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Strength and Ductility Behaviour of Steel Plate Reinforced Concrete Beams under Flexural Loading

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Abstract

Long-term durability is the main concern in the area of civil engineering due to safety considerations. This paper reports the strength and ductility behaviour of steel plate reinforced concrete beams under four-point bending. A total of three full-scale beams of 200 mm width, 300 mm height and 4000 mm length were cast and tested. All the beams had the same details of stirrups and compression reinforcement. The first beam was reinforced with ordinary reinforcement (2 deformed steel bars with a nominal diameter of 20 mm) and served as a reference beam. The second beam was reinforced with a chequer steel plate and provided with 20 steel bolts welded to the chequer steel plate at a regular distance of 200 mm centre to centre. The third beam was reinforced with a chequer steel plate and provided with 4 steel angles welded at the ends of the steel plate. Each plate reinforced concrete beam was designed to have an equivalent force to the ordinary reinforced concrete beam. The strengths, ductilities and analytical considerations of the beams are covered in this paper. The results showed no significant difference (less than 2%) between the strengths of ordinary and plate reinforced concrete beams. On the other hand, the steel plates significantly increased the ductility. The ductilities of plate reinforced concrete beams provided with steel bolts and angles increased by up to 3.7 and 2.3 times, respectively compared with the ordinary reinforced concrete beam. It was also observed, that the use of steel bolts in the plate reinforced concrete beam, improved the ductility by 43.2% compared to the steel angles.

Keywords: Steel plate, Concrete beam, Flexural behaviour, Ductility.

1. INTRODUCTION

In civil engineering investigations, understanding the behaviour of concrete members reinforced with steel bars has previously been the substantial aim of many researchers. On the other hand, only a few limited studies used steel plates as another concept of reinforcement, for example, Subedi and Coyle (2002), Su et al. (2008) and Su et al. (2009). The plate reinforced concrete beam (beam reinforced with an embedded steel plate(s)) is also a way to reduce the cross-section of the beam.

In the design of plate reinforced concrete beam, both the strength and ductility need to be recognized. The shear strength of reinforced concrete beam has been enhanced by using embedded steel plates. For instance, use of steel plate as shear reinforcement increased the shear resistance by about 75% compared to the conventional shear reinforcement (Subedi and Baglin 1999). The flexural strength of coupling concrete beams (with different depths) reinforced with vertical steel plates and steel bars together was investigated by Lam et al. (2013); the height of steel plates relied on the beam's depth. That study showed that the strength of beams was reduced with the use of the inadequate height of embedded steel plates. However, that study showed the combined effects of using steel bars and steel plates (only in vertical installation) on the flexural behaviour of concrete beams. Therefore, this study was conducted to investigate the flexural strength and ductility of the concrete beams reinforced with only steel plates installed in a horizontal way.

The performance of members reinforced with sections depends on the bond strength between the section and the surrounding concrete. The bond influences the serviceability aspects of the beam such as the width of cracks, the spacing of cracks and deflections. According to ACI-408R-03-Committee (2003), the interaction between the reinforcement and the surrounding concrete essentially relies on the mechanical anchorage of reinforcement. Thus, steel bolts, steel angles, and chequer surface of the steel plates were used as mechanical anchorages of reinforcement in this study.

2. EXPERIMENTAL PROGRAM

2.1. Beam design and preparation

In this study, three full-scale reinforced concrete beams were cast and tested under four-point bending. The dimensions of the beams were chosen to be 200 mm in width, 300 mm in height and 4000 mm in length. All the beams were reinforced with the same amount of stirrups and compression reinforcement. For stirrups, plain steel bars of 10 mm diameter (250 MPa nominal tensile strength) were used at 80 mm spacing centre to centre (R10 @ 80 mm). For compression reinforcement, two plain steel bars of 10 mm diameter were used. The clear cover of beams was maintained at 20 mm at the bottom and each side. The first beam (reference beam) was longitudinally reinforced with two deformed steel bars of 20 mm diameter (2N20) with 500 MPa nominal tensile strength. The second and third beams were longitudinally reinforced with chequer steel plates of 100 mm width and 10 mm thickness with 330-390 MPa typical yield tensile strength. One surface of the chequer steel plate was smooth, while the other had raised lozenges of 5.5 mm width, 26 mm length and about 1.5 mm height. In order to prevent or reduce the slippage between the steel plates and the concrete, steel bolts and equal steel angles were used. Twenty steel bolts of 20 mm diameter (460 MPa nominal tensile strength) were welded at 200 mm spacing to the steel plate of the second beam. Four equal steel angles (75 mm x 75 mm) of 8 mm thickness (480 MPa nominal tensile strength) were welded at the ends of the steel plate of the third beam. The second and third beams were designed to have an equivalent tensile force to the reference beam. Table 1 presents the main reinforcement details of the beams.

Table 1. Main reinforcement details of the tested beams

Beams	**Longitudinal reinforcement**				**Mechanical anchorage of steel plate**
	Type of reinforcement	Number of steel bars or steel plates	Diameter of steel bars (mm)	Dimensions of steel plate (mm)	
A	Steel bars	2	20	---	---
B	Steel plate	1	---	100x10	Steel bolts
C	Steel plate	1	---	100x10	Steel angles

2.2. Material properties

All the beams were cast on the same day with normal strength concrete provided by a local supplier. The average compressive strength was 42.3 MPa at 28 days. According to AS 1391-2007 (AS 2007), the tensile strengths of reinforcing steel bars (N20 and R10) and steel plate were found by using the 500 kN Instron testing machine. The average of yield tensile strengths were 365 and 540 MPa for R10 and N20, respectively, while it was 370 MPa for the steel plate. All the tests were carried out at the laboratories of the School of Civil, Mining and Environmental Engineering, University of

Wollongong, Australia.

2.3. Beam fabrication, casting and curing

Wooden formworks with inner dimensions of 200 mm wide, 300 mm height and 4000 mm length were used for casting the beams. The stirrups were prepared by forming a rectangle with 150 mm width and 250 mm height (centre to centre) by a local manufacturer. Steel chairs with a height of 20 mm were used to maintain the specified concrete cover (20 mm) at the bottom ends of the beams; these chairs were placed at a spacing of one meter. Small pieces of steel bars (20 mm length) were welded to the stirrups to obtain the specified cover at both sides. Before the concrete casting, the dust that may be inside the formworks was removed by using compressed air. The air bubbles inside the concrete were removed by using an electrical vibrator during the casting process. Thereafter, the beams were cured by covering them with wet hessian and a plastic sheet for 28 days.

3. TESTING PROCEDURE

All the beams were tested, under simply supported conditions, by a four-point bending test. The space between the two loading points (pure bending span) was 1200 mm. Four pieces of steel plates were used at the points of supports and loads to reduce stress concentration. The steel plate pieces had the dimensions of 100 mm width, 10 mm thickness, and 200 mm length. The deflection at the mid-span of each beam was measured by using a draw-wire transducer. The test was conducted using the 600 kN actuator. The actuator load was distributed into two applied loads by using a steel spreader of 870 N weight. The beams were tested under displacement control with a loading rate of 1 mm/minute. During the test, the data were recorded by a smart system installed on a computer.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Failure modes

In this study, all the beams were tested until the failure. Figure 1 shows the failure modes of the tested beams at the end of tests.

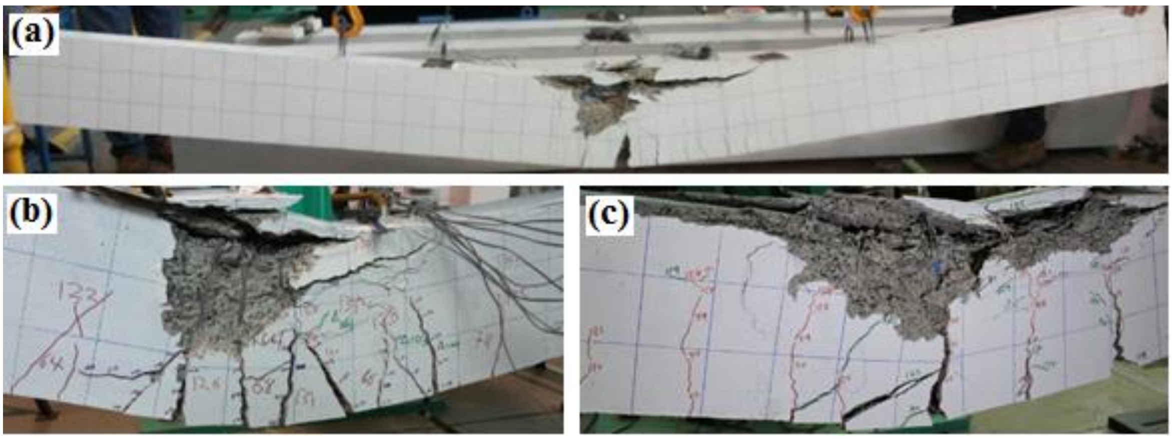

Figure 1. Failure modes of the beams; (a) Beam A; (b) Beam B and (c) Beam C

The failure modes relied on the type of reinforcement materials and the reinforcement details. During the loading, the behaviour of beams changed from elastic to plastic. The initial cracks formed at the tension zone of the pure bending span and then progressed towards the neutral axes. Before obtaining the load of failure, the tension reinforcement of all beams yielded; this indicates that the cross-sections of the beams were under-reinforced. It was also noticed that the yield took place before the concrete crush; this means that the beams' failure modes were flexural-tension. Afterward, the cracks exceeded the neutral axes of the cross-sections of the beams and became wider with the time of tests.

4.2 Load-midspan deflection behaviour

Figure 2 shows the load-midspan deflection curve of the tested beams. In general, all the beams approximately showed similar behaviour in the ascending part of the curve until the yield load. The ascending part of the curve was mainly controlled by the concrete stiffness. Yield loads of the beams are presented in Table 2. The yield loads of Beams B and C were similar, and they were higher than Beam A by 3%. After the yield loads, the beams showed different behaviour depending on the details of reinforcement of beams. The cover spalling approximately occurred at deflections of 65, 57 and 62 mm for Beams A, B and C, respectively. The maximum loads of the beams are also summarized in Table 2. It can be noticed that the maximum load of Beam A was 1.5% lower than Beam B and 1.2% higher than Beam C. This indicates that the tension forces of the beams are equivalent as were designed. However, there was a big difference in the ductility of the beams, as will be shown in the next subsection.

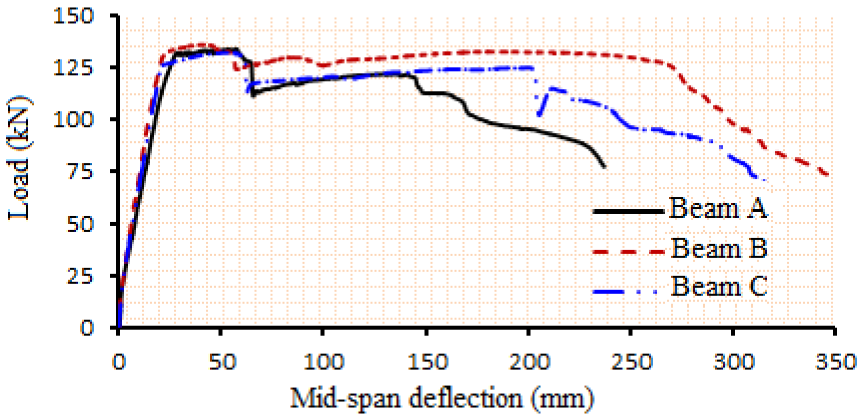

Figure 2. Load-midspan deflection curve of the tested beams

Table 2. Yield and maximum loads of the tested beams

Beams	Yield load (kN)	Maximum Load (kN)
A	122.8	134.2
B	126.5	136.2
C	126.5	132.6

4.3 Ductility of beams

Ductility can be defined as the ability of the member to undergo deflections without an essential reduction in the flexural capacity (Park and Ruitong 1988). The deflection can be influenced by some factors such as the compression/tension strength of concrete, the amount of tension and compression reinforcement and a number of stirrups (Xie et al. 1994). The ductility of beams (λ) can be presented as shown in Equation 1.

$$\lambda = \Delta_u / \Delta_y \quad (1)$$

where Δ_u represents the post-ultimate deflection at 85% of maximum load; Δ_y represents the deflection at yield load, Figure 3. Foster and Attard (1997) reported that the deflection at yield load can be obtained by three steps, as following:

(1) Draw a line from the origin point of the load-deflection curve passing through the point at 75% of the maximum load.
(2) Draw a horizontal line at the maximum load.
(3) The deflection at yield load represents the intersection point of those two lines.

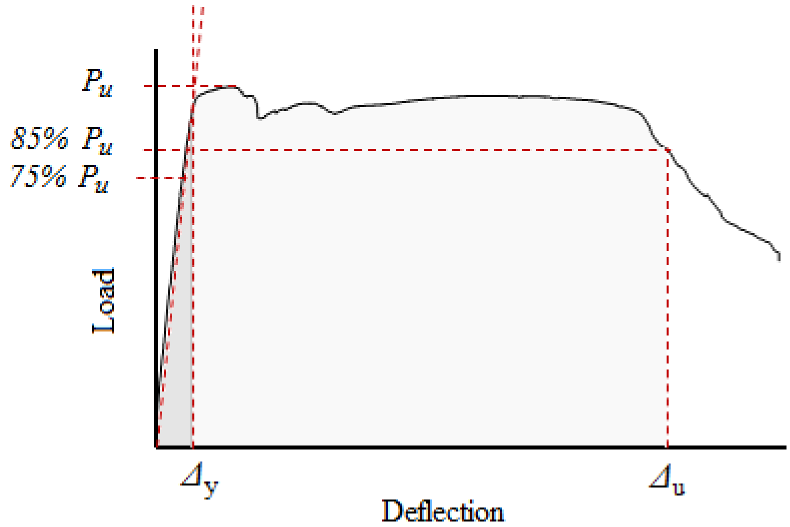

Figure 3. Ductility calculation of the tested beams

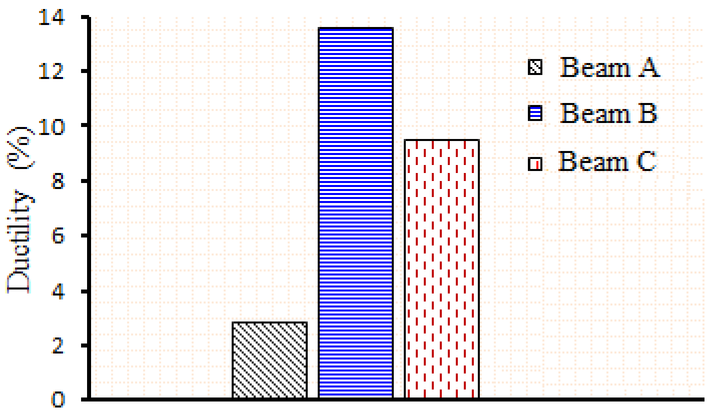

Figure 4. Ductility percentage of the tested beams

Figure 4 shows the ductilities of the tested beams. The ductilities of Beams A, B and C were 2.9, 13.6 and 9.5, respectively. It can be observed that the ductilities of Beams B and C (beams reinforced with steel plates) were higher than Beam A (beam reinforced with steel bars) by 3.7 and 2.3 times, respectively. This indicates that the use of steel plates, as the main reinforcement, makes the concrete beams more ductile. Furthermore, the ductility of Beam B was 43.2% higher than Beam C. This means that the use of steel bolts at regular distances along the beam better than the use of steel angles at the ends.

5. CONCLUSIONS

The behaviour of concrete beams reinforced with steel bars or steel plates was experimentally investigated. Three full-scale reinforced concrete beams were tested under four-point bending. Based on the results of this study, the following conclusions can be summarized:

1. All the test specimens failed in flexure with the reinforcement steel bars and horizontal steel plates fully yielded at the ultimate limit state.
2. The yield deflection of the specimen reinforced with steel bars was noticeably larger than that of the plate reinforced ones, even though their ultimate test loads are similar to each other.
3. The plate reinforced concrete beams showed much higher ductility in comparison with the ordinarily reinforced concrete beam.
4. The use of steel bolts welded at regular distances along the steel plate showed more ductile behaviour than the use of steel angles.

6. ACKNOWLEDGMENTS

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