- Technical paper -

SHEAR CAPACITY OF DAMAGED RC BEAM WITH PARTIAL LONGITUDINAL CRACKS IN SPACE

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ABSTRACT: Spatially localized cracking along corroded reinforcement was experimentally studied to clarify its effect on shear capacity. It was found that the effect of local damage be adverse, insignificant or even favourable depending on locations. The damage locations were examined 1) around compression and tension fibers at a mid-span, 2) near supports inside a shear span, 3) around anchorage zone including beam supports and 4) the whole shear span. Though the selective corrosion crack in between supports may elevate the shear capacity caused by an arch action, RC beams with cracking damage in the anchorage zone exhibited significantly reduced capacity accompanying sliding shear failure at the anchorage zone.

KEYWORDS: corrosion, localized cracking damage, shear capacity

1. INTRODUCTION

Structural mechanics has been applied for safety and serviceability assessment in a design scheme of practice. Here, some structural design detailing such as development length of reinforcement and the minimum concrete cover shall be satisfied so that specified structural analyses get applicable. However, when nonlinear analysis would be employed for performance assessment of existing structures, we have to bear in mind real damages caused by corrosion and other ambient actions. These sorts of damages represented by cracking, loss of section and rupture of reinforcement are not taken into account for design, and in general these damages violate some technological backgrounds on which the design oriented structural analysis is based. When a penetrating crack would be induced in concrete by steel corrosion around beam supports, sufficient anchorage is not expected. Thus, this cracking cannot be taken into account in simple design formulae but nonlinear finite element analysis of crack simulation is consequently required. Recently, alkali-aggregate reaction was reported to cause rupture of bent reinforcing bars [1, 2]. It means that hook anchorage of web reinforcement is lost and the design formula for shear capacity of RC beams cannot be directly employed.

Concerning these deteriorated members, experimental investigations have been performed and valuable knowledge has been earned. It is confirmed that flexural capacity of corroded members is directly proportional to the remaining sectional area of reinforcing bars [3] but the ductility or seismic performance is sacrificed. It is also known that corrosion of reinforcement affects the shear capacity, and some experiments showed that the loss of bond by corrosion induced cracking along longitudinal reinforcement increases in the shear capacity [4]. But other investigations conversely reported the decay of shear capacity and the ductility of RC [5, 6]. The structural effect of middle level corrosion of main reinforcement is now recognized as case by case. Thus, it is required to investigate the mechanism of gain and decay of shear capacity in more detail for consistent knowledge accommodated for maintenance engineering of infrastructures. In reality, in-situ corrosion cracks are not spatially uniform. In this study, the

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authors experimentally produced partial damage in space (steel corrosion and concrete cracking) into RC beams subjected to shear for identifying the effect of cracking location along main reinforcement on shear behaviours. The experiments were also conducted so that they can be used for verification of the nonlinear analysis [7, 8] in future.

2. EXPERIMENTS OF CORRODED RC BEAMS

RC beam specimens were structurally designed so that they may have higher shear capacities than flexural ones. Before applying loads, specimens were provided with local damage (cracking) in different locations by electrical charge. In this study, the local damage effect in space was investigated at five different positions, i.e. 1, 2) compressive and tensile fibers around a mid-span, 3) tensile fiber adjacent to at the beam support inside a shear span, 4) tensile anchorage zone including the beam support and 5) the whole shear span. After a local damage was introduced to a specimen, all RC beams were loaded under constant displacement rate over the post-peak regions.

2.1 DAMAGE INDUCED INSIDE THE SHEAR SPAN

2.1.1 Specimens

The series of experiment consist of four RC beams in total. Each beam has a tensile and compression steel without shear reinforcement so that the effect on shear failure can be focused. Figure 1 shows the specimen details. The specimens have the shear-span to depth ratio (a/d) of 3.2 with the tension reinforcement ratio of 1.5%. The anchorage length at the beam end is 0.2 m in both ends. Compressive strength of concrete tested after curing of 28 days is 34 MPa. Yielding strength of reinforcement is 343 MPa.

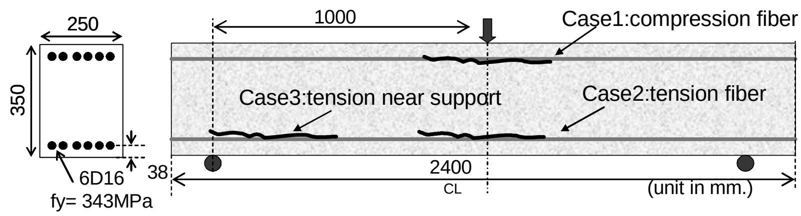


Figure 1 Specimen details and reinforcement

2.1.2 Accelerated spatially partial corrosion

To shorten the corrosion period, the accelerated method was employed by passing the direct electric current (by the electric power supply machine) through the connected wire between the six reinforcements and the power source in the parallel manner. The electric current level of 0.5 A was controlled throughout the corrosion period of several weeks for all three beams until reaching the desirable level of surface corrosive crack width (around 0.5mm). Instead of submerging the specimens into a sodium chloride solution container, which may cause uniform corrosive damage to reinforcement, the partial corrosion was produced by confining the ion transport (sodium chloride solution) solely in the specified zones. This selective corrosion can be realized by constructing the sodium chloride solution pond over the surface of the target RC beams. Figure 1 also shows the regions of corrosion damage in the experiment. After finishing corrosion, cracks width and corroded mass loss were measured and recorded as shown in Table1.

Table 1 Crack width and mass loss of steel from the accelerated corrosion method.

	Compression mid-span Case 1	Tension mid-span Case 2	Tension near support Case 3
Crack width (mm)	0*)~0.3~0.5	0.2~0.7	0.3~0.5
Mass loss (%)	1.89	8.76	6.7

***)** Visible cracking (0.3-0.5mm) in one side. but no cracking was seen on the other side.

2.1.3 Shear capacity and failure mode

After providing with steel corrosion and longitudinal cracks, static loading was conducted to the three beams as shown in Figure 1 and Figure 2. The experimental shear capacity of the non-damaged beam was found to be 162 kN, which favorably conforms to the calculated shear capacity by JSCE code [9] formulae. The beam having corrosion cracks around the compressive fiber was tested and Figure 3 shows the load-deflection relation and the failure crack pattern. The merged shear crack with initially induced corrosive one was identical around the compression zone but the shear capacity of this case was 152.86 kN which is just 8% decrease compared to the non-damaged one. Minor stiffness degrading can be seen after the occurrence of bending cracks.

The load-deflection response and corresponding failure mode of the tensile fiber damaged beam are shown in Figure 4. Its shear capacity was 140 kN or approximately 13.6% reduction of the non-damaged reference. The loss of stiffness was observed from the beginning of loads followed by further decrease in stiffness at the higher loads. Although failure crack pattern shows a localized inclined shear crack similar to the non-damaged one, fewer bending cracks were clearly seen around the mid-span due to loss of bond around the corroded main reinforcement. Figure 5 shows the experimental results of the case 3 where local corrosion crack was introduced adjacent to the beam support inside the shear span. Although the failure crack pattern indicates the merged corrosive crack around the support and the diagonal shear crack, the shear capacity of this case was 154.53 kN, just 4.61% decrease compared to the non-damaged one.

Although wholly corroded RC beams were reported to lead the shear capacity decay and pre-existing cracking around the main reinforcement in cases (1) and (3) also drives shear crack

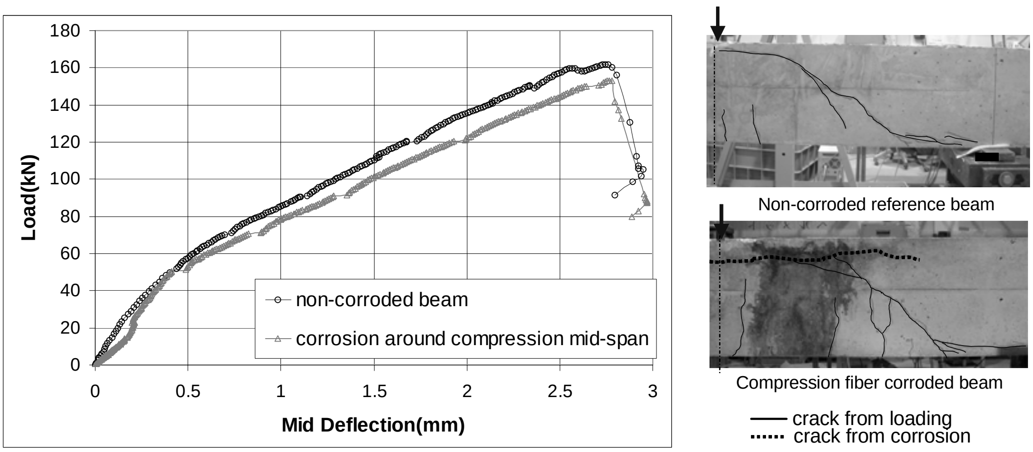


Figure 3 Load-deflection and failure crack of compression damaged-beam

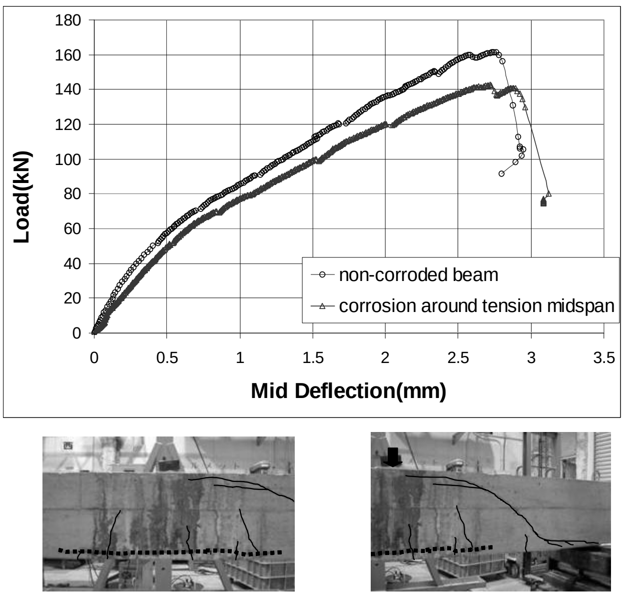


Figure 4 Damage at the tensile fiber

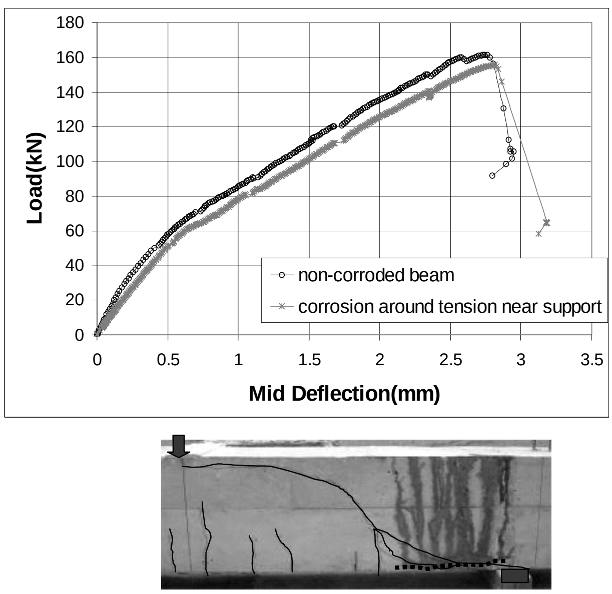


Figure 5 Damage at the inner side of support

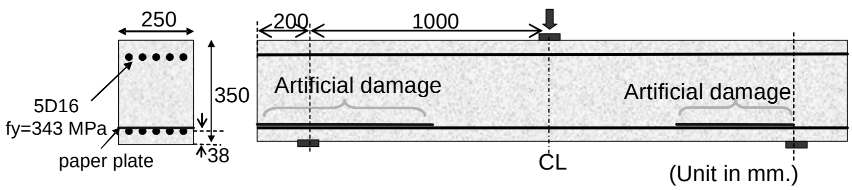
propagation ahead, partial damage merely resulted in slightly injured capacity. One of concerns is the state of anchorage zones, which was kept undamaged without any pre-cracking outside of the shear spans. Then, in the following section, the longitudinal cracking along main anchorage reinforcement will be focused with regard to resultant capacity of the damaged RC.

2.2 LOCAL DAMAGE AT ANCHORAGE ZONE CLOSE TO BEAM SUPPORT

The pre-existing damage around the anchorage zones of main reinforcement is the target of this section. Unlike the corroded experiments prepared by electric current to induce corrosive cracking, artificial crack-like defects made by pieces of hard-paper with one millimetre width were embedded in advance during the reinforcement fabrication before placing concrete. Artificial crack-like defect may create separated flat smooth planes when loaded and it leads to more severe damage than the rough cracks induced by corrosive expansion of steel. This artificial crack-like defect is thought to reflect and represent the critical or extreme damage condition of corroded RC where the bond between concrete and corroded reinforcement is completely lost.

Figure 6 shows the details of the specimen with embedded defects. The case (4) includes defects in both shear span (right side) and the anchorage zone over the beam support (left side) to clarify the effect of cracking damage around the anchorage zone. The shear-span to depth ratio (a/d) is 3.2 with the tension reinforcement ratio of 1.288% and the anchorage length of 0.2 m. Compressive strength of concrete tested after curing of 28 days period is 35 MPa. Yielding strength of reinforcement is 343 MPa. The non-damaged beam of the same dimension and materials was tested beforehand and a clear localized diagonal shear crack around the web was confirmed. Finally, propagation to the support and loading point formed the complete shear failure. The experimental shear capacity of the non-damaged reference beam was 150 kN.

The artificial damaged beam at the anchorage zone was tested and failed on the left side containing the pre-damage around the anchorage zone at the loading level about 60 kN, which is nearly 60% decrease in shear capacity compared with the non-damaged cases as shown in Figure 7. The crack propagation much differs from the reference case. The diagonal crack joined the extreme end of the artificial defect and the sliding shear along the tension main reinforcement penetrated through the anchorage of reinforcement. The sliding shear along the longitudinal artificial crack-like slit formed a path of premature shear failure. It is evident that the damage of anchorage (left side) is much more critical than the damage inside shear span (right side) and shall be taken into account when the corrosion crack is induced around the supports.



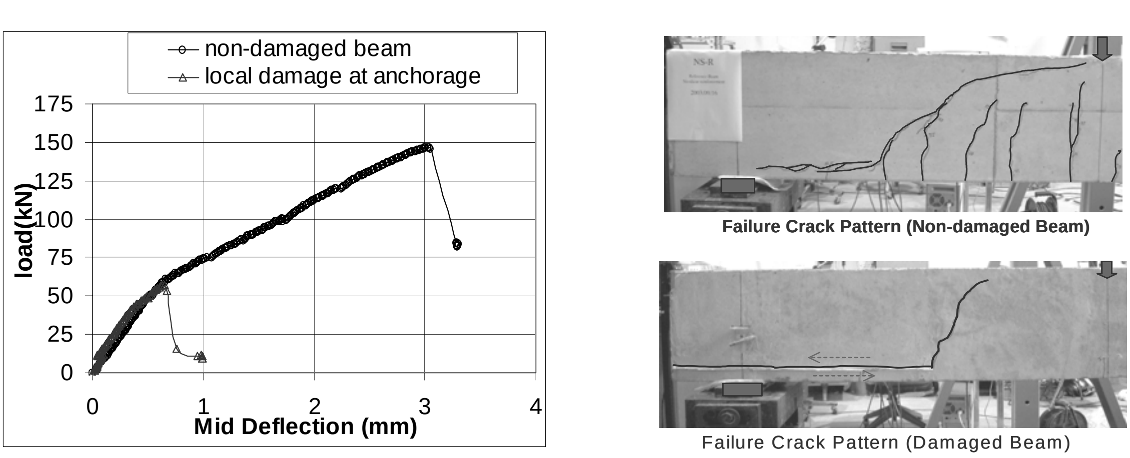
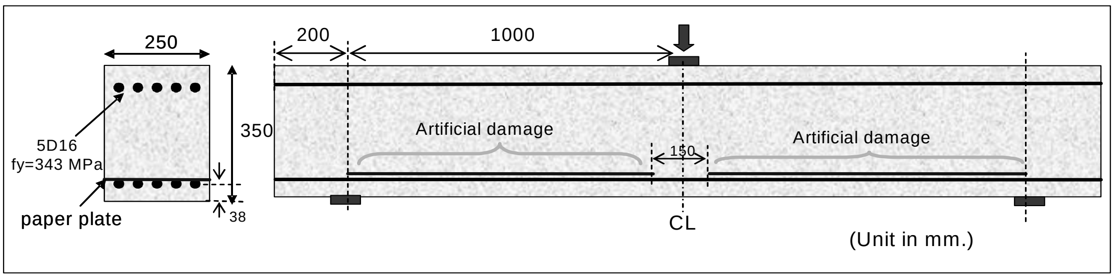


Figure 7 Load-deflection and failure mode of anchorage zone damaged beam – Case (4) -

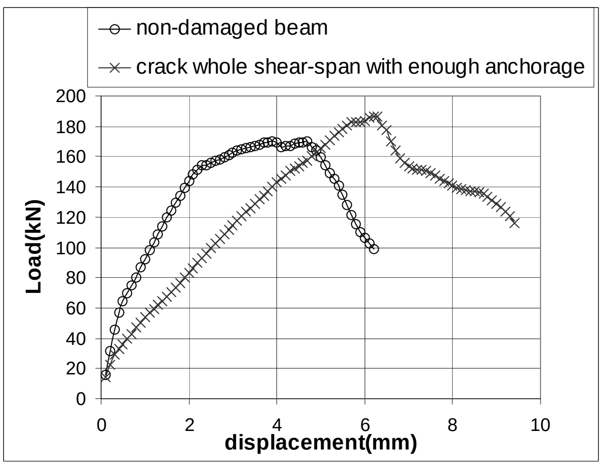
2.3 DAMAGE IN THE WHOLE SHEAR SPAN

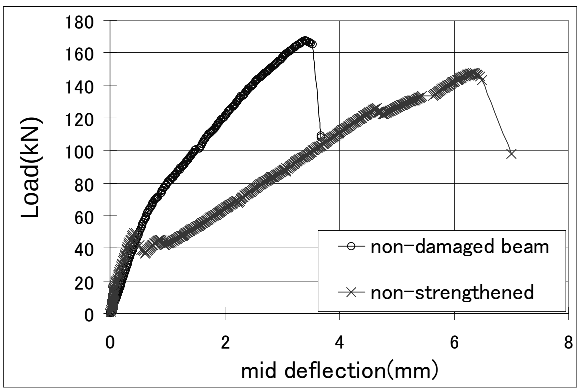
Ikeda and Uji [10] experimentally assured that the shear capacity is enhanced when bond between tension main reinforcement and concrete is erased, because the arch mechanism is forced to from or diagonal shear crack formation is much retarded. Thus, the selective damage over the shear span by artificial crack-like defect or corrosive cracking may lead to the advanced capacity. As a matter of fact, finite element analysis of beams including horizontal artificial defects shows the elevated capacity [11]. Thus, much web reinforcement of 3% is numerically placed to prevent the premature failure of anchorage zone in the analysis of the whole shear span damaged beam (case 5). As illustrated in Figure 8, with the non-linear FEM analysis program, WCOMD developed at concrete laboratory, the University of Tokyo [7, 8], by employing experimental material properties and introducing cracking in the whole shear span before numerically loading, the elevated shear capacity can be numerically observed. Also, the numerical crack pattern shows the failure crack propagation caused from arch action formation as shown in Figure 8.

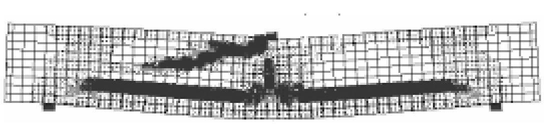
As stated above, the strength enhancement is preserved when the anchorage of longitudinal reinforcement is sufficiently provided. Actually, the arch mechanism requires higher anchorage performance. Thus, the corrosion of steel inside the shear span may cause failure of the anchorage, which results in total deterioration of member capacity. Figure 8 also shows the capacity and load-displacement relation without any special strengthening at the anchorage zones. In this case, the first shear crack appeared from the extreme end of the artificial slit. Afterward, the shear slip along the main reinforcement was provoked and finally the shear crack band reached the anchorage zone. The resultant capacity was about 146 kN, which is smaller than the full arch strength of the unbonded RC beam but higher than the case (4) as shown in Figure 7. The failure mode can be concluded as anchorage failure in shear.



Case (5)







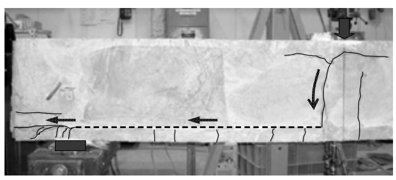


Figure 8 Inherent crack-like defect over the whole shear span and its elevated capacity
(analysis with no anchorage failure) (non-strengthened)

3. CONCLUSIONS

Spatially localized cracking along longitudinal reinforcement was experimentally and numerically investigated in terms of shear capacity of damaged RC members, and the shear capacity and corresponding failure mode were obtained as follows.

(1) Influence of local longitudinal cracking damage on shear capacity can be adverse, insignificant or even favourable, depending upon the specific damage location in space.

(2) The local damage inside shear spans at compression and tensile fibers, and damage near member supports, had slightly adverse effect on shear capacity, providing that the anchorage is free from cracking and functional enough to sustain the compressive strut of concrete in the web.

(3) A significant loss in shear capacity was clearly observed when the anchorage zone was deteriorated by a penetrating crack that meets the diagonal shear. The crack propagation was also observed to be greatly different from the non-damaged reference beam. The pre-mature failure path was triggered by sliding of shear crack along longitudinal reinforcement till the damaged anchorage area.

(4) When local damage is over a whole shear span, special caution should be paid to a condition of anchorage performance. Due to loss of bond along cracking in the whole shear span, higher anchorage performance is required. With enough anchorage performance, the arch mechanism can be achieved resulting in an improvement of shear capacity unless the pre-mature failure around anchorage zone may happen.

Consequently, damage location, magnitude and dimensioning in detail should be taken into account in a consideration of a resultant capacity of RC members containing longitudinal corrosive cracking. Thus, the numerical model with multi-directional cracking will be verified with these facts of partially damaged RC members. It is expected that these facts will be utilized for verifying numerical analyses of crack nonlinearity.

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