as the number of cycles at the intersecting point of the two slopes of the S-N curve of riveted details exposed to corrosive environments. This value may not be valid for the structural details, which are subjected to severe pitting/localized corrosion as it has a negligible crack initiation life relative to the crack propagation life. The relative difference in log scale is linearly deducted from the S-N curves of riveted details given in fatigue codes to obtain the S-N curves of riveted details, which are exposed to corrosive environments. The detailed derivation is presented in authors' previous publications.[3,16] Hence, the fatigue strength range of riveted details in corrosive environments, $\Delta\sigma_{cor}$, corresponding to N_R, can be derived, if $\Delta\sigma_{cor} \geq \Delta\sigma_{D,cor}$,

$$\log(\Delta\sigma_{cor}) = \log(\Delta\sigma) - \left[\frac{\log\Delta\sigma_D - \log\Delta\sigma_{D,cor}}{\log N_{f,CAFL} - \log N_{f,LCF}}\right](\log N_R - \log N_{f,LCF}) \tag{2}$$

where $\Delta\sigma_{D,cor}$ is the stress range corresponding to $N_{f,CAFL}$ cycles at the intersection of the two slopes of fatigue curves for corrosive environments. Here, $N_{f,LCF}$ is the number of cycles to fatigue failure of riveted details at the intersection point of their high-cycle fatigue (HCF) and LCF regions. This has been generally considered as 10^4 cycles, which is the lowest value of N_R given in fatigue design codes.[17,18] The proposed formula for the fatigue strength of riveted detail categories in corrosive environments can be simplified as

$$\frac{\Delta\sigma_{cor}}{\Delta\sigma} = \left(\frac{N_R}{N_{f,LCF}}\right)^{-c} \text{where } c = \frac{\log\Delta\sigma_D - \log\Delta\sigma_{D,cor}}{\log N_{f,CAFL} - \log N_{f,LCF}} \tag{3}$$

By substituting $\Delta\sigma$ from Equation (1), the proposed formula for the fatigue strength for the riveted detail exposed to a corrosive environment can be obtained as

$$\Delta\sigma_{cor} = \Delta\sigma_D\left[N_{f,LCF}^{c} N_{f,CAFL}^{1/m}\right] N_R^{(-c-1/m)} \tag{4}$$

If $\Delta\sigma_{cor} \leq \Delta\sigma_{D,cor}$, the fatigue strength of riveted details exposed to corrosive environments can be obtained,

$$\log(\Delta\sigma_{D,cor}) - \log(\Delta\sigma_{cor}) = \frac{[\log\Delta\sigma_{D,cor} - \log\Delta\sigma_{L,cor}]}{[\log N_{f,CAFL} - \log N_{f,VAFL}]}(\log N_{f,CAFL} - \log N_R) \tag{5}$$

or

$$\frac{\Delta\sigma_{cor}}{\Delta\sigma_{D,cor}} = \left(\frac{N_R}{N_{f,CAFL}}\right)^{\acute{c}} \text{where } \acute{c} = \frac{\log\Delta\sigma_{D,cor} - \log\Delta\sigma_{L,cor}}{\log N_{f,CAFL} - \log N_{f,VAFL}} \tag{6}$$

When $\Delta\sigma_{cor} \leq \Delta\sigma_{D,cor}$, the proposed formula for the fatigue strength of riveted details exposed to corrosive environments can be obtained,

$$\Delta\sigma_{cor} = \Delta\sigma_{D,cor}\left[N_{f,CAFL}^{-\acute{c}}\right] N_R^{\acute{c}} \tag{7}$$

Parameters c and $\acute{c}$ depend on the CF endurance of the riveted details, and values of the parameters are given in the following section.

2.3 | Corrosive environment dependent parameters of the proposed curve

The values of $\Delta\sigma_D$,$\Delta\sigma_L$,m,$N_{f,LCF}$,$N_{f,CAFL}$, and $N_{f,VAFL}$ are directly obtained from the code providing fatigue strength/S-N curves of riveted structural details.[4,17-19] Eurocode detail category 71 represents the fatigue strength of riveted members.[5] In addition to detail category 71, the WI-rivet detail category also represents riveted details, as proposed in the UK railway assessment code.[4,18,19] The $\Delta\sigma_{D,cor}$ and $\Delta\sigma_{L,cor}$ are the corrosive state and the environment-dependent parameters, and full-scale fatigue tests should be performed in the VHCF region to determine these parameters. The full-scale tests of riveted members and joints in simulated corrosive environments are challenging, in terms of both resources and time. Fracture mechanics approaches were very popular in the past for determining the above parameters in the presence of corrosion pits. However, recent investigations of carbon steel reveal that CF cracks initiate in any corrosive media, due to a different mechanism and not necessarily due to the presence of pits.[20,25-27]

Reasonable accurate values of c, $\acute{c}$ $\Delta\sigma_{D,cor}$, and $\Delta\sigma_{L,cor}$ for riveted details in urban environments are presented in this section. These parameters directly relate to the CF endurance of structural steel specimens tested in natural water. The fatigue limit for specimens tested in air, $\sigma_{\infty,}$ and the endurance limit for the specimens tested in natural water, $\sigma_{\infty,cor}$, were determined as corresponding to 10^7 cycles of fatigue tests of several grades of precorroded and uncorroded steel specimens, which were tested in natural water.[23,28,29] The ratio $\sigma_{\infty,cor}/\sigma_{\infty}$ varies in the range of 0.53 to 0.70. The mean and coefficient of variation (COV) of the ratio are 0.61 and 0.1. The conservative value for $\sigma_{\infty,cor}/\sigma_{\infty}$ ratio is proposed as 0.5, by considering a 5% failure probability. Hence, the values for $\Delta\sigma_{D,cor}$ and $\Delta\sigma_{L,cor}$ are obtained by interpolations and extrapolations of the $\sigma_{\infty,cor}/\sigma_{\infty}$ ratios corresponding to $N_{f,CAFL}$ and $N_{f,VAFL}$ for Eurocode detail category 71. The corresponding mean and conservative values (i.e. design value = mean-2×standard deviation) are calculated and listed in Table 1. Similarly, for the WI-rivet detail category, the corresponding values are calculated as shown in Table 1. Hence, the mean and design c and $\acute{c}$ values are calculated for both detail categories, as shown in Table 1. There is no discrepancy in the number of cycles at the curve slope changing point, $N_{f,CAFL}$ between the two S-N curves of riveted details (one which is exposed to air and another which is exposed corrosive environments).

3 | EXPERIMENTAL VERIFICATION OF THE PROPOSED CURVE

The proposed S-N curves of riveted detail categories are compared with full-scale fatigue tests of riveted joints, plate girders, and truss girders to confirm the validity of the proposed curve. The formulas in Equations (4) and (7) along with specific parameters given in Table 1 are used to obtain the S-N curve of riveted details exposed to corrosive environments. The formula given in Equation (1) with the parameters in Table 1 are utilized to predict the corresponding S-N curve in air of the same detail. Commonly used fatigue codes in Europe have defined only two detail categories for riveted structural details, i.e. detail category 71, which is given in Eurocode[17] and WI-rivet detail category, which is given in the UK railway assessment code.[4,18,19] As shown in Equation (1), slope (s) of the S-N curves in air is $-1/m$. The slopes before and after the knee point (i.e. S-N curve slope changing point) of S-N curve for riveted details exposed to corrosive environments are $-c-{}^1\!/_m$ and $\acute{c}$, respectively, as shown in Equations (4) and (7). The corresponding values of the plotted curves are shown in Figures 2–4 and 8.

Larsson[5] collected fatigue test results of riveted bridge components from the literature. These results were obtained from full-scale testing of riveted plate girders. Most of the components were subjected to a four-point bending test. One of the reports states the frequency of the fatigue tests as 520 cycles/minute.[6] The frequency is vital for CF tests as the effect of corrosive environment to the steel is time dependent. As mentioned in the Sections 2.1 and 2.3, the concept of the S-N curve and curve parameters were studied from the standard CF results of different types of steel specimens (both precorroded and uncorroded) tested in corrosive environments.[3,16] In these tests, the frequency of CF tests were determined based on the testing standards.[16]

The reported fatigue lives are compared with the predicted fatigue curve for riveted plate girders, as shown in Figure 2. Eurocode detail category 71 represents the fatigue strength of riveted members.[5] The proposed S-N curve for an urban environment was plotted using the formulae given in Equations (4) and (7), as shown in Figure 2. The model parameters are selected from Table 1, corresponding to detail category 71. Figure 1B shows that the fatigue test results of corroded plate girders have a good match with the proposed fatigue curve formula, and this deviates from the detail category 71 curve. The fatigue lives of 7 out of 131 test results are below the predicted fatigue curve, and some of the rivet heads of these plate girders were severely corroded. Those girders were extracted from Blumberg Bridge and Westkreuz Bridge, which are old. The chemical composition of the material might be quite different from the structural steel, and different temperature conditions were reported during the test. Apart from detail category 71, the WI-rivet detail-based S-N curve, which is given in the UK railway assessment code,[4,18,19] has also been used for fatigue life estimation of many ageing riveted bridges. The proposed S-N curve, based on the WI-rivet detail category, was plotted using the formula given in Equations (4) and (7), as shown in Figure 3. The model parameters given in Table 1 have been used. The proposed S-N curve, which was predicted by the WI-rivet detail category, shows a good match with the test results, as shown in Figure 3, in the case of those joints whose rivet heads have severely corroded.

Full-scale test results of riveted truss girders/lattice girders[5] are compared with proposed Equations (4) and (7), as shown in Figure 4. The full-scale test includes a four-point bending test, cantilever test, and tension test. Two sets of the proposed S-N curves were predicted, based on detail categories 71 and WI-rivets, respectively, and compared with test results: the same

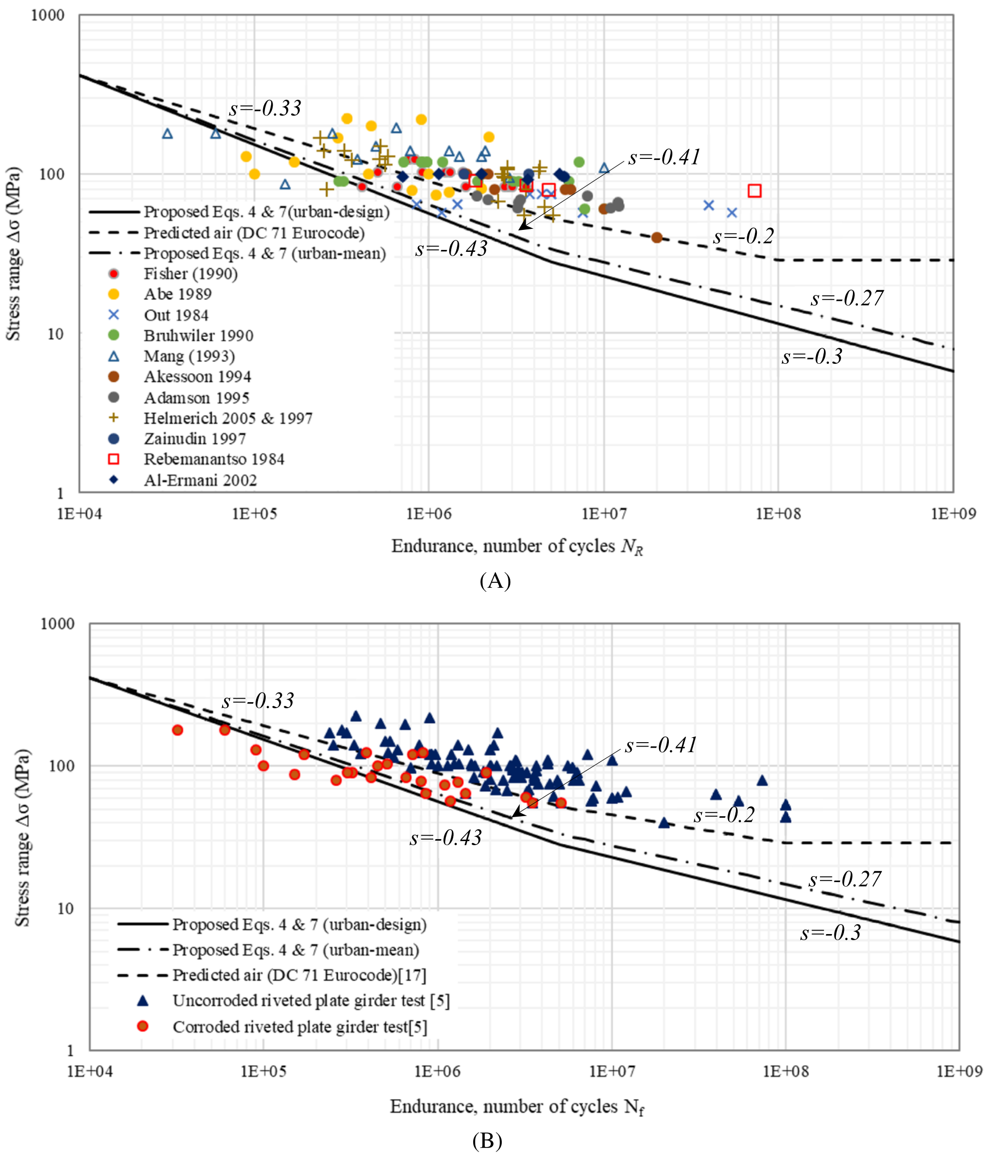


FIGURE 2 Comparison of proposed S-N curve corresponds to detail category 71, with full-scale fatigue tests of riveted plate girders: (A) for all the girders and (B) for corroded and uncorroded girders separately [Colour figure can be viewed at wileyonlinelibrary.com]

as previous verification of the riveted plate girder. As the corrosion state was not properly reordered in the dissertation,[5] both corroded and uncorroded test results were used in the comparison. Figure 4 shows that the fatigue test results of corroded truss girders have a reasonable match with the proposed fatigue curve formula.

A recently proposed strain-life model[7,8] predicted sample S-N curves of three different corrosion rates, which are compared with the S-N curves for marine and urban environments predicted by Equations (4) and (7), as shown in Figure 5. The corrosion factor of zero was considered for obtaining the S-N curve in air. Both proposed models show good agreement, as shown in Figure 5.

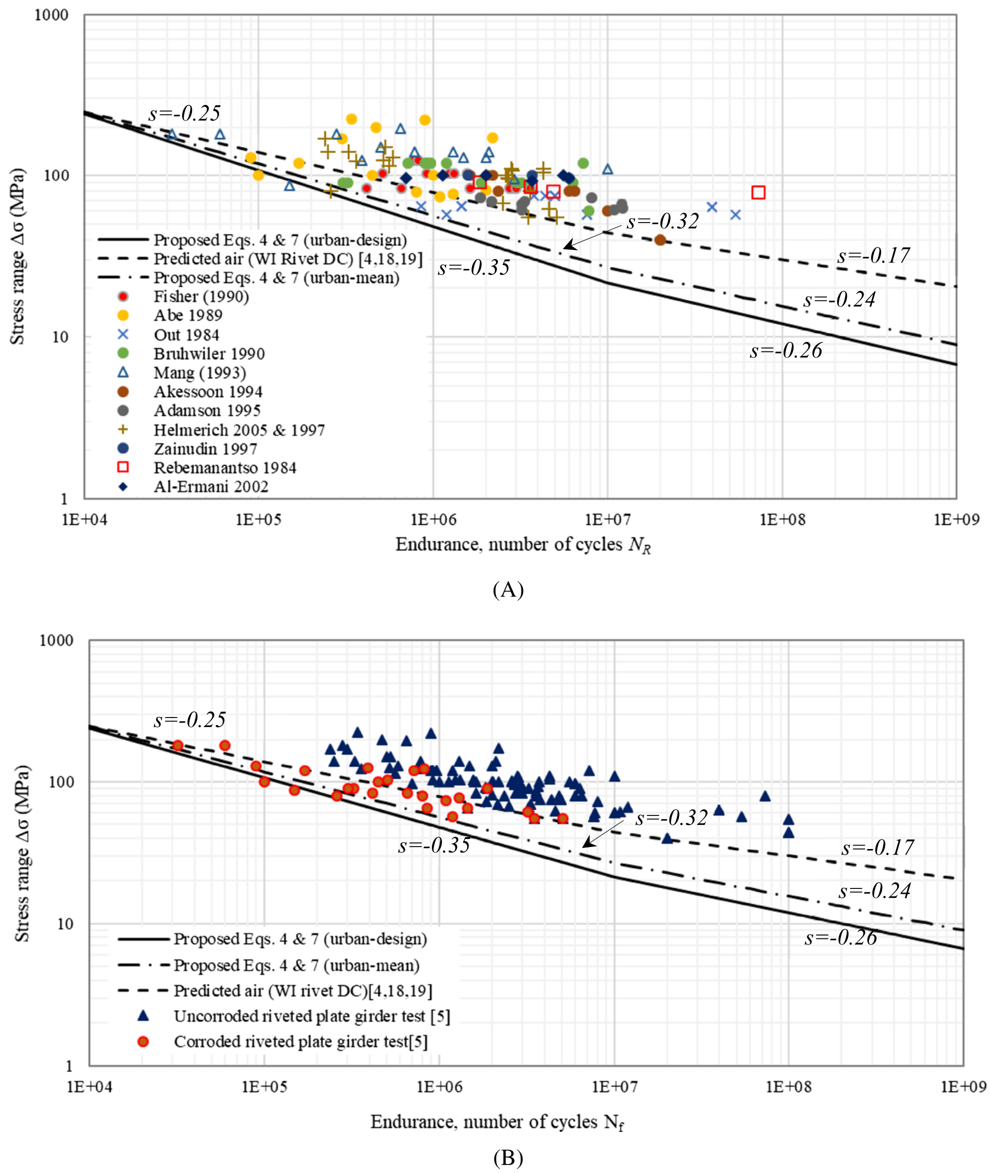
4 | CASE STUDY BRIDGE AND STRESS EVALUATION

A riveted railway bridge in an urban corrosive environment is considered for fatigue life estimation in this paper.

4.1 | Considered riveted bridge and current status

The considered riveted railway bridge (Figure 6) was constructed in 1885. It is a Warren truss girder bridge and 160 m in length. The bridge material is wrought iron. The use of wrought iron was replaced by that of mild

FIGURE 3 Comparison of proposed S-N curve corresponds to WI-rivet detail category, with full-scale fatigue tests of riveted plate girders: (A) for all the girders and (B) for corroded and uncorroded girders separately [Colour figure can be viewed at wileyonlinelibrary.com]



steel throughout the world by the end of the 19th century. The full-scale fatigue test results of riveted members illustrate no significant difference between steel and wrought iron.[5] The loading details and geometrical details were presented in the first author's previous article.[4] The members of the bridge are categorized into several sets, based on similar cross-sectional properties, as shown in Figure 7.

Uniform corrosion has been investigated during many periodical inspections, which are reported in Tables 2 and 3 of the first author's previously published paper.[4] Cross girders, stringers, the bottom chord of the Warren truss and truss diagonal members have been mainly subjected to corrosion, as shown in Figure 6. Patch corrosion has been detected, and minor maintenance activities have been carried out. Surface treatments and overcoating have not been properly attended to, due to lack of funding and facilities. Therefore, a sign of corrosion was observed in the same locations before the end of the coating life.[4] Pitting and crevice corrosion have been reported in a few places of the bridge where water and soil deposits accumulate. A detailed assessment of the structural integrity was carried out in 2001, and the mechanical properties, geometric details, and loading details were obtained from the published literature.[4,30]

4.2 | Determination of stress histories/stress evaluation

The time-dependent loss of material due to uniform corrosion (i.e. corrosion wastage) changes the cross-sectional properties; hence, the overall structural stiffness changes with the service life. The corrosion wastage has been presented by a nonlinear function for the considered bridge, as below,[4,22]

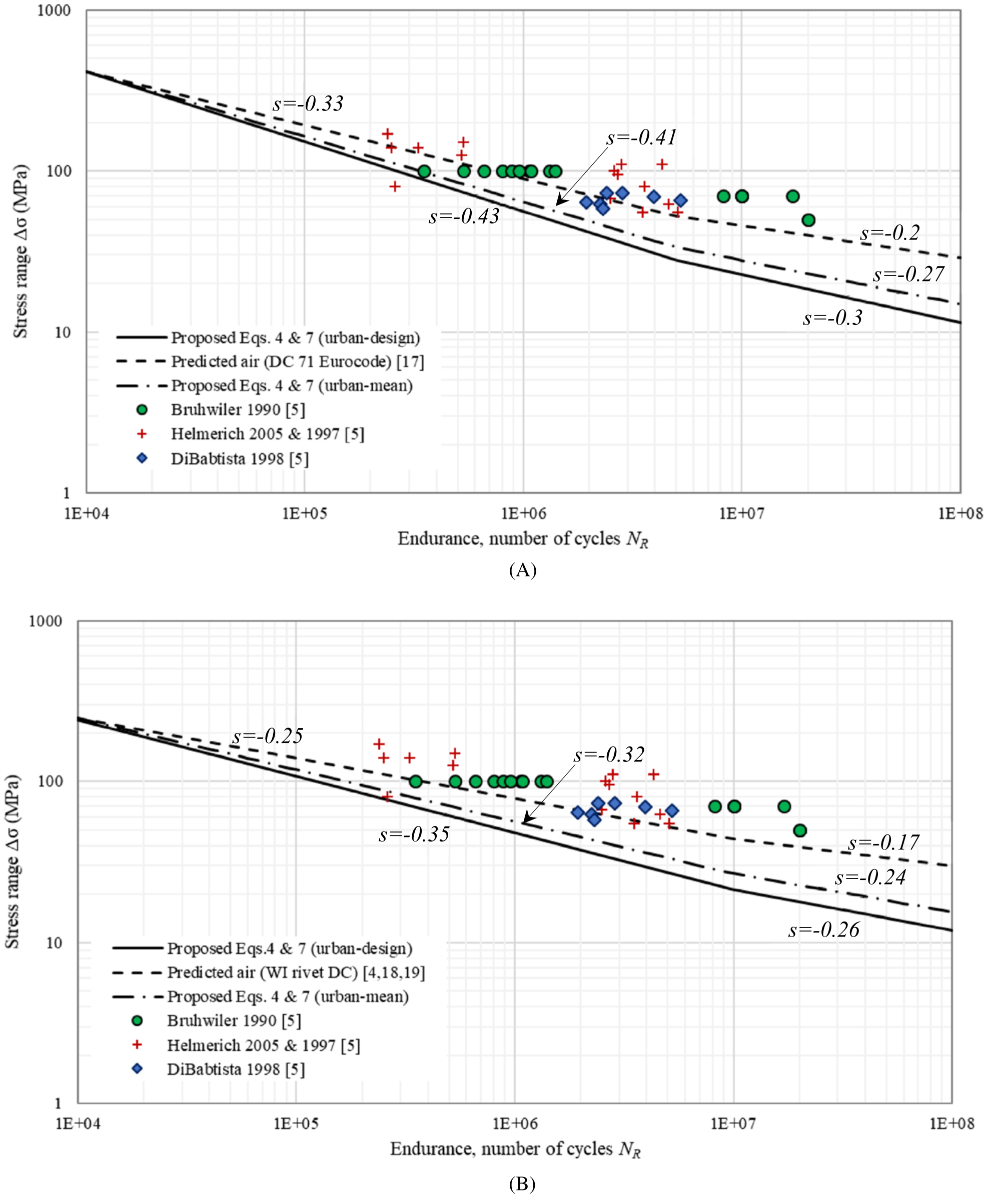


FIGURE 4 Comparison of proposed S-N curve with full-scale fatigue tests of riveted truss girders: (A) S-N curve for urban environment predicted by detail category 71 (B) S-N curve for urban environment predicted WI-rivet detail category [Colour figure can be viewed at wileyonlinelibrary.com]

$$C(t) = 0.0706(t - t_0)^{0.789}; t > t_0 \tag{8}$$

where $C(t)$ is the average corrosion penetration in millimetres, t is the age in years, and t_0 is the time in years of the first appearance of general corrosion. The effective cross-sectional area, the second moment of area, the torsional constants, and the warping constants were calculated, considering the reduction in plate thickness due to corrosion by the following proposed formulae in previously published paper.[4] These cross-sectional properties were utilized with a validated finite element model[30] to obtain the stress histories of the fatigue-critical members. A time history, dynamic analysis was conducted for each train passage, based on past, present, and future time schedules. The rain-flow cycle counting algorithm was used to calculate the equivalent nominal stress ranges.

5 | FATIGUE LIFE ASSESSMENT BY DETERMINISTIC APPROACH

The fatigue assessment for the above-mentioned railway bridge was performed by deterministic stress-life approach. The proposed S-N curve in an urban corrosive environment was used, and obtained lives were then compared with the conventional approach-predicted fatigue lives.

FIGURE 5 Comparison of proposed S-N curve with Aghoury's strain-life model's[7,8] predicted fatigue endurances for different corrosion factors [Colour figure can be viewed at wileyonlinelibrary.com]

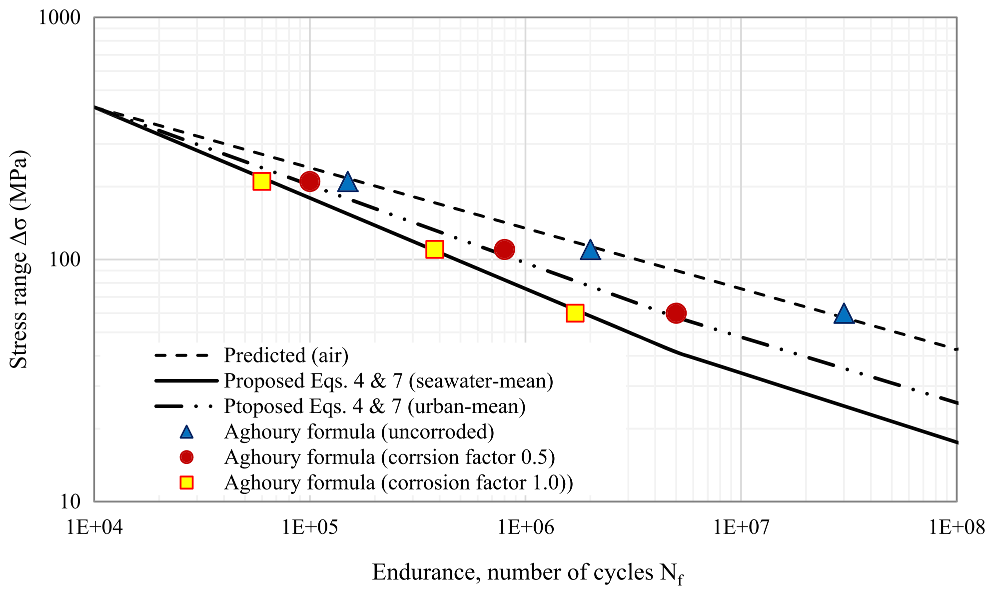


FIGURE 6 General view and some of the corroded locations of the bridge[4] [Colour figure can be viewed at wileyonlinelibrary.com]

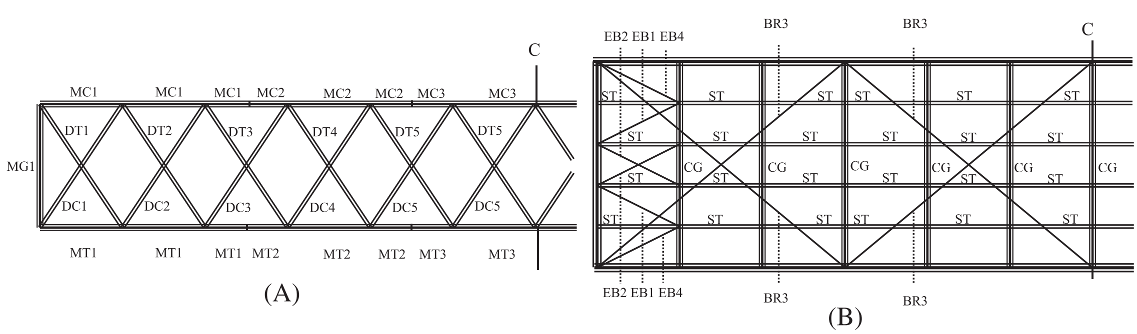


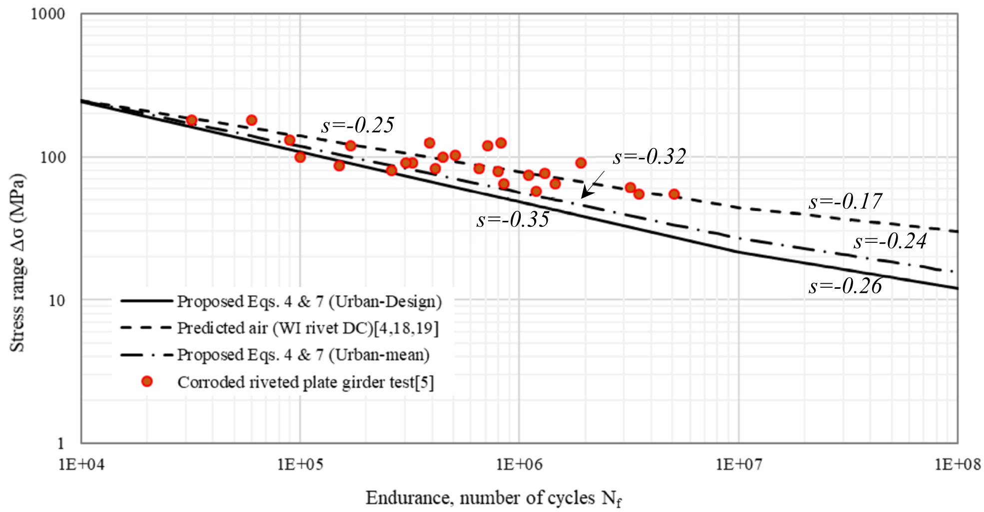
FIGURE 7 Member designations: (A) main truss girder and (B) horizontgal bridge deck[4]

TABLE 2(A) Fatigue lives calculated by deterministic approach based on WI-rivet detail category S-N curve

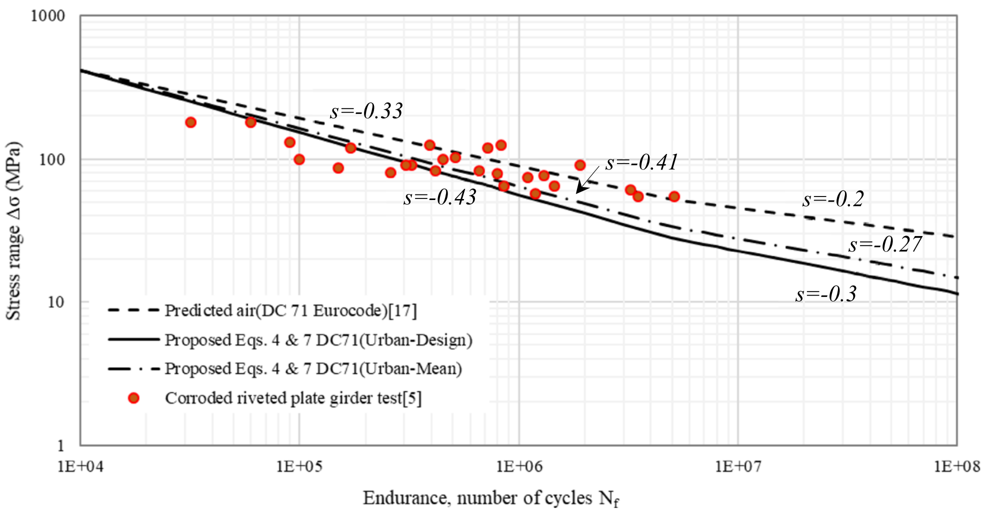
		Fatigue Life, years			
				Method 3	
Bridge Component	Member Set	Method 1	Method 2	Mean	Design
Truss diagonal (tension members)	DT3	247	228	144	134
Main girder bottom chord	MT2	272	248	147	136
Cross girders	CG	136	132	120	118
Stringers	ST	140	138	122	119

TABLE 2(B) Fatigue lives calculated by deterministic approach based on DC 71 detail category S-N curve

		Fatigue Life, years			
				Method 3	
Bridge Component	Member Set	Method 1	Method 2	Mean	Design
Truss diagonal (tension members)	DT3	271	215	152	140
Main girder bottom chord	MT2	300	228	157	143
Cross girders	CG	141	129	122	120
Stringers	ST	146	133	123	121



(A)



(B)

FIGURE 8 S-N curves for riveted details/joints in the bridge in urban corrosive environment: (A) developed based on WI-rivet detail category and (B) developed based on detail category 71 in Eurocode [Colour figure can be viewed at wileyonlinelibrary.com]

5.1 | Fatigue strength curves/S-N curves

The bridge was constructed by means of built-up members, connected by rivets. Figure 2 shows that the obtained S-N curves of the corroded riveted joints (refer to air S-N curve of detail category 71) have good agreement with former fatigue test results, if the state of corrosion is not severe and the rivet heads are protecting the holes from corrosion.[5] The WI-rivet detail category, which is given in the UK railway assessment code,[4,18,19] shows a good match with test results, as shown in Figure 3, in the case of the joints whose rivet heads have severely corroded. Therefore, both of the curves were used for fatigue life calculation in this case study. The proposed S-N curves for corroded riveted joints are plotted by Equations (4) and (7), as shown in Figure 8. The model parameters given in Table 1 were used to obtain the proposed fatigue curves.

5.2 | Fatigue life estimation

The fatigue lives of the bridge were calculated based on a combination of the obtained nominal stress ranges in Section 4.2, the S-N curve shown in Figure 8 and Miner's rule.[31] The calculated fatigue lives of critical members of each member set (Figure 7) are shown in Table 2. Three different methods were considered in this life estimation. In Method 1, lives were calculated based on a combination of nominal stress histories, without considering corrosion wastage, the uncorroded S-N curve, and Miner's rule. A combination of the nominal stress ranges obtained by considering corrosion wastage (i.e. Section 4.2), the S-N curve without cut-off limit (i.e. without constant amplitude fatigue limit),[4,11,12,15] and Miner's rule[31] is used in Method 2. In Method 3, the calculation was performed based on a combination of the nominal stress ranges obtained by considering the corrosion wastage (i.e. Section 4.2), the proposed S-N curve obtained by Equations (4) and (7), and Miner's rule.[31]

5.3 | Comparison and discussion of results

The fatigue lives predicted by the proposed curve (i.e. Method 3) are compared with the previous conventional approaches (i.e. Methods 1 and 2). The time-dependent change of member stiffness, which was discussed in Section 4.2, was not taken into account in the previous fatigue assessment approach. Lives calculated by Method 3, which includes the proposed fatigue strength curve shown in Equations (4) and (7), show a significant reduction in fatigue lives from Method 1. This reduction is observed when the precise fatigue strength curve and the time-dependent change of stiffness of the members are considered. About 50% and 15% reductions in the fatigue lives, which refer to Method 1, were observed for the truss girder members and deck members, respectively. The reductions,which refer to Method 2, are about 40% and 10% for the truss girder members and deck members, respectively. This comparison reveals the significance of using the proposed fatigue curve to perform safe life assessment of corroded constructional details.

6 | FATIGUE LIFE ASSESSMENT BY PROBABILISTIC APPROACH

The fatigue assessment was performed for the considered riveted railway bridge by means of the probabilistic stress-life approach in this section. The proposed S-N curve for WI-rivet detail category in an urban corrosive environment is only used for the probabilistic fatigue life assessment. The obtained lives were then compared with the conventional approach-predicted fatigue lives.

6.1 | Fatigue reliability index

The fatigue reliability index is determined for the riveted bridge, based on a probabilistic bilinear S-N approach. The definition of the fatigue reliability index is given as

$$\beta = \emptyset^{-1}\left(1 - P_f\right) \tag{9}$$

where $\emptyset^{-1}$ is the inverse of the standard normal distribution function. The P_f is the failure probability of the fatigue limit state, and the function of the limit state is defined as,

$$g(t) = \Delta - D_{cor} \tag{10}$$

where Δ is fatigue damage accumulation threshold. The Δ follows lognormal distribution with a mean value of 1.0 and COV of 0.3. The D_{cor} is the cumulative damage of the riveted detail in a corrosive environment, which can be derived as

$$D_{cor} = \frac{N(t)}{A_{cor}}\left(S_{re}\right)^{m_{cor}} \tag{11}$$

where S_{re} is the equivalent constant amplitude stress range, calculated using a bilinear *S-N* approach, as shown in Equation (12). The $N(t)$ is the subjected number of cycles of the considered detail at age t. From Equations (4) and (7),

If $S_{re} \geq \Delta\sigma_{D,cor}; m_{cor} = m_1 = 1/_{c+1/m}$ and $A_{cor} = A_1 = \left[\Delta\sigma_D N_{f,LCF}^{c} N_{f,CAFL}^{1/m}\right]^{m_1}$

If $S_{re} < \Delta\sigma_{D,cor}; m_{cor} = m_2 = -1/\acute{c}$ and $A_{cor} = A_2 = N_{f,CAFL} \Delta\sigma_{D,cor}^{-1/\acute{c}}$

The m_1 and m_2 are slopes of the bilinear S-N curve of riveted details in corrosive urban environments. The considered deterministic parameters are m_1, m_2, $\Delta\sigma_{D,cor}$, and $N(t)$. The stress range, S_{re}, and fatigue detail coefficient, A_{cor}, are considered random variables. The corrosive parameters of mean *S-N* curves of the WI-rivet detail category are obtained from Figure 8A and Table 1. Hence, the values of m_1, m_2, A_1, and A_2 were calculated as 3.11, 4.2, 2.785×10^{11} and 1.023×10^{13}, respectively. The S_{re} can be determined for a bilinear S-N approach as[32]

$$S_{re} = \left[\frac{\sum\left(n_i^o S_{ri}^{m_1}\right) + \left(CAFT^{m_1 - m_2}\right).\sum\left(n_j^o S_{rj}^{m_2}\right)}{\sum\left(n_i^o\right) + \sum\left(n_j^o\right)}\right]^{1/m_1} \tag{12}$$

where n_i^o is the number of cycles in the i^{th} stress range when S_{ri} is greater than the $\Delta\sigma_{D,cor}$, and n_j^o is the number of cycles in j^{th} stress range when S_{rj} is less than the $\Delta\sigma_{D,cor}$. If the probability density faction (PDF) is available for stress ranges of the riveted detail, S_{re} can be calculated by[30]

$$S_{re} = \left[\int_0^{CAFT} \left(CAFT^{m_1 - m_2}\right).S^{m_2}.f_s(s).ds + \int_{CAFT}^{\infty} S^{m_1}.f_s(s).ds\right]^{1/m_1} \tag{13}$$

Monte Carlo simulation is utilized with Equations (10) and (11) to calculate the fatigue reliability index (β) versus lifetime of the riveted details of the bridge. The fatigue life of each detail can be predicted when β reaches the target reliability index (β_{target}).

6.2 | Fatigue assessment

The equivalent nominal stress ranges of each member obtained in Section 4.2 were plotted in histograms, and PDFs were obtained. These PDFs follow lognormal distribution. Then Equation (13) was used to determine S_{re} for each critical riveted detail of the bridge. The COVs of S_{re}, A_{cor}, and Δ are 0.1, 0.45, and 0.3, respectively.[33,34] The fatigue reliability index β can be derived, based on Equations (10) and (11), as all the random variables follow the lognormal distribution,

$$\beta(t) = \begin{cases} \dfrac{\lambda_\Delta + \lambda_{A_1} - m_1.\lambda_{S_{re}^L} - \ln N(t)}{\sqrt{\zeta_\Delta^2 + \zeta_{A_1}^2 + \left(m_1.\zeta_{S_{re}^L}\right)^2}} & for\, N(t) \leq \dfrac{A_1}{CAFT^{m_1}} \\ \dfrac{\lambda_\Delta + \lambda_{A_2} - m_2.\lambda_{S_{re}^B} - \ln N(t)}{\sqrt{\zeta_\Delta^2 + \zeta_{A_2}^2 + \left(m_2.\zeta_{S_{re}^B}\right)^2}} & for\, N(t) > \dfrac{A_1}{CAFT^{m_1}} \end{cases} \tag{14}$$

where λ and ζ are lognormal parameters of the various random variables. The equivalent constant amplitude stress ranges, S_{re}, can be calculated using either linear or bilinear S-N approaches, respectively. The S_{re}^L is the one calculated by a linear *S-N* approach, while S_{re}^B is calculated by a bilinear *S-N* approach. Hence, the fatigue reliability profiles were obtained by Equation (14) for each critical member and plotted in Figure 9. Based on a

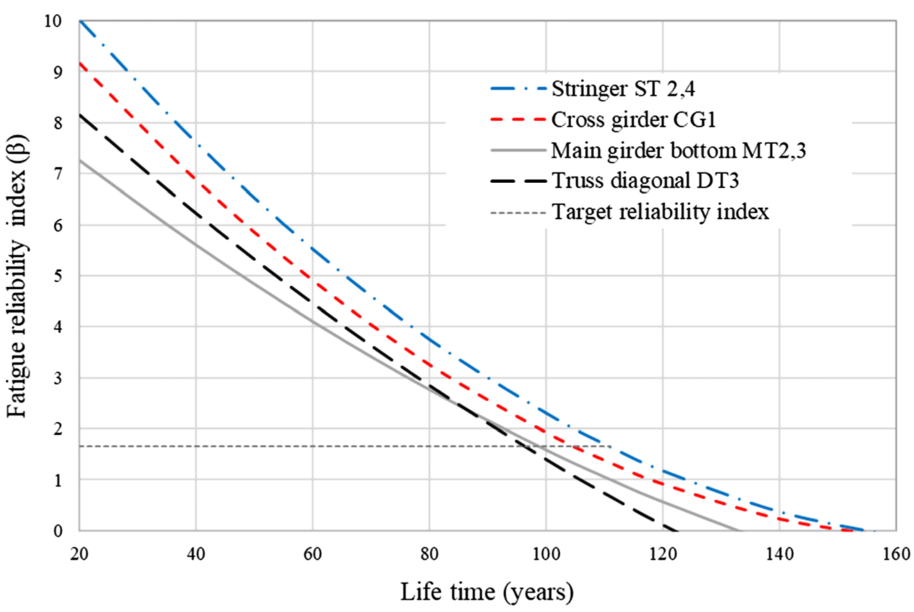


FIGURE 9 Fatigue reliability index versus life of the bridge components [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Fatigue lives calculated by probabilistic approach based on WI-rivet detail category S-N curve

		Fatigue Life, years			
		Method 1		Method 2	
Bridge Component	Member Set	$\beta_{target} = 1.65$	$\beta_{target} = 0$	$\beta_{target} = 1.65$	$\beta_{target} = 0$
Truss diagonal tension	DT3	108	157	95	123
Main girder bottom	MT2,3	102	150	99	132
Cross girders	CG1	119	170	105	151
Stringers	ST2,4	135	191	110	154

survival probability of 95%, the target reliability indices were considered as 1.65. The calculated fatigue lives are shown in Table 3.

6.3 | Comparison and discussion of results

The probabilistic fatigue lives predicted by the proposed curve (i.e. Method 3) are compared with those of the previous conventional Method 1. In the Method 1 (i.e. conventional probabilistic approach), lives were calculated based on the combination of nominal stress histories, without considering corrosion wastage, the uncorroded S-N curve and Miner's rule (as discussed in Section 5.2). Equation (11) is not used in Method 1. The cumulative damage of the riveted detail in air is obtained based on Equation (1). The corresponding values of m_1, m_2, and $\Delta\sigma_D$ are taken from Table 1. Hence, the values of m_1, m_2, A_1, and A_2 were calculated as 4, 6, 3.117×10^{13} and $5.489\times \times10^{16}$ respectively. Lives calculated by Method 3, which includes the proposed fatigue strength curve shown in Equations (4) and (7), show a significant reduction in fatigue lives from Method 1. This reduction emphasizes the importance of using the proposed S-N curve formula to perform safe life assessment of the riveted joints, members, and components, which are exposed to corrosive environments.

7 | CONCLUSIONS

A fatigue strength formula is proposed for riveted structural details, which are exposed to urban corrosive environments. The S-N curves predicted by the proposed formula are in very good agreement with experimentally obtained fatigue lives of riveted plate girders and truss girders tested in urban environments. Some of the test members are already weathered and deteriorated. The main reason for having a good match with the full-scale fatigue test results is that the CF mechanism and concept of the derivation have been studied at a microstructural level, in specimen scale, and finally incorporated into structural member and joint scale. The values of the curve parameters were determined for two commonly used detail categories, i.e. detail category 71 given in Eurocode and WI-rivet detail category given in the UK railway assessment code. The main advantage of the proposed formula is that it can directly apply to any steel or wrought iron riveted structural details, without requiring additional CF tests or any corrosive parameters. Fatigue lives calculated by a deterministic approach show a significant reduction when the effect of corrosion is considered. This reduction is not very significant when probabilistic fatigue life estimation is used, as this approach takes into account the uncertainties of the mean S-N curve and stress evaluation. These reductions in fatigue lives further highlight the importance of having accurate S-N curves for ageing riveted bridges for conservative maintenance practices. The effect of the frequency in variable amplitude CF tests should be studied, especially for full-scale structural details.

NOMENCLATURE

CF corrosion fatigue
$C(t)$ average corrosion penetration in millimetres
DC detail category
HCF high-cycle fatigue
LCF low-cycle fatigue
m negative inverse slope of the S-N curve
N_R number of cycles to fatigue failure
$N_{f,FL}$ endurance number of cycles
$N_{f,LCF}$ number of cycles to fatigue failure of the uncorroded materials at the yield strength
$N_{f,CAFL}$ number of cycles at constant amplitude fatigue limit
$N_{f,VAFL}$ number of cycles at variable amplitude fatigue limit; t, age in years
t_0 time in years of the first appearance of general corrosion
VHCF very high cycle fatigue
WI wrought iron
$\Delta\sigma$ stress range
$\Delta\sigma_{cor}$ fatigue strength range of corroded constructional detail

$\Delta\sigma_D$, stress range at constant amplitude fatigue limit
$\Delta\sigma_{D,cor}$, stress range at intersecting points of two slopes of corroded fatigue curve at $N_{f,CAFL}$ cycles
$\Delta\sigma_L$ stress range at variable amplitude fatigue limit
$\Delta\sigma_{L,cor}$ stress range at $N_{f,VAFL}$ cycles
β reliability index
Δ Miner's critical damage accumulation index
D_{cor} Miner's damage accumulation index in corrosive environment
S_{re} equivalent constant amplitude stress ranges calculated using bilinear S-N
s slope of the S-N curve
$N(t)$ subjected number of cycles of the considered detail at age t
A_{cor} fatigue detail coefficient
n_i^o the number of cycles in ith stress range when S_{ri} is greater than the $\Delta\sigma_{D,cor}$
n_j^o number of cycles in jth stress range when S_{rj} is less than the $\Delta\sigma_{D,cor}$
β_{target} target reliability index

ORCID

N.D. Adasooriya https://orcid.org/0000-0001-8412-8009

REFERENCES

1. Imam BM, Righiniotis TD. Fatigue evaluation of riveted railway bridges through global and local analysis. *J Constr Steel Res*. 2010;66:1411-1421.
2. Helmerich R, Kuhn B, Nussbaumer A. Assessment of existing steel structures: a guideline for estimation of the remaining fatigue life. *J Struct Infrastruct Eng*. 2007;3:245-255.
3. Adasooriya ND, Hemmingsen T, Pavlou D. Fatigue strength degradation of metals in corrosive environments. *Proceedings of First Conference of Computational Methods in Offshore Technology-COTech 2017, IOP Conf Ser: Mater Sci Eng.*: IOP Publishing; Stavanger, Norway: 2017: Article number 276 012039.
4. Adasooriya ND, Siriwardane SC. Remaining fatigue life estimation of corroded bridge members. *Fatigue Fract Eng Mater Struct*. 2014;37:603-622.
5. Larsson T. *Fatigue assessment of riveted bridges, PhD dissertation*. Sweden: Luleå University of Technology; 2009.
6. Johannes MM. *Fatigue strength of weathered and deteriorated riveted members, MSc dissertation*. USA: Lehigh University; 1984.
7. El Aghoury I. Numerical tool for fatigue life prediction of corroded steel riveted connections using various damage models, PhD thesis. Canada, Montreal: Concordia University; 2012.
8. El Aghoury I, Galal K, Corrosion fatigue strain-life model for steel bridge girders under various weathering conditions. *J Struct Eng*. 2014;140(6):04014026.
9. Kayser JR, The effects of corrosion on the reliability of steel girder bridges. *PhD thesis.* Ann Arbor. Mich., USA. University of Michigan; 1998.
10. Mohamed ELM, Thierry PL, Nicolas S, Olivier D. Effect of corrosion on the high cycle fatigue strength of martensitic stainless steel X12CrNiMoV12-3. *Int J Fatigue*. 2013;47:330-339.
11. Wahab MA, Sakano M. Corrosion and biaxial fatigue of welded structures. *J. Mat. Proc. Tech. 3*. 2003;143-144:410-415.
12. Nguyen KT, Garbatov Y, Soares CG. Spectral fatigue damage assessment of tanker deck structural detail subjected to time-dependent corrosion. *Int J Fatigue*. 2013;48:147-155.
13. Roberge PR. *Handbook of Corrosion Engineering*. 1st ed. New York: McGraw Hill; 2000.
14. Mikkelsen O, Rege K, Hemmingsen T, Pavlou D. Numerical estimation of the stop holes-induced fatigue crack growth retardation in offshore structures taking into account the corrosion effect. *Proceeding of International Society of Offshore and Polar Engineers Conference Series.* San Francisco: American Society of Mechanical Engineers, 2007: ISOPE-I-17-552: 451-458.
15. Gerhard S, Christian K, Bertram K, Hensen W. *Condition assessment and inspection of steel railway bridges, including stress measurements in riveted, bolted and welded structures: sustainable Bridges-Background document SB3.4*. Digital Vetenskapliga Arkivet: Sweden; 2007.
16. Adasooriya ND, Pavlou D, Hemmingsen T. Fatigue strength degradation of corroded structural details: A formula for *S-N* curve. *Fatigue Fract Eng Mater Struct*. 2019;1-13. https://doi.org/10.1111/ffe.13156
17. NS EN 1993-1-9. *Eurocode 3: Design of steel structures—Part 1-9: fatigue*. Belgium: European Committee for Standardization 2005+NA 2010.
18. Imam B, Righiniotis TD, Chryssanthopoulos MK. Fatigue assessment of riveted railway bridges. *Int J Steel Struct*. 2005;5: 485-494.
19. RT/CE/C/025, Railtrack Line Code of Practice: The structural assessment of underbridges, Railtrack, 2001.
20. Zhao T, Liu Z, Du C, Dai C, Li X, Bowei Z. Corrosion fatigue crack initiation and initial propagation mechanism of E690 steel in simulated sea water. *Mat Sci & Eng A*. 2017;708: 181-192.
21. Gangloff RP. In: Baboian R, Dean SW Jr, Hack HP, Hibner EL, Scully JR, eds. *Environmental cracking - corrosion fatigue*. Corrosion Tests and Standards Manual. ASTM Internationals; 2005.
22. Yasser Y, Jeom KM. Ultimate strength reliability analysis of corroded steel-box girder bridges. *Thin-Walled Struct.* 2011;49: 157-166.
23. Revie RW, Uhlig HH. *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering*. 4th ed. US, Wiley and Sons; 2008.
24. Glaser W, Wright LG. *Mechanically Assisted Degradation. ASM Handbooks*. ASM Internationals; 1992:137-144.
25. Vucko F, Bosch C, Delafosse D. Effects of cyclic plastic strain on hydrogen environment assisted cracking in high-strength steel. In: *International Hydrogen Conference (IHC 2012): Hydrogen-Materials Interactions*. WY, United States: American Society of Mechanical Engineering:2012.
26. Vucko F, Bosch C, Aoufi A, Delafosse D. Palladium coating on quenched-tempered martensitic steel for hydrogen electrochemical permeation tests. Technical Reports- ENSMSE-SMS-2014-01. France: EMSE-00951142; 2014.

27. Wang R. Corrosion fatigue of metal materials. *Xi'an: Press of Northwestern Polytechnical University*. 2001.
28. Boyer HE. *Atlas of Fatigue Curves*. USA: ASM International; 1986.
29. Bandara CS. *Fatigue Damage Assessment of Steel Structures and Components, Improvements in Stress-Life Approach*. Germany: LAP Lambert Academic Publishing; 2015.
30. Siriwardane S, Ohga M, Dissanayake R, Taniwaki K. Structural appraisal-based different approach to estimate the remaining fatigue life of railway bridges. *Int Health Monitoring*. 2010;9: 323-339.
31. Miner MA. Cumulative damage in fatigue. *J Appl Mech*. 1945; 12:159-164.
32. Soliman M, Frangopol DM, Kown K. Fatigue assessment and service life prediction of existing steel bridges by integrating SHM into a probabilistic bilinear S-N approach. *J Struc Eng*. 2013;139:1728-1740.
33. Kwon K, Frangopol DM, Soliman M. Probabilistic fatigue life estimation of steel bridges by using a bilinear S-N approach. *J Bridge Eng*. 2012;17:58-70.
34. Kwon K, Frangopol DM. Bridge fatigue reliability assessment using probability density functions of equivalent stress range based on field monitoring data. *Int J Fatigue*. 2010;32:1221-1232.

How to cite this article: Adasooriya ND, Hemmingsen T, Pavlou D. S-N curve for riveted details in corrosive environment and its application to a bridge. *Fatigue Fract Eng Mater Struct*. 2020; 43:1199–1213. https://doi.org/10.1111/ffe.13193