

Corrosion-Fatigue Strain-Life Model for Steel Bridge Girders under Various Weathering Conditions

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Abstract: Corrosion of existing infrastructure, such as steel bridges, would significantly reduce its anticipated fatigue life. There are very few corrosion-fatigue models that address civil engineering applications. To account for corrosion in the fatigue life prediction of steel bridges, a new fatigue strain-life model based on the Smith-Watson-Topper model is proposed. The proposed model provides the fatigue life predictions in the form of ranges with a minimum and a maximum value. The model takes into account the corrosivity of the environment, the stress level, and the corrosive behavior of the material used. The resulting fatigue life predictions using the proposed model matched well with the experimental results reported in the literature for 24 steel beams that were subjected to various fatigue and weathering conditions. The analytical predictions show that the proposed model is accurate, simple, and practical and can be easily calibrated for different materials. DOI: 10.1061/(ASCE)ST.1943-541X.0000992. © 2014 American Society of Civil Engineers.

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Introduction and Background

Corrosion is the process of degradation of a metal through an electrochemical reaction with its surrounding environment, i.e., loss of the electrons of the metal as it reacts with water and oxygen. The weakening of iron attributable to the oxidation of the iron atoms is a well-known example of electrochemical corrosion, which is commonly known as rust (Trethewey and Chamberlain 1996). Much of the corrosion damage in structures within the last 40 years might have been caused by a change in the chemical composition of the air attributable to the increased industrial activity (Boden 1989). Atmospheric deterioration of exposed steel bridges is influenced by the following natural factors: moisture, temperature (mean value and variations), sunlight, air movement (wind speed and direction), sea salt, and fog. However, rain reduces the corrosion rate by washing away dangerous pollutants.

Corrosion-fatigue behavior for 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 equations available for engineers to design structural steel elements or predict their fatigue lives in corrosive environments, mainly because of the scarceness of experimental research because of the associated complexity, cost, and time. Typically, structural engineering practitioners would assume an anticipated reduced section (after corrosion) and derive their fatigue life predictions from that reduced 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.

Corrosion fatigue is a complex phenomenon that is highly dependent on the material and the surrounding environment. Fatigue life prediction in corrosive environments has always been important to study in the fields of aerospace. Most of the research work in this area has been done on materials such as aluminum and titanium and several alloys used in aerospace structures to determine their fatigue behavior in corrosive environments using concepts of fracture mechanics. For a comprehensive resource on previous work in this area, refer to Metal Properties Council (1983). On the other hand, very little work has been done on steel structures from the structural engineering point of view and intended civil engineering applications. Novak (1983) has investigated the corrosion fatigue crack initiation (CFCI) behavior for four types of steel: A36, A588-A, A517-F, and V-150 steels. The main observation was that there is no clear corrosion fatigue crack initiation threshold for the four types of steel after corrosion, in contrast to the fatigue crack initiation thresholds that are clearly obtained from tests in non-corrosive environments. Despite its merit, Novak's approach was still addressing the corrosion-fatigue phenomenon using fracture mechanics approach, not providing structural engineers a simple way of evaluating the fatigue life of corroded steel members without getting into the details of crack sizes, crack initiation, or crack propagation phases.

There are very limited tests available in the literature for full-scale specimens of structural elements that are cyclically loaded while simultaneously subjected to environmental effects of corrosion. Albrecht (Albrecht 1983; Albrecht and Jian-Guo 1983; Albrecht and Maher 1989; Albrecht and Shabshab 1994; Albrecht and Lenwari 2008, 2009) is one of the few researchers who thoroughly investigated experimentally the effect of corrosion on the fatigue life on structural steel elements for more than 30 years. Also, Zuraski and Johnson (1990) studied the effect of long-term exposure of bridges and conducted fatigue tests on specimens removed from the tension flange of truss stringers salvaged from four bridge replacement projects. There is also several research work on corrosion-fatigue behavior of steel reinforcement bars in concrete by DeJong et al. (2009).

The objective of this study is to propose a new practical approach for solving the corrosion-fatigue problem without the difficulties of fracture mechanics approach. To achieve this goal,

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a strain-life fatigue-corrosion model that can be calibrated based on the material properties and the corrosivity of the environment is proposed. Such a model will be a valuable analytical tool that would assist in estimating the corrosion-fatigue life for steel elements in corrosive environments, such as exposed steel bridges, without the costly experimental work and its complex test setups.

Proposed Corrosion Fatigue Strain-Life Model

Proposed Factors

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 a material property called the fatigue strength exponent, b , which is 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 the current model, 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 and can be used in any strain-life model to include the effect of corrosion. Fig. 1 schematically shows the relationship between total strain amplitude and endurance in a highly corrosive environment versus a noncorrosive environment.

Four new factors will be introduced in the proposed model, namely α_b , α_c , γ_{corr} , and γ_σ . In this model, the factor α_b will be taken to be equal to $(b'_{\text{fit}}/b) - 1.0$ where the modified fatigue strength component for corrosive environment, b'_{fit} , can be measured by curve fitting the experimental fatigue tests results done in a standard highly corrosive environment (e.g., NaCL 3.5% testing environment or equivalent). Similarly, α_c will be equal to $(c'_{\text{fit}}/c) - 1.0$ where the modified fatigue ductility coefficient for corrosive environment, c'_{fit} , can be obtained from fatigue tests done in a standard highly corrosive environment, similar to b'_{fit} . The factor γ_{corr} is introduced and defined as the environmental corrosivity intensity factor that would typically vary from 0 to 1.0, where 0 corresponds to a totally noncorrosive environment. To quantify the severity or corrosivity of the environment on a scale from 0 to 1.0, the corrosivity corresponding to $\gamma_{\text{corr}} = 1.0$ should be standardized. In this research, the limit of $\gamma_{\text{corr}} = 1.0$ was arbitrarily chosen to correspond to a highly corrosive environment equivalent to the NaCL 3.5% solution simulation environment that is usually

used in accelerated corrosion tests. Nevertheless, values of γ_{corr} greater than unity can be obtained in some rare severely corrosive environments stronger than the NaCL 3.5% solution simulation environment. Once the experimental data of typical fatigue tests (done on the subject material in a standard highly corrosive environment) are obtained, b' and c' corresponding to $\gamma_{\text{corr}} = 1.0$ can be easily calculated, then both α_b and α_c can be obtained and hence identified as material constants for a harsh environment corresponding to $\gamma_{\text{corr}} = 1.0$. The factor γ_σ is introduced as a correction factor to account for effect of the mean stress on the fatigue life, as will be shown later in details.

For any corrosive environment corresponding to γ_{corr} between the value of 0 and 1.0 (or more than 1.0 in case of corrosion exposure that is more than NaCL 3.5% solution) both b' and c' can be easily calculated using the following equations:

$$b' = b(1 + \gamma_{\text{corr}}\gamma_\sigma\alpha_b) \quad (1)$$

$$c' = c(1 + \gamma_{\text{corr}}\gamma_\sigma\alpha_c) \quad (2)$$

The two previous equations were proposed in this format such that the values of b' and c' simplifies back to the conventional b and c values when there is no corrosion (i.e., $\gamma_{\text{corr}} = 0$). In this study, the Smith-Watson-Topper (SWT) strain-life method (Smith et al. 1970) was chosen as the base strain-life model to build on using the proposed modification for corrosion. This could be done by replacing b with b' and replacing c with c' . Thus the modified SWT model format becomes

$$\frac{\Delta\varepsilon}{2}\sigma_{\text{max}} = \frac{(\sigma'_f)^2}{E}(2N_f)^{2b'} + \sigma'_f\varepsilon'_f(2N_f)^{b'+c'} \quad (3)$$

where the factors b' and c' = modified exponents in corrosive environments that can be obtained from Eqs. (1) and (2); $\Delta\varepsilon$ = strain range; σ_{max} = maximum applied normal stress; σ'_f = fatigue strength coefficient; ε'_f = fatigue ductility coefficient; E = modulus of elasticity; and N_f = number of cycles to failure.

The assumptions made in the current proposed strain-based corrosion model are based on reported observations of the corrosion-fatigue behavior, where the constants proposed for each material can be obtained from experimental data. For example, it is expected that the values of b and c will change as consistently observed in the reported S-N curves obtained in corrosive environments (ISO 1992a, b). The aim of the current proposed model is to quantify this change. As such, there would be a future need for developing a comprehensive database for fatigue response of various structural materials tested under corrosive environment.

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 $\mu\text{m}/\text{year}$. This relationship was deduced by calibrating the obtained fatigue lives along with the corrosion penetration rates reported by Albrecht and Shabshab (1994) and comparing them with the ISO-9224 corrosion penetration rates. Eq. (4) shows the proposed relation between the common logarithm of the average annual penetration, p_a , in $\mu\text{m}/\text{year}$ versus the proposed corrosion factor γ_{corr} .

$$\gamma_{\text{corr}} = 0.0776 \log(p_a)^2 + 0.2121 \log(p_a) + 0.2179 \quad (4)$$

Fig. 2 shows the p_a - γ_{corr} proposed relationship where it shows good correlation with test results from Albrecht and Shabshab

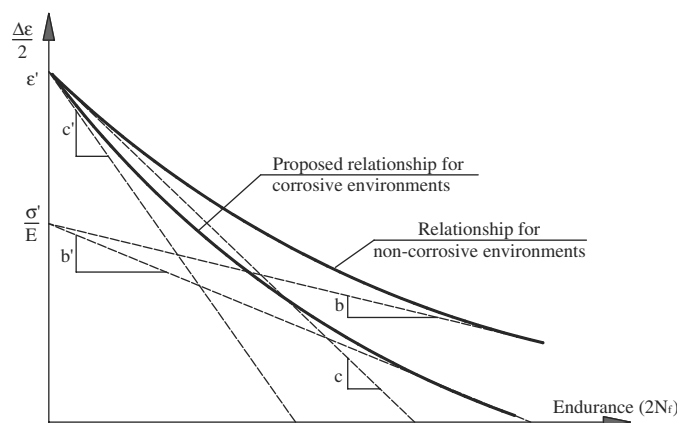


Fig. 1. Relationship between total strain amplitude and endurance in a highly corrosive environment

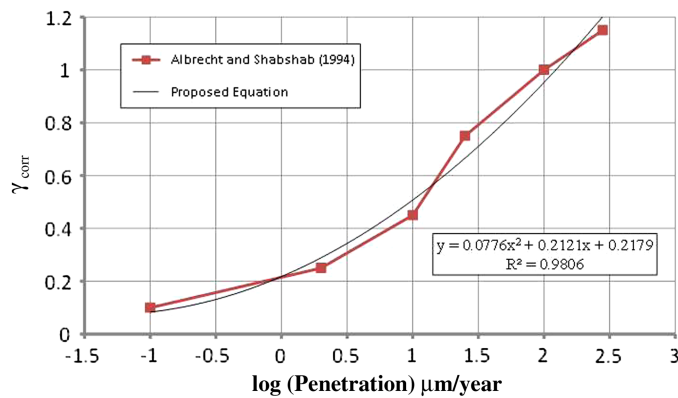


Fig. 2. Proposed relation between the log of the penetration versus the corrosion factor γ_{corr}

(1994). Furthermore, the proposed environmental corrosivity intensity factor γ_{corr} could be correlated to the categories provided by ISO-9223 (1992a) and ISO-9224 (1992b) as shown in Table 1.

Because of the limited long-term experimental corrosion fatigue life data available for the plain specimens made of structural steel presented in the form of strain-life data points, it would be useful to convert any available S-N data points for a corrosive environment to strain-life data points. In this study, the stress life (S-N) corrosion fatigue life data for plain coupons of weathering steel (which is usually used in steel bridges) tested for 2 years by Kunihiro et al. (1972) will be used. Kunihiro et al. tested plain specimens fabricated from JIS-SMA weathering steel (commonly used in Japan), which is also similar in composition and corrosion rates to the A588 weathering steel (commonly used in North America) as reported by Albrecht and Shabshab (1994). All specimens were $19 \times 50 \times 459$ mm. Fig. 3 shows a typical set of Kunihiro's data showing the 0-year (unweathered) coupons versus the 2-year weathered coupons.

The data was then digitized and transformed into strain-endurance life data points by using the cyclic fatigue properties of this steel using the cyclic strain hardening coefficient K' and the cyclic strain hardening exponent n' in Eq. (5):

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma / 2}{E} + \left(\frac{\Delta \sigma / 2}{K'} \right)^{1/n'} \quad (5)$$

The properties of JIS-SMA weathering steel is an average 580-MPa tensile strength, 355-MPa yield point, and $E = 200,000$ MPa. Using the universal material method of Baumele and Seeger (1990), $K' = 1,400$ MPa, $n' = 0.15$, $\sigma'_f = 870$ MPa, $b = -0.09$, $\varepsilon'_f = 0.59$, and $c = -0.58$ are obtained. To get the values of stresses

Table 1. Correlation between γ_{corr} and the ISO-9224 Corrosivity Categories

Corrosion level	ISO-9224 Category (r_a = average corrosion rate, $\mu\text{m}/\text{year}$)	Proposed values for γ_{corr}
Very low corrosivity	C1 ($r_a \leq 0.1$)	0 to 0.09
Low corrosivity	C2 ($0.1 \leq r_a \leq 2$)	0.09 to 0.29
Medium corrosivity	C3 ($2 \leq r_a \leq 8$)	0.29 to 0.47
High corrosivity	C4 ($8 \leq r_a \leq 15$)	0.47 to 0.57
Very high corrosivity	C5 ($15 \leq r_a \leq 80$)	0.57 to 1.00 ^a

^aBased on NaCl 3.5% solution simulation environment; γ_{corr} could be >1.00 for corrosive environments with concentrations that are more than NaCl 3.5% solution.

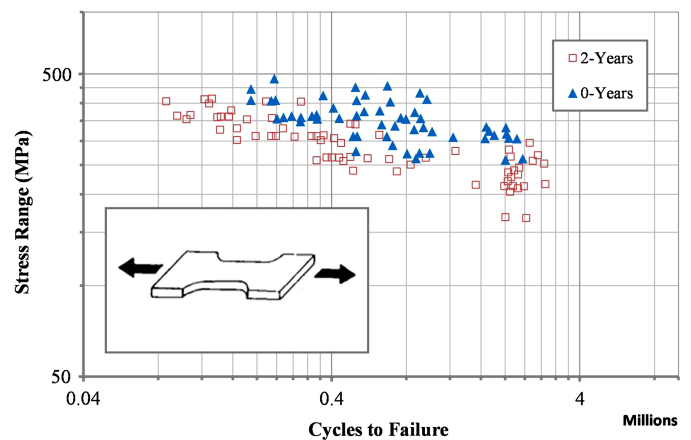


Fig. 3. Fatigue strength of two-year weathered plain rolled SMA steel specimens (adapted from Kunihiro et al. 1972)

at the stress concentration zone (hot-spot), the S-N data points were adjusted by using an average fatigue notch factor of 1.3, as reported by Kunihiro et al. (1972) for these specimens. By processing the data using Eq. (5), e-N data points for the steel are obtained as shown in Fig. 4. The curve fitted with no corrosion had a best fit with the fatigue exponents $b = -0.11$ and $c = -0.59$, which are very reasonable values for steels (Draper 2008). The curve fitted with 2-year corrosion had a best fit of $b'_{\text{fit}} = -0.13$ and $c'_{\text{fit}} = -0.61$. Thus, the proposed corrosion material constants to be $\alpha_b = 0.182$ and $\alpha_c = 0.034$ for this material.

Because of the complexity of the corrosion-fatigue phenomenon coupled with the probabilistic nature of fatigue as well as the difficulty of accurately determining the exact corrosion state, it was chosen not to present the predicted fatigue life as a definite value, but rather as an expected range. To account for the aforementioned effects, a range for values of γ_{corr} corresponding to $\gamma_{\text{corr}} \pm 0.05$ was chosen and will be used to estimate the predicted life range.

Verification of the Model

To calibrate the proposed model for other corrosive environments, a real case study will be simulated and verified against its published

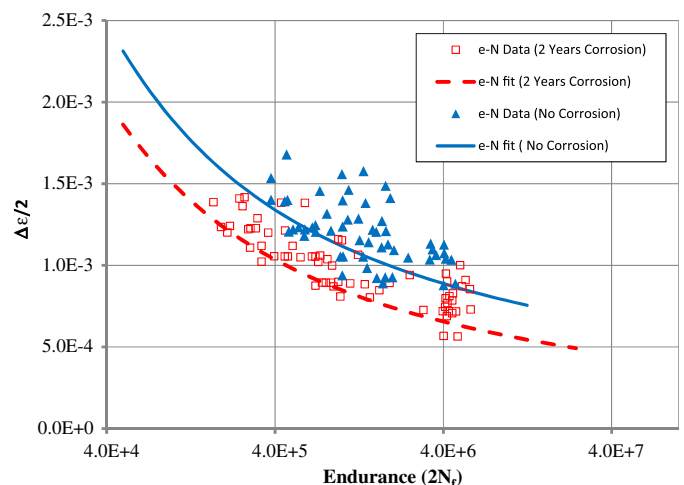


Fig. 4. e-N relationships of unweathered and two-year weathered plain rolled SMA steel specimens based on tests reported by Kunihiro et al. (1972)

test results. The chosen experimental investigation was conducted by Albrecht and Shabshab (1994) to investigate the fatigue behavior of 24 corroded rolled beams made of A588 steel. The beams were weathered for about five to six years under three conditions (see Table 2). The first group of beams was boldly exposed to air for 59 months. Group 2 beams were weathered for 63 to 66 months, subjected to a moist freshwater environment. Both group 1 and 2 beams were subjected to stress cycling. On the other hand, group 3 beams were placed under a metal deck—which simulated the shelter provided by highway bridge decks—for 65 to 71 months and was lightly sprayed with a salt solution during the winter months to simulate the use of deicing salts for snow removal. All 24 preweathered beams were then tested in the lab to evaluate their residual fatigue load capacity. A spreader beam distributed the load to two points spaced 914 mm (3 ft) apart, as shown in Fig. 5. The loading frequency was 0.75 Hz. The loading period of $1/0.75 = 1.33$ s corresponds to the time needed for a truck to cross a 30-m-long highway bridge at a speed of 80 km/h (50 mi/h). The corrosion rates were monitored and reported by Albrecht and Shabshab (1994), as listed in Table 2.

Material Properties

The beams were made of A588 grade B weathering steel ASTM A588 (ASTM 1992) with average 577-MPa tensile strength, 408-MPa reported yield load (nominally 345 MPa), and $E = 200,000$ MPa. Using the universal material method by Baumel and Seeger (1990) values of $K' = 1,400$ MPa, $n' = 0.15$, $\sigma'_f = 870$ MPa, $b = -0.09$, $\varepsilon'_f = 0.59$, and $c = -0.58$ were

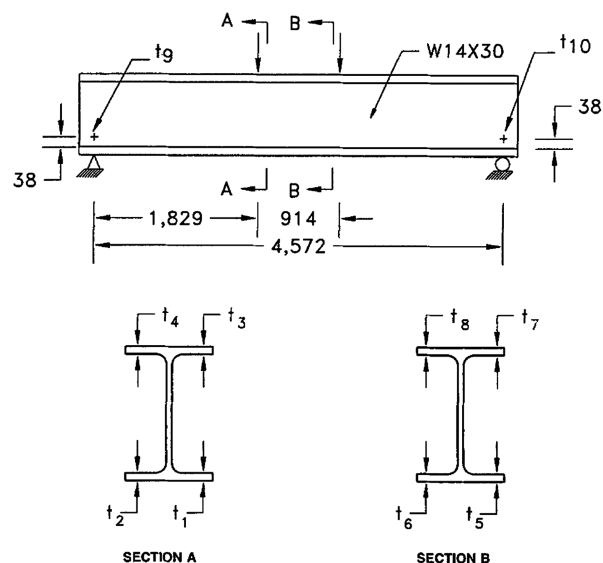


Fig. 5. Configurations of tested beams tested by Albrecht and Shabshab (1994)

obtained. Because it was reported by Albrecht (1983) that the properties of SMA steel are similar in composition to those of A588 steel, the proposed environmental constants will be taken for the boldly exposed specimens as $\alpha_b = 0.182$ and $\alpha_c = 0.034$ obtained previously. By comparing the values of corrosion penetration rates reported by Albrecht and Shabshab (1994) and the values listed in

Table 2. Test Matrix and Corrosion Rates Table of Beams Tested by Albrecht and Shabshab (1994)

Beam	Weathering time (months)	Mean corrosion penetration (μm) ^a				Mean corrosion rate ($\mu\text{m}/\text{year}$) ^a			
		Bottom flange	Top flange	Web		Bottom flange	Top flange	Web	
				Exposed ^b	Sheltered ^c			Exposed ^b	Sheltered ^c
Group 1: boldly exposed beams in air									
B3	59	49	28	47	—	12	12	5.4	—
B4	59	49	28	47	—	12	12	5.4	—
B5	59	49	28	47	—	12	12	5.4	—
B6	59	49	28	47	—	12	12	5.4	—
Group 2: boldly exposed beams subjected to moist freshwater environment									
B11	66	85	55	51	—	16	10	9.1	—
B12	66	85	55	51	—	16	10	9.1	—
B8	63	64	62	55	—	12	12	5.4	—
B10	63	64	62	55	—	12	12	5.4	—
B1	63	64	62	55	—	12	12	5.4	—
B2	63	64	62	55	—	12	12	5.4	—
B9	63	64	62	55	—	12	12	5.4	—
Group 3: sheltered beams subjected to moist saltwater environment									
B15S	65	1,560	236	419	1,350	267	41	71	231
B7S	65	1,170	307	244	1,280	284	76	36	284
B8S	66	1,560	236	419	1,350	267	41	71	231
B9S	66	1,560	236	419	1,350	267	41	71	231
B10S	71	1,680	312	526	1,940	284	53	89	328
B11S	71	1,680	312	526	1,940	284	53	89	328
B13S	71	1,680	312	526	1,940	284	53	89	328
B5S	65	1,170	307	244	1,280	284	76	36	284
B4S	65	1,170	307	244	1,280	284	76	36	284
B6S	65	1,170	307	244	1,280	284	76	36	284
B1S	65	1,170	307	244	1,280	284	76	36	284
B2S	65	1,170	307	244	1,280	284	76	36	284
B3S	65	1,170	307	244	1,280	284	76	36	284

^aValues of corrosion penetration and rate are per exposed surface.

^bBeam end experienced rain-washing.

^cBeam end sheltered and not experiencing rain-washing.

Table 3. Input Data for the Analysis Using the Experimental Observations of Albrecht and Shabshab (1994)

Beam	Nonweathered section					Weathered section					Corrosion rate					Corrosion					Number of cycles to failure
	Stress range (MPa)	Minimum stress (MPa)	Maximum stress (MPa)	Pmin (N)	Pmax (N)	Maximum strain range (MPa)	Stress range (MPa)	Maximum stress (MPa)	Strain range (MPa)	Weathering time (months)	bottom flange (mm/year)	Corrosion penetration bottom (mm)	rate top flange (mm/year)	Corrosion penetration top (mm)	Corrosion rate web (mm/year)	Corrosion penetration web (mm)					
Group 1: boldly exposed beams tested in air																					
B3	248	7	255	2,633.13	95,921.27	0.001240	250.40	257.47	0.001252	59.00	0.0100	0.0492	0.0058	0.0285	0.0100	0.0492	1,750,000				
B4	248	7	255	2,633.13	95,921.27	0.001240	250.41	257.47	0.001252	59.00	0.0100	0.0492	0.0058	0.0285	0.0100	0.0492	4,042,600				
B5	248	7	255	2,633.13	95,921.27	0.001240	250.41	257.47	0.001252	59.00	0.0100	0.0492	0.0058	0.0285	0.0100	0.0492	4,424,600				
B6	248	7	255	2,633.13	95,921.27	0.001240	250.41	257.47	0.001252	59.00	0.0100	0.0492	0.0058	0.0285	0.0100	0.0492	1,734,200				
Group 2: boldly exposed beams tested in moist freshwater environment																					
B11	165	7	172	2,633.13	64,699.84	0.000825	167.71	174.83	0.000839	66.00	0.0170	0.0935	0.0110	0.0605	0.0091	0.0501	1,595,500				
B12	165	7	172	2,633.13	64,699.84	0.000825	167.71	174.83	0.000839	66.00	0.0170	0.0935	0.0110	0.0605	0.0091	0.0501	1,576,600				
B8	214	7	221	2,633.13	83,131.77	0.001070	216.40	223.48	0.001082	63.00	0.0120	0.0630	0.0120	0.0630	0.0054	0.0284	1,036,000				
B10	214	7	221	2,633.13	83,131.77	0.001070	216.40	223.48	0.001082	63.00	0.0120	0.0630	0.0120	0.0630	0.0054	0.0284	940,500				
B1	276	7	283	2,633.13	106,453.80	0.001380	279.09	286.17	0.001396	63.00	0.0120	0.0630	0.0120	0.0630	0.0054	0.0284	386,400				
B2	276	7	283	2,633.13	106,453.80	0.001380	279.09	286.17	0.001396	63.00	0.0120	0.0630	0.0120	0.0630	0.0054	0.0284	456,700				
B9	276	7	283	2,633.13	106,453.80	0.001380	279.09	286.17	0.001396	63.00	0.0120	0.0630	0.0120	0.0630	0.0054	0.0284	435,600				
Group 3: sheltered beams tested in moist saltwater environment																					
B15S	47	7	54	2,633.13	20,312.74	0.000235	66.56	76.48	0.000333	70.00	0.2670	1.5575	0.0410	0.2392	0.2310	1.3475	6,943,200				
B7S	69	7	76	2,633.13	28,588.30	0.000345	91.43	100.70	0.000457	65.00	0.2260	1.2242	0.0560	0.3033	0.2440	1.3217	4,952,100				
B8S	69	7	76	2,633.13	28,588.30	0.000345	99.99	110.13	0.000500	66.00	0.2840	1.5620	0.0760	0.4180	0.2840	1.5620	1,884,600				
B9S	69	7	76	2,633.13	28,588.30	0.000345	99.99	110.13	0.000500	66.00	0.2840	1.5620	0.0760	0.4180	0.2840	1.5620	1,551,300				
B10S	110	7	117	2,633.13	44,010.93	0.000550	169.20	179.97	0.000846	71.00	0.2840	1.6803	0.0530	0.3136	0.3280	1.9407	468,900				
B11S	110	7	117	2,633.13	44,010.93	0.000550	169.20	179.97	0.000846	71.00	0.2840	1.6803	0.0530	0.3136	0.3280	1.9407	497,400				
B13S	110	7	117	2,633.13	44,010.93	0.000550	169.20	179.97	0.000846	71.00	0.2840	1.6803	0.0530	0.3136	0.3280	1.9407	420,000				
B5S	147	7	154	2,633.13	57,928.92	0.000735	194.78	204.06	0.000974	65.00	0.2260	1.2242	0.0560	0.3033	0.2440	1.3217	132,900				
B4S	152	7	159	2,633.13	59,809.73	0.000760	201.41	210.68	0.001007	65.00	0.2260	1.2242	0.0560	0.3033	0.2440	1.3217	201,800				
B6S	152	7	159	2,633.13	59,809.73	0.000760	201.41	210.68	0.001007	65.00	0.2260	1.2242	0.0560	0.3033	0.2440	1.3217	105,500				
B1S	208	7	215	2,633.13	80,874.79	0.001040	275.61	284.89	0.001378	65.00	0.2260	1.2242	0.0560	0.3033	0.2440	1.3217	154,400				
B2S	214	7	221	2,633.13	83,131.77	0.001070	283.56	292.84	0.001418	65.00	0.2260	1.2242	0.0560	0.3033	0.2440	1.3217	112,400				
B3S	214	7	221	2,633.13	83,131.77	0.001070	283.56	292.84	0.001418	65.00	0.2260	1.2242	0.0560	0.3033	0.2440	1.3217	16,200				

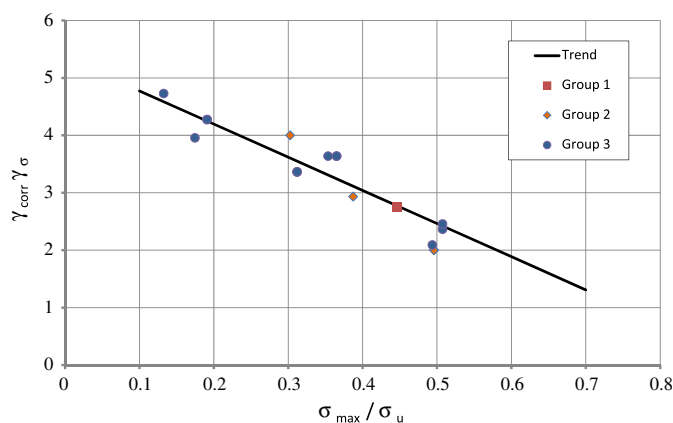


Fig. 6. Plot of $\gamma_{\text{corr}}\gamma_{\sigma}$ values versus $\sigma_{\text{max}}/\sigma_u$ for the three beam groups tested by Albrecht and Shabshab (1994)

Table 1, the factor $\gamma_{\text{corr}} = 0.45$ (corresponding to ISO-9224 category C3 corrosion rate) was selected as an average for the group 1 specimens boldly tested in air. Also, the factor $\gamma_{\text{corr}} = 0.75$ (corresponding to ISO-9224 category C5 corrosion rate) was selected as an average value for the group 2 specimens tested in moist freshwater environment. For the group 3 sheltered specimens tested in moist saltwater environment, which is a very harsh environment, the values from the ISO-9224 were extrapolated and the factor $\gamma_{\text{corr}} = 1.1$ was used as an average value to represent this environment. The value obtained for γ_{corr} is found to be greater than unity (that corresponds to the upper limit exposure to NaCl 3.5% solution that is typically used in fatigue tests by most researchers), which highlights the aggressive corrosive testing environment for this particular group. This observation is further confirmed from the high corrosion penetration rates reported by Albrecht and Shabshab (1994) (from 231 to 328 $\mu\text{m}/\text{year}$ in the web and bottom flange) in comparison to the C5 ISO-9224 (1992b) corrosion category (maximum of 80 $\mu\text{m}/\text{year}$).

The 24 beams tested by Albrecht and Shabshab (1994) were analytically studied by obtaining the strain ranges at the point of maximum stress of the weathered section at the midspan of the beams. The stresses and stress ranges reported by Albrecht and Shabshab (1994) were for unweathered sections; thus, a conversion of these ranges was necessary. Fatigue calculations were based on the final weathered sections. Corrosion rates for each part of the specimens were reported by Albrecht and Shabshab (1994), and all the geometric and loading input values are listed in Table 3.

Fatigue Life Prediction

In addition to the environmental coefficient, γ_{corr} , it was anticipated that the ratio of the mean-to-ultimate stress ratio has an influence on the corrosion-fatigue life prediction. To further investigate such mean stress effects, values of the $\gamma_{\text{corr}}\gamma_{\sigma}$ product are plotted against the values of the maximum stress normalized to the ultimate stress $\sigma_{\text{max}}/\sigma_u$ of the three groups of the 24 tested beams by Albrecht and Shabshab (1994), as shown in Fig. 6.

As can be seen from Fig. 6, the introduction of the factor γ_{σ} was useful in calibrating the model, as it was clear that the results were stress-level dependent. The curve fitting in Fig. 6 was optimized to be an upper bound to most of the sample points to obtain conservative fatigue life predictions for most of the test specimens. From the figure, it could be also seen that as the ratio $\sigma_{\text{max}}/\sigma_u$ decreases, the sensitivity of the factor $\gamma_{\text{corr}}\gamma_{\sigma}$ increases.

By curve fitting, Eq. (6) was derived for the product $\gamma_{\text{corr}}\gamma_{\sigma}$ as follows:

$$\gamma_{\text{corr}}\gamma_{\sigma} = 5.77 \left(\frac{\sigma_{\text{max}}}{\sigma_u} \right) + 5.35 \quad (6)$$

Several trends were examined, where the linear trend proposed in Eq. (6) was selected for its simplicity and accurate results. As has been the case for all fatigue-related models, having more experimental data points would help in further calibration of this proposed equation.

By having the values of γ_{corr} defined for each environment, the values of the $\gamma_{\text{corr}}\gamma_{\sigma}$ product can be derived and thus the expected fatigue life for each specimen based on the modified SWT model proposed in Eq. (3) can be determined. Values of all factors and predicted lives are listed in Table 4.

Discussion of Results

Albrecht and Shabshab (1994) grouped the test results in three groups representing three different aggressive environments that the steel beams can be in. The results obtained for the expected life for each specimen are presented as a range corresponding to $\gamma_{\text{corr}} \pm 0.05$ for each testing environment. The range of ± 0.05 was chosen after examining several values for the range, and this value proved to result in very good predictions of the fatigue life, as will be shown subsequently. The ranges of the values of the predicted number of cycles to failure are plotted versus the experimentally determined values from Albrecht and Shabshab (1994), as shown in Fig. 7. Despite the valuable reported data and results regarding the tested 24 beams that were used to calibrate the analytical model, the experimental data are scattered for different loading environmental conditions, and that there is still a need for more available data points to further calibrate the proposed model.

Discussion of Group 1 Results

Beams in this group have the same values for stress ranges and maximum applied stresses. There is already a considerable scatter in the reported results of the identical tested beams in group 1, with a standard deviation of about 1.45 million cycles, which is 70% of the minimum experimentally obtained results and 28% of the maximum experimental result. Analytical simulations of the predicted fatigue life of this group could be visually compared by the range bars plotted in Fig. 7. From Fig. 7, it can be seen that the upper bound predicted value is close to the mean of the experimental bar, whereas the lower bound expected value is less (i.e., more conservative prediction) than the minimum experimental result by 22%. From the previous observations, it could be concluded that the predicted fatigue lives using the proposed model (in term of ranges) are in good agreement with the available experimental results and tend to be on the conservative side.

Discussion of Group 2 Results

Beams in this group have different values for stress ranges and maximum applied stresses. Beams B8 and B10 had the closest mean predicted fatigue life as compared with the mean experimental value, for which the difference between the means of the predicted and the experimental values was about 12%. The maximum predicted life is almost the same as the mean of the experimental result, whereas the minimum predicted life was 31% less than the minimum experimental result. Beams B1, B2, and B9 had the most conservative life predictions as all the analytical results were below

Table 4. Derived Corrosion Factors and Estimated Number of Cycles to Failure Using Both the SWT and Modified SWT Models

Beam	Nonweathered section				Weathered section		Experimental number of cycles to failure	Estimated number of cycles (SWT)	Estimated number of cycles (Modified SWT) (lower bound)	Estimated number of cycles (modified SWT) (upper bound)	$\gamma_{\text{corr}}\gamma_{\sigma}$ (Min)	$\gamma_{\text{corr}}\gamma_{\sigma}$ (Max)	γ_{σ}	$\sigma_{\text{max}}/\sigma_u$	γ_{corr} (Min)	γ_{corr} (Max)
	Stress range (MPa)	Minimum stress (MPa)	Maximum stress (MPa)	Maximum strain range (MPa)	Maximum stress (MPa)	Strain range (MPa)										
Group 1: boldly exposed beams tested in air																
B3	248	7	255	0.001240	257.47	0.001252	1,750,000	19,000,000	1,350,000	2,350,000	1.11	1.39	2.775	0.45	0.4	0.5
B4	248	7	255	0.001240	257.47	0.001252	4,042,600	19,000,000	1,350,000	2,350,000	1.11	1.39	2.775	0.45	0.4	0.5
B5	248	7	255	0.001240	257.47	0.001252	4,424,600	19,000,000	1,350,000	2,350,000	1.11	1.39	2.775	0.45	0.4	0.5
B6	248	7	255	0.001240	257.47	0.001252	1,734,200	19,000,000	1,350,000	2,350,000	1.11	1.39	2.775	0.45	0.4	0.5
Group 2: boldly exposed Beams tested in moist freshwater environment																
B11	165	7	172	0.000825	174.68	0.000838	1,595,500	82,000,000	1,700,000	3,300,000	2.52	2.88	3.603	0.30	0.7	0.8
B12	165	7	172	0.000825	174.68	0.000838	1,576,600	82,000,000	1,700,000	3,300,000	2.52	2.88	3.603	0.30	0.7	0.8
B8	214	7	221	0.001070	223.48	0.001082	1,036,000	58,000,000	650,000	1,000,000	2.18	2.49	3.115	0.39	0.7	0.8
B10	214	7	221	0.001070	223.48	0.001082	940,500	58,000,000	650,000	1,000,000	2.18	2.49	3.115	0.39	0.7	0.8
B1	276	7	283	0.001380	286.17	0.001396	386,400	6,300,000	250,000	370,000	1.74	1.99	2.488	0.50	0.7	0.8
B2	276	7	283	0.001380	286.17	0.001396	456,700	6,300,000	250,000	370,000	1.74	1.99	2.488	0.50	0.7	0.8
B9	276	7	283	0.001380	286.17	0.001396	435,600	6,300,000	250,000	370,000	1.74	1.99	2.488	0.50	0.7	0.8
Group 3: sheltered beams tested in moist saltwater environment																
B15S	47	7	54	0.000235	76.48	0.000333	6,943,200	53,000,000	9,300,000	19,000,000	4.81	5.27	4.59	0.13	1.05	1.15
B7S	69	7	76	0.000345	100.70	0.000457	4,952,100	254,000,000	2,650,000	5,000,000	4.56	4.99	4.34	0.17	1.05	1.15
B8S	69	7	76	0.000345	110.13	0.000500	1,884,600	230,000,000	1,800,000	3,300,000	4.46	4.89	4.25	0.19	1.05	1.15
B9S	69	7	76	0.000345	110.13	0.000500	1,551,300	230,000,000	1,800,000	3,300,000	4.46	4.89	4.25	0.19	1.05	1.15
B10S	110	7	117	0.000550	179.97	0.000846	468,900	77,500,000	305,000	480,000	3.73	4.08	3.55	0.31	1.05	1.15
B11S	110	7	117	0.000550	179.97	0.000846	497,400	77,500,000	305,000	480,000	3.73	4.08	3.55	0.31	1.05	1.15
B13S	110	7	117	0.000550	179.97	0.000846	420,000	77,500,000	305,000	480,000	3.73	4.08	3.55	0.31	1.05	1.15
B5S	147	7	154	0.000735	204.06	0.000974	132,900	115,500,000	200,000	300,000	3.47	3.81	3.31	0.35	1.05	1.15
B4S	152	7	159	0.000760	210.68	0.001007	201,800	93,000,000	190,000	270,000	3.41	3.73	3.24	0.37	1.05	1.15
B6S	152	7	159	0.000760	210.68	0.001007	105,500	93,000,000	190,000	270,000	3.41	3.73	3.24	0.37	1.05	1.15
B1S	208	7	215	0.001040	284.89	0.001378	154,400	6,800,000	90,000	120,000	2.63	2.88	2.50	0.49	1.05	1.15
B2S	214	7	221	0.001070	292.84	0.001418	112,400	5,150,000	90,000	110,000	2.54	2.78	2.42	0.51	1.05	1.15
B3S	214	7	221	0.001070	292.84	0.001418	16,200	5,150,000	90,000	110,000	2.54	2.78	2.42	0.51	1.05	1.15

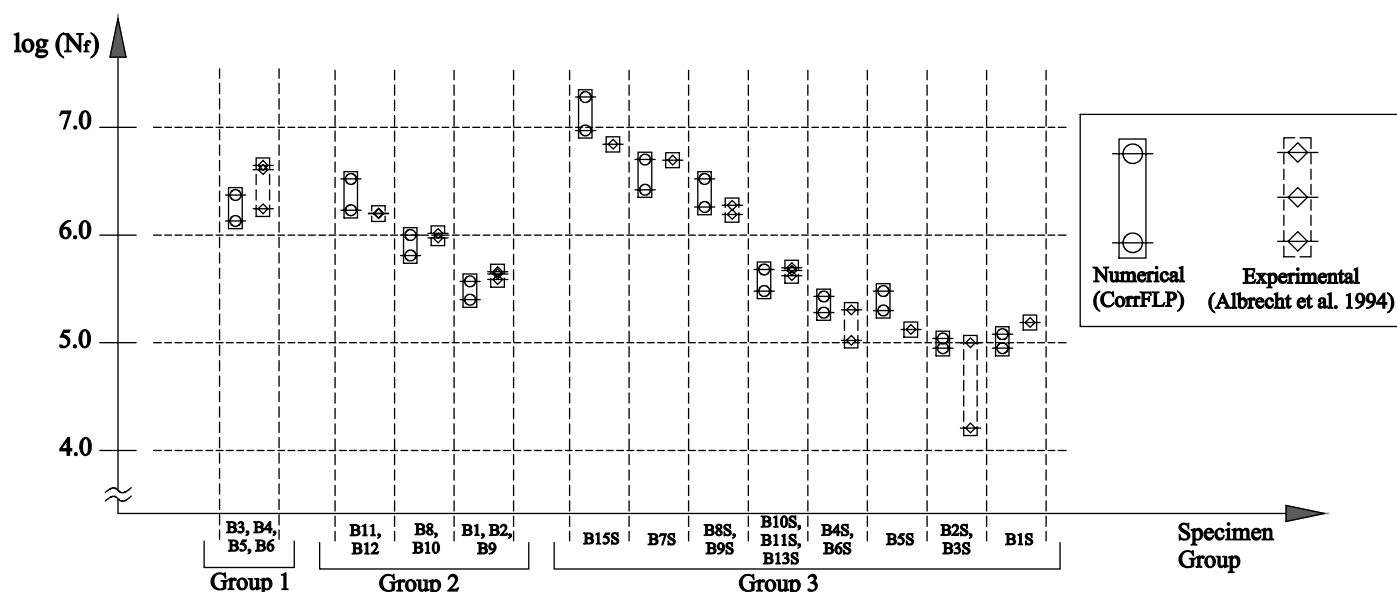


Fig. 7. Predicted lives using the proposed model versus experimentally measured by Albrecht and Shabshab (1994)

the experimental, with a difference of 4% between the maximum expected result and the minimum experimental value obtained. Beams B11 and B12 had the most nonconservative life predictions as all the predicted results were above the experimental, with a difference of 8% between the minimum predicted result and the maximum experimental value obtained.

Discussion of Group 3 Results

Beams in this group have a very wide spectrum of different values for stress ranges and maximum applied stresses. All the predicted lives in this group using the proposed model were on the conservative side except for beams B15S and B5S. This could be attributed to the need for more experimental tests, which would further fine tune the proposed $\gamma_{\text{corr}}\gamma_{\sigma}$ function, particularly for beams subjected to extremely corrosive environment along with high mean stresses. Specimens B2S and B3S have a relatively high stress range and the highest ratio of $\sigma_{\text{max}}/\sigma_u$ being equal to 0.51. There is a considerable scatter in the experimental results between these two identical specimens, which could imply that specimen B3S might have experienced premature failure. This is seen to be likely, especially that the predicted analytical range of the fatigue life is close to that of B2S.

From the preceding results, it could be concluded that the analytical predictions of fatigue life of corroded steel beams using the proposed model correlates very well with the reported measured experimental fatigue life of the 24 beams tested by Albrecht and Shabshab (1994).

Remarks on Fatigue Life Predictions Using Simple Reduced Section Properties

As can be seen from the results listed in Table 4, the corrosion-fatigue life predictions using the simple reduced section properties and following the regular SWT model results in unrealistic fatigue life predictions compared with the reported experimental results by Albrecht and Shabshab (1994). The comparison clearly shows that modeling the steel plates with their expected reduced section after anticipated future corrosion and analyzing the system using regular fatigue life prediction rules is not representative of the

corrosion-fatigue phenomenon. On the other hand, the estimated range of fatigue life of corroded steel beams using the newly proposed modified SWT strain-life model proved to account for the effects of corrosion and different levels of maximum applied stresses.

Concluding Remarks

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 24 weathered steel beams tested by Albrecht and Shabshab (1994). The proposed model generally gives conservative corrosion-fatigue life predictions. There is a considerable scatter in the results of some of the reported identical experimental specimens, which emphasizes the practicality of providing the corrosion-fatigue life predictions in the form of ranges instead of a single definite value.

It was found that the predicted range of corrosion-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 $\gamma_{\text{corr}}\gamma_{\sigma}$, which is a function in the ratio $\sigma_{\text{max}}/\sigma_u$. The maximum-to-ultimate stress ratio was found to have an inversely proportional relationship with the corrosion related factors, and a simple linear relationship is proposed. Further experimental work is needed to calibrate the proposed function for other types of steel. It is found 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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Notation

The following symbols are used in this paper:

- b = fatigue strength exponent;
- b' = fatigue strength exponent in an NaCL 3.5% corrosive environment;
- c = fatigue ductility exponent;
- c' = fatigue ductility exponent in an NaCL 3.5% corrosive environment;
- E = elasticity modulus in tension (MPa);
- K' = cyclic strength coefficient (MPa);
- m = slope of S-N curve (MPa);
- N_f = number of cycles to failure;
- n' = cyclic strength exponent;
- p_a = average annual penetration due to corrosion;
- α_b = material constant = $(b'/b) - 1$;
- α_c = material constant = $(c'/c) - 1$;
- γ_{corr} = environment corrosivity intensity factor;
- γ_σ = correction factor depending on the maximum applied stress;
- $\Delta\varepsilon$ = strain range;
- ε'_f = fatigue ductility coefficient;
- σ_{max} = maximum normal stress (MPa);
- σ_u = ultimate tensile strength (MPa); and
- σ'_f = fatigue strength coefficient (MPa).

References

- Albrecht, P. (1983). "Fatigue design stresses for weathering steel structures." *Corrosion fatigue: Mechanics, metallurgy, electrochemistry, and engineering*, Vol. 801, ASTM International, 445.
- Albrecht, P., and Jian-Guo, C. (1983). "Fatigue tests of 8-yr weathered A588 steel weldment." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1983)109:9(2048), 2048–2065.
- Albrecht, P., and Lenwari, A. (2008). "Fatigue strength of trolley bridge stringers made of ASTM A7 steel." *J. Bridge Eng.*, 10.1061/(ASCE)1084-0702(2008)13:1(67), 67–74.
- Albrecht, P., and Lenwari, A. (2009). "Fatigue strength of weathered A588 steel beams." *J. Bridge Eng.*, 10.1061/(ASCE)1084-0702(2009)14:6(436), 436–443.
- Albrecht, P., and Maher, S. (1989). "Fatigue of eight-year weathered A588 steel stiffeners in salt water." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1989)115:7(1756), 1756–1767.
- Albrecht, P., and Shabshab, C. (1994). "Fatigue strength of weathered rolled beam made of A588 steel." *J. Mater. Civil Eng.*, 10.1061/(ASCE)0899-1561(1994)6:3(407), 407–428.
- ASTM. (1992). "A588 standard specification for high strength low alloy structural steel with 345 MPa (50 ksi) minimum yield point." Annual book of ASTM standards, A01.04, Philadelphia, PA.
- Baumel, A., Jr., and Seeger, T. (1990). *Materials data for cyclic loading, supplement 1*, Elsevier Science, Amsterdam, Netherlands.
- Boden, H. (1989). *Approaches in modeling the impact of air pollution-induced material degradation*, International Institute for Applied Systems Analysis, Laxenburg, Austria.
- DeJong, S. J., Heffernan, P. J., and MacDougall, C. (2009). "Periodic overload corrosion fatigue of MMFX and stainless reinforcing steels." *J. Mater. Civil Eng.*, 10.1061/(ASCE)0899-1561(2009)21:1(1), 1–9.
- Draper, J. (2008). *Modern metal fatigue analysis*, EMAS Publishing, Warrington, U.K.
- ISO. (1992a). "Corrosion of metals and alloys—Corrosivity of atmospheres—Classification." *ISO-9223*, Geneva.
- ISO. (1992b). "Corrosion of metals and alloys—Corrosivity of atmospheres—Guiding for the corrosivity categories." *ISO-9224*, Geneva.
- Kunihiro, T., Inove, K., and Fukuda, T. (1972). "Atmospheric exposure study of weathering steel." *Public Works of Research Laboratory Rep. Br. 71–08*, Ministry of Construction, Tokyo, Japan (in Japanese).
- Metal Properties Council. (1983). *Corrosion fatigue: Mechanics, metallurgy, electrochemistry, and engineering*, Vol. 801, ASTM International, West Conshohocken, PA.
- Novak, S. R. (1983). "Corrosion-fatigue crack initiation behavior of four structural steels." *Corrosion fatigue: Mechanics, metallurgy, electrochemistry, and engineering: A symposium*, STP 801, T. W. Crooker, and B. N. Leis, eds., ASTM, West Conshohocken, PA, 26–63.
- Smith, K., Topper, T. H., and Watson, P. (1970). "A stress-strain function for the fatigue of metals." *J. Mater.*, 5(4), 767–778.
- Trethewey, K. R., and Chamberlain, J. (1996). *Corrosion: for science and engineering*, 2nd Ed., Longman Sc & Tech.
- Zuraski, P. D., and Johnson, J. E. (1990). "Fatigue strength of deteriorated steel highway bridges." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1990)116:10(2671), 2671–2690.