[2116] 鉄筋腐食が鉄筋コンクリートはりの静的耐力に及ぼす影響

EFFECT OF CORROSION OF REINFORCEMENT ON THE LOAD CARRYING CAPACITY OF RC BEAMS

Sudhir MISRA* and Taketo UOMOTO**

1. INTRODUCTION

Reinforced concrete is one of the most important construction materials in use in the present day. Though it has shown excellent structural and durability characteristics, of late there have been instances of premature deterioration of some of the structures, especially in and around the coastal areas. One of the main causes for this deterioration is the corrosion of reinforcing bars. The presence of chloride ions near the bar surface is the primary cause of the corrosion.

The chlorides in concrete could have been present in fresh concrete either from the use of sea-sand as fine aggregate, or the use of salts (e.g. calcium chloride) as accelerators. The other possibility is the penetration of chloride ions from the environment into hardened concrete. Structures built off-shore or close to the shoreline are susceptible to the ingress of chloride ions from splash of sea water or sea breeze. In colder countries, the deicing salts used during winter, could serve as the source of chloride ions.

Most of the previous papers , deal with the mechanisms of the corrosion process, protection of structures and field survey of deteriorated concrete structures (1-4). The available literature on the structural implications of the corrosion on parameters like the load carrying capacity, etc. is rather limited (5,6).

This study was undertaken to primarily determine the extent of reduction, in the load carrying capacity of RC beams when reinforcing bars were subjected to corrosion.

2. TEST PROGRAMME

The test programme of this study is summarized in Table 1 and includes 4 beams of series A and 6 beams of series B. The details of the reinforcements of the specimens are shown in Figs. 1 and 2. No stirrups were used in series B. All reinforcing steel bars used in the specimens were SD 35. Ready mixed concrete, the mix proportions of which are given in Table 2, was used for the casting of the specimens. Further details of the test

* Graduate student, Dept. of CE, IISc., University of Tokyo, Tokyo
** Associate Professor, Dept. of CE, IISc., University of Tokyo, Tokyo

Table 1 Summary of the test programme

Series	Size (cm)	A_s (%)	f_c' (kg/cm^2)	a/d	parameter varied
A	10 x 20 x 210	2.3	300	3.6	extent of corrosion
B	10 x 15 x 120	1.2	380	2.5 and 3.6	a/d ratio

Table 2 Mix proportion of concrete

w/c	s/a	W	C	S	G	Admixture	Sl	Air
0.53	0.43	152.5	284	789	1121	0.710	11	5

Note 1: Quantities for cement, water, sand, aggregate and admixture are in kg/m^3.
2: The slump and air given are for series A. The corresponding values for series B were 10.5 cm and 4.5%.
3: NaCl (1.25 kg/m^3) were added to the concrete.
4: The admixture used was pozzolith.

Table 3 Summary of results for series A

No	Corrosion Current x duration	Pmax (t)	wt.loss (%)	corr.area (%)	Energy (Joules)	Pmax ratio
A1	No corrosion	9.6	-	-	75.6	1.00
A2	1A x 7 days	9.2	1.0	54	62.6	0.96
A3	1A x 14 days	8.8	1.2	65	50.2	0.92
A4	1A x 14 days	8.0	2.4	87	40.5	0.83

Note: A4 was left in the air for 3 months before static test

Table 4 Summary of results for series B

No	Corrosion Current x Duration	Bottom cover(mm)	Side cover(mm)	a/d	Pmax (t)	Wt. loss (%)
B1	-	10	10	2.5	4.9	-
B2	500 mA x 2 days	10	10	2.5	4.1	4.3
B3	-	10	10	3.6	2.5	-
B4	500 mA x 2 days	10	10	3.6	3.0	3.0
B5	500 mA x 2 days	10	20	2.5	5.0	2.9
B6	500 mA x 2 days	10	30	2.5	3.3	1.6

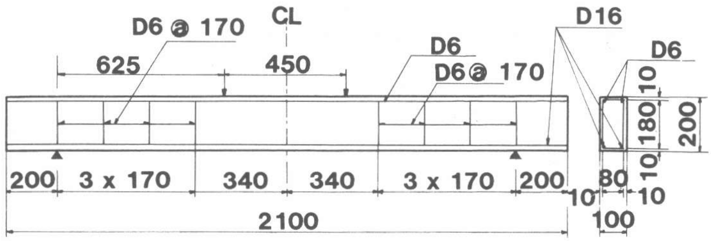

FIG 1. Reinforcement in the beam for series A

programme along with the results obtained are given in Tables 3 and 4.

In reinforced concrete, it could take upto a very long time for the reinforcement to corrode to any appreciable and measurable extent, in that the effects are aesthetically and structurally evident. There are several methods to study the phenomenon in the laboratory using accelerated corrosion methods. The galvanostatic method (5) was used in this study. The method involves passing a direct current through the reinforcement as shown schematically in Fig.3. The specimens were cured for 4 weeks and the specimens to be corroded were immersed in the pool, having 3.3% NaCl, one day before switching the current on.

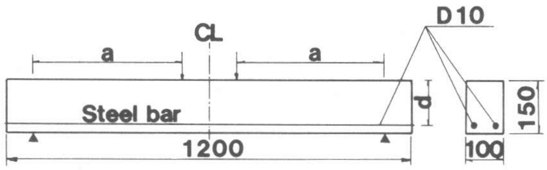

FIG 2. Beam specimen for series B

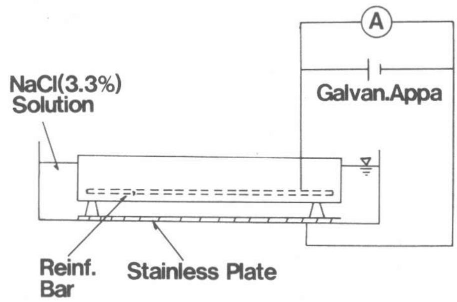

FIG 3. Galvanostatic corrosion method

3. RESULTS

3.1 CRACKS DURING GALVANOSTATIC CORROSION

Corrosion of the reinforcing bars involves the conversion of iron to it's oxides, which occupy greater volume. The corrosion process is, thus, always accompanied by the cracking of cover concrete.

The propogation and growth of cracks caused by the corrosion of reinforcement in the specimens for series A was monitored. It was observed that the cracks along the stirrups, which had a lesser cover than the main reinforcing bars, were formed within 10 hours of starting the corrosion process, and the crack formation was essentially completed, including along the main reinforcement within 36 hours of switching the current on. As more and more current was passed the crack width grew upto about 0.10 mm,

Table 5 Growth of cracks

Time (days)*	4	5	6	7**	8	9
Crack width (mm)	0.04	0.06	0.08	0.10	0.11	0.11

* : After switching on the current
** : Current stopped at this point

when the current was switched off. For specimen A4, the crack width continued to increase and it was about 0.8 to 0.9 mm, at the time the static test was performed. Table 5 gives the data on the growth of the average crack width measured along the main reinforcement over time. The results indicate that the propogation and growth of the cracks are functions of not only the extent of corrosion, measured as the amount of current impressed on the specimen, but also factors as the diameter of the bars, thickness of cover, etc..

3.2 BEHAVIOUR OF CORRODED BEAMS UNDER STATIC LOADING

The test programme and the results obtained from the experiments of series A have been summarised in table 3. Also the load deflection curves obtained for the specimens tested are shown in Fig.4.

Fig. 4 shows that there is hardly any difference in the characteristics of the load-deflection curves for the four specimens. However it was observed, during the experiments, that the failure of the corroded beams was accompanied by excessive central deflections and the failure was quite "brittle". The plot in Fig. 5 shows that though the reduction in the load carrying capacity of the beams was only about 17%, there is a more than 40% reduction in the absorbed energy, when there was a 2.4% loss in weight of the main reinforcing bars. The absorbed energy in this case was calculated as the area under the load-deflection curves till the maximum load is reached.

The testing conditions and the results obtained in

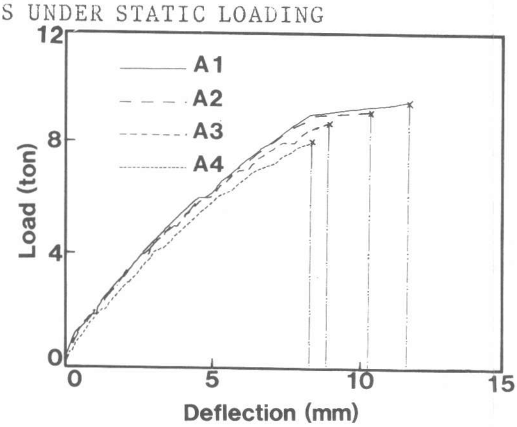

FIG 4. Load-deflection curves in series A

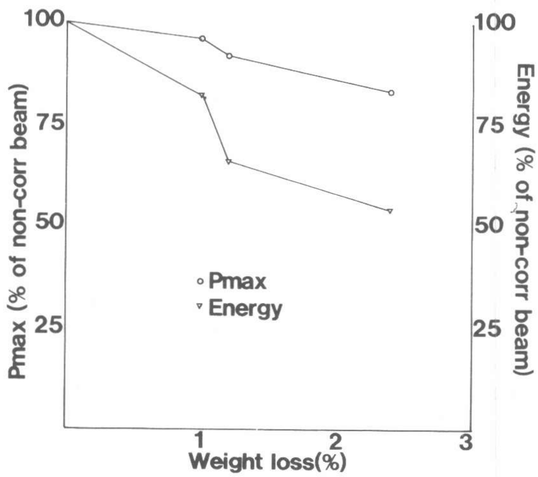

FIG 5. Reduction in Pmax and energy upon corrosion

series B have already been summarised in Table 4. Uomoto et al (7) have reported a reduction of upto 33% in the load carrying capacity of RC beams depending upon the extent of corrosion of the bars, when the shear span ratio (a/d) was 1.6. But in this study at an a/d value of 2.5, a reduction of only 16% was observed. Further, at an a/d of 3.6, the failure load was only 6% lower than the calculated value, though the non-corroded beam (B3, Table 4) failed at a much lower value due to experimental error.

It is important to note further from Table 4, that if the reinforcing bars are too close to each other (beam B6), the load carrying capacity changes drastically. It has been pointed out (7) that the minimum distance between reinforcing bars should be two times the cover thickness, to prevent the formation of internal cracks in the beams which make the spalling off of the cover concrete.

However, it should be borne in mind that there is a basic difference between the studies carried out in series A and B, and that is the presence of stirrups in series A. The presence of stirrups tends to reduce the effects that the reinforcement corrosion may otherwise have on the load carrying capacity of beams, and further work needs to be done to clarify the actual changes in the load carrying mechanism that occur.

3.3 REINFORCING BARS AFTER CORROSION

In Tables 3 and 4 the weight loss in the reinforcing bars due to corrosion has been given. Further, it was found that the static tensile strength of the bars after corrosion is 95-98% of the non-corroded bars, in conformity with the results obtained earlier (7). That is to say, that a weight loss of as much as 3 to 4 % does not necessarily result in substantial reduction in the cross-sectional area of bars, so long as the corrosion is general in nature.

Table 3 also lists the corroded surface area of the main reinforcing bars in series A. For series B, the corroded surface area was almost 100%. The corroded surface area can be used as an important parameter when we consider the implications of the corrosion of reinforcments on the bond strength.

4. DISCUSSION OF RESULTS

The appreciable reduction in the load carrying capacity of the beams on account of reinforcement corrosion cannot be explained by the reduction of the tensile strength of the bars alone. The cracks formed, by the corrosion, play an important role in changing the load carrying mechanism and capacity of RC beams depending on several factors such as the failure type, loading conditions and presence of stirrups.

It should be further appreciated that the galvanostatic corrosion is carried out while no load is applied on the beams, which is quite different from the corrosion in actual structures. From this standpoint, the corrosion rate and also the type may be different in actual structures compared with the galvanostatic corrosion. Whereas the corrosion by the galvanostatic method is "general", actual structures have some specific areas that are more prone to corrosion. Thus in the latter case, there is always the possibility of "pitting" corrosion wherein the cross-sectional area of the reinforcing bars could be significantly reduced, thereby reducing the tensile strength of the reinforcing bars too.

5. CONCLUSIONS

Based on the experiments carried out as part of this study, the following conclusions can be drawn:

1) General corrosion within the limits of this study, does not result in appreciable reduction in the tensile strength of reinforcing bars.

2) When the corrosion occurs, there could be substantial reduction in the load carrying capacity of beams even though the tensile strength of the reinforcing bars does not reduce much.

3) Corrosion of reinforcing bars may result in reduced ductility of beams, and this is specially relevant in the present day, when the actual loads to the structures are closer to the design loads.

4) The extent of reduction in the load carrying capacity depends upon a lot of factors such as, loading conditions, presence of shear reinforcement, type of loading, etc..

REFERENCES

(1) Brown, R.D., "Mechanism of Corrosion of Steel in Concrete in Relation to Design, Inspection and Repair of Offshore and Coastal Structures," ACI, SP-65,1980, pp 169-204.
(2) Kobayashi, K. and Takewaka, T., "Experimental Studies on Epoxy Coated Reinforcing Steel for Corrosion Protection," Cement Composites and Lightweight Concrete, Vol. 6, No. 2, 1984, pp 99-116.
(3) Stratfull, R.F., "Corrosion Autopsy of a Structurally Unsound Bridge Deck," Highway Research Record No. 433, Dec. 1973, pp 1-10.
(4) Beeby, A.W., Technical Report No 1, Cement and Concrete Association, 1978.
(5) Takewaka, T. and Matsumoto, S., Annual Meeting of the JSCE, No. 38, V-131, 1983.
(6) Okamura, H. and Hisamatsu, Y., "Effect of Use of Galvanised Steel on the Durability of Reinforced Concrete", Materials Performance, Vol. 15, No. 7, July 1976, pp 43-47.
(7) Uomoto, T. et al, "Deterioration of Concrete Beams and Columns Caused by Corrosion of Reinforcing Steel," 4th Asian Pacific Corrosion Control Conference, Tokyo, May, 1985.