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A State-of-the-Art of Flat-Slab Connections Reinforced with GFRP Bars under Gravity and Lateral Loading

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Abstract: **Flat plates are widely used in reinforced concrete (RC) structures due to their functional and economic advantages. Their design is usually governed by the punching shear stress surrounding the slab-column connections. In seismic zones, slab-column connections must possess adequate strength and ductility to undergo inelastic deformations without fail during and after the earthquake occurrence. Nowadays, fiber-reinforced polymer (FRP) reinforcing bars have gained wide acceptance in the construction industry to use effectively as an alternative to steel bars, particularly when steel corrosion is a major concern. Concerns are questioning the applicability of using the FRP as longitudinal and transverse reinforcements in the slab-column connections under lateral loads. Due to the growing use of GFRP bars in flat slab parking structures and such field applications, there is a need for a deeper knowledge of the behavior of these elements as part of the whole system of the building. This paper presents a critical review of the state of the art of experimental and analytical research concerning the punching shear response of RC flat slab reinforced with GFRP bars subjected to gravity load and lateral loads. Besides, the newly developed techniques and innovations for enhancing the punching shear behavior of flat slabs totally reinforced with FRP are highlighted.**

Keywords: **Slab-Column Connection; Lateral Loads, Gravity Load; GFRP; Unbalanced Moment; Punching Shear.**

I. INTRODUCTION

Flat slabs are a common structural system used in concrete construction such as parking structures due to economical and architectural considerations. The design of reinforced concrete (RC) flat slabs structures is usually governed by the punching shear stress surrounding the slab-column connections. In a typical slab-column connection, the unbalanced moments occur due to loading conditions, different lengths of adjacent spans, discontinuity of slabs at exterior connections and, more significantly, by lateral loads such as wind or seismic loads. One of the major limitations of flat slab structures is their inability to sustain large lateral loads such as those due to earthquakes. Moment and loads created by lateral forces will be transferred through the slab-column interface. The unbalanced moment is transferred by a combination of flexure, torsion, and shear in the slab around the periphery of the column faces. Fig. 1 shows the punching shear stress under a combination of gravity and unbalanced moments. When shear stresses in the region of the slab around the column become dominant, a punching failure will occur. This kind of failure is undesirable as it occurs without warning and may lead to progressive collapse of the structure resulting in human casualties and extensive damage [1].

In seismic zones, the slab–column connection must possess adequate strength against punching shear failure during and after earthquake occurrence and adequate ductility to undergo inelastic deformations without failure. This is required to ensure flat slab systems can maintain their gravity load capacity with a minimum level of ductility that is able to accommodate the seismically induced lateral displacements [2]. However, the connections should not be considered as part of the primary system resisting lateral forces (i.e., shear walls). The expansive corrosion of steel reinforcing bars is a significant factor shortening the service life of RC structures. The deleterious effects due to significant temperature fluctuations, de-icing salts, and chlorides have created harsh environment conditions accelerating the corrosion of steel reinforcement in concrete structures such as parking garages. Deterioration of concrete slabs is faster than any other structural elements because of direct exposure to high concentrations of chlorides used for snow and ice removal during winter seasons, which lead to accelerate the corrosion of steel reinforcement. To overcome the corrosion-related problems, steel bars can be replaced with non-corrodible materials, such as glass fiber-reinforced polymer (GFRP) bars, which can extend the service lifetime and reduce maintenance costs of the structure. A significant research effort over the past two decades has shown that FRP reinforcing bars can be used effectively as an alternative to the steel bars in RC structures, particularly where steel corrosion is a major concern. FRPs are corrosion-free and nonmagnetic materials with high strength-to-weight ratios, which can extend the service lifetime and reduce maintenance costs of the structure. On the other hand, unlike steel-RC members, FRP RC members experience wider and deeper cracks than their steel-RC counterparts due to the relatively low modulus of elasticity of FRP reinforcement. Wider cracks reduce the aggregate interlock contribution to the shear strength, while deeper cracks reduce the un-cracked concrete contribution. Furthermore, the dowel action of the longitudinal FRP reinforcement is considerably lower than that of steel reinforcement due to the low transverse shear strength of FRP reinforcement. Accordingly, the shear capacity of FRP-RC members is expected to be considerably lower than that of their steel-RC counterparts with the same flexural reinforcement ratio ([3] a & b). Therefore, the feasibility of using the FRP as internal reinforcement for RC structures in seismic zones is questionable.

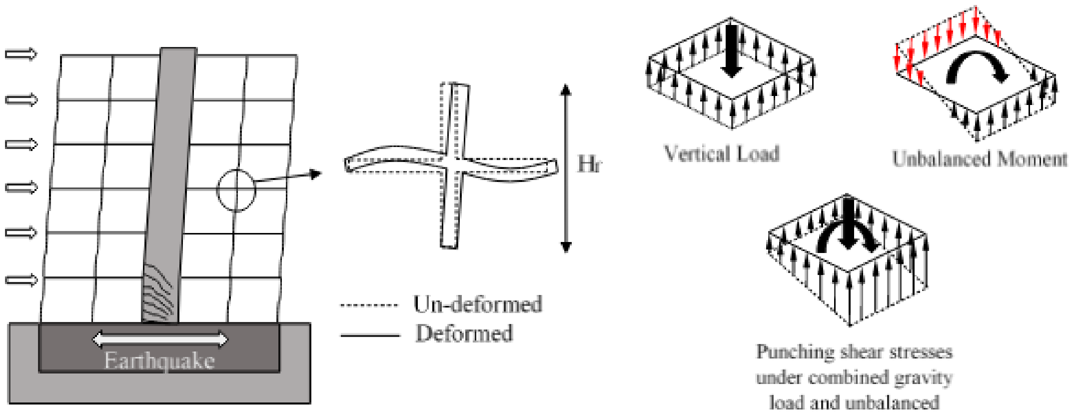

Fig. Error! No text of specified style in document.**: Punching stress under a combination of gravity and unbalanced moments**

To date, considerable research efforts have been contributed to better understanding the behavior of slab-column connections internally reinforced with GFRP bars under concentric axial loads with and without FRP shear reinforcement [3], [4], [5], [6] and [7]. However, limited research has been conducted on FRP RC slab-column connections subjected to lateral loads. Accordingly, it is necessary to investigate the seismic response of FRP-RC slab-column connections to verify the feasibility of using FRP as longitudinal and transverse reinforcements in the shear-critical slab-column connections. In addition, the current codes and guidelines did not include any requirements concerning the nominal punching shear strength and deformability limits of FRP RC flat slab structures with FRP bars subjected to lateral loading. Therefore, in order to provide a safer design for FRP RC flat slab structure system, these critical issues should be examined. The aim of this paper is to describe the state of the art of experimental and numerical research concerning the response of RC flat slab connections reinforced with GFRP bars under gravity and lateral loading, and to describe the main research needs in this field. Due to the growing use of GFRP bars in flat slab parking structures and such field applications [3], there is a need for a greater and deeper knowledge of the behavior of these elements as part of the whole system of the building.

II. EXPERIMENTAL STUDIES

Shear behaviour of RC members is a complex phenomenon that relies on the development of internal carrying mechanisms, the magnitude and combination of which is still a subject of debate. The direct implementation of FRP instead of steel bars, however, is not possible due to the differences in the mechanical and bond characterises compared to steel bars. A summary of the previous studies on the punching shear behavior of FRP RC two-way slabs are briefly reviewed:

A. Slab-Column Connections Subjected to Shear Force and Static Lateral Loading

Gouda et al. [8] & [9] assessed the performance of ten full–scale interior slab-column specimens reinforced with GFRP bars subjected to shear forces and unbalanced moments. The GFRP–RC interior slab-column connections side length was 2800 mm and thickness of 200 mm and column had a 300 mm square section and was extended above and below the slabs for a length of 1000 mm. The specimens were categorized into two series. Series I comprised six slabs were reinforced with sand–coated GFRP bars, Series II comprised three slabs were reinforced with ribbed–deformed GFRP bars, two slabs had been provided with shear reinforcement (shear studs) as shown in Fig. 2. The slabs were supported on four sides and subjected to a vertical shear force (V) simultaneously with the unbalanced moment (M) with a constant M/V ratio of 0.15. The authors concluded that increasing the moment–to–shear ratio increased the deflection and reinforcement strain but significantly reduces the ultimate punching shear capacity. Increasing concrete compressive strength slightly enhanced the punching shear capacity. It was also reported that increasing the GFRP reinforcement ratio from 0.65 to 0.98 and further to 1.3% increased the post-cracking stiffness by 51 and 110% and the punching capacity by 8 and 20%, respectively. Furthermore, Gouda and El-Salakawy (2016b) [9] used a new type of GFRP shear studs with headed ends in interior connections under the same load combination. Again, the presence of the well-anchored shear reinforcement resulted in increasing the ultimate deflection and punching capacity of the shear-reinforced connections.

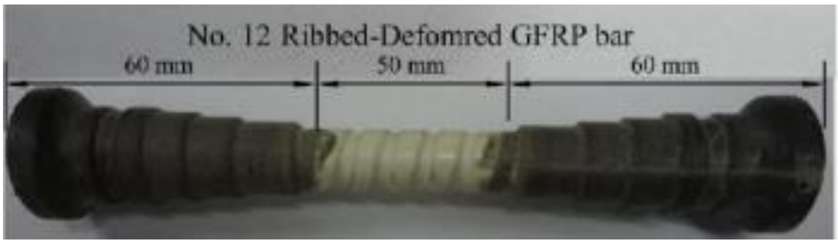

Fig. Error! No text of specified style in document. **: Newly developed GFRP shear studs [8]**

Hussein and El-Salakawy [10] investigated the effect of flexural reinforcement ratio on interior connections made with high strength concrete (HSC) and normal strength concrete (NSC). They also introduced a new type of GFRP shear reinforcement in the form of corrugated bars, which are sand-coated bent bars with a 90° angle between the vertical stems and the horizontal portions (Fig 3). Each corrugated bar comprised five vertical stems spaced at 120 mm centre-to-centre. Furthermore, they tested a modified type of GFRP shear studs with a considerably higher design capacity. It was demonstrated that increasing the concrete strength by 111% (from 38 to 80 MPa) increased the punching capacity by only 22% with a considerable reduction in the deflections at the same load level. It was also concluded that both types of shear reinforcement managed to control the widening and propagation of shear cracks, which significantly enhanced the post-cracking stiffness and punching capacity of the connections.

El-Gendy and El-Salakawy [11] was tested full-scale edge connections reinforced with GFRP bars. In addition, it was concluded that increasing the GFRP reinforcement ratio from 0.9 to 1.35 and further to 1.8% increased the post-cracking stiffness by 62 and 119% and the punching capacity by 14 and 21%, respectively. Mostafa and El-Salakawy (2018) studied the effect of high strength concrete on GFRP-RC edge connections. The authors reported a relatively low increase of 7 and 15% in the punching capacity of connections made of HSC when the reinforcement ratio was increased by 50 and 100%, respectively.

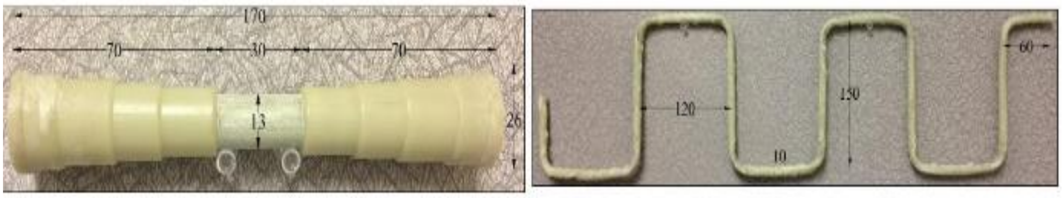

Fig. 3: GFRP headed studs and GFRP corrugated bars [10].

An extension of the first phase for interior slab connections under concentric loads by Hassan et al. 2013 a&b, 2014, 2017, Salama et al. [3],[5],[6],[12],[13],[14] & [15] conducted a full-size testing of GFRP-reinforced edge connections reinforced with and without closed and spiral GFRP stirrups. Nine connections—one reinforced with steel bars for comparison, five reinforced solely with GFRP bars in flexural, and three reinforced with GFRP bars and stirrups—were constructed and tested to failure under combined vertical shear force and unbalanced moment. All slabs had identical geometries of 2500×1350×200 mm with a 300-mm square column stub protruding 700 mm above and below the slab surfaces. The investigated parameters are: (1) GFRP stirrups type (closed and spiral); (2) stirrups extension (1.75d and 4.25d); (3) flexural reinforcement ratio (1.04% and 1.55%) and type (steel and GFRP); (4) concrete strength (normal and high-strength concretes); and (5) moment-to-shear (M/V) ratios (0.3 m and 0.6 m). **Error! Reference source not found.** shows FRP punching shear stirrups used in this investigation.

The test results revealed that the final mode of connections without shear reinforcement was punching shear failure with no signs of concrete crushing. However, existence of GFRP stirrups shear reinforcement was shown to be essential for significant warning before failure. GFRP stirrups shear reinforcement extended to 4.25d yielded a significant effect in enhancing the shear strength, deformation capacity and leading to mixed flexure/punching shear failure with considerable deformability. High-strength concrete directly enhanced punching-shear capacity, load-deflection response, initial stiffness as well as evidenced fewer and narrower cracks compared to their counterparts constructed with normal-strength concrete. Meanwhile, increasing the M/V ratio for normal and high strength concrete connections evidenced significant punching shear stresses causing reduction in the strength and limits the deformation capacity with subsequent brittle punching shear failure. It was concluded that both types of GFRP shear reinforcement offered sufficient confinement to control the development of shear cracks. It was reported that spiral stirrups provided better performance than that of the closed stirrups.

Fig. 4: GFRP stirrups as shear reinforcement [3]

B. Slab-Column Connections Subjected to Shear Force and Cyclic Lateral Loading

To date, limited research has been conducted to investigate the seismic response of FRP RC slab-column interior and edge connections. The following section summarizes the previous studies carried out to investigate the punching-shear behavior of FRP-reinforced concrete two-way slabs with and without FRP shear reinforcement under cyclic lateral loads:

An extensive research project has been conducted at University of Sherbrooke to develop and implement GFRP reinforcement bars for RC two-way slabs parking garages. In the first phase project, a total of 30 GFRP-reinforced two-way slabs with and without shear reinforcement were tested under concentric punching shear failure [3],[5],[6] & [7]. A third phase have been conducted by the second author to investigate the punching shear behaviour of FRP-reinforced two-way slabs under lateral cyclic loading [16],[17] & [18]. In this research study, a total of nine full–scale interior slab-column connections were constructed and tested to understanding and assessing the seismic performance of GFRP–reinforced two–way slab-column connections with and without shear reinforcement. The main test variables were flexural–reinforcement type (GFRP and steel bars); the flexural–reinforcement ratio; service gravity load intensity; concrete compressive strength (NSC and HSC); GFRP stirrups type (closed and spiral); and GFRP stirrups distribution. Gravity load was simulated by vertically applying a downward load through the column using a 1500-kN hydraulic jack. The vertical Gravity load was approximately 140 kN simulating the full dead load and 30% of the live load or 180 kN simulating the service gravity load (the dead load plus the live load). Two 250-kN servo-controlled horizontal hydraulic actuators, which were used to apply cyclic lateral displacements on the top and bottom column ends. All specimens were subjected to an incrementally increasing cyclic displacement routine. The intent of this routine was to study the connection behavior under increasing levels of lateral drift. Each increment represents an approximate increase in the lateral inter-storey drift ratio, δ, of 0.25%.

Each amplitude cycle was performed twice to evaluate the strength degradation and the loss of stiffness in the specimens during the repeated cycles. Lateral displacement routine is shown in **Error! Reference source not found.**. 5.

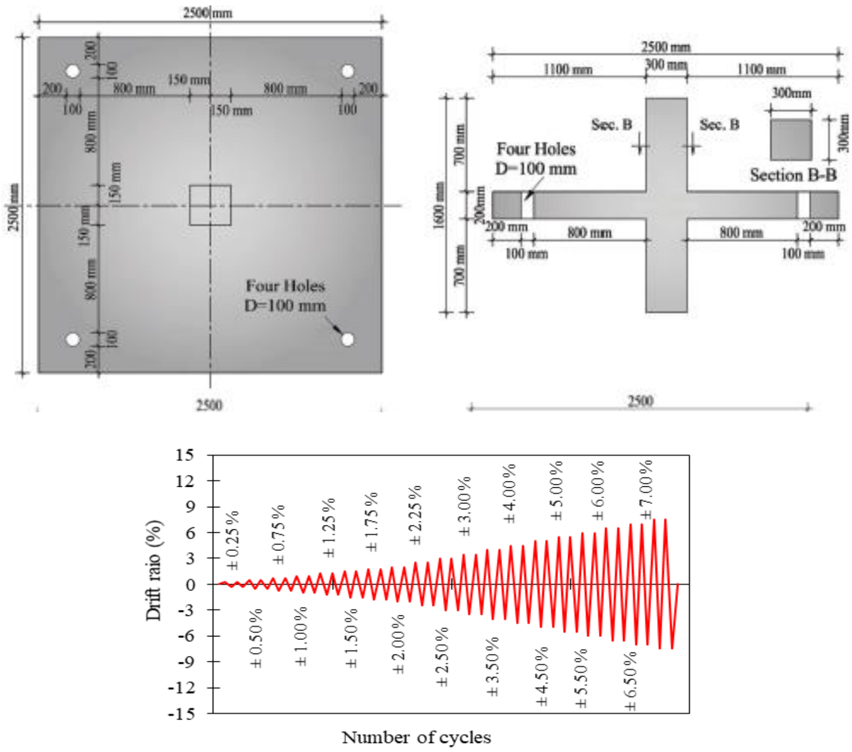

Fig. 5: test specimens' geometry and loading routine [16],[17],[18]

The results revealed that all GFRP specimens achieved adequate punching strength and lateral deformation capacity against punching–shear failure during and after the reversed lateral cyclic load conditions. Consequently, GFRP reinforcing bars could be used effectively as reinforcement in slab-column connections subjected to gravity and reversed lateral cyclic loads. The GFRP–RC specimens achieved lateral inter-story drift capacities over 1.50% satisfying the limits in CSA A23.3 and ACI 421.3R [19],[20]. The GFRP–RC specimens also had adequate drift–ductility indices, dissipated energy, and connection stiffness. On the other hand, increasing the flexural reinforcement ratio or gravity–load intensity in GFRP–RC specimen without shear reinforcement significantly affected the performance of the slab-column connection subjected to reversed lateral cyclic loads. Using high–strength concrete (HSC) in GFRP–RC specimen without shear reinforcement enhanced the slab' punching resistance. Furthermore, provision of shear reinforcement around slab-column connections was proved to be an efficient means in enhancing the overall connections' seismic performance. The GFRP stirrups, either closed or spiral, could be used effectively as shear reinforcement in the concrete slab-column connections reinforced with GFRP bars and subjected to gravity and reversed lateral cyclic loads. All GFRP–RC specimens with GFRP shear reinforcement achieved a high lateral drift of 4.0% to 7.50% with the ability to sustain the gravity load.

El-Gendy and El-Salakawy [11], [21-23] investigated the feasibility of using the FRP reinforcement in slab-column edge connections subjected to simulated seismic loads. The experimental phase involved the construction and testing of seven full-scale glass FRP (GFRP)-RC edge connections under simultaneous gravity and reversed-cyclic lateral loads. The test parameters were the flexural reinforcement type (steel and GFRP) and ratio (0.7 and 1.4%), the gravity shear ratio (0.4, 0.5, and 0.6), and the GFRP shear reinforcement type (shear studs and corrugated bars). Edge connections with 3300 x 3100 mm slab dimensions and a 300 mm square edge column extending 1900 mm from the top of the slab surface and 970 mm from the bottom, were constructed and tested. Typical dimensions and reinforcement details of a test connection are shown in Fig. 6. The reversed-cyclic lateral load was applied by means of a horizontally placed, dynamic hydraulic actuator with load and stroke capacities of 1000 kN and 500 mm, respectively. On the other hand, the gravity load was applied to the slab by a set of three hydraulic jacks. The jacks were used to tension four steel threaded (dywidag) bars running through pre-made holes in the slab and anchored at the laboratory's floor. The results showed that GFRP reinforcement can be used in edge connections subjected to simulated seismic loads. The large elastic deformations of GFRP bars compensated for the absence of yielding. Furthermore, GFRP-RC edge connections without shear reinforcement were able to undergo 1.50%

drift ratio if the gravity shear ratio does not exceed 0.5. The stiffness of the connections decreased as the gravity shear ratio increased due to the excessive slab cracking in the column vicinity as a result of the increased gravity loads. Increasing the gravity shear ratio from 40 to 50 and 60% reduced the initial stiffness of the connections by 10 and 23%, respectively.

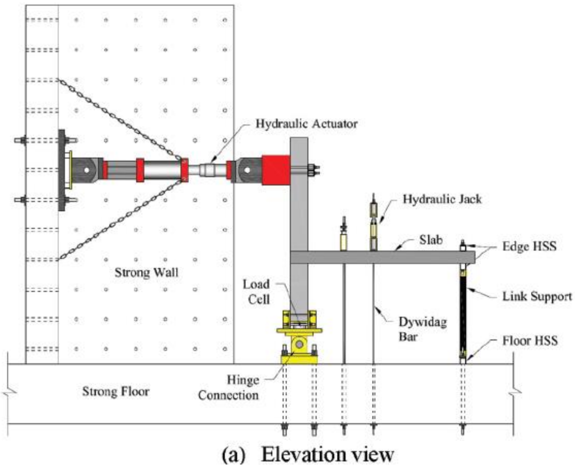

Fig. 6 : Schematic test setup [21].

El-Gendy and El-Salakawy [21] tested three full-scale connections were tested under gravity and uniaxial reversed-cyclic lateral loading, one connection was reinforced with GFRP shear studs, one with GFRP corrugated bars, and one had no shear reinforcement. Fig 7 shows the investigated FRP shear reinforcement. The test results showed that the use of GFRP shear studs and corrugated bars increased the lateral load capacity of the connections by 47% and 44%, respectively. In addition, both types of GFRP shear reinforcement were able to enhance the deformability of the connections significantly, whereas the connection with shear studs was able to sustain deformations associated with 3.50% drift ratio without jeopardizing its gravity load capacity. Moreover, the use of well-anchored GFRP shear reinforcement resulted in a substantial increase in the drift capacity of the connections. Without shear reinforcement, the GFRP-RC connections were not able to dissipate a sufficient amount of energy. The presence of GFRP shear reinforcement, which prevented punching failure at low drift ratios, resulted in a substantial increase in the energy dissipation capacity of the connections.

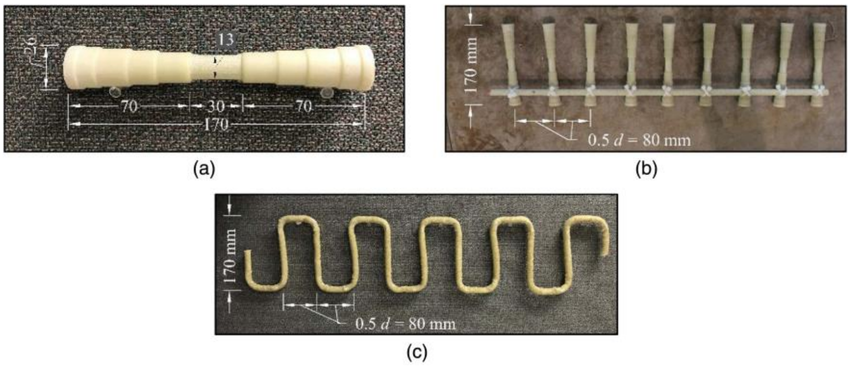

Fig. 7 : GFRP shear reinforcement (dimensions in millimeters): (a) shear stud; (b) shear studs' rail; and (c) corrugated bar [21].

III. ANALYTICAL STUDIES

The punching-shear behavior of two-way slabs is complex with a large number of variables interacting, so that even an experimental program cannot fully cover all combinations. Therefore, finite element analysis (FEA) is essential in modern structural-engineering research to supplement experimental research so as to provide insight into structural behavior and mechanisms. Nonlinear FEA can depict crack formation and propagation, deflections, and possible failure modes, while supplementing experimental observations for which test measurements are not known. Properly calibrated finite element analysis (FEA) can be a cost-effective way to expand the existing experimental database and verify the accuracy of current design code provisions. In this section, the response of RC slab-column connections reinforced with GFRP bars under axial shear force and lateral loading is examined theoretically using FEA.

Gouda and El-Salakwy (2016) [9] constructed a FEM, using specialized 3D software (ATENA) to investigate the punching shear behaviour of interior slab-column connections subjected to a moment-to-shear ratio of 0.15 m. Fig. 8 shows the FE model constructed in ATENA. The constructed model was able to predict the behaviour of the slab-column connections in terms of ultimate capacity, load-deflection curve, and load-strain curve with a reasonable accuracy. The average experimental-to-FEM shear strength ratio was approximately 1.03.

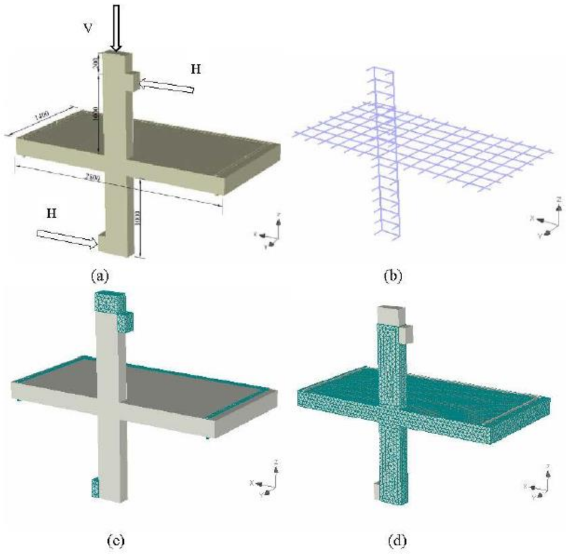

Fig. 8: ATENA-3D model. (a) Model geometry; (b) Reinforcement configuration; (c) Loading and supporting plates (meshed); (d) Slab and column (meshed) [9].

Salama et al. [24] carried out a FEA using a finite-element software package: ANSYS (2018). A FEA simulation was developed to investigate the punching-shear response and strength of edge slab connections. An eight-node 3D solid element, SOLID 65, was used to model the concrete. A 3D spar element, LINK 180, was used to the model steel and FRP reinforcement. Fig. 9 gives a complete view of the overall mesh of the concrete, reinforcement configuration, loading plates, and boundary conditions of the FE model. The numerical FEA results were quite consistent with the experimental results in terms of ultimate load, cracking patterns, reinforcement strains, and load-deflection relationships. The FEA and test results confirm the significant detrimental effect of M/V on punching-shear strength and behavior, increasing the likelihood of brittle punching-shear failure. Increasing the GFRP-stirrup extension significantly improved the punching-shear and deformation capacities, which is in good agreement with the experimental results. Increasing the stirrup diameter has a direct contribution to the ultimate capacity, whereas the shear-reinforcement area at the critical section of the punching shear is increased.

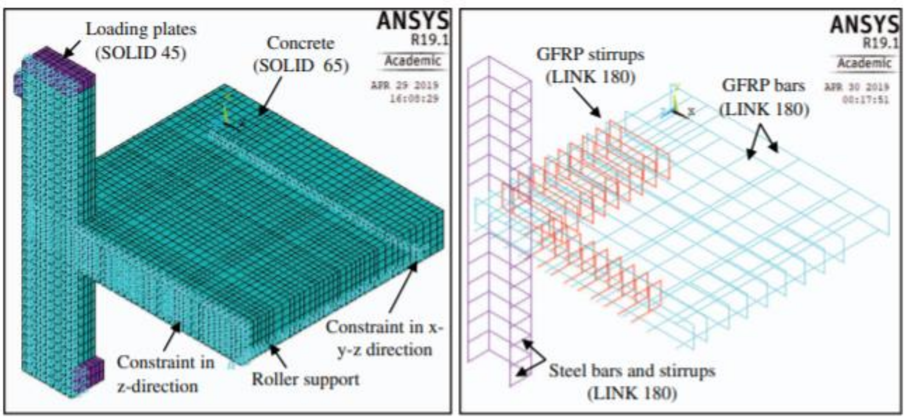

Fig. 9. Geometry and reinforcement details of ANSYS model [24].

El-Gendy and El-Salkawy [25] conducted a 3-D nonlinear FEM using ATENA to investigate the behvaior of edge slab–column connections reinforced with FRP reinforcement under reversed-cyclic lateral load. The key parameters including the gravity shear ratio (0.2–0.8), flexural reinforcement type [glass and carbon FRP (GFRP and CFRP, respectively)], column aspect ratio (0.25–4.00), flexural reinforcement ratio (0.7%–1.4%), and slab thickness (150–400 mm). The constructed FEM is shown in Fig. 10. The hysteretic response predicted by the FEM was in good agreement with the experiments for the tested connections. The FEM was capable to capturing the behavior as well as ultimate peak lateral load with a reasonable degree of accuracy. The results showed that the drift capacity of edge connections reinforced with either GFRP or CFRP reinforcement is reduced when the applied gravity shear ratio increases. However, GFRP RC connections were able to undergo larger drift ratios than their CFRP-RC counterparts. In addition, increasing the slab thickness reduced the punching shear strength of GFRP-RC connections, even for slabs with an effective depth less than 300 mm.

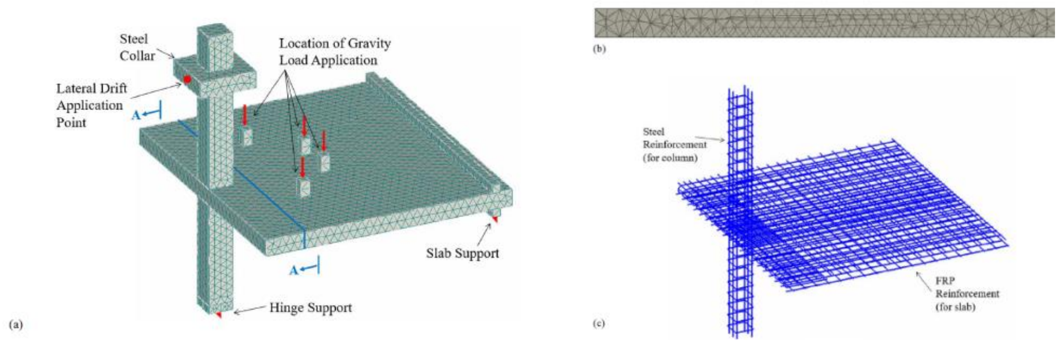

Fig. 10. Typical details of FEM: (a) macroelements and boundary conditions; (b) mesh discretization at Section A-A; and (c) discrete reinforcement [25].

Demissie et al. (2022) [26] performed a numerical study to investigate the behavior of GFRP reinforced edge slab–column connections under monotonically applied gravity and lateral loads. The effects of the size of the spandrel beam, column rectangularity, column shape, and extension distance of the slab beyond the column were examined. A 3-D nonlinear FEM using ABAQUS was developed, and the accuracy of the numerical model was verified by experimental tests conducted by other researchers. The test results showed that providing spandrel beams at the free edge and extending the slab section beyond the outer face of the column significantly enhanced the cracking and ultimate loads, and post-cracking stiffness of the connections. Besides, providing a spandrel beam without an offset from the column centerline significantly increased the ultimate shear capacity of the connection by about 64%. Increasing the rectangularity index of the column under the same punching shear perimeter length exhibited a slight reduction in ultimate load capacity. Extending the slab beyond the free edge slightly increased the strength of the connections, similar to the spandrel beam. Increasing the rectangularity of the column reduced the capacities of the connection.

IV. CONCLUDING REMARKS AND RECOMMENDATIONS

The present paper provides a comprehensive state-of-the-art review of the literature to tackle the response of RC flat plate systems reinforced with FRP bars under axial shear forces and lateral loading through experimental and analytical studies that are available. Besides, the newly developed techniques and innovations for enhancing the punching shear behavior of flat slabs totally reinforced with FRP ae highlighted. The concluding remarks and recommendations based on the database of the literature are presented as follows:

– GFRP bars can be used as main slab reinforcements in RC interior and edge slab-column connections subjected to shear force and simulated lateral loads. The large elastic deformations of GFRP bars resulting from the combination of their low modulus of elasticity and high ultimate strength can compensate for the absence of the yielding plateau of steel.

– Like steel reinforced slab-column connections, the gravity shear ratio is a primary factor affecting the seismic response of GFRP-RC slab-column connections. Increasing the gravity shear ratio reduced the drift capacity, deformability, stiffness, energy dissipation, lateral load capacity of the connections.

– GFRP–reinforced slab-column connections can be designed with adequate strength and deformation capacity against punching–shear failure during and after reversed lateral cyclic–loading conditions. The recommended allowable design drift in the codes used for seismic analysis of 1.50% if the gravity shear ratio does not exceed 0.4.

– Reinforcing against shear failure can be accomplished by different FRP systems of shear reinforcement i.e., stirrups (closed or spiral), studs or corrugated bars. The use of well-anchored GFRP shear reinforcement can a substantial increase in the drift capacity and deformability of connections under a high gravity shear ratio, which allowed the connections to sustain large seismically induced deformations without jeopardizing their gravity load capacity. This indicates that using FRP as shear reinforcement has a reasonable potential to research further.

– The GFRP reinforcement is recommended to be used in concrete flat plate structures located in the seismic zone, although further research is needed to implement adequate design guidelines for such structural element.

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