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IMPACT LOAD EFFECTS ON CORRODED REINFORCED CONCRETE BEAMS

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Abstract: Bridges and road infrastructure in North America and around the world where deicing salts are used is suffering deterioration due to corrosion of steel reinforcement. A lot of research in the past several decades has targeted reduction of corrosion rates or replacement of the corrosion-prone steel in bridge structures with varying level of success. Bridge guardrails are particularly susceptible to steel reinforcement structural steel corrosion and deterioration, however little to no research is dedicated to their behaviour under severe impact loading. The research reported in this paper is from a preliminary program designed to investigate the effect of impact loading on corroded reinforced concrete elements. Small-scale reinforced concrete beams were subjected to accelerated current-impressed corrosion in the laboratory and then tested under impact loading in a drop-mass test frame. Two different degrees of corrosion were investigated: 2.67% and 5.11%. A control beam with no corrosion was also tested for comparison. The impact test results show that, in general, there is not a marked effect of the degree of corrosion on the impact resistance of the beams. These preliminary results show that at the level of corrosion investigated, impact loading on corroded bridge guardrails might not pose serious safety hazards.

Keywords: - Corrosion, reinforced concrete, drop-mass test, impact load, load rate.

1 INTRODUCTION

Reinforced concrete bridges and parking garages in North America and around the world where deicing salts are used are deteriorating due to corrosion of steel reinforcement. A lot of research in the past decades has been devoted to corrosion prevention and replacement of the corrosion-prone steel reinforcements from the deck slabs and supporting beams/girders. It has been suggested that corrosion costs the Canadian economy about 23.6 billion dollars while the indirect costs due to corrosion brings the total to about 46.4 billion dollars (1). Whereas a lot of research has been targeted at the load bearing elements such as the deck slab and supporting beams/girders, little has been done to address reinforcement corrosion in bridge guardrails. Guardrails are often subjected to high amplitude and short duration loading from vehicle impact. Failure of the guards can lead to serious safety hazards on bridges.

Corrosion is the process by which a refined metal reverts back to its natural state by an oxidation reaction with non-metallic environment (2). Deicing salts, climatic conditions, poor design and construction methods are some of the factors that contribute to corrosion of steel reinforcement in concrete (3). Corrosion of steel reinforcement can lead to damage such as loss of steel cross-sectional area, cracking and spalling of concrete and reduction of load carrying capacity. The corrosion damage ultimately increases the risk of failure of infrastructure. Corrosion damage of bridges can cost billion dollars in rehabilitation and repair (4).

There are many reports of bridge failures in the literature due to steel reinforcement corrosion. These include the failure of the Kansas Avenue Bridge, Silver Bridge, Mianus River Bridge in the USA and De La Concorde Overpass in Canada. The guardrails on bridges are not less important when it comes to safety of vehicles as they protect vehicles drifting off the bridge. According to Sgambi (5) degradation of a post of a guardrail caused failure of the guardrail in an accident and led to the death of the vehicle driver. The impact resistance of the guardrail was impaired because of active corrosion at the base of the post. It is therefore clear that the effect of corrosion on the impact resistance of reinforced concrete members must be investigated.

2 LITERATURE REVIEW

The deterioration of reinforced concrete structures due to steel reinforcement corrosion is a major concern for infrastructure engineers. The problem is exacerbated in areas where deicing salts are used on roads and bridges. Corrosion of reinforcements leads to loss of cross-sectional area, reinforcement-concrete bond deterioration, cracking and spalling of reinforced concrete members. These detrimental effects of corrosion in reinforced concrete members has been reported to cause loss of capacity. A majority of the research on corrosion effects has focused on corrosion damage under sustained load (6). Moreover, most of the research carried out on the corroded reinforced concrete beams has been under constant sustained loading. The research works sought to investigate the degree of corrosion on the capacity of structural members (7). Ballim and Reid (7) investigated the effect of reinforcement corrosion on the deflection of RC beams and reported increased deflections with increased degree of corrosion.

When corroded reinforced concrete beams are subjected to repeated loading, the widths and spacing of the cracks increase. The longitudinal tensile strains (crack width and spacing) under constant sustained loads are influenced, partly by the magnitude of the applied loads but mostly by the degree of corrosion of steel reinforcement. Prior to yielding of the steel reinforcement, the mid-span deflection of corroded beams was observed to be lower than that of non-corroded beams (8). When a reinforced concrete beam is subjected to impact load, however, the behaviour is markedly different due to the transient nature of impact loading. The properties of materials under dynamic loading is different from those under static loading due to strain rate sensitivity of the materials. Both concrete and steel have been reported to be strain rate sensitive (9, 10, 11, 12, 13).

3 MOTIVATION

When a corroded structural element is subjected to static loading, loss of reinforcement cross-sectional area could lead to failure under the static service load. Under high strain rates of loading such as under impact loading, both concrete and steel exhibit increased strengths. The increase in strength is expressed by the dynamic increase factor of the material for design. The effect of high strain rate on reinforcement undergoing corrosion is poorly understood. Thus the effect of impact loading on bridge guardrails undergoing active corrosion is not well established and needs further study.

Guardrails are designed to resist impact loads from vehicles on bridges and parking garages. Corrosion of steel in structural steel and reinforced concrete guardrails such as shown in Figure 1 could compromise their strength. There are lots of research works done on uncorroded reinforced concrete structures subjected to impulse load. However, as discussed previously, little research exists in the literature on corroded reinforced concrete structures subjected to impact load. During dynamic events, a large amount of energy is imparted to the structure over a very short time. If the structure fails to absorb this energy, a sudden and catastrophic failure may occur (14). In order to prevent the failure of guardrails, the behaviour of corroded reinforced concrete structures under impact loading must be investigated and understood.

Figure 1: Corrosion of steel reinforcement in bridge guardrails

4 EXPERIMENTAL INVESTIGATION

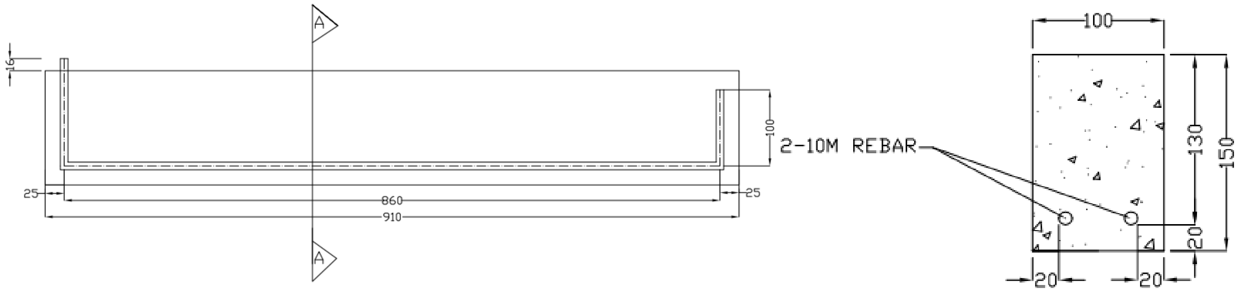
This section presents the experimental program presented in this paper. The primary objective of the experimental program is to assess the effect of impact loads on reinforced concrete beams with different levels of corrosion of steel reinforcement. Accelerated corrosion of the steel reinforcement was induced by an external impressed current. The beams were categorized in accordance with the degree of corrosion (DOC) achieved in each beam (Table 1).

Table 1: Degree of corrosion of test specimens

Designation of the Beam	Duration of corrosion (Days)	Degree of corrosion (%)
Beam 1 (Control)	0	0
Beam 2 (DOC 2.67%)	4.5	2.67
Beam 3 (DOC 5.11%)	9	5.11

4.1 Geometric Design of Beams

The beam specimens were rectangular in cross-section: 100×150 mm and 910 mm long and reinforced with 2-10M bars (12). The steel bars were 1100 mm long, including anchorage on either side. One end of the steel bars was protruded 15 mm out of the top of the beam specimen to facilitate the installation of induced corrosion wiring. Stirrups were not provided in the beam specimen in order to eliminate the difficulty in accurately predicting and controlling the degree of induced corrosion on the main reinforcement as the applied current would also corrode the stirrups. All the concrete beams had a cover of 20 mm on all sides. Figure 2 shows the cross-sectional and longitudinal view of the test specimens. The beams were originally designed and cast by Porcari (15).



(a) (b)

Figure 2: Concrete beam specimen: (a) Longitudinal view (b) Cross sectional view (15)

4.2 Accelerated Corrosion Process

The accelerated corrosion process was used in this study as natural reinforcement corrosion would have taken a very long time to achieve. The basic principle of accelerated corrosion process is to introduce an electro-chemical potential through the reinforcing steel (anode) and a sacrificial cathode, which forces the corrosion process to take place on the steel rebar within the concrete (15). In order to accelerate the actual corrosion process, a constant current density was applied to the rebars. The test specimens were placed in an electrolytic solution (3.5 % NaCl) in a plastic tank and submerged to a level just above the tensile reinforcement in the specimens. Detailed description of the accelerated corrosion process is presented by Porcari (15) and is not repeated here. The longer the beams were subjected to the impressed current, the higher the DOC. Beams with three DOC of 0%, 2.67%, and 5.11% were tested in the research program.

4.3 Impact Load Testing

The impact load testing was carried out in an instrumented drop-mass frame. The drop-mass frame is capable of dropping a 236-kg (519-lbs) mass from height of up to 2 m on to a test specimen (Figure 3). For this experimental test the drop-mass was dropped from heights of 175 mm and 200 mm on each beam to analyze the effect on the behaviour of reinforced concrete beams. When the drop-mass strikes the beam, a sudden transfer of momentum occurs from the drop-mass to the beam. As the energy transfer from the drop-mass to the beam occurs suddenly, it results in build-up of strain energy in the beam. Strain gauges were mounted on the tup of the drop-mass to measure the contact load between the drop-mass and the beam.

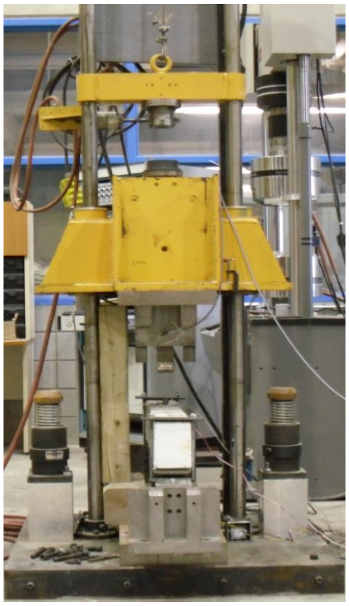


Figure 3: Impact load test frame (drop-mass test frame)

The beams were placed and supported on a fixed span of 820 mm, and then the drop-mass was raised to the required height and allowed to drop freely on to the beam at mid-span. As the beams were not reinforced for shear, external shear reinforcement was provided by six shear clamps equally spaced at 115 mm to prevent shear failure.

5 RESULTS AND DISCUSSION

Each of the three specimens was tested under drop-mass impact from two drop heights. The tup load and mid-span deflection were measured during each test. The results are discussed and compared in this section.

5.1 Analysis of Results

The load-time plot of the Beam 1 (DOC 0%) at the two drop heights is shown in Figure 4 while post-test photographs of the beam is shown in Figure 5. The instrumented tup was unable to capture the peak load from the 175-mm and 200-mm drop heights. The peak impact load was cut-off at 26.9 kN. Moreover, the impact load from the 200-mm drop height is expected to be higher than from the 175-mm height as is observed for the second peak. The displacement-time plot of the control beam at the two drop heights is also shown in Figure 4. The maximum mid-span displacements for the 175-mm and 200-mm drop tests were 11.1 mm and 13.7 mm respectively. The displacement is higher for the 200-mm drop test. The increased displacement can be attributed to the higher impact energy and reduced stiffness from cracking induced during the 175-mm drop test. The 200-mm drop test was performed on the beam in the permanently displaced position while the string potentiometer used to record displacement was zeroed. Thus the total permanent mid-span displacement of the beam from the two drop tests was 16.6 mm (Table 2).

Figure 5 presents the post-test photographs of Beam 1 showing flexural cracking after each drop test. One primary crack is observed from the bottom of the beam at mid-span with the root of the crack in the upper third of the beam (Figure 5(a)). After the 200-mm drop test, the cracks in the bottom coalesced and increased in width and propagated to the load point (Figure 5(b)).

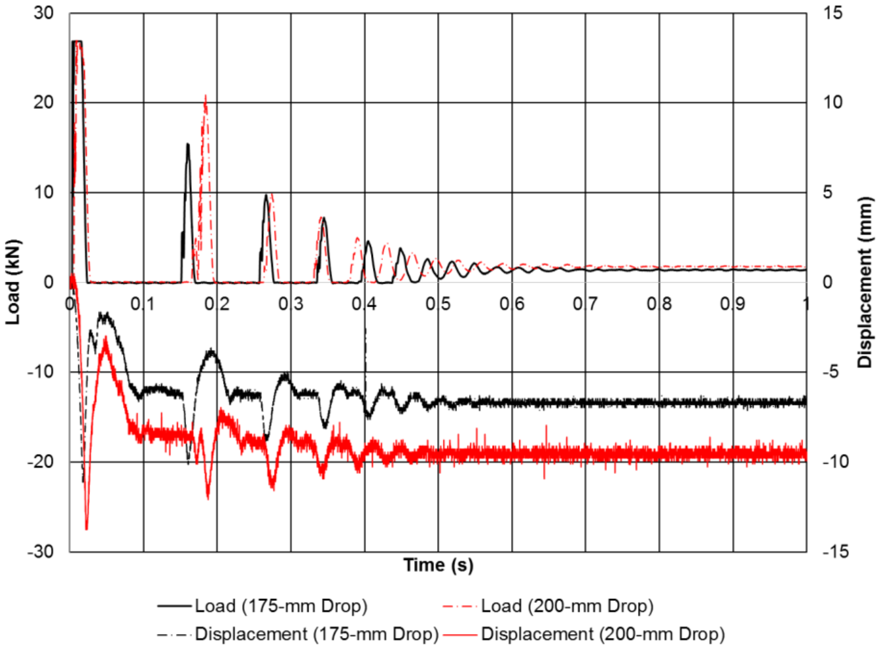


Figure 4: Load and mid-span displacement vs time graph of Beam 1 (Control)

(a) (b)

Figure 5: Post-test photos of Beam 1 (Control): (a) post 175-mm (b) post 200-mm drop

Figure 6 presents the load-time plot for Beam 2 (DOC 2.67%). It can be observed that, once again, the peak impact load was cut-off at 26.9 kN. Also, due to equipment malfunction no displacement data was recorded for the 175-mm drop test. The maximum mid-span displacement for the 200-mm drop test was 10.9 mm.

From the post-test photographs presented in Figure 7, however, the level of damage from the 200-mm drop test is observed to be substantially more than for the 175-mm drop test. An initial crack at the mid-span after the 175-mm drop test opened up after the 200-mm drop test and propagated to the load point on the top of the beam (Figure 7(b)).

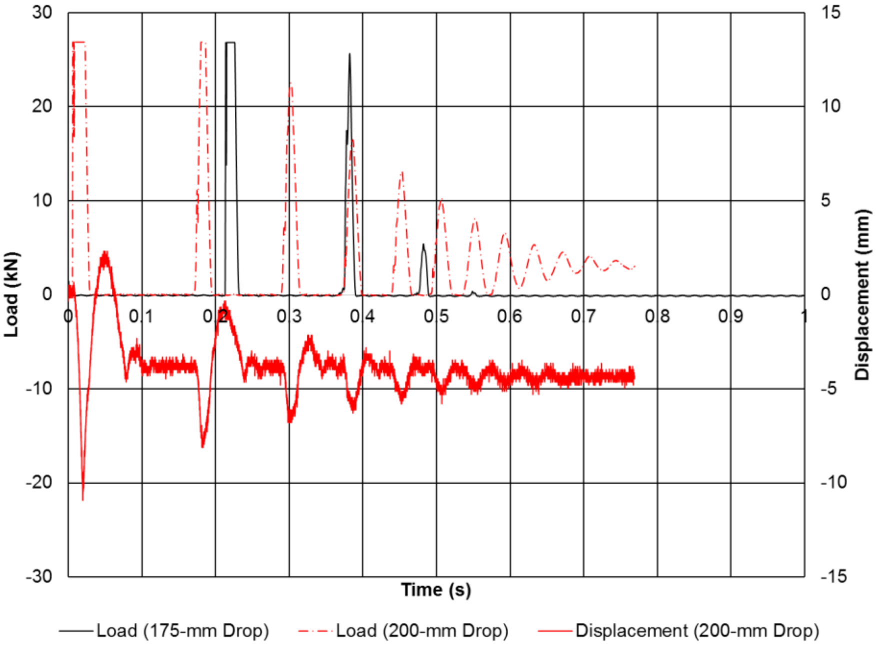


Figure 6: Load and mid-span displacement vs time graph of Beam 2 (DOC 2.67%)


(a) (b)

Figure 7: Post-test photos of Beam 2 (DOC 2.67%): (a) post 175-mm (b) post 200-mm

Load-time plot for the Beam 3 (DOC 5.11%) is presented in Figure 8 and shows similar peak impact load cut-offs. The mid-span displacement-time plot however shows maximum displacements of 11.1 mm and 13.4 mm for 175-mm and 200-mm drop tests, respectively. This represents a marginal increase in total mid-span displacement of the beam in comparison with the control Beam 1.

Figure 9 presents the post-test photographs of Beam 3 (DOC 5.11%). The beam shows an advanced state of corrosion of the steel reinforcement. A horizontal crack due to rust products can be observed on the side of the beam prior to impact testing. Cracking under the 175-mm drop test appeared at the bottom of the beam at about mid-span and coalesced with the horizontal corrosion crack. The cracks appear wider and the root of the crack propagated to the load point under the 200-mm drop test.

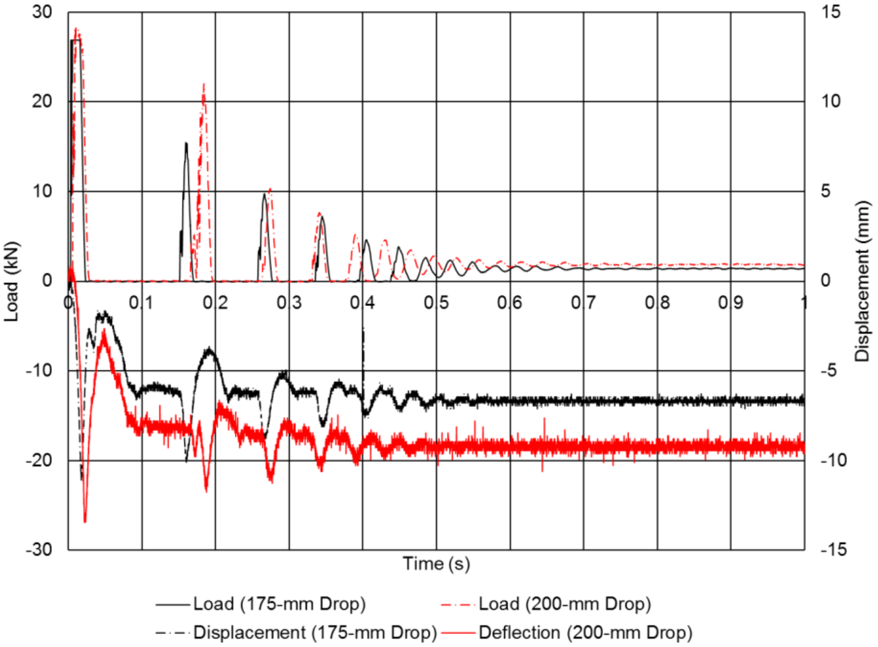


Figure 8: Load and mid-span displacement vs time graph of Beam 3 (DOC 5.11%)

(a) (b)

Figure 9: Post-test photos of Beam 3 (DOC 5.117%): (a) post 175-mm (b) post 200-mm

Table 2 presents the results from the experimental test program and shows marginal change in the mid-span displacements and total displacements with an increase in the DOC of steel reinforcement. Figure 10 present a comparison of the mid-span displacements of the beams from the 175-mm drop tests and shows marginal increase in the peak mid-span displacement of Beam 3 (DOC 5.11%) over Beam 1 (DOC 0.0%). The mid-span displacement and residual displacement of Beam 1 and Beam 3 are almost identical even though Beam 3 showed higher corrosion damage.

Figure 11 presents a comparison of mid-span displacement of the beams under the 200-mm drop tests. The mid-span displacement and residual displacement of Beam 1 and Beam 3 are, again, almost identical, however Beam 2 exhibited slightly lower mid-span displacement and residual displacement under the 200-mm drop test in comparison with the other beams.

Table 2: Result comparison of beams at 175 mm drop height

Beam Designation	175-mm Drop Test		200-mm Drop Test	
	Mid-span Displacement (mm)	Residual Displacement (mm)	Mid-span Displacement (mm)	Residual Displacement (mm)*
Beam 1 (DOC 0.00%)	11.1	6.79	13.7	9.76 (16.6)
Beam 2 (DOC 2.67%)	-		10.9	5.30
Beam 3 (DOC 5.11%)	11.1	7.12	13.4	10.6 (17.7)

* - the number in parenthesis is the total permanent displacement after drop tests

In general, the limited drop-mass test results does not show conclusive effect of DOC on the beam behaviour. In fact the beam with the highest degree of corrosion (5.11%) exhibited the same peak mid-span and residual displacements after both impact tests. It is likely that the level of corrosion measured was distributed over the entire length of the steel reinforcement and thus had negligible effect on the cross-sectional area. Also, earlier test programs on behaviour of reinforced concrete beams undergoing corrosion indicated an increase in reinforcement-concrete bond (8). The increase in bond could lead to reduction in displacement prior to reinforcement yielding. There is however the need to test more samples to determine material strength variability and also to investigate the effect of higher degrees of corrosion on the response of reinforced concrete beams.

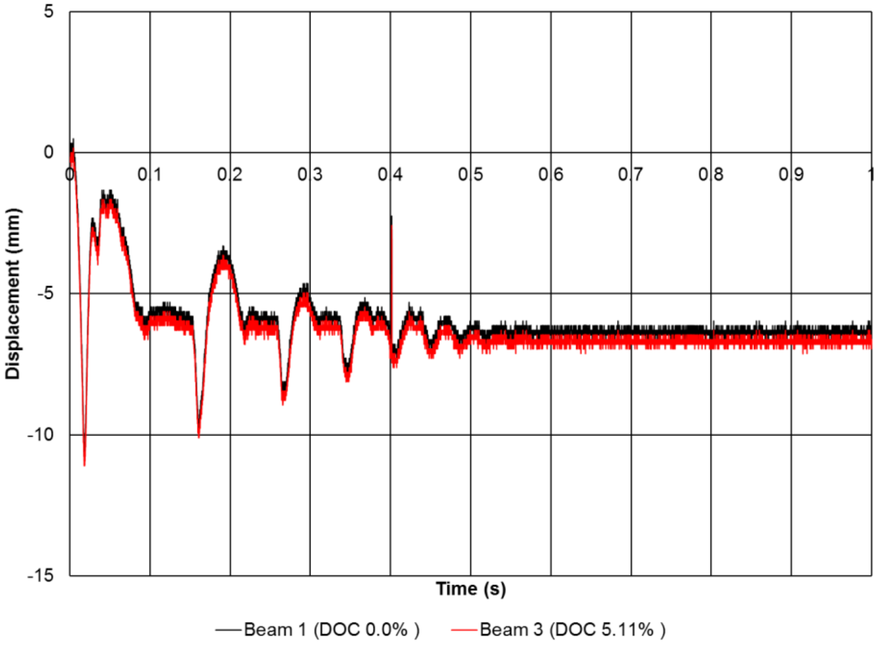


Figure 10: Comparison of displacement vs time responses for 175-mm drop tests

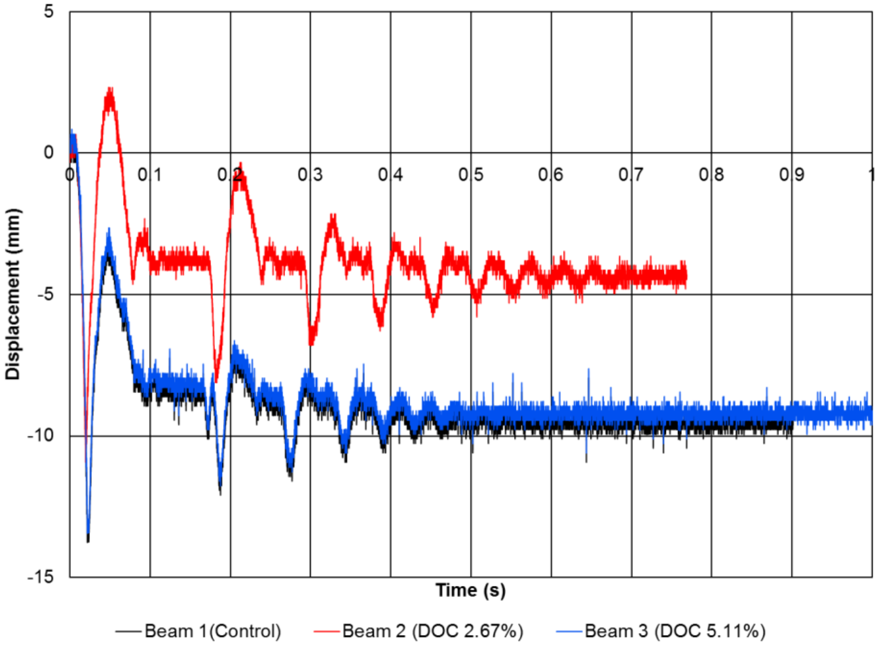


Figure 11: Comparison of displacement vs time responses for 200-mm drop tests

6 CONCLUSIONS

The effect of DOC on the behaviour of reinforced concrete beams under impact loading was investigated in this preliminary experimental program. The major conclusion drawn from the preliminary experimental investigation is that the level of corrosion of steel reinforcement in structures does not seem to have a marked effect on the beams at the level of corrosion tested.

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