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A New Type of GFRP Shear Reinforcement for Slab-Column Edge Connections subjected to Reversed-Cyclic Lateral Load

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Abstract
In regions of high seismic activities, flat plate systems can be used as gravity force resisting systems, where special moment frames are provided to resist seismic forces. Nevertheless, all the elements of the reinforced concrete (RC) structure are required to have the ability to deform into the inelastic range. An efficient method to enhance the deformability of flat plate systems is to provide shear reinforcement in the slab. This paper presents the results of an experimental program carried out to evaluate the efficiency of a new type of glass fibre-reinforced polymer (GFRP) shear reinforcement in enhancing the deformability of GFRP-RC slab-column edge connections. Two full-scale connections were constructed and tested under gravity and uniaxial reversed-cyclic lateral load. The slabs of both connections were reinforced with the same GFRP flexural reinforcement ratio; one with GFRP shear studs and one without shear reinforcement. It was evident that the GFRP shear studs significantly enhanced the deformability of the connection, which allowed it to experience deformations associated with 5.00% drift ratio without jeopardizing its gravity load capacity.

Keywords: Deformability, Flat plate, GFRP, Gravity force resisting system, Punching shear, Seismic loading, Shear reinforcement.

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Introduction

Fibre-reinforced polymer (FRP) bars are increasingly used to replace steel bars in reinforced concrete (RC) structures. Unlike steel bars, however, FRP bars do not yield; instead, they behave elastically up to failure. This behavior raises concerns about the seismic response of FRP-RC flat plate systems, which consist of slabs supported directly on columns without protruding beams. On the other hand, research conducted on slab-column connections reinforced with GFRP shear studs demonstrated the efficiency of this type of GFRP shear reinforcement in increasing the deformability of connections subjected to monotonically-increased axial load and unbalanced moment [1, 2, 3]. Recently, the authors [4] demonstrated the feasibility of using GFRP bars as longitudinal slab reinforcement in edge connections subjected to simulated seismic loads, where the large elastic deformations of the GFRP bars resulting from their low modulus of elasticity and high strength compensated for the absence of yielding. Thus, the main objective of this paper is to examine the efficiency of GFRP shear studs in edge connections subjected to simulated seismic loads.

Experimental Program

Material properties

Ready-mix concrete with a target 28-day compressive strength of 40 MPa was used for both connections. The concrete strength for both connections on the test day was approximately 48 MPa. The slabs of both connections were reinforced with top and bottom orthogonal reinforcement assemblies of size No.15 sand-coated GFRP bars. For the shear reinforcement, 170-mm long, No.13 GFRP bars with headed ends were used as shear studs. The 70-mm long heads had an outer 26-mm diameter flange as shown in Figure 1.

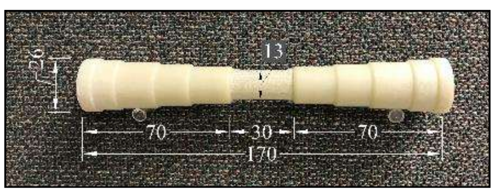


Figure 1: GFRP shear stud (dimensions in mm)

Test specimens

Two full-scale isolated slab-column edge connections were constructed and tested under simulated seismic loads. Both connections were similar in all aspects; however, one specimen did not have shear reinforcement (Connection EXX), while the other one was reinforced with nine peripheral rows of GFRP shear studs spaced at 80 mm (Connection ESS) as shown in Figure 2. The isolated connections had slab dimensions of 3,300 × 3,100 × 200 mm with 300-mm square columns.

Test setup and procedure

As shown in Figure 3, the specimens were pinned at the top of the column to a hydraulic actuator, where the lateral drift was applied. They were also pinned at the column base to a steel hinge connection, and at the slab edge to an assembly of link supports. The gravity load was applied to the slab using hydraulic jacks to tension dywidag bars running through holes in the slab, while the actuator was locked. Both specimens were subjected to a gravity shear ratio of 60%. The gravity load was maintained during the test, while the actuator started to apply the reversed-cyclic lateral load in a displacement-controlled mode.

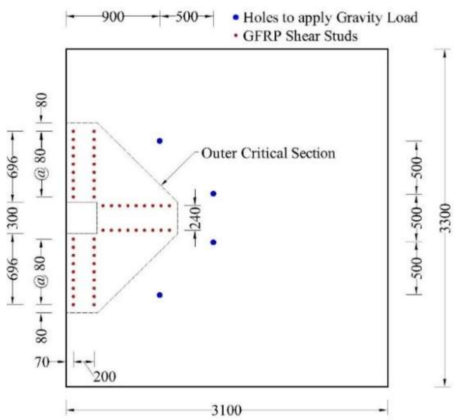


Figure 2: GFRP shear studs arrangement for Connection ESS (dimensions in mm)

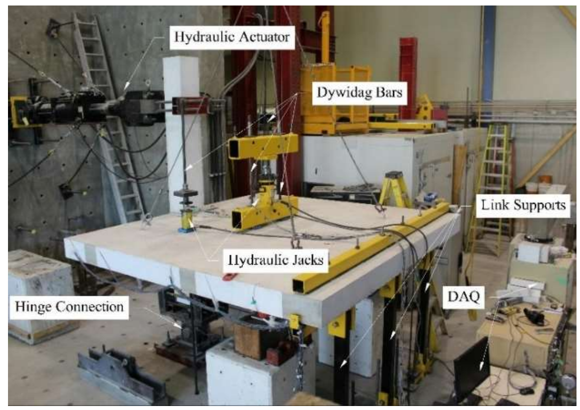


Figure 3: Test setup

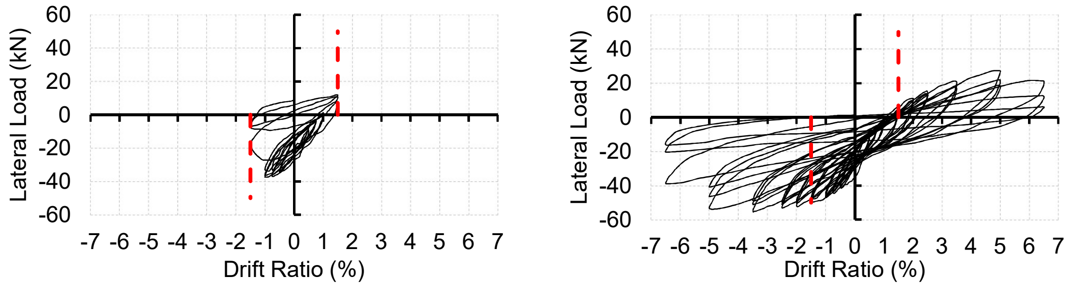
Experimental Results and Discussion

Mode of Failure and Hysteretic Response

Both connections exhibited punching shear failure of the slab in the column vicinity as shown in Figure 4. While the failure of Connection EXX was abrupt, Connection ESS encountered significant deformations and crack widening before failure. As shown in Figure 5, Connection EXX was able to undergo a drift ratio of only 1.00% at a peak lateral load of 37.4 kN. Once the drift ratio was increased to 1.50%, the lateral load dropped and punching failure occurred. On the other hand, the presence of GFRP shear studs allowed Connection ESS to sustain higher drift ratios and lateral loads. The lateral load of Connection ESS continued to increase until it reached a maximum of 55.1 kN (47% higher than that of Connection EXX) at the first cycle of the 3.50% step. Then, the lateral load dropped gradually until it reached 40.8 kN, which indicates more than 25% loss of the lateral load.

a) Connection EXX b) Connection ESS

Figure 4: Cracking pattern at failure



a) Connection EXX b) Connection ESS

Figure 5: Hysteresis diagrams

Stiffness

As shown in Figure 6, Connection ESS had 19% higher stiffness than Connection EXX at 0.50% drift ratio. The stiffness of both connections decreased rapidly with the application of successive cycles of increasing drifts. Nevertheless, the stiffness degradation of Connection EXX was more severe than that of Connection ESS. Accordingly, at 1.00 and 1.50% drift ratios, Connection ESS had 15 and 267% higher stiffness, respectively, than connection EXX.

Energy dissipation

As shown in Figure 7, before it fails in punching after 1.00% drift ratio, Connection EXX dissipated 3.0 kN.m of the seismic energy. Its energy dissipation behavior was similar to that of Connection ESS, which dissipated 3.1 kN.m of the seismic energy up to the same drift ratio. However, the presence of the GFRP shear studs in Connection ESS, which prevented punching failure at low drift ratios, significantly increased the energy dissipation capacity. At failure, Connection ESS dissipated 32.7 kN.m of the seismic energy, which is approximately 11 times that dissipated by Connection EXX at failure as well.

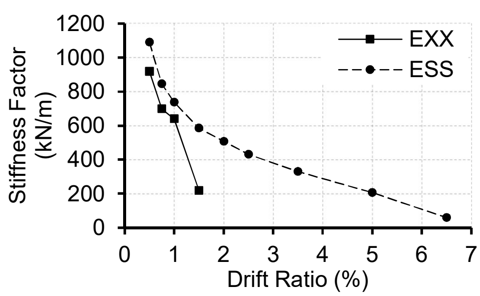


Figure 6: Stiffness degradation

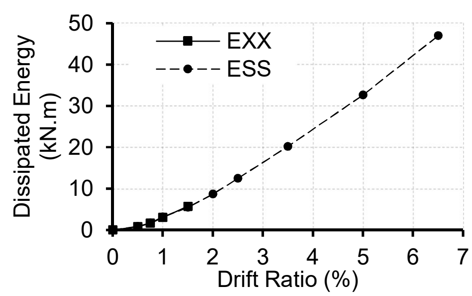


Figure 7: Energy dissipation

Conclusions

Based on the observed behavior, the following main conclusions can be drawn:

1. When subjected to simulated seismic loading conditions, the GFRP-RC slab-column edge connection without shear reinforcement and subjected to high gravity shear ratio of 60% was not able to sustain 1.50% drift ratio before punching failure.

2. The use of GFRP shear studs resulted in a substantial increase in the deformability and drift capacity of the connection, which allowed it to withstand up to 5.00% drift ratio without jeopardizing its gravity load carrying capacity.

References

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