Drift capacity of GFRP-RC slab-column edge connections

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ABSTRACT

Although reinforced concrete (RC) flat plate systems are only allowed to be used as gravity force resisting systems in regions of high seismic activities, they must possess adequate drift capacity to accommodate the seismically-induced lateral drifts without punching failure. A drift capacity of 1.50% was recommended as the minimum interstory drift ratio which a steel-RC flat plate system, without shear reinforcement, should withstand without punching failure. One of the main parameters affecting the drift capacity of slab-column connections is the gravity shear ratio, which is the ratio of the gravity shear transferred between the slab and the column to the theoretical punching shear strength provided by concrete. Based on extensive research studies, the current codes and standards in North America limit the allowable gravity shear ratio in steel-RC flat plate systems without shear reinforcement to 0.4 for the system to be able to sustain the 1.50% drift capacity.

This paper reports the results of an experimental study investigating the effect of gravity shear ratio on the drift capacity of slab-column edge connections reinforced with glass fibre-reinforced polymers (GFRP) reinforcement. Three full-scale GFRP-RC edge connections were tested under a combination of gravity and uniaxial reversed-cyclic lateral loading. The only parameter was the gravity shear ratio, where the first connection was subjected to a ratio of 40%. This value was increased to 50 and 60% in the second and third connections, respectively. The dimensions of the slab were 3,300 × 3,100 × 200 mm with a 300-mm square edge column extending above and below the slab. It was concluded that, for GFRP-RC edge connections without shear reinforcement to sustain a drift ratio of 1.50% without punching failure, the gravity shear ratio can reach up to 0.5. This value is higher than the 0.4 gravity shear ratio limit associated with steel-RC connections.

Keywords: Cyclic loading, drift capacity, GFRP, gravity shear ratio, punching shear.

INTRODUCTION

In regions of high seismic activities, the Canadian standard CSA A23.3-14 [1] and the American code ACI 318-14 [2] for steel-reinforced concrete (RC) buildings allow the use of flat plate systems only as gravity force resisting systems (GFRS), where special moment frames or shear walls should be provided as the main seismic force resisting system (SFRS). However, the flat plate system has to be designed for deformation compatibility with the primary SFRS. In other words, the flat plate system must have adequate drift capacity to be able to accommodate the seismically-induced lateral drifts without experiencing punching failure of the slab-column connections. Sozen [3] recommended a minimum drift capacity of 1.50% interstory drift ratio, which is defined as the ratio of the relative lateral drift of two successive floors to the floor height, which an RC flat plate system without shear reinforcement should withstand, without punching failure. This capacity, however, cannot be achieved if the gravity shear ratio, which is the ratio of the gravity shear transferred between the slab and the column to the theoretical punching shear strength provided by concrete, exceeds 0.4 [4, 5].

Although fibre-reinforced polymer (FRP) composites represent a smart solution to the corrosion problem associated with steel-RC structures, their elastic nature raises concerns about the seismic response of FRP-RC slab-column connections, where significant amounts of energy need to be dissipated by the inelastic behaviour of the connections. In a recent pioneer study, El-Gendy and El-Salakawy [6] demonstrated that the large elastic deformations of glass FRP (GFRP) bars resulting from their low modulus of elasticity can replace the yielding plateau of steel and, thus, GFRP bars can be used as longitudinal slab reinforcement in slab-column edge connections subjected to simulated seismic loading conditions. The experimental results discussed in this paper are part of an extensive program currently on progress at the University of Manitoba, Canada to study the seismic response of GFRP-RC slab-column edge connections. The main objective of this paper is to recommend a maximum value of the gravity shear ratio that a GFRP-RC slab-column edge connection can withstand while experiencing the minimum 1.50% drift capacity suggested by Sozen [3].

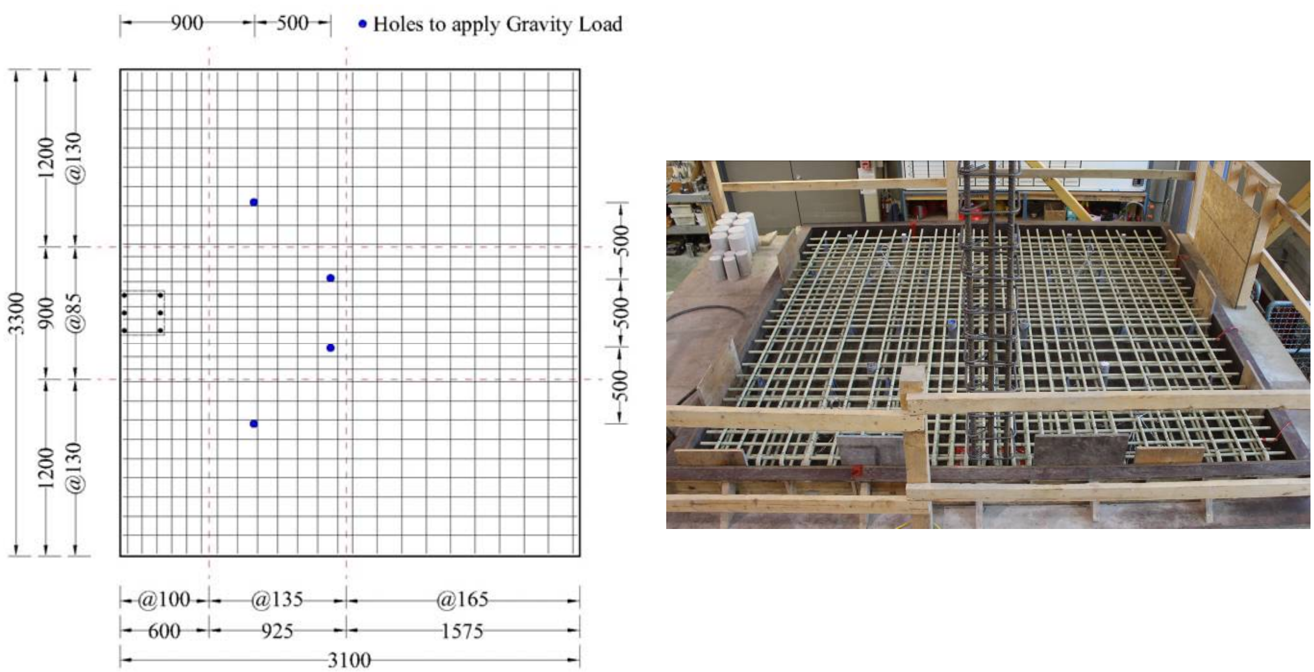
EXPERIMENTAL PROGRAM

Test specimens

Three full-scale isolated slab-column edge connections were constructed and tested under gravity and uniaxial reversed-cyclic lateral loading. The details of the tested connections are listed in Table 1. All connections were identical in all aspects with the only parameter being the amount of gravity shear applied to them; three different gravity shear ratios of 40, 50 and 60% were applied to connections E40, E50 and E60, respectively. As shown in Figure 1, the slabs of the isolated connections had dimensions of 3,300 × 3,100 × 200 mm with300-mm square columns extending 1,900 and 970 mm above and below the slab surfaces, respectively. Top and bottom flexural reinforcement assemblies were used in all specimens, with a top reinforcement ratio of 1.5% in the perpendicular direction of the column strip.

Table 1. Details of Test Specimens.

Specimen	Concrete Strength [MPa]	Gravity Shear Ratio [%]
E40	49.4	40
E50	47.3	50
E60	48.4	60



a) b)

Figure 1. Typical details of test connections (dimensions in mm): (a) top reinforcement mesh layout, (b) reinforcement configuration.

Material properties

Normal-weight, ready-mix concrete with a target 28-day compressive strength of 40 MPa was used for all connections. The concrete strength on the day of testing is listed in Table 1. The slabs were reinforced with top and bottom orthogonal reinforcement assemblies. Size No. 16 sand-coated GFRP bars were used to reinforce the slabs; hooked bars were used in the perpendicular direction of the top assembly to provide the required anchorage, while straight bars were used elsewhere. The mechanical properties of the used GFRP reinforcement are listed in Table 2.

Table 2. Mechanical Properties of the used GFRP Reinforcement.

Bar Shape	Tensile Strength [MPa]	Modulus of Elasticity [GPa]	Ultimate Strain [%]
Straight	1,712	66	2.6
Hooked (straight portion)	1,405	52	2.7

Test setup and instrumentation

The connections were tested under a combination of uniaxial reversed-cyclic lateral loading and a constant level of gravity load. As shown in Figure 2, the connections were pinned at the top of the column to a horizontally-placed hydraulic actuator (where the lateral drift was applied and monitored), at the column base to a steel hinge connection, and at the slab edge running parallel to the slab's free edge. Three hydraulic jacks were used to apply the gravity load to the slab. The jacks were used to tension four dywidag bars running through pre-made holes in the slab and anchored at the laboratory's strong floor.

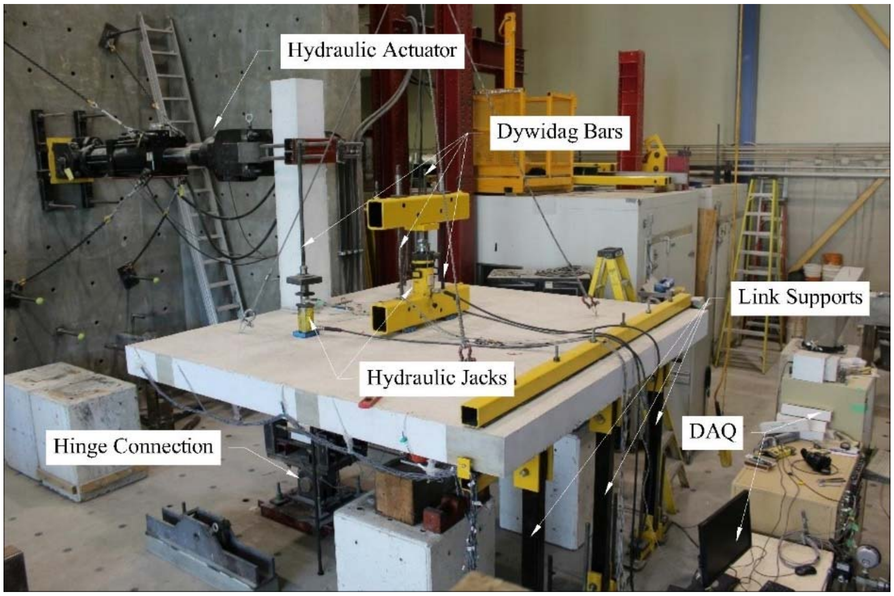


Figure 2. Test setup.

Loading Procedure

The test started by applying the gravity load, while the horizontal hydraulic actuator was locked to prevent lateral displacement of the connection. Once the target gravity load was reached, it was maintained throughout the remainder of the test, while the horizontal hydraulic actuator started to apply the lateral load. The lateral load was simulated by a displacement-controlled uniaxial quasi-static reversed-cyclic loading at the column tip, where the specimens were subjected to increasing drift ratios in several steps of three fully reversed cycles as shown in Figure 3.

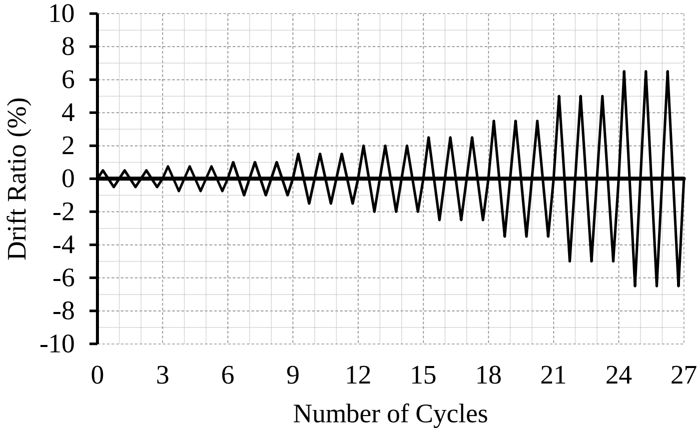
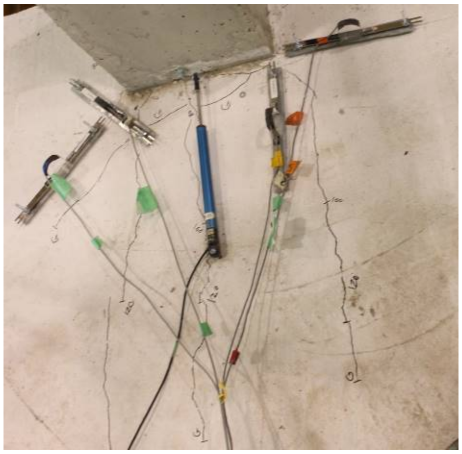


Figure 3. Lateral drift sequence.

TEST RESULTS AND DISCUSSION

Cracking pattern and mode of failure

All connections failed by punching shear of the slab in the column vicinity, where the column along with a surrounding part of the slab suddenly punched through the remainder of the slab. However, the failure of connection E40 was less sudden than that of the other two connections subjected to higher gravity shear ratios. In general, cracking on the top surface of the slab was limited to the location of the negative bending moment in the column vicinity. During the application of gravity loads, a circumferential flexural crack on the slab top surface was observed when the gravity shear transferred to the column was 85, 56 and 39% of the target gravity shear for connections E40, E50 and E60, respectively. No more cracks were observed in connection E40 after the target gravity shear was reached. With increasing the gravity loads applied to connections E50 and E60, however, radial cracks formed in the column vicinity and propagated away from the column. Figure 4 shows the cracking pattern on the top surface of the slab after the application of gravity loads for connections E50 and E60.



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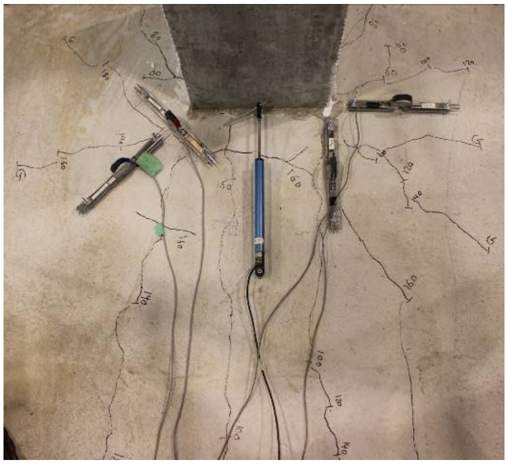

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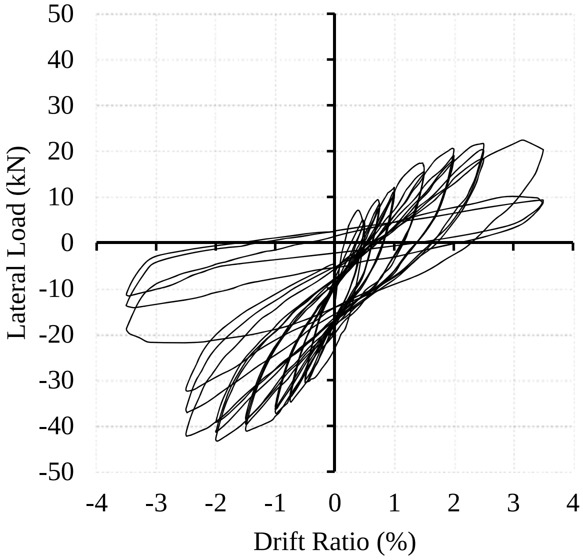
Figure 4. Cracking pattern after the application of gravity load: (a) connection E50, (b) connection E60.

During the application of lateral drifts, additional radial cracks on the slab top surface for all connections. These cracks spread and opened as the test progressed until the final typical cracking pattern developed. Considerable concrete spalling took place in connection E40 before failure which resulted in a less brittle punching shear failure. This was not the case for connections E50 and E60, where the failure with considerably sudden with minimal warning. Figure 5 shows the cracking pattern on the top surface of the slab at failure for connection E60.

Figure 5. Cracking pattern at failure for connection E60.

Hysteretic response

The relationship between the lateral load and the drift ratio for all connections is shown in Figure 6. Connection E40 (subjected to 40% drift ratio) was able to sustain the suggested seismic drift ratio of 1.50% [3, 5] before punching failure. It reached a peak lateral load of 43.3 kN at the first cycle of the 2.00% drift ratio. When the drift ratio was increased to 2.50%, the lateral load gradually decreased until it reached 32.4 kN at the third cycle of the 2.50% drift ratio. Increasing the gravity shear ratio resulted in a decrease in the drift and lateral load capacity. Connections E50 and E60 were able to sustain drift ratios of 1.50 and 1.00%, respectively, and had 5 and 15% less lateral load capacity than that of connection E40. Accordingly, for GFRP-RC slab-column edge connections to be able to undergo 1.50% drift ratio, the applied gravity shear ratio must not exceed 50%.



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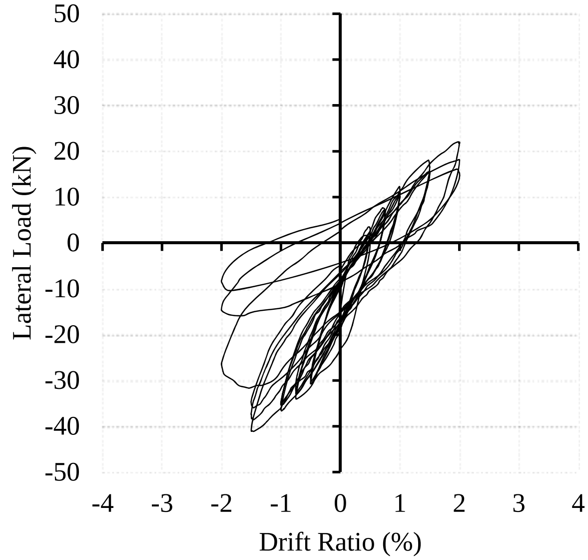

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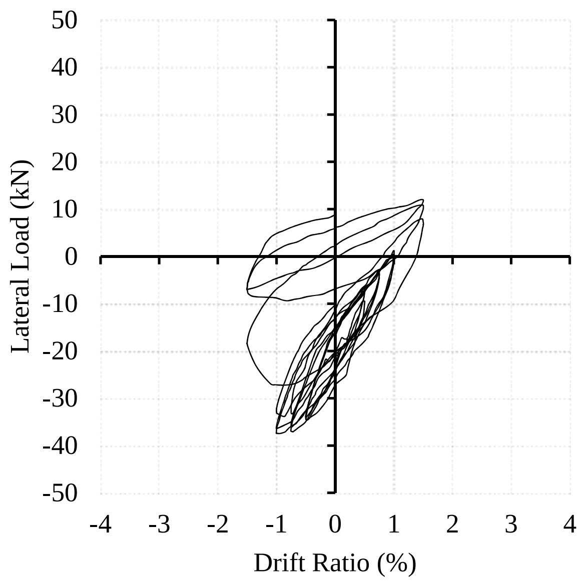

c)

Figure 6. Hysteresis diagrams: (a) connection E40, (b) connection E50, (c) connection E60.

Stiffness

Increasing the gravity load decreased the initial stiffness of the connections. Connections E50 and E60 had 10 and 23% less initial stiffness than that of connection E40, respectively. This is attributed to the 25 and 50% higher gravity load applied to connections E50 and E60, respectively, compared to that applied to connection E40, which resulted in significant cracking under gravity loads before the application of lateral loads.

Energy dissipation

Although all connections demonstrated similar energy dissipation behaviour at the same drift ratio, the total energy dissipated by connection E40 was 1.8 and 3.0 times higher than thosedissipated by connections E50 and E60, respectively. This is attributed to the lower gravity shear ratio applied to connection E40, which allowed the connection to undergo higher drift ratios, and thus be able to dissipate more energy, than that of the other two connections.

CONCLUSIONS

Three full-scale isolated GFRP-RC slab-column edge connections were constructed and tested to failure under gravity and uniaxial reversed-cyclic lateral loading. The three connections were identical with the only parameter being the gravity shear ratio; one connection was subjected to a low ratio of 40%, the second one was subjected to a moderate ratio of 50%, while the third one was subjected to a high ratio of 60%. Based on the observed behaviour of the test connections, the following main conclusions can be drawn:

1. The gravity shear ratio is a primary variable affecting the seismic response of GFRP-RC slab-column connections. Increasing the applied gravity shear ratio from 40 to 50 and 60% reduced the initial stiffness by 10 and 23%, respectively, and the energy dissipation capacity by 45 and 67%, respectively.
2. The magnitude of the gravity shear ratio must be controlled to ensure the integrity of slab-column connections under seismic loading. For GFRP-RC connections without shear reinforcement to achieve a minimum drift capacity of 1.50% without punching failure, the applied gravity shear ratio must not exceed 50%.

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