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Predicting the Fatigue Life of Unpainted Steel Structures

Prédiction de la durée de vie de fatigue des structures métalliques non peintes

Vorhersage der Lebensdauer von Stahlkonstruktionen ohne Anstrich

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SUMMARY
Unpainted steel structures that are exposed to atmospheric environments loose initiation life due to rust pitting and propagation life due to corrosion fatigue. The former loss is determined from an analysis of 1,195 fatigue tests of six types of details that were weathered up to four years, the latter from corrosion fatigue crack growth rates. Proposed equations predict the total loss in life of stress range for Category A through Category E details. The losses are largest for Category A and diminish with increasing severity of the detail. The findings are applied to simple-span bridges.

RESUME
Les structures métalliques non peintes qui sont exposées aux conditions atmosphériques voient leur durée de vie à la fatigue sous corrosion diminuée, ceci aussi bien pour la durée d'initiation que pour la durée de propagation. On a déterminé cette perte à partir de l'analyse de 1195 essais de fatigue pour six types de détails qui furent exposés durant plus de quatre ans, dont la dernière consacrée à l'observation de l'accroissement des fissures de fatigue sous corrosion. Des équations sont proposées pour prédire la perte totale de durée de vie ou de différence de contrainte pour les catégories A à E de détails. Les pertes sont plus grandes pour la catégorie A et elles diminuent avec l'accroissement de la sévérité du détail. Les résultats sont appliqués au cas de ponts à portée simple.

ZUSAMMENFASSUNG
Bei Stahlkonstruktionen ohne Anstrich reduzieren sich die Phasen des Rissbeginns durch den Lochfrass und die Phase der Rissfortpflanzung durch Ermüdungskorrosion. Der Verlust in der Phase des Rissbeginns wurde durch 1195 Ermüdungsversuche an sechs verschiedenen Details, die bis zu vier Jahren im Freien gelagert wurden, bestimmt. Der Verlust an Lebensdauer infolge Korrosionsermüdung wird mit der Beobachtung des Risswachstums hergeleitet. Die vorgeschlagenen Gleichungen sagen den totalen Verlust an Lebensdauer oder an ertragbarer Spannungsamplitude für Details der Kategorie A bis E voraus. Die Verluste sind am grössten für die Details der Kategorie A und nehmen mit zunehmend ungünstigen Details ab.

Structures fabricated from atmospheric corrosion resisting steels, so-called weathering steels, [8,15] are expected to develop a dense patina which would greatly reduce the long-term corrosion of the underlying steel base. Necessary conditions for such behavior are bold exposure, intermittent wetting and drying, and absence of heavy concentrations of corrosive pollutants, especially roadway deicing salts. Under those ideal conditions of exposure, weathering steel structures are not normally painted. Bare steel is subjected to rust pitting and to corrosion fatigue under cyclic loading, phenomena known to decrease the crack initiation and propagation lives, respectively. This paper shows how to account in design for the loss in fatigue life. The background information is presented in great detail in Ref. 4.

Three sets of data are available for steels that were weathered naturally for up to four years prior to fatigue testing. Attempts to artifically accelerate the weathering process were not successful [1]. Kunihiro, et.al., [9] tested plain specimens and butt-welded ground flush specimens fabricated from either SMA weathering steel [8] or SM rolled steel with no enhanced atmospheric corrosion resistance [11]. Figure 1 shows a typical set of data. The 0-year nonweathered control specimens exhibited a fatigue strength slightly greater than the mean for Category A. Four years of weathering significantly reduced that strength, with 18.3 percent (15 out of 82) of the data points falling below the AASHTO allowable Category A line [14]. Albrecht, et.al., [2,4,7] tested specimens with transverse stiffeners and 102-mm attachments fabricated from A588 steel [15].. The third set of data comes from Nihei, et.al., [10] who tested notched plate specimens and butt-welded specimens with the weld reinforcement not removed. Both were fabricated from SM steels [11]..

Table 1 summarizes the results of the 1,195 fatigue tests cited previously. The data from all series were compared at 500,000 cycles, in the manner illustrated in Fig. 2. The fatigue notch factor [3] , defined as the ratio of mean stress ranges for Category A (solid circle) and the detail under consideration (open circle),

$$K_f = \frac{f_{rA}}{f_{r2}} = \frac{350\ \mathrm{MPa}}{f_{r2}} \tag{1}$$

established the severity of the detail before weathering. The relative loss in stress range, Δf_r, between the weathered and nonweathered specimens was:

$$\Delta f_r = 1 - \frac{f_{r1}}{f_{r2}} \tag{2}$$

where f_{r1}/f_{r2} is the ratio of the smaller to larger stress range at 500,000 cycles. See the two open circles on the solid mean lines in Figs. 1 and 2. Since the fatigue life, N, is about a third-power expontential function of f_r, $m \doteqdot 3$, the corresponding relative loss in fatigue life is:

$$\Delta N = 1 - \left(\frac{f_{r1}}{f_{r2}}\right)^3 \tag{3}$$

This procedure compares data about midway in the range of cycles to failure usually measured in testing programs. It estimates mean changes in life in a way that makes them relatively insensitive to slope variations of the two S-N lines being compared.

The calculated losses in stress range and fatigue life due to weathering are listed in Table 1. Each data point in Fig. 3 shows the mean loss in life for one type of specimen and length of weathering, as a function of the fatigue notch factor of the corresponding nonweathered control specimens. Vertical lines were drawn at the fatigue notch factors for the mean regression line of the Category A through Category E data [3] to permit a comparison of the results with the AASHTO fatigue specifications [14].

The following equation, drawn solidly in Fig. 3, envelops the points for relative loss in life due to weathering.

$$\Delta N_w = 1 - 0.38\ K_f \tag{4}$$

It is backed by data in the region $0.69 \leq K_f \leq 2.04$ and assumed to be valid up to $K_f \leq 2.63$. Above that value, the loss in life would vanish, $\Delta N_w = 0$. The only data point that falls above Eq. 4 in Fig. 3 was excluded because of the uncertainty in using the stress amplitude, $f_a = 0.5\ f_r$, to calculate K_f for Nihei's nonwelded notched plate specimens. Note also that weathering steels (A588 and SMA) and regular steels (SM) exhibit comparable losses in life.

The total fatigue life consists of a crack initiation phase plus a crack propagation phase. Weathering reduced only the crack initiation phase, because all but 48 specimens were fatigue tested after the weathering periods shown in Table 1. In reality, unpainted steel structures are exposed to the environment during both phases of fatigue cracking. The latter effect, termed corrosion fatigue, can be estimated from measurements of crack growth rate for A588 steel in distilled water and 3-percent sodium chloride solution [5]. The aqueous data fell along the upper bound of the factor-of-two scatter band for the air data. Hence, the aqueous environments increased the crack growth rate by a factor of $\sqrt{2} = 1.4$. For the purpose of this estimation, it is assumed that the crack growth rate and the crack propagation life are proportional, and that weathering consumes the crack initiation life. Under these assumptions, the area above the weathering line, Eq. 4 in Fig. 3, represents the crack propagation life, 0.4/1.4 = 29 percent of which is lost to corrosion fatigue.

$$\Delta N_{cf} = 0.29(1-\Delta N_w) = 0.11\ K_f \tag{5}$$

Adding Eq. 4 and Eq. 5 gives the total relative loss in life due to weathering and corrosion fatigue, ΔN_t, shown with a dashed line in Fig. 3.

$$\Delta N_t = \Delta N_w + \Delta N_{cf} = 1 - 0.27\ K_f \tag{6}$$

When $K_f \geq 2.63$, the effect of weathering vanishes, and the total loss in life remains at 29 percent, equal to the loss due to corrosion fatigue alone.

Subtracting Eq. 6 from unity yields the relative net life after weathering and corrosion fatigue

$$N_{net} = 1 - \Delta N_t = 0.27\ K_f \tag{7}$$

with the corresponding relative net stress range given by

$$f_{r,net} = (0.27\ K_f)^{1/3} \tag{8}$$

The net relative life (stress range) varies from 27 percent (65 percent) for Category A to 71 percent (89 percent) for Category D and below.

The fatigue notch factors and, hence, all previous equations were derived for the mean regression lines. To obtain allowable stress ranges for fatigue design of unpainted steel structures, it seems reasonable to multiply the AASHTO allowable stress ranges [14], which are based on clear air data, by the net relative stress range given by Eq. 8. For redundant load-path structures:

$$F_{sr,t} = \left(\frac{10^{b-2s}}{N_d}\, 0.27\, K_f\right)^{1/3} \tag{9}$$

where N_d = design fatigue life, b = intercept of mean S-N Line, and s = standard deviation on log of life. The same reductions should also be applied to the fatigue limit until better threshold data are developed.

Figure 4 compares the AASHTO allowable stress ranges for redundant load-path structures at 500,000 cycles [14] with those proposed herein for: (1) weathering; and (2) weathering and corrosion fatigue. The reductions are largest for Category A and diminish with increasing severity of the detail, that is K_f.

As an example, to assess the potential impact on existing highway bridge designs, the stress ranges were calculated at various details of simple-span bridges with multiple rolled beams [12,13] and compared in Fig. 5 with the values allowed by AASHTO and with those proposed herein. For the type of bridge examined, fatigue would control the design of unpainted Category A rolled beams and Category C diaphragm gussets. Transverse stiffeners in welded plate girders are another example of bridge details that would be affected.

In summary, weathering steels offer potentially large savings in maintenance costs and are basically a sound concept. Unpainted weathering steel should not be specified for structures exposed to a salt-bearing environment, as the Michigan experience shows [6]. In suitable applications, new designs should counter the anticipated losses in fatigue life with moderate reductions in allowable stress ranges, at low additional cost, and without sacrificing the economic advantages gained from reduced maintenance.

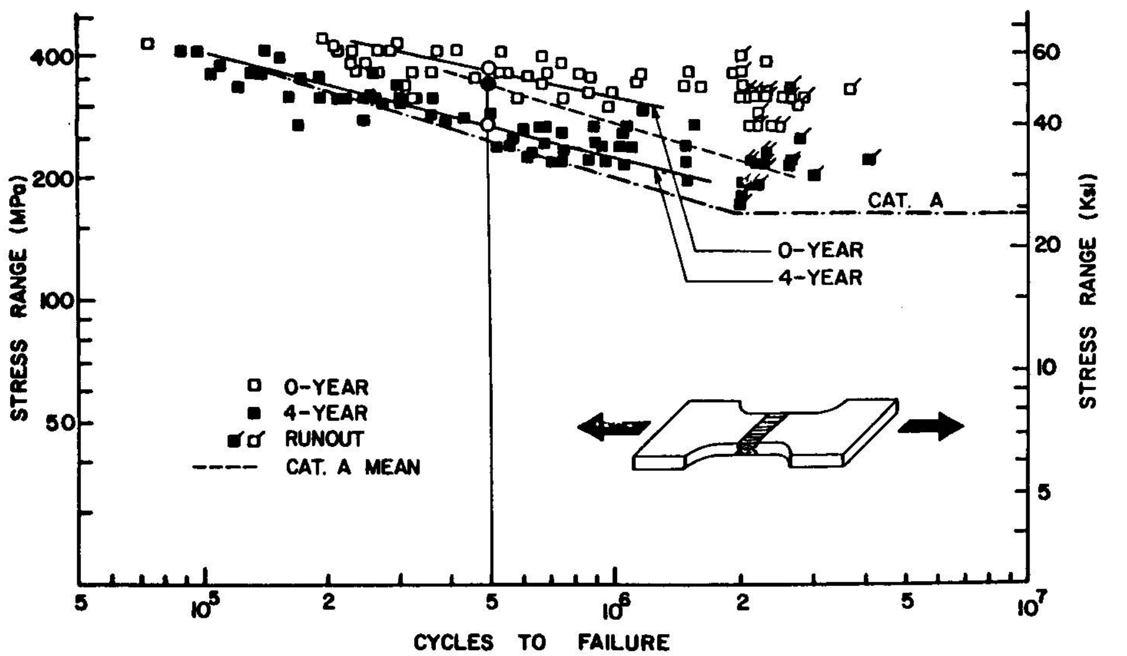

Fig. 1 Fatigue Strength of 4-Year Weathered Butt-Welded Ground Flush Specimens Fabricated from SMA steel [9].

Table 1 Summary of All Fatigue Test Data (Bold Exposure, Salt-free Environment)

Ref.	Type of Detail	No. of Specim. Tested	Weather. Time, in Years	Str. Range at 500,000 Cycles f_r(MPa)	Loss in Stress Range Δf_r(Pct)	Loss in Fatigue Life ΔN(Pct)	Fatigue Notch Factor K_f
			ASTM A588 and JIS SMA Steels				
9	Base metal	73	0	373	--	--	0.94
		56	2	287	23	54	1.22
		83	4	294	21	51	1.19
9	Butt weld ground flush	64	0	380	--	--	0.92
		70	2	285	25	58	1.23
		82	4	278	27	61	1.26
2	Transv. stiffener	12	0	221	--	--	1.59
		16	3	189	15	38	1.85
4,7	Transv. stiffener	29	0	172	--	--	2.04
		20	2 cont.	160	7	19	2.18
		16	2 alt.	175	2[a]	5[a]	2.00
		20	4 cont.	159	8	21	2.19
		16	4 alt.	163	5	15	2.15
4,7	102 - mm attachm.	24	0	179	--	--	1.95
		15	2 cont.	177	--	6	1.98
		8	2 alt.	-	--	8[a]	--
		20	2 alt.	173	4	10	2.03
		8	4 alt.	-	--	9	--
			JIS SM Steels				
9	Base metal	62	0	359	--	--	0.98
		69	2	274	24	56	1.28
		85	4	265	26	60	1.32
9	Butt weld ground flush	50	0	362	--	--	0.97
		71	2	272	25	58	1.29
		88	4	264	27	61	1.33
10	Notched Plate	11	0	506	--	--	0.69
		11	3	332	34	72	1.05
10	Notched plate	17	0	257[b]	--	--	1.36[b]
		9	3	196[b]	24	55	1.79[b]
10	Butt weld as welded	18	0	302	--	--	1.16
		10	3	252	17	42	1.39
10	Butt weld as welded	41	0	396[c]	--	--	0.88[c]
		11	3	279[c]	30	65	1.25[c]

[a] Increase in life. [b] R = - 1; based on amplitude. [c] R = - 1; based on range.

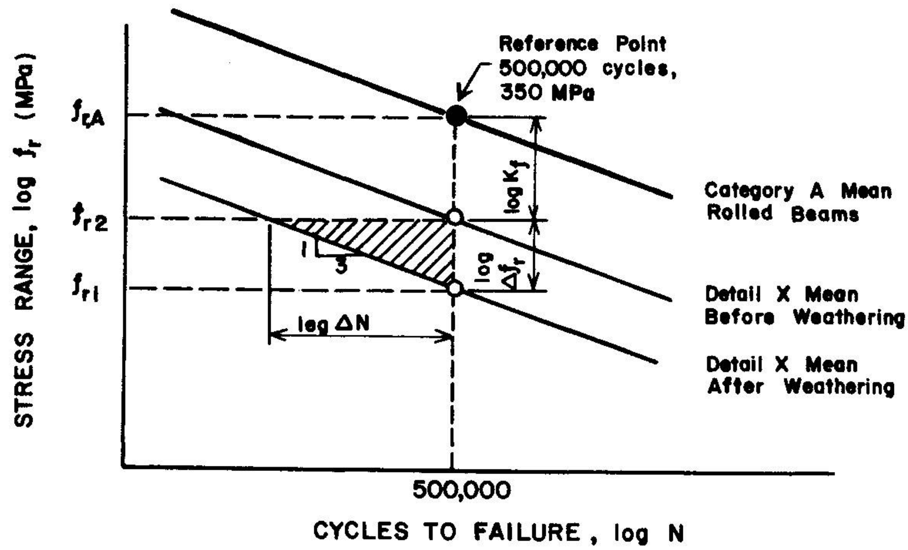

Fig. 2 Definition of Fatigue Notch Factor, Loss in Stress Range, and Loss in Fatigue Life.

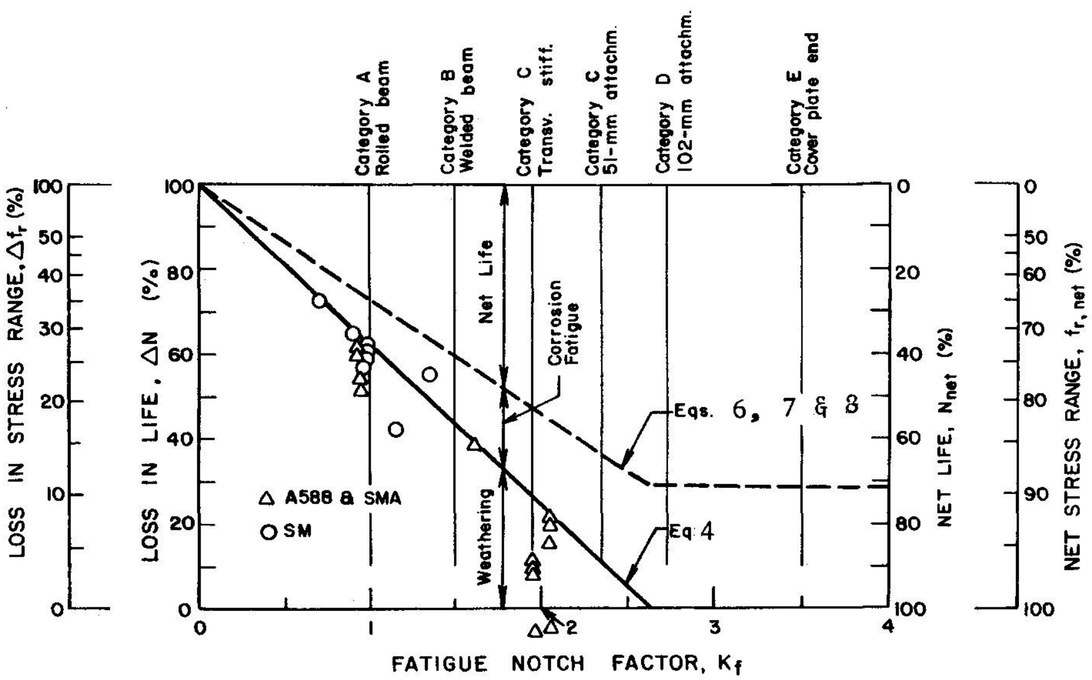

Fig. 3 Net Life and Net Stress Strange after Losses due to Weathering and Corrosion Fatigue.

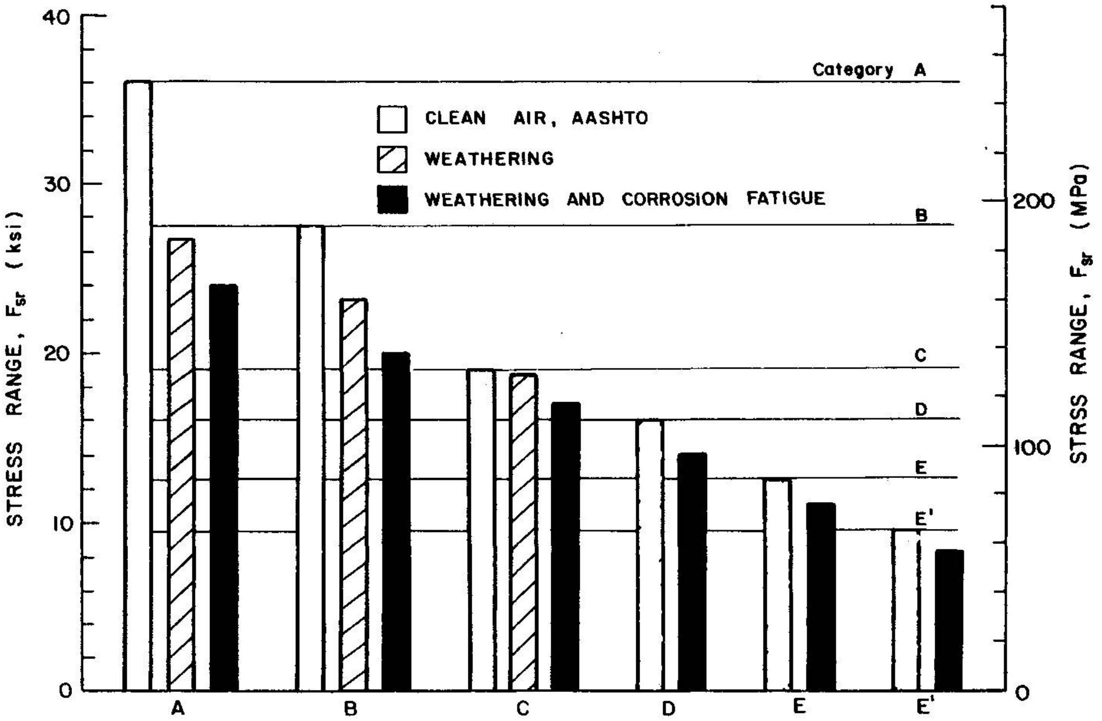

Fig. 4 Comparison of Allowable Stress Ranges for Redundant Load-Path Structures at 500,000 Cycles: (1) Current AASHTO, in Clean Air; (2) after Weathering; and (3) after Weathering and Corrosion Fatigue.

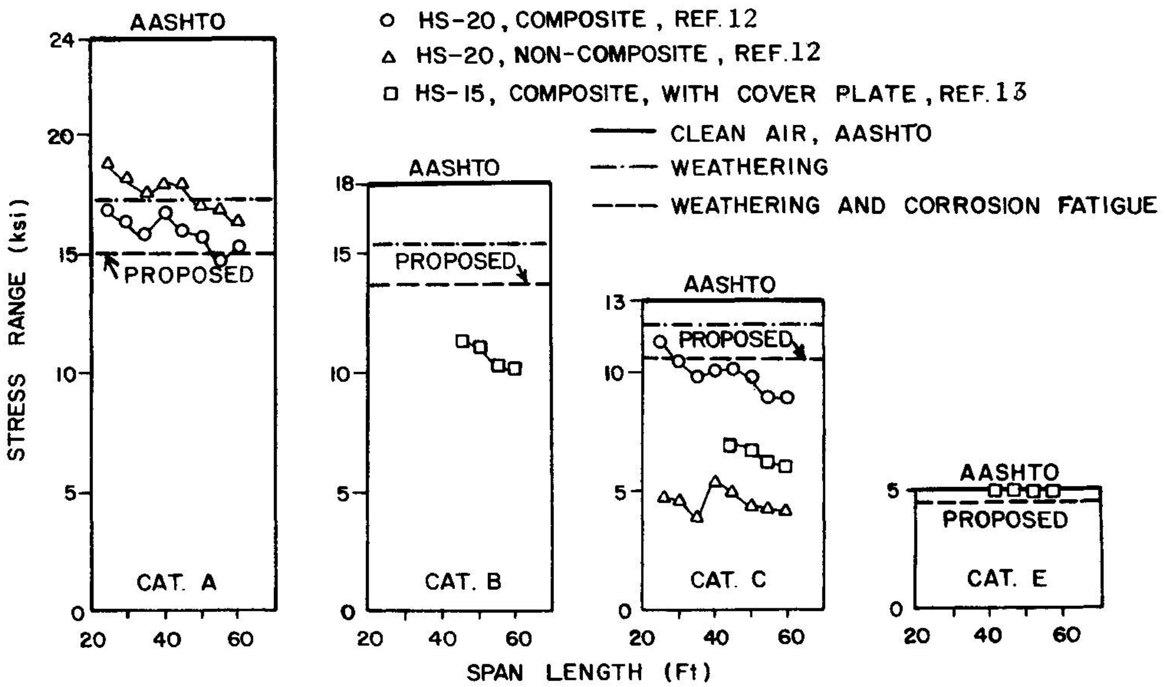

Fig. 5 Comparison of Calculated Stress Ranges in Simple-Span Bridges and Allowable Stress Ranges for: (1) Clean Air, Current AASHTO; (2) after Weathering; and (3) after Weathering and Corrosion Fatigue.

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