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TOWARDS A CORROSION-FATIGUE STRAIN-LIFE MODEL FOR STEEL BEAMS IN CORROSIVE ENVIRONMENTS

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Abstract: Corrosion is considered to be an influential factor that significantly contributes to the reduction of the fatigue life of steel structures. Corrosion-Fatigue is a complex phenomenon which is not easy to simulate. Very few corrosion-fatigue models exist in literature for civil engineering applications. To account for corrosion in fatigue life prediction, the methodology of a new fatigue strain-life model based on the Smith-Watson-Topper model is proposed. The proposed modified SWT model provides minimum and maximum fatigue life predictions in the form of ranges. The model takes into account the corrosivity of the environment, the stress level, and the corrosive behaviour of the material used. The preliminary resulting fatigue life predictions matched well with the experimental results of thirteen steel beams subjected to various fatigue and weathering conditions that are reported in the literature.

1 Introduction

Corrosion is a process of degradation of a metal by an electrochemical reaction with its surrounding environment due to the loss of the electrons of the metals reacting with water and oxygen. Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Corrosion-fatigue behaviour of a given material-environment system refers to the characteristics of the material under fluctuating loads in the presence of a particular corrosive environment. There are not many standardized design procedures available for engineers to design steel elements or predict their fatigue lives in corrosive environments. This is because the required tests to calibrate these procedures would take a long time and need special configurations. Regularly, for design simplicity, engineers would assume a reduced section in future (after corrosion) and would predict the fatigue life based on that section. This is not an accurate approach as corrosion-fatigue damage occurs more rapidly than would be expected from the algebraic sum of the individual effects of fatigue and corrosion.

2 Literature Review

Corrosion-fatigue is a complex phenomenon which is also highly dependent upon the material and the surrounding environment. Fatigue life prediction in corrosive environments has always been so important to study in the fields of aerospace using the concepts of fracture mechanics as provided in the ASTM STP 801 (1983). Very little work has been done on steel structures from the structural engineering point of view. Novak (1983) has investigated the corrosion fatigue crack initiation (CFCI) behaviour for several types of steel from the point of view of fracture mechanics. The fracture mechanics approach doesn't provide the structural engineers with a simple way for evaluating the fatigue life of corroded steel members without getting into the details of crack sizes nor the crack initiation or propagation phases. Experimentally, there are very limited tests available for full scale specimens that are cyclically loaded along with the environmental effect of corrosion being simulated simultaneously. Albrecht et al. (1983, 1994, and 2009) has thoroughly (for more than 30 years) experimentally investigated the effect of corrosion on the fatigue life of structural steel elements.

This research focuses more on providing a methodology for structural engineers to estimate the corrosion-fatigue life of steel members in corrosive environments. Therefore, the objective of this study is to highlight the main methodology of a proposed strain-life fatigue-corrosion model and to suggest ways of calibrating based on the material properties and the corrosivity of the environment. Such a model will be a valuable analytical tool that would assist in estimating the fatigue life for corroded steel elements, without the costly experimental work and its complex test setups.

3 Corrosion-fatigue strain-life model

3.1 Proposed Factors

It is well known that the fatigue life of metallic materials degrades quickly in corrosive environments. In this research, an analytical approach will be taken to standardize a procedure to quantify this degradation of material properties.

The endurance of any material to cyclic loading can be determined using any strain-life method by using an elastic part and a plastic part. The elastic part is usually defined by the fatigue strength exponent, *b*, which is a material property also known as Basquin's exponent. The plastic part is defined by the fatigue ductility coefficient, *c*, which is a material property known as the Coffin-Manson exponent. In this research, it is proposed to adopt modified values for b and c for a certain corrosive environment and they will be denoted as *b'* and *c'*, respectively. Similar to the tabulated values of *b* and *c* for different materials, the values of b' and c' could be easily obtained through material testing. Figure 1 schematically shows the relationship between total strain amplitude and endurance in a highly corrosive environment versus a non-corrosive environment.

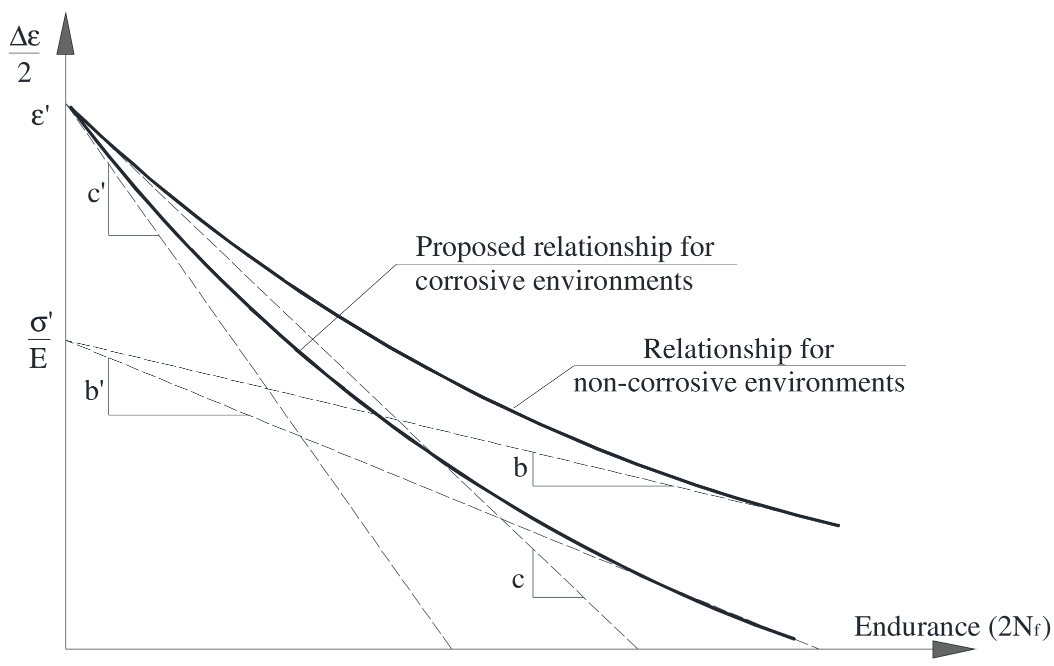

Figure 1: Relationship between total strain amplitude and endurance in a highly corrosive environment

In order to evaluate the modified material properties b' and c', four new factors will be proposed, namely α_b, α_c, γ_{corr}, γ_σ. To be used as shown in equations 1 and 2:

[1] $$b' = b\,(1 + \gamma_{corr}\gamma_\sigma\alpha_b)$$

[2] $$c' = c\,(1 + \gamma_{corr}\gamma_\sigma\alpha_c)$$

The factor α_b will be taken to be equal to *(b' / b) - 1* where *b'* can be measured by curve fitting the experimental results in a standard highly corrosive environment (i.e. NaCL 3.5% testing environment or equivalent). Similarly, α_c will be equal to *(c' / c) - 1* where *c'* can be measured similar to *b'*. The factor γ_{corr} will be the environmental corrosivity intensity factor that typically varies from 0 to 1, where 0 corresponds to a totally non-corrosive environment. In order to quantify the corrosivity of the environment on a scale from 0 to 1, the corrosivity corresponding to 1 should be standardized. In this research this value corresponds to a highly corrosive environment equivalent to the NaCL 3.5% solution simulation environment usually used in accelerated corrosion tests. However, values of γ_{corr} greater than unity can be obtained in some special severely corrosive environments stronger than the NaCL 3.5% solution simulation environment. Once the experimental data is plotted, *b'* and *c'* corresponding to $\gamma_{corr} = 1$ can be easily calculated, then both α_b and α_c can be obtained and saved as material constants for a harsh environment corresponding to $\gamma_{corr} = 1$. The factor γ_σ is introduced as a correction factor for the mean stress effects which depends on the maximum applied stress σ_{max}. Equations 1 and 2 were proposed in this format such that if there is no corrosion (i.e. $\gamma_{corr} = 0$), the equations will lead to the regular *b* and *c*.

In this paper, the Smith-Watson Topper (SWT) strain-life method by Topper et al. (1970) was chosen as the base strain-life model to build the proposed modification upon for corrosion. This could be done by replacing *b* with *b'* and replacing *c* with *c'*. Thus the modified SWT model format becomes:

[3] $$\frac{\Delta\varepsilon}{2}\sigma_{max} = \frac{\left(\sigma_f^{'}\right)^2}{E}\left(2N_f\right)^{2b'} + \sigma_f^{'}\varepsilon_f^{'}\left(2N_f\right)^{b'+c'}$$

3.2 Calibration of the proposed model

In this study, a relation is proposed to correlate the environmental corrosivity intensity factor γ_{corr} with the average annual penetration in (μm/year). This relationship was deduced by calibrating the obtained fatigue lives along with the corrosion penetration rates reported by Albrecht et al. (1994) and compared them to the ISO-9224 corrosion penetration rates. Equation 4 was derived for the A588 steel by El-Aghoury (2012) as a relation between the logarithm of the penetration versus the proposed corrosion factor γ_{corr} .

[4] $$\gamma_{corr} = 0.0761\log(p_a)^2 + 0.2109\log(p_a) + 0.221$$

where p_a is the average annual penetration in (μm/year). The proposed environmental corrosivity intensity factor γ_{corr} for A588 steel has been correlated by El-Aghoury (2012) to the categories provided by the ISO-9223 (1992) and the ISO-9224 (1992) as shown in Table 1.

Table 1: Correlation between γ_{corr} and the ISO-9224 corrosivity categories

	ISO-9224 Category (*r_a* = average corrosion rate)	γ_{corr}
Very low corrosivity	C1 ($r_a \leq 0.1 \mu m/year$)	0→0.09
Low corrosivity	C2 ($0.1 \leq r_a \leq 2 \mu m/year$)	0.09→0.29
Medium corrosivity	C3 ($2 \leq r_a \leq 8 \mu m/year$)	0.29→0.47
High corrosivity	C4 ($8 \leq r_a \leq 15 \mu m/year$)	0.47→0.57
Very High corrosivity	C5 ($15 \leq r_a \leq 80 \mu m/year$)	0.57→0.9

After calibration with several experimental tests, it was found that for A588 steel, *b'* = -0.13 and *c'* = -0.61. The properties of the A588 steel can be presented for a regular service environment as the product $\gamma_{corr}\,\gamma_{\sigma}\;\;\alpha_b$ = 0.182 and the product $\gamma_{corr}\,\gamma_{\sigma}\;\;\alpha_c$ = 0.034 (El-Aghoury, 2012). Due to the complexity of the corrosion-fatigue phenomenon, the probabilistic nature of fatigue and the difficulty of accurately determining exact the corrosion state, it was chosen not to present the predicted fatigue life as a definite value, but rather as an expected range. To consider these effects, a range of values of γ_{corr} corresponding to $\gamma_{corr} \pm 0.05$ was chosen and will be used to give a predicted life range.

4 Verification of the Model

In order to calibrate the proposed model in other corrosive environments, a real case study will be simulated and verified against published test results. The chosen experimental investigation was done by Albrecht et al. (1994) to investigate the fatigue behaviour of 24 corroded rolled beams made of A588 steel. In this paper, 13 beams out of 24 are selected for verification for a certain corrosive environment. This set of 13 beams was exposed for 67 months under a metal deck that simulated the shelter provided by highway bridge decks and was lightly sprayed with a salt solution during the winter months to simulate the use of de-icing salts for snow removal. A spreader beam distributed the load to two points spaced 914 mm (3 ft) apart as shown in Figure 2.

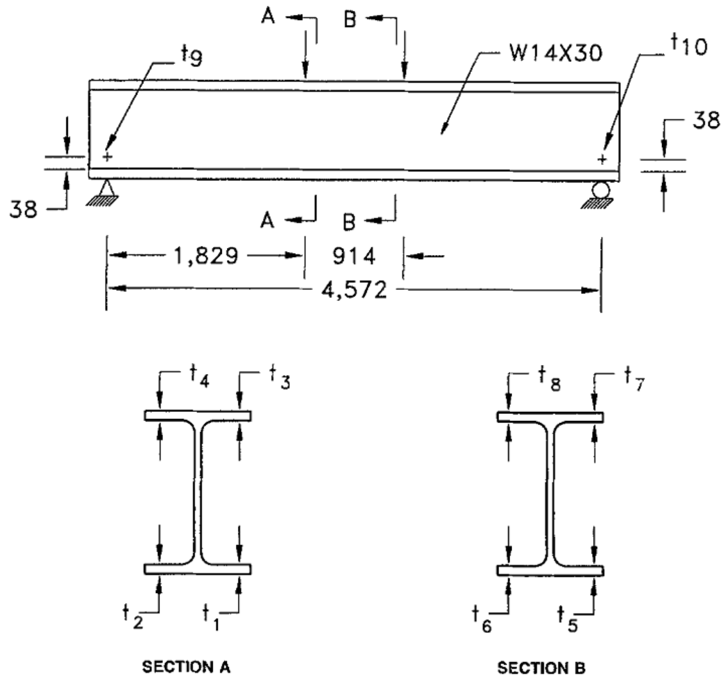

Figure 2: Configurations of tested beams tested by Albrecht et al. (1994)

4.1 Material properties

The studied beams were made of A588 grade B weathering steel ("A588 Standard" 1992) with average 577 MPa tensile strength, 408 MPa reported yield point (nominally 345 MPa) and E = 200 000 MPa. The proposed environmental constants will be taken for the boldly exposed specimens as $\gamma_{corr}\,\gamma_{\sigma}\,\alpha_b$ = 0.182 and $\gamma_{corr}\,\gamma_{\sigma}\,\alpha_c$ = 0.034 obtained in section 3.2. By comparing the values of corrosion penetration rates reported by Albrecht et al. (1994) for the sheltered specimens tested in moist saltwater environment (which is a very harsh environment), the values from the ISO-9224 were extrapolated and the factor γ_{corr} = 1.1 was used as an average value to represent this environment. It is worthy to note that the value obtained for γ_{corr} is found to be greater than unity which means that the testing environment was so corrosive, this is clear from the other corrosion penetration rates reported by Albrecht et al. (1994) in comparison to the ISO-9224 (1992) corrosion categories.

Thirteen beams were studied; the loading was based on stress ranges for the unweathered sections. Fatigue calculations were based on the final weathered sections. Corrosion rates for each part of the specimens were reported by Albrecht et al. (1994).

4.2 Fatigue Life Prediction

In order to include the mean stress effects and relate it to the material properties, values of $\gamma_{corr}\,\gamma_{\sigma}$ were plotted against the values of the maximum stress normalized to the ultimate stress $\sigma_{\max} / \sigma_u$ reported by Albrecht et al. (1994). The introduction of the factor γ_{σ} was useful in calibrating the model as it was clear that the results were stress level dependant. As the ratio $\sigma_{\max} / \sigma_u$ gets less, the sensitivity of the factor $\gamma_{corr}\,\gamma_{\sigma}$ gets higher.

By curve fitting, an equation (5) was derived as follows:

[5] $$\gamma_{\text{corr}}\gamma_{\sigma} = 5.77\left(\frac{\sigma_{\max}}{\sigma_u}\right) + 5.35$$

5 Discussion of results

The results obtained for the expected life for each specimen are presented as a range corresponding to $\gamma_{corr} \pm 0.05$ for each testing environment. The range of ±0.05 was chosen after examining several values for the range, and it proved to result in very good predictions of the fatigue life, as will be shown later. The ranges of the values of the predicted number of cycles to failure are plotted versus the experimentally determined values from Albrecht et al. (1994) as shown in Figure 3. Despite the valuable reported data and results regarding the beams that were used to calibrate the analytical model, it is worth mentioning that the experimental data is a bit scattered with different loadings and the environmental conditions and that there is still a need for more available data points to further calibrate the model.

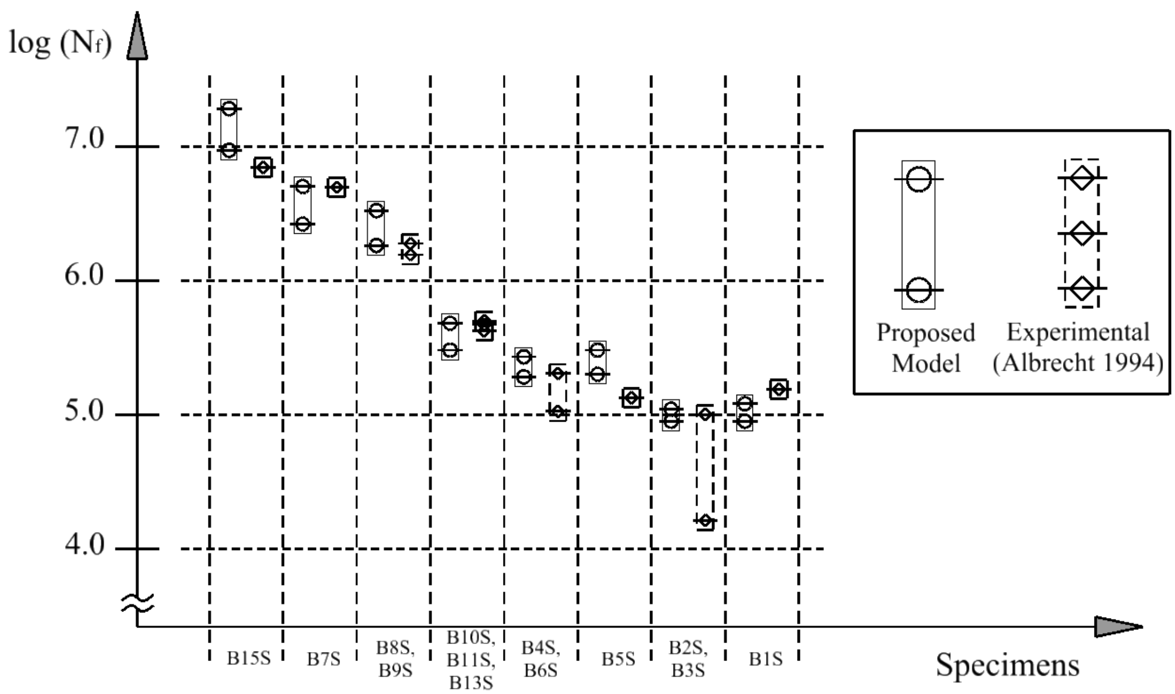

Figure 3: Predicted lives using the proposed model versus experimentally measured by Albrecht et al. (1994)

The set of tested beams have a very wide spectrum of different values for stress ranges and maximum applied stresses. All the predicted lives in this group were on the conservative side except for beams B15S and B5S. This highlights the need for more experimental tests in order to further calibrate the proposed $\gamma_{corr}\ \gamma_{\sigma}$ function. Specimens B2S and B3S are important to mention as they have a relatively high stress range and the highest ratio of $\sigma_{\max} / \sigma_u$ being equal to 0.51. There is a very big scatter in the experimental results between these two identical specimens which indicates that specimen B3S might have experienced premature failure. This is highly probable, especially given that the predicted analytical range of the fatigue life is so close to that of B2S. It is important to mention that by applying the regular SWT on the corroded sections, the expected life is very high and very non-conservative in comparison to the use of the proposed modified SWT model.

From the above, it could be concluded that the analytical predictions of fatigue life using the proposed model correlates very well with the measured experimental fatigue life of the thirteen tested beams.

6 Conclusions and future work

Taking into consideration the complexity of the corrosion-fatigue phenomenon, there is a relatively good agreement between the results obtained using the proposed model and the reported experimental values of thirteen weathered steel beams tested by Albrecht et al. (1994). The proposed model generally gives conservative results. Moreover, there is a big scatter in the results of some of the experimental specimens, this shows the efficiency of providing the results in the form of ranges rather than providing a single definite value.

It can be noticed from the analytical results that the predicted range of fatigue cycles increases as the stress level decreases, and vice versa. The effect of the maximum applied stress was found to be of significant importance in this study and was taken into account by the factor $\gamma_{corr}\ \gamma_{\sigma}$ which is a function in the ratio $\sigma_{\max} / \sigma_u$. The relation between the ratio $\sigma_{\max} / \sigma_u$ and the factor $\gamma_{corr}\ \gamma_{\sigma}$ was found to be inversely proportional with a linear trend. It should be noticed that further experimental work is needed to calibrate the proposed function and to check if the observed behaviour would be the same for other types of steel. Moreover, this research highlights the need for testing enough structural materials in order to have a comprehensive database of their proposed environmental properties.

By comparing the predicted fatigue lives with the available experimental results and with the regular SWT model without considering the effects of corrosion, it can be said that it is not sufficient to model corrosion just by geometrically reducing the section, as this would not provide an accurate estimation for the fatigue life. Hence, it is important to implement the newly proposed modified SWT strain-life model to account for the effect of corrosion and different levels of maximum applied stresses.

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