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Remaining Fatigue Strength of Corroded Steel Beams

Réserve de résistance à la fatigue de poutres en acier corrodées

Verbleibende Ermüdungsfestigkeit korrodierter Stahlträger

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SUMMARY

A method is proposed for determining the remaining fatigue strength of corroded beams. The method accounts for the loss of cross-sectional area, aqueous environment, and stress concentration factors of rust pits. These three parameters can be considered separately or in any combination, depending on the type of corrosion and exposure.

RÉSUMÉ

Une méthode est proposée pour la détermination de la réserve de résistance à la fatigue de poutres corrodées. Cette méthode tient compte de la perte en section, de l'humidité ambiante, ainsi que du facteur de concentration de contrainte des piqûres de rouille. Ces trois paramètres peuvent être considérés séparément ou combinés, selon le type de corrosion et d'environnement.

ZUSAMMENFASSUNG

Vorgeschlagen wird eine Methode zur Bestimmung der verbleibenden Ermüdungsfestigkeit korrodierter Stahlträger. Berücksichtigt werden dabei der Verlust an Querschnittsfläche, die feuchte Umgebung sowie Spannungskonzentrationsfaktoren infolge der Rostkerben. Diese drei Parameter können sowohl einzeln als auch in beliebiger Kombination in Rechnung gestellt werden, je nach der Art und der Schwere der auftretenden Korrosion.

1. INTRODUCTION

Highway and railway bridges fabricated from ASTM A7, A36, and A572 steels corrode if the paint system is allowed to fail for lack of maintenance. Those fabricated from ASTM A588 atmospheric corrosion resistant (weathering) steel corrode by virtue of the steel's use in a nonpainted condition. Corroding members lose cross section and pit. The loss in cross-sectional area in the plane through a fatigue critical detail increases the nominal stress range. The pits act as stress raisers that may lead to rapid crack initiation. Precipitation, moisture, and contamination with salt from any source help to create an aqueous environment at the crack tip that accelerates crack propagation. These three effects combine to reduce the fatigue strength of corroding steel members, with the losses becoming greater the longer the exposure time.

To date, the remaining life of corroded beams has been calculated simply on the basis of the uniform corrosion loss of a member's cross section. The effect of pitting, an important factor contributing to the loss in fatigue strength, has not been included in such calculations because no information is available on the stress concentration of rust pits in structural members. the present study infers the severity of rust pits from fatigue tests of corroded A7 carbon steel [1] and A588 weathering steel beams [2] and uses this information, along with the effects of section loss and aqueous environments, to recommend a method for predicting the remaining fatigue life of corroded members.

2. EXPERIMENTS

2.1 Carbon Steel Beams

The remaining fatigue strength of the A7 rolled steel beams was determined with tests of trolley bridge stringers that were exposed to the environment for long periods of time. These stringers consisted of 4.72 m long standard beams of W 15x42 (380 mm deep and weighing 62.4 kg/m) cross section. They were removed in 1985 from a bridge carrying the Maryland Line over the Paint Branch in College Park, Maryland. The bridge was built in 1900 and abandoned in 1985. Figure 1 shows a cross section of the bridge.

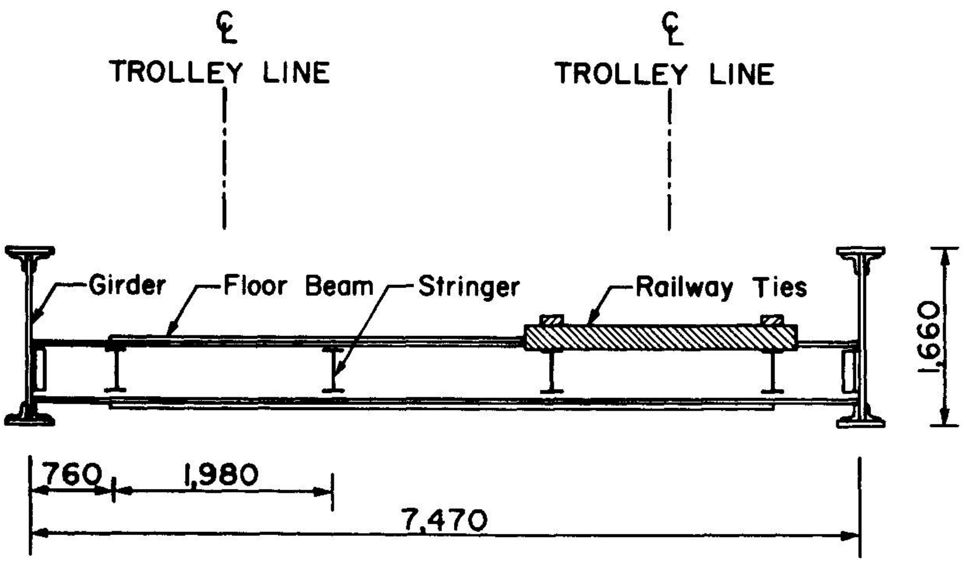

Fig. 1 Cross Section of Trolley Bridge

The trolley bridge was located in an environment of moderate corrosivity. The stringers were directly exposed to precipitation and sunshine, except for the partial shelter provided by the railway ties. The stringers corroded severely in the crevices between the railway ties and the top of the top flange, on the top of the bottom flange where debris had accumulated, and in the lower part of the web from moisture wicking up from the bottom flange by capillary action. Judging by the history of the Maryland Line, and allowing for graduate failure of the paint system, the bare steel exposure of the stringers was about 25 years.

A fatigue rating of the bridge showed that between 1900 and 1958 the stringers were subjected to about 1,900,000 cycles of 68-MPa stress range. Since the calculated mean stress range was only 41 percent of the 165-MPa fatigue limit for Category A rolled beams, the previous load history had no effect on the remaining fatigue life and was neglected. Therefore, the loss in fatigue strength observed in the test was a result of corrosion alone.

Of the 22 beam tests, nine were performed with the beams in the normal position, that is, in the same position as they were in the bridge (upside up); and 13 with the beams in the inverted position (upside down) so that the severe pits that had formed in the crevice between the top flange and the railway ties were in the tension flange during the fatigue test. In this way, the effect on fatigue could also be determined for deep pits that might occur under railway ties in a region of negative bending moment. The beams were tested in dry laboratory air.

Fatigue cracks initiated and propagated to failure in 19 beams. The tests of three beams were discontinued when no visible cracks were found after seven to ten million cycles of loading. The cracks that were found in 19 test beams initiated from the following types of defects: seven from rust pits at railway ties, eight from rust pits away from railway ties, three from imperfections at rolled-in seams, and one from an indentation at the flange tip. Eighteen beams failed from cracks that initiated in the tension flange and one in the web.

The fatigue test data for the trolley bridge stringers are compared in Fig. 2 with the allowable S-N lines for the AASHTO Category A through E details. The aforecited defects reduced the fatigue strength of the standard rolled beams from Category A for base metal to Category C for transverse stiffeners and 50 mm long attachments. The reduction in fatigue strength was greatest for rust pits at railway ties, followed by rust pits away from railway ties, and smallest for rolled-in seams and indentations.

The total reduction in fatigue strength of the trolley bridge beams can be separated into two parts. The first is attributed to the loss in cross-sectional area due to corrosion of the beam in the plane of the crack, and the second to the stress concentration effect of the rust pits. Accordingly, the fatigue notch factor (also called fatigue strength reduction factor) is equal to the product of the corrosion and pitting factors.

2.2 Weathering Steel Beams

The remaining fatigue strength of the weathering steel beams was determined with tests of 28 rolled beams of W 14x30 (360 mm deep and weighing 44.8 kg/m) cross section. The beams were placed on racks and were weathered under bold and sheltered exposures. In the former case, the beams were boldly exposed to sunshine and rain. In the latter case, the beams were covered with metal decking that simulated the sheltering of highway bridge girders by a concrete deck. Furthermore, they were sprayed three times per week during the three winter months with a three-percent sodium chloride solution to simulate the contamination of bridge girders with deicing salt. According to the steady-state corrosion rates listed in the ISO Draft Standard for Corrosion of Metals and Alloys, the bold exposure corresponded to an environment of moderate corrosivity, the bold exposure

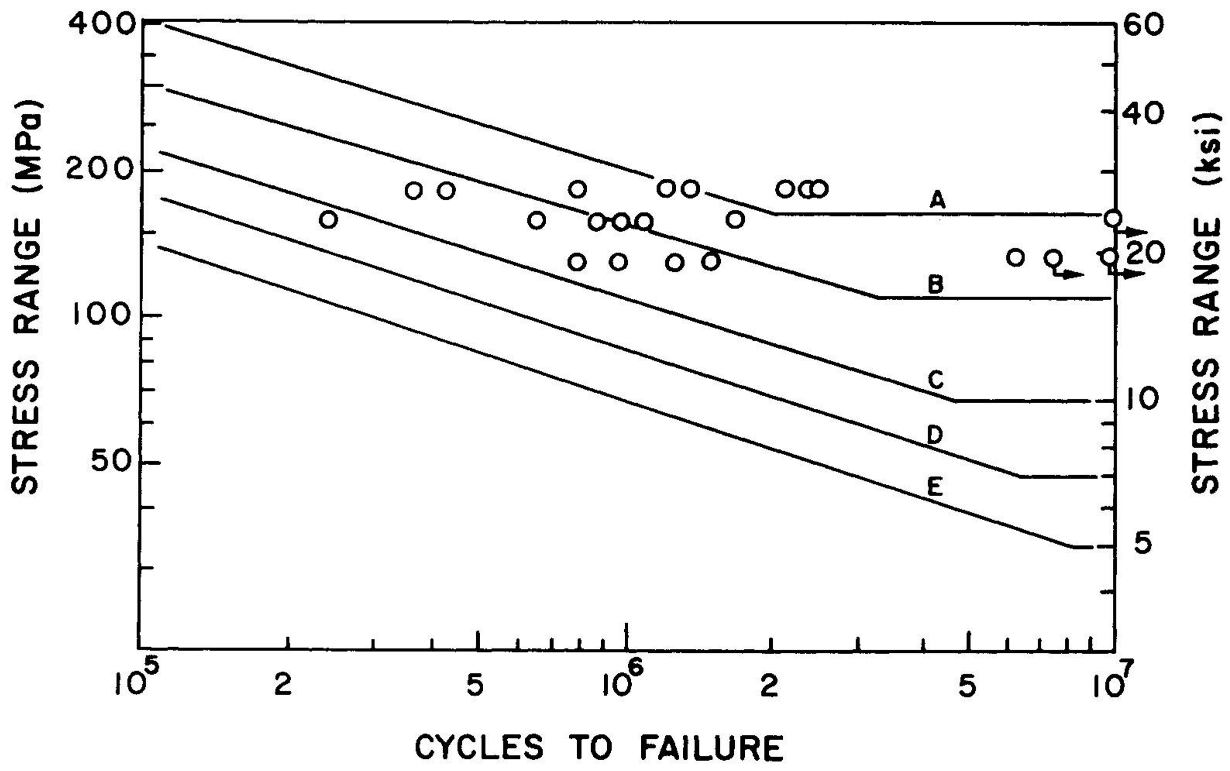

Fig. 2 Fatigue Test Data for Carbon Steel Beams

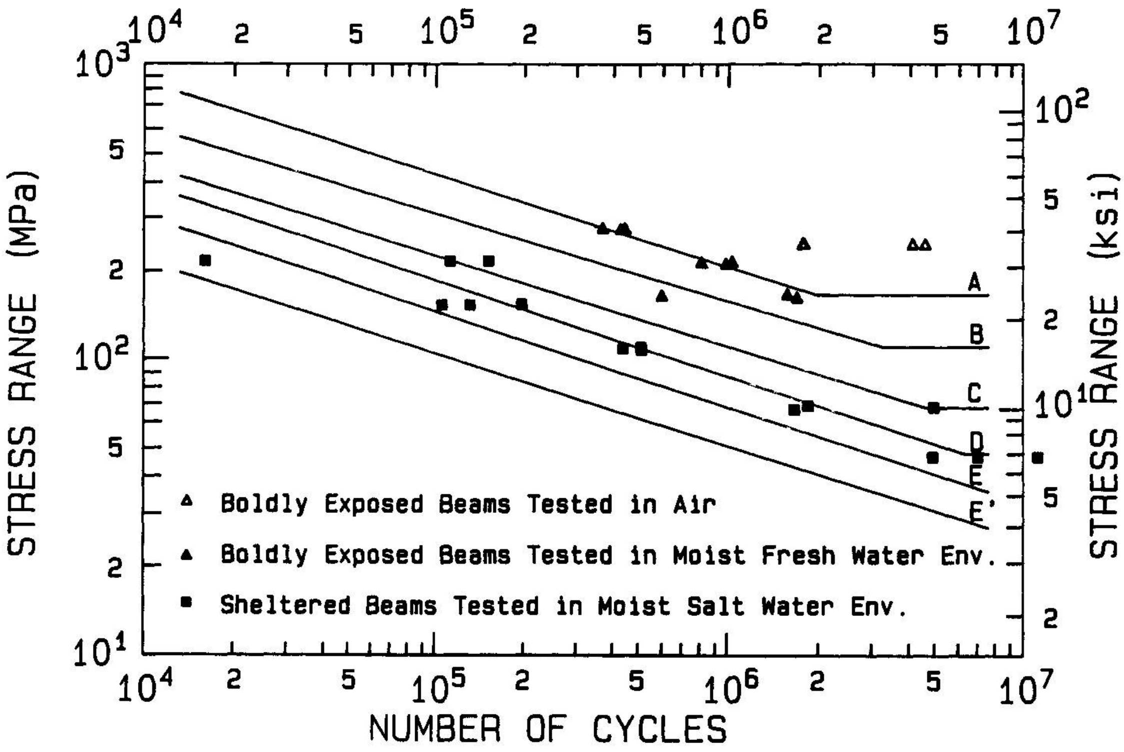

Fig. 3 Fatigue Test Data for Weathering Steel Beams

corresponded to an environment of moderate corrosivity, the sheltered exposure to an environment of very severe corrosivity. The web and flanges of the boldly exposed beams corroded to about the same degree. The bottom flange and the lower 75 mm of the web of the sheltered beams corroded much more than the top flange and upper portion of the web. The exposure time varied from five to six years.

The boldly exposed beams were fatigue tested in a moist fresh water environment, the sheltered beams in a moist salt water environment. the cyclic loads were applied at a frequency of 0.75 Hz. After an average weathering time of about 5 years, the boldly exposed beams exhibited a corrosion penetration of 0.06 mm, which is representative of bold exposure in an industrial environment. After an average weathering time of about 5.7 years, the sheltered beams exhibited a corrosion penetration of 0.32 mm for the top flange and 1.45 mm for the bottom flange. This high corrosion penetration reflects the very severe corrosivity of deicing salts.

All cracks initiated from rust pits located at the bottom of the bottom flange, except in two cases in which the pit was located on the top of the bottom flange. The deepest pit in each beam was on the average 0.34 mm for the boldly exposed beams and 2.46 mm for the sheltered beams.

The fatigue test data for the weathering steel beams are compared in Fig. 3 with the allowable S-N lines for the AASHTO Category A through E' details. As can be seen, the boldly exposed beams had Category A fatigue strength when tested in air, and B when tested in a moist fresh water environment. The sheltered beams tested in a moist salt water environment had Category E fatigue strength, with one beam failing below Category E. The loss in fatigue strength was 31 percent for the boldly exposed beams and 69 percent for the sheltered beams. The total reduction in fatigue strength exhibited by the beams tested in the aqueous environments is attributed to (a) the loss in cross-sectional area due to corrosion in plane of crack, (b) the aqueous test environment, and (c) the stress concentration effect of the rust pits. Accordingly, the fatigue notch factor of a bare exposed weathering steel beam can be expressed as the product of the corrosion, environment, and pitting factors.

3. METHOD OF ANALYSIS

3.1 General Equations

The total reduction in fatigue strength of a corroded beam is the vertical distance in Fig. 4 between the solid data point D for that beam and point A on the mean S-N line for Category A rolled beams given by

$$\log N = b - m \log f_r \tag{1}$$

where N = number of cycles to failure, f_r = stress range based on dimensions of beam before weathering, m = 3.178, and b = 13.785 for f_r in units of MPa [3]. The following three factors contribute to that reduction: (1) loss in cross-sectional area due to corrosion of beam in plane of crack, (2) stress cycling in aqueous environment, and (3) stress concentration effect of rust pits.

The total reduction in fatigue strength can be expressed in terms of the fatigue notch factor for the corroded beam

$$K_{fc} = \frac{f_{r,A}}{f_r} \tag{2}$$

where $f_{r,A}$ = mean stress range for AASHTO Category A rolled beams obtained by substituting the fatigue life of the test beam, N, into Eq. 1.

The total reduction in fatigue strength can then be separated into the three factors

$$K_{fc} = K_c \, K_e \, K_p \qquad (3)$$

where K_c = strength reduction factor attributed to loss in cross-sectional area due to corrosion of beam in plane of crack, K_e = strength reduction factor attributed to effect of aqueous environment, and K_p = strength reduction factor attributed to stress concentration effect of rust pits.

The terms K_c, K_e, and K_p are hereafter referred to as the corrosion factor, environment, and pitting factors, respectively. Their logarithms are equal to the distances CD, BC, and AB shown in Fig. 4. The corrosion factor is calculated from

$$K_c = \frac{f_{r,c}}{f_r} \qquad (4)$$

where $f_{r,c}$ = stress range at bottom flange of corroded section in plane ofcrack.The test environment factor is related to the ratio of the crack growth rates in aqueous and air environments.

$$K_e = \left\{ \frac{(\frac{da}{dN})_{aq.}}{(\frac{da}{dN})_{air}} \right\}^{1/n} \qquad (5)$$

where n = slope constant in plot of crack growth rate versus range of stress intensity factor.

Knowing K_c, K_e, and K_{fc} for a given set of fatigue test data, Eq. 3 can then be solved for the pitting factor, K_p.

$$K_p = \frac{K_{fc}}{K_c \, K_e} \qquad (6)$$

The calculation of the values K_c, K_e, and K_{fc} for the beams tested in the present study are described in the following.

3.2 Corrosion Factor

The stress range, f_r, to which a beam was subjected is given by

$$f_r = \frac{M_r \, y}{I} = \frac{M_r}{S} \qquad (7)$$

where M_r = moment range; and the properties of the section before corrosion are y = distance from neutral axis to extreme tension fiber, I = moment of inertia, and S = section modulus.

Figs. 5 and 6 show with solid lines the corroded section in the plane of the crack and with dashed lines the non-corroded section. The section loss in the plane of the crack affects the stress range in two ways: (1) the loss in cross sectional area reduces the moment of inertia, and (2) the unequal thickness losses of the top and bottom flanges shift the neutral axis of the section. The stress range at the bottom flange of the corroded section in the plane of the crack is given by

$$f_{r,c} = \frac{M_r\, y_c}{I_c} = \frac{M_r}{S_c} \tag{8}$$

where, for the corroded section, y_c = distance from neutral axis to extreme tension fiber, and I_c = moment of inertia in plane of crack, and S_c = section modulus. Substituting Eqs. 7 and 8 into Eq. 4 gives the following expression for the corrosion factor:

$$K_c = \frac{S}{S_c} \tag{9}$$

The cross-sectional properties needed to calculate the corrosion factor for a standard beam section (Fig. 5) are the moment of inertia of the noncorroded section

$$I = \frac{1}{12}\left\{ b_f d^3 - \frac{(b_f - t_w)}{8\,(m-n)}\,[(d-2n)^4 - (d-2m)^4] \right\} \tag{10}$$

the position of the centroidal axis of the corroded section

$$y_c = \frac{A\frac{d}{2} - [\Delta A_b \frac{m+n}{4} + \Delta A_w \frac{d}{2} + \Delta A_t\,(d - \frac{m+n}{4})]}{A - (\Delta A_b + \Delta A_w + \Delta A_t)} - C_b \tag{11}$$

and the moment of inertia of the corroded section

$$I_c = I + A\,(y_c + C_b - \frac{d}{2})^2 - \Delta A_b\,(y_c + C_b - \frac{m+n}{4})^2 - \frac{2C_w d^3}{12}$$

$$- \Delta A_w\,(y_c + C_b - \frac{d}{2})^2 - \Delta A_t\,(d - y_c - C_b - \frac{m+n}{4})^2] \tag{12}$$

where

$$\Delta A_b = 2C_b(b_f - 2C_w) \qquad \Delta A_w = 2C_w d \qquad \Delta A_t = 2C_t(b_f - 2C_w) \tag{13}$$

For the wide flange section, the moment of inertia is given by (Fig. 6)

$$I = \frac{b_f d^3 - (b_f - t_w)\,(d - 2t_f)^3}{12} \tag{14}$$

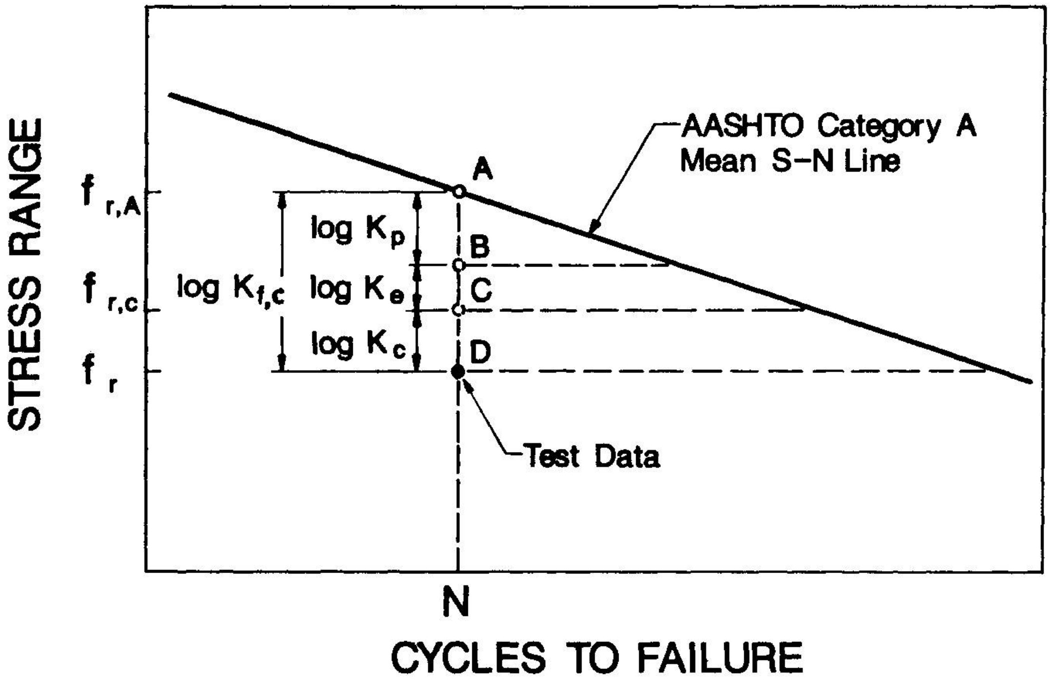

Fig. 4 Illustration of Fatigue Strength Reduction Factors

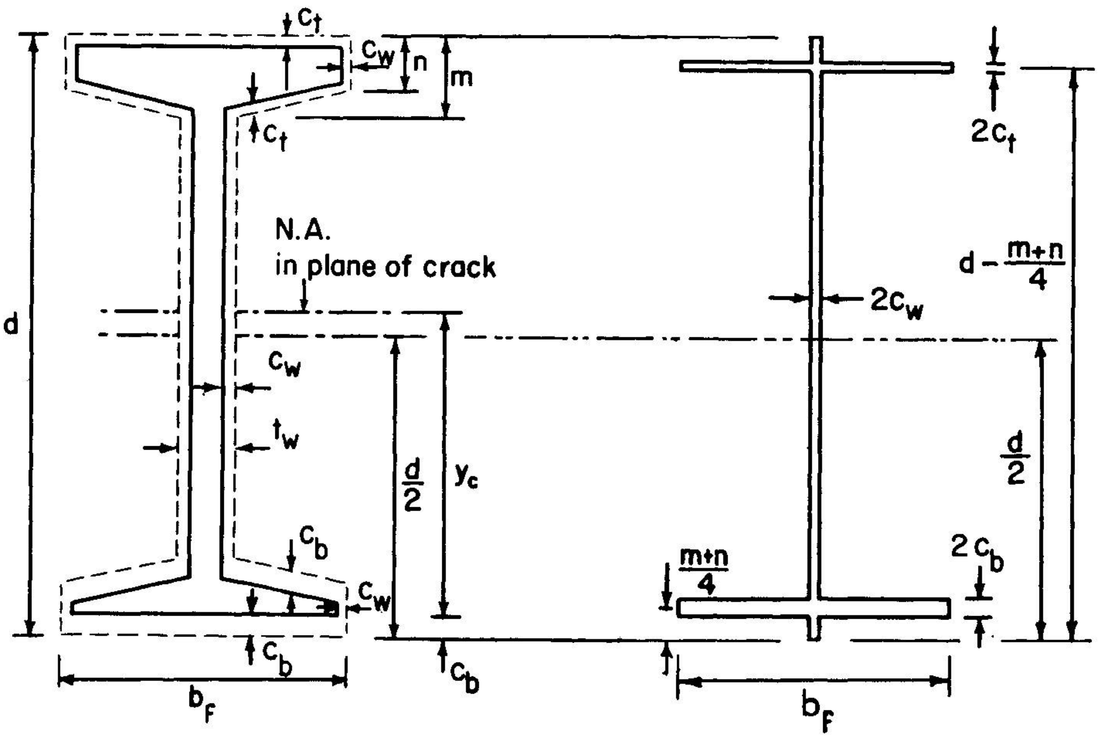

Fig. 5 Standard Beam with Noncorroded and Corroded Sections on left, Section Loss on Right

while the position of the centroidal axis and the moment of inertia of the corroded section are obtained by substituting $m+n = 2t_f$ in Eqs. 11 through 13. All dimensions are defined in Figs. 5 and 6.

The corrosion factor was calculated individually for each beam. It was on the average $K_c = 1.09$ for the carbon steel beams, 1.02 for the boldly exposed weathering steel beams, and 1.37 for the sheltered weathering steel beams.

3.3 Environment Factor

The crack growth rate for mild and high-strength low-alloy (HSLA) steels stress cycled in air differs significantly from that for the same steels stress cycled in an aqueous environment. The crack growth rate is, in air [5]:

$$\left(\frac{da}{dN}\right)_{air} = 1.537\times10^{-12}\ (\Delta K_{eff})^{3.344} \qquad (15)$$

and in aqueous environments

$$\left(\frac{da}{dN}\right)_{aq.} = 4.161\times10^{-12}\ (\Delta K_{eff})^{3.279} \qquad (16)$$

where da/dN = crack growth rate in m/cycle and ΔK_{eff} = stress intensity factor in $MPa\sqrt{m}$.

Eqs. 15 and 16 appear as nearly parallel lines in a base-10 logarithmic plot of da/dN versus ΔK_{eff}. Hence, the effect of the aqueous environment on the crack growth rate is uniform over the range of data.

The fatigue life reduction factor due to the aqueous environment is the ratio of the crack growth rates. The fatigue strength reduction factor is then given by the n-th root of the fatigue life reduction factor (Eq. 5) where n = 3.3 is the average exponent in Eqs. 15 and 16. At the lowest stress intensity factor range [$\Delta K_{eff} = 14.8\ MPa\sqrt{m}$ ($13.5\ ksi\sqrt{in.}$)] at which corrosion fatigue crack growth rates were measured, cracks grew a factor of 2.3 faster in aqueous environments than in air [5]. Hence, the environment factor is on the average $K_e = (2.3)^{1/3.3} = 1.3$ for the wide flange beams tested in aqueous environments.

3.4 Pitting Factor

Knowing the values of K_{fc}, K_c, and K_e, the strength reduction factor attributed to the stress concentration effect of the rust pits, K_p, was then calculated with Eq. 6. The value of K_p for the carbon and weathering steel beams were plotted in Figs. 7 and 8 against the maximum measured pit depth in the plane of the crack. The mean regression lines going through the point with coordinates $d_p = 0$ and $K_p = 1.0$ are, for the carbon steel beams:

$$K_p = 1.0 + 0.22\ d_p \qquad (17)$$

and for the weathering steel beams

$$K_p = 1.0 + 0.40\ d_p \qquad (18)$$

where d_p = pit depth in units of millimeter. The depth was used in the present study as the simplest measure of the severity of the stress concentration factor caused by a pit. Other measures also affect the stress concentration such as the

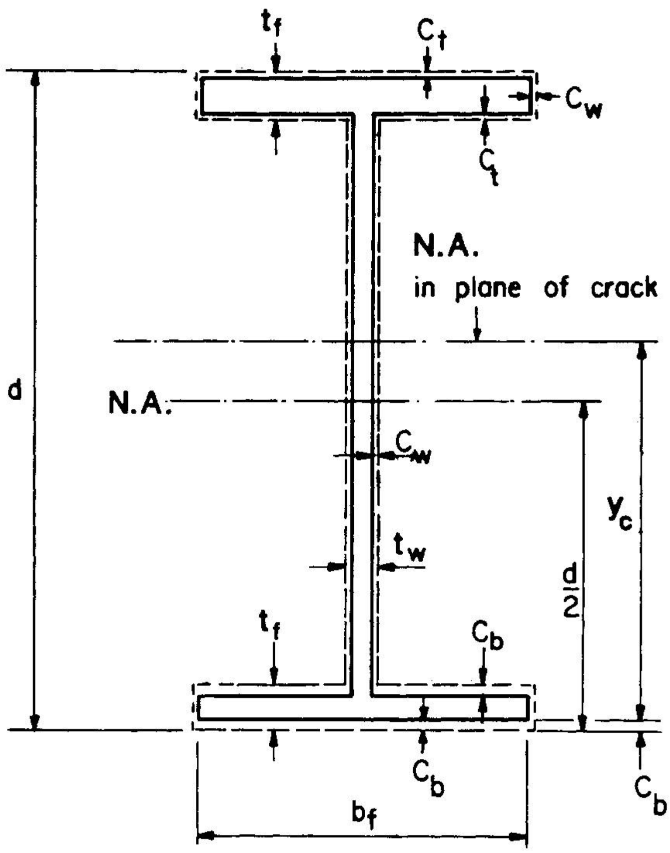

Fig. 6 Wide Flange Beam with Noncorroded and Corroded Sections

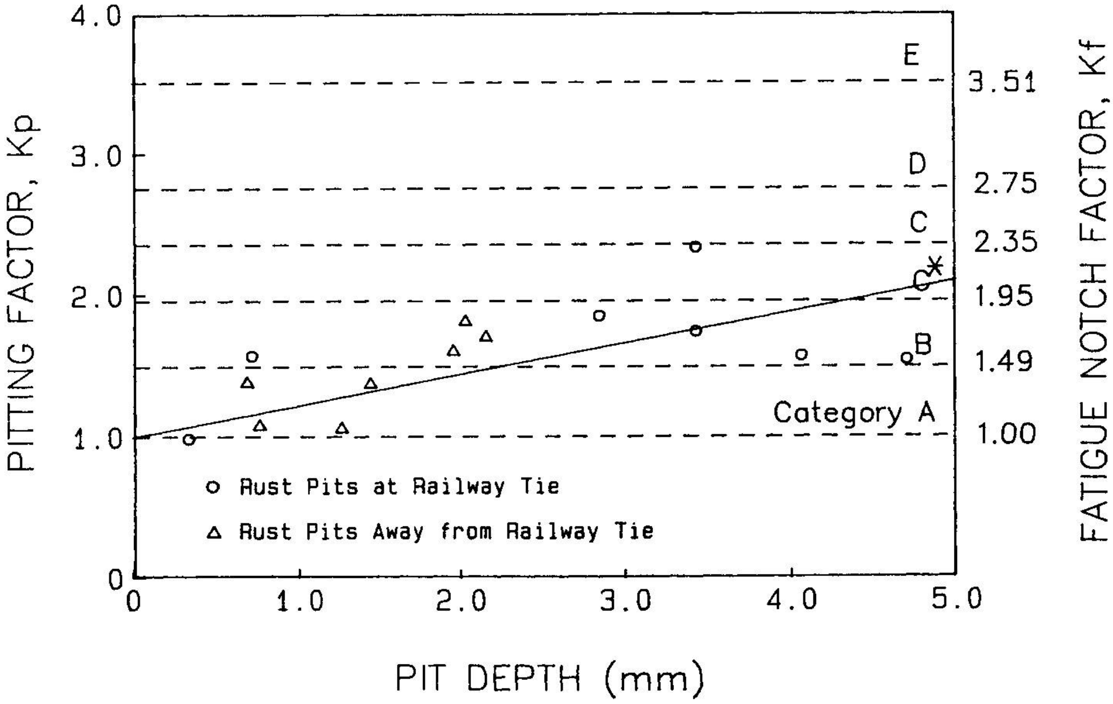

Fig. 7 Pitting Factor for Carbon Steel Beams

slope of the pit walls and the depth-to-diameter ratio. Including them could lead to more accurate results if each pit were separate from the others. However, this was rarely the case.

The pitting factors are compared with the fatigue notch factors, K_f, of the mean S-N lines for Category A--base metal, B--welded beams, C*--transverse stiffeners, C--50 mm long attachments, D--100 mm long attachments, and E--partial length cover plates. The values of K_f are shown as horizontal lines in Figs. 7 and 8. The following conclusions can be drawn from these results. First, the pitting factor increased on the average with pit depth. Second, for equal depths, a pit induced a much higher stress concentration in a weathering steel beam than in a carbon steel beam. Indeed, the pits in the weathering steel beams were found to have steeper walls and at times flat bottoms, while those in the carbon steel beams had a more rounded profile. Third, pitting reduced the fatigue strength more than section loss, $K_p > K_c$.

As an example of the severity of the rust pits in weathering steel beams, substituting the fatigue notch factors listed on the right vertical axis of Fig. 8 into Eq. 17 in place of K_p and solving for d_p, one finds that pit depths of d_p = 1.2, 2.4, 3.4, and 4.4 mm, respectively, reduced the fatigue strength of the weathering steel beams on the average to the mean fatigue strength of Category B welded beams, Category C* transverse stiffeners, Category C 50-mm attachments, and Category D 100-mm attachments.

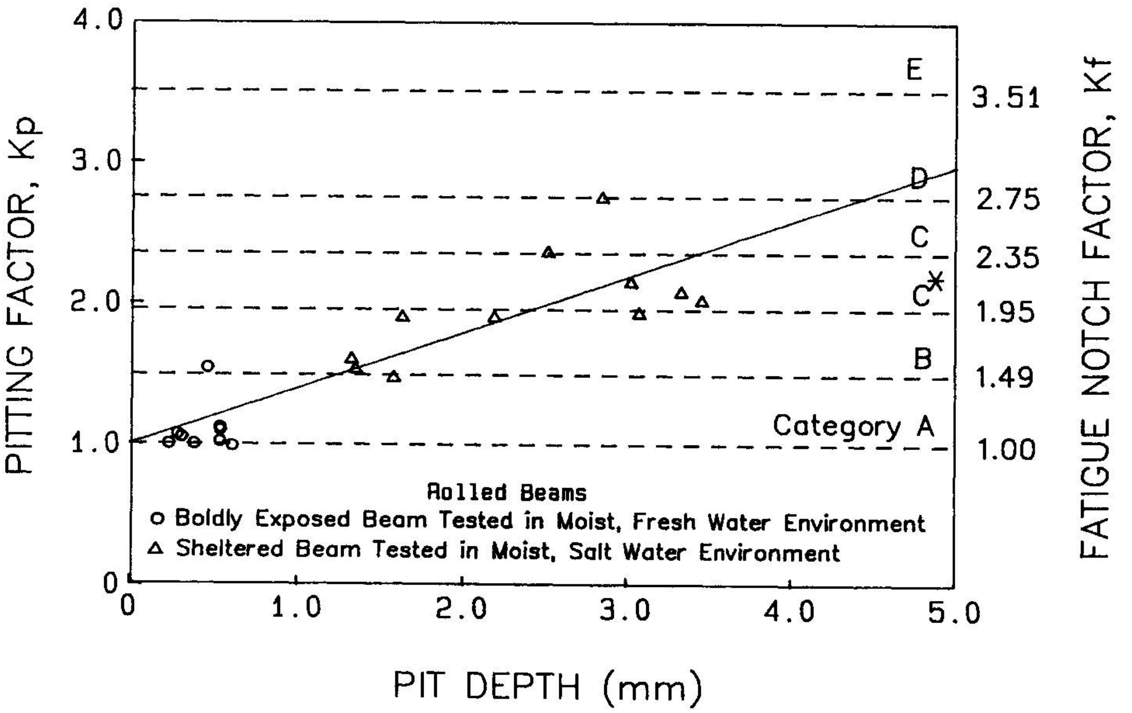

Fig. 8 Pitting Factor for A588 Weathering Steel Beam

4. DESIGN RECOMMENDATIONS FOR EXISTING STRUCTURES

The remaining fatigue life of corroded rolled beams in existing structures may be calculated following the procedure outlined below.

1. Calculate with Eq. 7 the stress range, f_r, at the critical section of the non-corroded beam.

2. Measure the corrosion penetration using an electrically powered disk grinder and an ultrasonic thickness gage as follows [6,7,8]:

   - Grind a 25 mm wide strip across one surface of the bottom flange, web, and top flange until bare metal is exposed on the highest points of the corroded surfaces, leaving the depressions filled with dense oxide. Approximately 30 percent of the so-ground surface should have a metallic appearance.

   - Measure the thickness of the web and flanges with the ultrasonic thickness gage at 20-mm intervals along the ground strips. At each measurement point, move the ultrasonic probe in an area of 20-mm diameter and retain the smallest reading. This peak-to-valley reading gives a good estimate of the plate thickness.

   - Average the measured thicknesses of the web and each flange separately.

   - Subtract the measured plate thicknesses from the original thicknesses of the members specified on the as-built drawings. Divide the difference by two to obtain the uniform corrosion penetration per side of the web and each flange plate.

3. Using the Eqs. 10 through 14 listed in Section 3.2, calculate the cross-sectional properties of the beam before and after corrosion, the latter being based on the corrosion penetration values measured in Step 2.

4. Calculate the corrosion factor, K_c, with Eq. 9.

5. Continuing the process described in Step 2, measure the pit depth as follows:

   - Continue to grind the strips until only traces of oxide remain.

   - Measure again the thickness with the ultrasonic thickness gage and retain the smallest reading. This represents the valley-to-valley thickness.

   - Substract the valley-to-valley thickness from the peak-to-valley thickiness measured in Step 2 to obtain the pit depth.

   Alternatively, pit depths can be measured with a depth gage after blast cleaning the non-ground surface to bare metal.

6. Calculate the pitting factor, K_p, with Eq. 17 for carbon steel beams and Eq. 18 for weathering steel beams, using the pit depth measured in Step 5.

7. If the structure will remain exposed in a bare condition, as may be the case for weathering steel, assume a value for the environment factor, say, $K_e = 1.3$. If the structure is to be painted, set $K_e = 1.0$.

8. Calculate the allowable fatigue life as

$$N_d = \frac{10^{b-2s}}{(K_c K_e K_p f_r)^m} \tag{19}$$

where b, m, and s are the intercept, slope, and standard deviation of the mean S-N line for Category A base metal (see for example Table 1 of Ref. 4).

9. Estimate the number of stress range cycles, N_{used}, that were applied on the structure to date.

10. Calculate the remaining number of stress range cycles, $N_{rem.}$, that may be applied on the structure until it reaches the allowable fatigue life.

$$N_{rem.} = N_d - N_{used} \tag{20}$$

5. APPLICATION TO OTHER TYPES OF DETAILS

The recommendations for calculating the remaining fatigue life of corroded rolled beams, outlined in Section 4, can also be applied to other types of details. Two cases are possible, depending on whether the notch effect of a pit is smaller or greater than that of a given type of detail. If the pitting factor is smaller than the fatigue notch factor for the noncorroded detail, $K_p < K_f$, the fatigue notch factor for the corroded detail is given by

$$K_{fc} = K_c\ K_e\ K_f \tag{21}$$

If, on the other hand, $K_p > K_f$, then

$$K_{fc} = K_c\ K_e\ K_p \tag{22}$$

The authors have verified the extension of this method to two other types of details that were exposed in a sheltered condition for 4.3 to 6.5 years and then fatigue tested in a moist salt water environment. These details consisted of Category B welded beams and Category E rolled beams with partial-length cover plates fabricated from A588 weathering steel [2].

Like the Category A rolled beams of A588 steel whose data were presented in this paper, the fatigue strength of the corroded Category B welded beams was reduced to that of Category E, meaning that $K_p > K_f$. Furthermore, the equation relating pit depth to pitting factor for the welded beams was about the same as the corresponding Eq. 18 for the rolled beams.

Finally, sheltered exposure and stress cycling in a moist salt water environment did not significantly affect the fatigue strength of the Category E coverplated beams of A588 steel, meaning that $K_p < K_f$.

So, Eq. 21 should be used for the Category B welded beams and Eq. 22 for the Category E welded beams. If at the time the analysis is performed it is decided to paint the weathering steel beams, then a value of K_e = 1.0 should be chosen in the calculation of remaining life.

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