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IN SERVICE 10 YEARS, this corroded 3/4 inch nut is part of a fixture on a swimming pool boundary fence. The bolt is vertical and attaches paling to the foundations just above ground level. Adhering corrosion products double the size of the nut which can still be seen inside the castellated ring of corrosion products—providing a fine example of exfoliation corrosion. Photograph courtesy of the Department of Scientific and Industrial Research, Chemistry Division, Private Bag, Petone, New Zealand.

Effect of Use of Galvanized Steel on the Durability of Reinforced Concrete*

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Results of atmospheric exposure with cyclic application of NaCl solution on prestressed black and galvanized steel reinforcing bars are reported. Fatigue tests were conducted after 8 months. High strength reinforcing steel bars require limited crack widths for proper durability, so galvanized bars have an added safety factor in aggressive exposures. After vibration testing to failure, black bars were rusted at cracks while galvanized bars showed little attack. Concrete adhered tightly to galvanized bars near cracks. Tests showed galvanized bars lost less fatigue strength than black bars, and that they could tolerate greater crack widths.

REINFORCING STEEL BARS in concrete usually have little chance to become corroded as long as widths of cracks in the concrete are within a certain limit.[1] When reinforced concrete develops an excessive crack width while being subjected to stress, bars in concrete may become corroded and affect its durability. Corrosion of reinforcing bars depends not only on crack widths, but also on crack directions, qualities of the concrete, the reinforcing bar material, and thickness of concrete over the bars. The exposure conditions of the reinforced concrete member, in particular, is a very influential factor affecting corrosion. Thus, allowable limits of crack width in reinforced concrete, which are intended to ensure durability, are determined in degree according to the exposure conditions for the member. For example, the European Concrete Committee[1] specifies allowable crack widths of 0.3, 0.2, and 0.1 mm for reinforced concrete members under 3 different conditions: (1) indoor, (2) outdoor, and (3) in a highly corrosive atmosphere, respectively.

The widths of cracks increase proportionally to the applied stress on the reinforcing bars involved. This means that the effective use of high tensile strength deformed bars is limited by the allowable limit of the crack width. The use of galvanized steel bars may be cited as a practical solution to this problem. In other words, it has been pointed out that the corrosion rate of the reinforcing steel bars in concrete can be reduced by galvanizing treatment.[2,3] However, the relationship between crack width and corrosion of bars in concrete reinforced with galvanized steel bars is not yet definite, and it remains to be clarified how much the allowable limit of the crack width can be increased using galvanized steel bars, rather than black steel bars.

Accordingly, research on the relationship between corrosion and crack width was carried out. Reinforced concrete beams in a cracked condition, with galvanized steel bars or black bars, were exposed to a 3% solution of sodium chloride sprayed twice a day for 1 year. The reinforced concrete beams that had undergone the exposure test were then subjected to a fatigue test. After this, they were crushed to investigate the relationship between corrosion of the galvanized steel bars and crack width compared with black steel bars.

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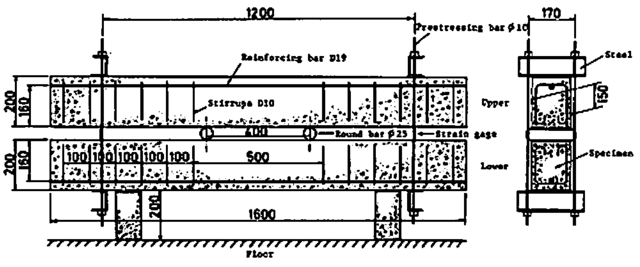

FIGURE 1 — Test specimens (all dimensions are in mm).

TABLE 1 — Crack Widths of Beams at Loading

Specimen No.	Stress of Reber MPa[2]	Number of Cracks	Width of Each Crack[1] 1/100 mm								Average of 3 Main Cracks
62	303	7	32 33	28 30	22 27	21 27	19 26	19 19			27.3 30.0
38	308	8	35 43	26 32	23 30	23 30	20 29	19 15	19 20		28.0 35.0
60	265	8	27 32	25 27	19 18	19 16	10 14	8 14	 13	 13	23.7 25.7
61	265	7	26 29	25 27	22 25	18 24	17 21	14 18	11 13		24.3 27.0
59	316	7	32 34	29 29	28 27	23 23	17 21	 18			29.7 30.0
37	316	7	31 41	28 39	28 35	27 33	22 30	21 27	16 17		29.0 38.3
53	267	8	27 36	25 32	25 30	18 24	14 18	12 11	6 11		25.7 32.7
57	261	8	30 40	29 39	28 29	24 27	22 26	14 15			29.0 36.0
54	267	8	26 32	25 29	22 28	18 24	15 22	14 17	5 10		24.3 29.7
58	261	7	35 39	26 30	26 30	22 28	16 20	15 14			29.0 33.0
51	312	7	26 31	25 30	21 24	15 23	15 21	12 17	12 12		24.0 28.3
55	298	7	34 29	29 28	21 26	21 26	17 26	16 17			28.0 27.7
52	312	7	24 31	23 28	22 27	20 23	20 22	12 15	11		23.0 28.7
56	298	6	29 38	28 35	26 35	26 31	18 21	6 13			27.7 36.0
43	257	8	25 32	24 31	18 29	16 25	14 20	13 17	7 14		22.3 30.7
47	269	7	34 37	29 33	23 27	23 24	16 19	9 17			28.7 32.3
44	257	7	27 32	26 28	21 28	20 28	15 23	14 18			24.7 29.3
48	269	6	32 39	26 34	22 29	21 27	10 16				26.7 34.0
39	302	8									
45	303	9	26 34	22 29	22 28	22 21	17 20	11 20	10 13		23.3 30.3
49	298	7	26 34	26 31	24 31	23 30	22 25	18 22	12 20		25.3 31.3
40	302	7	43 –	34 41	32 41	23 –	20 24	16 –			39.7
46	303	7	36 40	31 36	23 28	21 26	16 16	12 15			30.0 34.7
50	298	6	33 40	32 37	30 36	28 35	27 26	19			31.7 37.7

[1] Widths at the side of the specimen and the bottom (Figure 2).
[2] 1 MPa = 0.145 ksi.

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High strength deformed bars with a yield strength of 600 MPa (87 ksi) were used. The bar diameter was 19 mm, the angle of inclination formed by lugs and bar axes was 90°, and arcs at the bases of lugs with radii of lug-height were provided. These two parameters have been recognized to affect the fatigue properties of deformed bars. The zinc coating weight on the galvanized bars was 0.6 kg/m^2 (2 oz/ft^2).

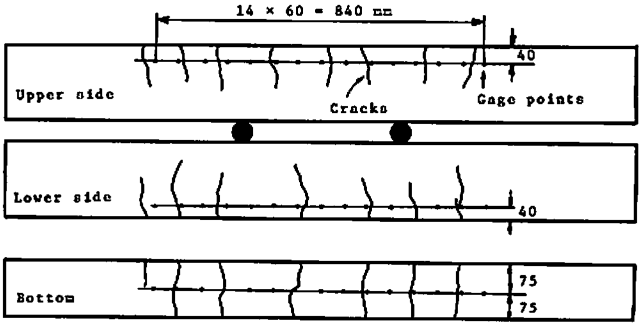

FIGURE 2 — Schematic representation of cracks developed in concrete beams and sites of gage points to measure the crack width.

FIGURE 3 — Exposure test.

The concrete was made with high early strength portland cement, whose compressive strength was about 40 MPa (5.8 ksi) after 28 days. However, the cement content was relatively low, or only 276 kg/m^3 (17 lbs/cu ft). Yet, the concrete itself had a relatively high durability against freezing and thawing or other atmospheric action because it had a low unit water content with the addition of a surface active agent,[4] with an air content of about 3%. Concrete with 25 mm maximum sized coarse aggregate had a water-cement ratio of 0.55, and a slump of approximately 40 mm. Specimens were stripped from the molds at 2 days, and concrete surfaces were covered with wet cloth which was covered again with vinyl sheet for moist curing until testing.

Specimens and Test Procedures

Each specimen consisted of a set of two rectangular beams, each measuring 150 mm in width, 200 mm in height, and 1600 mm in length, arranged in such a manner that one beam was put on the other, with two 25 mm diameter round bars in between, and bending moment was imparted to them stretching 4 prestressing steel bars (Figure 1). The prestressing bars were checked for strain

TABLE 2 – Results of Fatigue Tests After the Exposure Tests

Exposure Tests					Fatigue Tests					
Period of Exposure (Months)	Galv. or Black	Position of Specimen	Specimen No.	Stress of Rebar MPa(2)	Stress Range MPa(2)	Cycles N $\times 10^3$	N_{20} $\times 10^3$	ΣN_{20} $\times 10^3$	Log ΣN_{20}	fs(3) MPa(2)
		Upper	62	308	196	771	771	771	5.887	172
3	Black	Lower	38	308	196	1960	1960			
					235	2230	10370	12330	7.091	242
		Upper	60	265	196	2310	2310			
					235	340	1580	3890	6.590	213
6	Black	Lower	61	265	196	2310	2310			
					235	57	265	2575	6.411	203
		Upper	59	316	196	1950	1950	1950	6.290	195
8	Galv.	Lower	37	316	196	1950	1950			
					235	536	2490	4440	6.480	207
		Upper	53	267	157	1970	425	425	5.628	157
			57	261	157	1920	414	414	5.617	156
			54	267	157	1970	425			
		Lower			196	220	220	645	5.810	168
			58	261	157	1760	379	379	5.579	154
	Black		51	312	157	2360	508			
					196	810	810	1318	6.120	185
		Upper	55	298	157	2630	565			
					196	704	704	1269	6.104	184
			52	312	157	2360	508			
		Lower			196	593	593	1101	6.046	181
			56	298	157	1664	358	358	5.554	152
			43	257	157	2300	495			
					196	2030	2030			
		Upper			235	1840	3960	6485	6.812	226
			47	269	157	2250	484			
					196	987	987	1471	6.168	188
12			44	257	157	2300	495			
					196	2030	2030			
		Lower			216	1215	2620	5145	6.712	221
			48	269	157	2250	484			
					196	90	90	574	5.759	164
			39	302	157	2340	505			
	Galv.				196	630	630	1135	6.055	181
			45	303	157	2260	486			
		Upper			196	1460	1460	1946	6.289	195
			49	298	157	2230	480			
					196	731	731	1211	6.083	183
			40	302	157	2340	505			
					196	483	483	988	5.995	178
			46	303	157	2260	486			
		Lower			196	2410	2410			
					216	1830	3940	6836	6.835	227
			50	298	157	2230	480			
					196	89	89	569	5.755	164

(1) See Figure 2.
(2) fs = fatigue stress.
(3) 1 MPa = 0.145 ksi.

by wire strain gages on the bars to determine two cases where tensile stress acting on reinforcing bars in beams would become about 275 MPa (40 ksi) and about 314 MPa (45 ksi), and the tensile force against prestressing steel bars was adjusted accordingly. After imparting tensile force to the prestressing bars, they were fixed with nuts and subjected to the exposure tests. The tensile force was a little reduced when the bars were fixed, and calculated values of the tensile stress acting on the reinforcing bars were as shown in Table 1.

Due to the bending moment each beam developed 6 to 9 transverse cracks as shown in Figure 2. Crack width is one of the most important factors affecting the corrosion of reinforcing bars. Therefore, crack widths on the surface of the concrete beams were measured with contact type strain gages at two levels: at the center of the bottom, and on the side of the specimen 40 mm from the bottom where the bar was located (Figure 2). Elongations between gage points which had been put on the surface of concrete were measured, and these were assumed to be the widths of cracks. Because, the elongations of uncracked sections were very small, the elongations were considered to be concentrated in the cracks. Table 1 shows widths of the main cracks developed in the beams. The width of the widest crack on the side and bottom of each beam

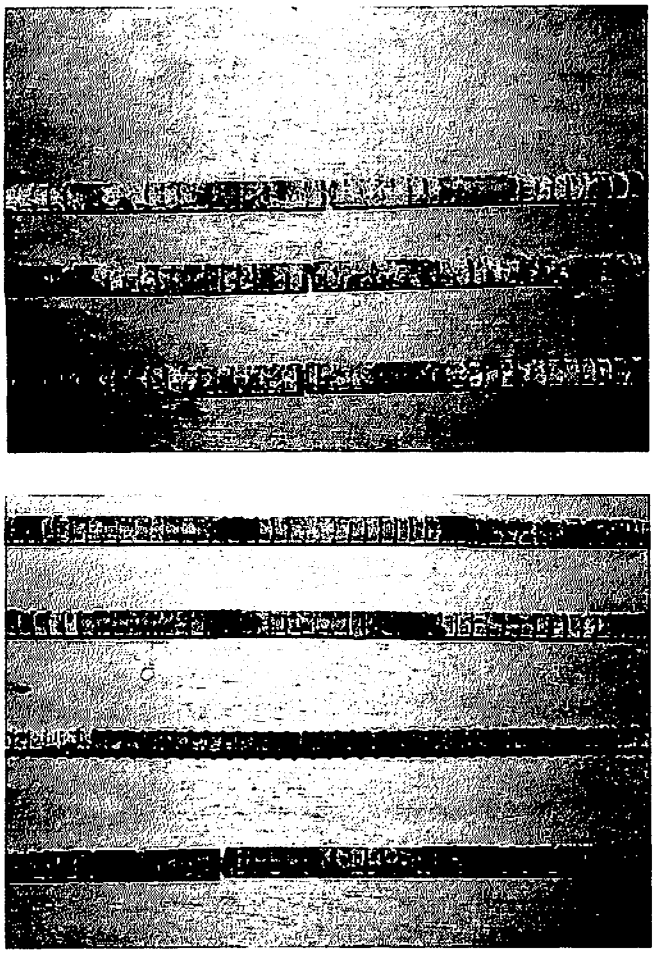

FIGURE 4 — Reinforcing bars corroded near cracks. Top: galvanized steel, and bottom: black steel.

ranged from 0.24 to 0.43 mm, and 0.27 to 0.41 mm, respectively, which was considerably larger than the allowable width limits for ordinary reinforced concrete.

The exposure test was conducted at the University of Tokyo as shown in Figure 3. The beams were exposed directly to sunshine and rain. Each pair of specimens was sprayed with 1.0 liter of 3% sodium chloride solution every morning and afternoon, with a flower watering pot. The spraying was daily, regardless of weather, except Sundays and holidays. It was assumed that as the solution penetrated through the cracks to deprive the concrete of alkalinity and supply oxygen, corrosion of the reinforcing bars would be considerably accelerated. Corrosion would be far more rapid if drying and wetting was repeated inside the cracks, than in a condition where the cracks were always filled with solution, and accordingly, the spraying method was employed for the test.

The exposure test began in June, 1972, and it was scheduled that, of the total of 12 pairs of beams, 3 pairs would be subjected to a fatigue test at 3, 6, and 8 months during the exposure test. From the results obtained, it was decided to terminate the test after 12 months. The pairs of beams were not inverted during the experiment. After the fatigue tests, the specimens were crushed to observe the degree of corrosion on the galvanized and black steel bars. This was compared to investigate the effect of crack width on corrosion.

The bending fatigue test apparatus consisted of a jack of 10 ton capacity and cycle of 5 Hz. The beams were supported by rollers on ball bearings. Tests were conducted by two point loading at span of 1200 mm, with 400 mm between loading points. The tests were generally continued to failure, but the maximum loads were increased at 2 million cycles if failure was not reached by that level (Table 2). The load used in the fatigue test was determined based on reinforcing bar stress calculated from elastic theory. The minimum load was selected to obtain a reinforcing bar stress of 39 MPa (5.6 ksi), while maximum loads were varied in several stages (Table 2).

Results and Discussion

The results of the fatigue tests conducted after exposure to the sodium chloride solution are shown in Table 2. All beams failed at last due to fatigue rupture of the reinforcing steel. Therefore, from the test results, the relation between the calculated stress ranges (σ_{max}-σ_{min}) of the reinforcing bars and cycles of load to rupture was investigated. A 2 million cycle fatigue stress range of each specimen was estimated by applying Miner's rule.[5] For calculation of the fatigue stress range, the following hypotheses were used, considering the previous test results.[6]

$$\text{Log}N_{f_2} = \text{Log}N_{f_1} + (f_1 - f_2)/59$$

$$f_{sr} = f_2 + 59\,[\text{Log}\,\Sigma N_{f_2} - \text{Log}\,(2 \times 10^6)]$$

where f_1 = a certain stress range, MPa; f_2 = a certain stress range, MPa; N_{f_1} = cycles under stress range of f_1; N_{f_2} = equivalent cycles under stress range of f_2 corresponding to N_{f_1} under f_1; ΣN_{f_2} = total equivalent cycles under stress range of f_2; and f_{sr} = 2 million cycle fatigue stress range, MPa.

The results of the calculations are shown in Table 2. Before the exposure tests, the averages of the 2 million cycle fatigue stress for galvanized steel was 250 MPa, while that of black steel was 267 MPa. These results may indicate that the effect of galvanizing treatment on fatigue strength of bars will be negligible compared with the remarkable effect of the difference in the deformations on bar. Therefore, it is important to select a bar with good deformations for fatigue resistance, and there will be practically no need to consider the effect of galvanizing treatment on the fatigue strength of reinforced concrete beams.

The first thing to be pointed out from Table 2 is that the longer the duration of exposure, the lower the fatigue strength of a bar due to corrosion of the bars near the crack openings. In the case of black steel, the 2 million cycle fatigue stress before the exposure test was 267 MPa (39 ksi), but reduced to about 200 MPa (29 ksi) at 6 months' exposure, and to 167 MPa (24 ksi) after exposure of 1 year. In the case of galvanized steel, the reduction of fatigue stress due to corrosion was also seen and the 2 million cycle fatigue stress was 200 MPa (29 ksi) for 8 months exposure and 195 MPa (28 ksi) for 1 year. However, the degree of the reduction in fatigue strength was smaller for galvanized steel. It seems that galvanizing will alleviate the corrosion of reinforcing steel in cracked concrete.

Figure 4 shows an example of reinforcing bars which were taken from the beam after the fatigue tests. Red rust was found on the black steel bars near the position of each crack in the concrete. On the other hand, little such rust was found on the galvanized bars. However, galvanized steel seemed to react with the concrete near the cracks, as concrete near the cracks adhered tightly to the steel bars.

Figure 5 shows the relationship between width of the maximum crack and the fatigue stress. The crack width at the bottom of a specimen seems to have a remarkable effect on the fatigue strength of bars subjected to exposure tests compared to the crack width at the side of a specimen. Although the rupture of some bars occurred near wide cracks, this did not happen in every case.

All the beams had a constant depth of concrete cover. There is evidence now that surface crack widths alone are not a sufficient indicator of corrosion resistance.[7]

Summary

Fatigue tests were conducted on 60 stressed concrete beams reinforced with galvanized bars or black steel bars. Twenty-four of these were tested after exposure to sodium chloride solution for a duration of 6 to 12 months in cracked condition. Within the scope of the experiment, the following can be said:

1. The longer the duration of exposure to sodium chloride solution, the lower the fatigue strength of a bar in concrete due to corrosion of the bar near the crack openings. However, the degree of

reduction of fatigue strength was less for galvanized steel bars. The durability of reinforced concrete against sodium chloride solution or sea water will be improved by using galvanized reinforcing bars. By using galvanized steel, the durability of concrete members with cracks of about 0.3 mm width will have the same durability as ordinary reinforced concrete with crack width of about 0.2 mm.

2. The use of galvanized steel does not significantly affect the fatigue strength of reinforced concrete beams.

Acknowledgment

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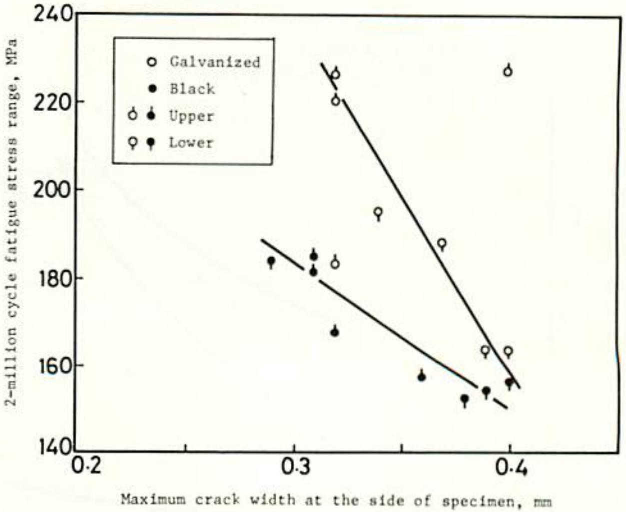

FIGURE 5 — Effects of maximum crack width in beam on the fatigue strength of reinforcing bars in concrete exposed to a solution of sodium chloride for a duration of 1 year.

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