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INVESTIGATION OF PUNCHING SHEAR RESPONSE OF GFRP REINFORCED CONCRETE FLAT PLATE SLAB USING CDP MODEL IN ABAQUS

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Abstract- In this paper, the punching shear of glass fiber reinforced polymer (GFRP)-reinforced concrete two-way square flat slabs was investigated using the non-linear finite element analysis (NLFEA) and its comparison with experimental results from 2500 mm x 2500 mm x 200 mm including top and bottom square column stubs. The size of stubs was 300 mm reinforced with GFRP bars along with conventionally steel bars being tested under the monotonic loading. A commercial software ABAQUS Standard 6.14-1 was used for the NLFEA model of the concrete flat slab's specimens. The numerical results were calibrated by using the varying material strengths along with different geometric properties likely dilation angle, element types, mesh sizes, and viscosity parameters which are based on the earlier experimental test results. Furthermore, Concrete Damaged Plasticity (CDP) model is used for the reinforced concrete behavior, while linear elastic behavior for GFRP and steel bars is used in ABAQUS. Calibration of these 3D slab model analyses is completely done by simulating the slabs without shear reinforcement. Failure of punching shear and cracking patterns are examined by using these test prototypes. Finite Element Analysis (FEA) of these prototypes using GFRP bars also showed identical shear failure and the patterns of cracking at failure. The numerical modeling of flat plate slabs in Abaqus presented the load-deflection curves with a close relation with experimental results.

Keywords- Punching Shear, Flat plate slabs, Non-Linear Finite Element Analysis (NLFEA), Failure Behavior

1 Introduction

Slabs (Flat Slabs / Flat Plate Slabs) are a major constituent / flexural element of concrete structures which are frequently used in the construction of high-rise commercial buildings. Punching shear behavior in these buildings with flat or flat plate slabs and footings is a major damaging issue that is produced due to high shear stresses. Shear distribution in these slabs and foundations also impacts the performance along with failure mode. Although when Punching shear failure occurs in flat slabs, it shows no warning signs earlier due to slight deflection capabilities with internal and external cracks invisible at the top surface of the slab. These slabs/footings are cast with and without column capitals to safe design for punching shear failure. Failure of punching shear is produced due to larger shear stresses at the slab column junctions in reinforced concrete flat and flat plate slabs. Researchers observed different approaches for FRP flat slabs/footings structural behavior using analytical models, numerical models, and finite element analysis [1].

In ASIA, Pakistan is an arid area in which some of the areas are humid / semi-humid due to heavy or sudden rains and snowfalls throughout the year due to which corrosion is a major problem on construction sites. To overcome this phenomenon, de-icing salts or other products are used. Specifically, Glass Fiber Reinforced Polymer (GFRP) bars are also used for such projects as mentioned above. GFRP bars are more valuable here due to their uniqueness and this material is flimsy (lightweight), has a lesser modulus of elasticity, is non-magnetic, environment-friendly, electrically insulating (especially for Electric substations) and corrosion free has low thermal conducting as one-half of steel, very high tensile strength and cost-effectively [2].

Several Reinforced Concrete Slabs with and without shear transverse reinforcement used to envisage load-deformation response was conducted at the (ETH) in Zurich, Switzerland. The experiments demonstrate the impact of shear strength and deformation capacity of RC slabs [3]. Polak et al. also examined the response of punching shear in different steel reinforced slabs with column connections at the center and edges without shear reinforcement. They have analyzed parametric investigations using material properties in ABAQUS affected FEA of concrete structures and predict good agreement. Also, it gives enough results for cracking propagation along with load-displacement response using ABAQUS standard and Explicit.

Evaluation of the literature comes to know that limited work related to the numerical behavior of GFRP-reinforced flat slabs using the ABAQUS standard is demarcated. Also, there are limited geometrical and numerical parametric investigations on punching shear failure in GFRP reinforced slabs without shear reinforcement that have been conducted using Non-Linear FEA in ABAQUS with ACI codes. The critical parameters needed to examine the experimental/numerical parametric investigation which influences the punching shear behavior of these slabs. An innovative goal of the author in current research of flat slabs without shear reinforcement is to investigate the numerous parametric behavior of GFRP and steel-reinforced flat slabs with proposed Non-Linear FEA models of slabs specimen in software (ABAQUS Standard 6.14) to validate accurately against load-deflection curves of preceding experimental test results from Christian Dulude and Brahim Benmokrane [4]. Subsequently, a numerical study of different parameters from a controlled specimen of steel and GFRP has been done.

2 Experimental Procedures

A total of 03 full-scale rectangular RC flat plate slab prototypes (Notation 'S' is for Steel slabs and notation 'G' is used for GFRP slabs) were modelled using ABAQUS. Modeling of 2500 mm x 2500 mm x 200 mm including square column stubs of 300 mm without shear reinforcement along with GFRP and steel bars were used [4]. All the bars of GFRP reinforcement were kept free (in X, Y, and Z directions) when the slab was loaded with the applied axial load. A static monotonic Axial Load has been applied on the top of the square column stub central surface of two-way slabs for a load-deflection response till the punching shear failure occurred by using the displacement control technique at an equal rate of 25 mm at the center of square column stub in ABAQUS. For tie constraint, the load has been applied on the central surface of column stubs whose purpose was to monitor actual load distribution on slab through column stubs.

2.1 Geometric Model, Loadings, and Boundary Conditions

In this research, the different material proportions of concrete and size of loading with loading increments including controlled model properties and sizes of the ABAQUS Standard step module are discussed below in Table 1. In current modelling research, a concept of master and slave surface is used. This concept defines the properties of the interaction between the two-way concrete slab and column stubs. The bottom external surface of the top column stub and the lower bottom external surface of the two-way concrete slab was presented as master surfaces in Abaqus. Top external surface of the concrete slab and the top external surface of the bottom column stub were considered and monitored as slave surfaces. The whole analysis worked when load is transfer from master surfaces to slave surface. Figure 01 presenting the geometry configuration including FE modelling of GFRP reinforced concrete slabs.

Table 01: Different Parameters of Concrete properties including FEA model loads

Parameter	Value
Density of concrete in ton/mm3	2.4×10^{-9}
Young's modulus, Ec (N/mm2)	31842
Poisson's ratio, ν	0.2
Increment in size of loading (Initial and Maximum)	0.01
Number of increments	1000
Minimum increment size	10^{-10}

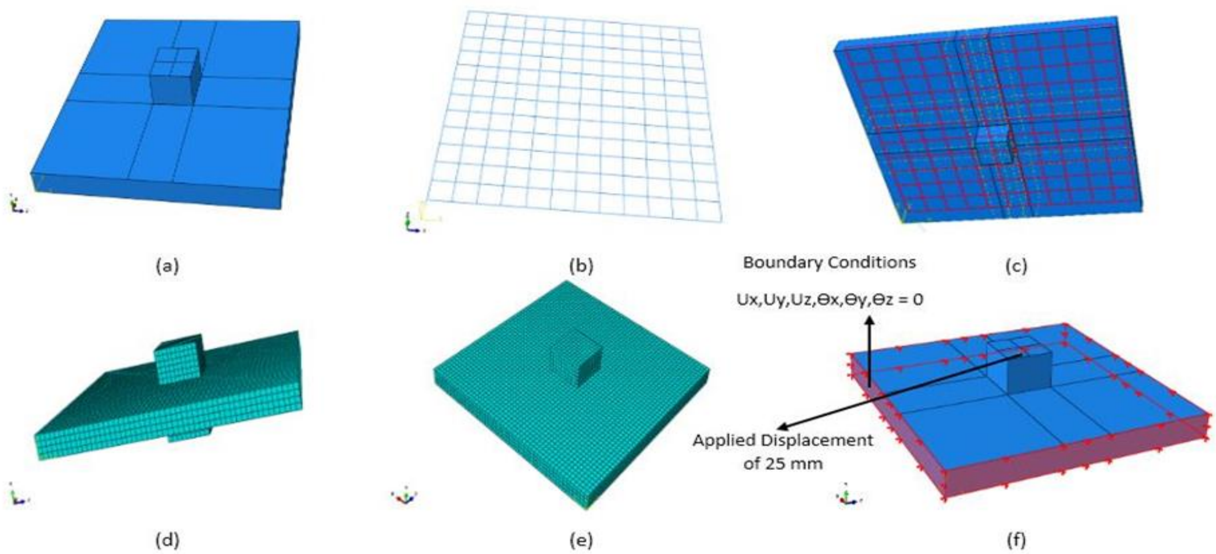

Figure 1. Flat Plate Slabs with Column Stub reinforced with GFRP (a) geometry configuration, (b) GFRP mesh, (c) slab with GFRP model, (d) FE meshing, (e) FE meshing top, (f) boundary conditions.

These prototypes were utilized from the paper [4] under different loading conditions. Only one prototype ($S_{1.7}$ 30/20) was reinforced by steel bars longitudinally and transversely and the remaining specimens were included with GFRP reinforced bars. Different types of reinforcement ratios (6%), miscellaneous bar numbers (15mm, 18mm, and 20mm), and various compressive strengths (34.3 MPa, 44.9 MPa, and 45.4 MPa) based on cylindrical testing of 150 x 300 mm including square column stub has been used to study their impact on load-deflection behavior. Material characteristics of these all specimen are given in Table 2.

Table 2. Appropriate Geometric along with material aspects of two-way Concrete Slab specimens

Prototype Sample	Reinfor-cement type	Compressive strength of concrete (MPa)	Reinforcement		Concrete Cover (mm)	Reinfor-cement Ratio(%)	Column Stub Dimension Top/Bottom (mm(in))
			Bars No.	Spacing (mm)			
$S_{(1.7)}$30/20	Steel	45.4	ϕ18~20 M	160	50	6.35	300 (11.8)
$G_{(0.7)}$30/20	GFRP	34.3	ϕ15 mm	160	50	6	300 (11.8)
$G_{(1.6)}$30/20	GFRP	44.9	ϕ20 mm	160	50	6.35	300 (11.8)

2.2 Concrete Damaged Plasticity (CDP) Model.

In ABAQUS concrete inelastic behavior has been defined by three constitutive models which are as defined by Concrete Damaged Plasticity (CDP) model, Concrete Smeared Cracking model (CSCM), and another Brittle Cracking Concrete (BCC) model. In this research, only CDP model is discussed which deals with plastic as well as compressive and tensile behavior. CDP Model gives two types of concrete failure compressive crushing along with tensile cracking. In the current study, the Nonlinear behavior of RC concrete is commonly used by the CDP model as presented in Figure 2. CDP model in this study illustrates the correlation of concrete strain between plastic strain, inelastic strain, and compression stress [5].

2.3 Plastic Behavior of Concrete

The concrete plasticity model is precisely discussed by using concrete elastic potential eccentricity (ε), dilation angle (ψ), the biaxial compressive strength factors in the shape of compressive stress ratio in the biaxial state to the uniaxial state $(\sigma_{b0}/\sigma_{c0})$ including viscosity parameter and (K_c) which is defined as the shape factor of yielding surface in the deviatoric plane. After calibration, different values of viscosity and dilation angle parameters were attained. It is also worth mentioning that this stress ratio is also quantified by Papanikolaou and Kappos [6] as projected in Eq. (1).

$$\frac{\sigma_{bo}}{\sigma_{co}} = 1.5(f_c')^{-0.075} \quad (1)$$

The CDP model recommended Also, different values of K_c, eccentricity (ε), and yield shape surface are 0.1 and 2/3, respectively. As per the ABAQUS manual, the specified value of $(\sigma_{b0}/\sigma_{c0})$ is 1.16 [7].

2.4 Compressive and Tensile Performance of Concrete

To express the compressive and tensile performance/response of concrete during CDP model simulations, the behavior of compression failure can be obtained by increasing strain and ultimate elastic stress of concrete. Also, it is worth mentioning that the compression failure occurred due to an increased degree of inelastic strain ε^{in}. In this research, concrete modulus of elasticity (Ec) was considered through ACI code using Eq. (2) as mentioned below:

$$E_c = 4700\sqrt{f_c'} \qquad (2)$$

Furthermore, Fig 3 expressed the concrete compressive stress-strain diagram according to Eurocode 2, in which the linear elastic behavior has been used $0.4f_{cm}$ as mentioned in P. Kmiecik et al. [8]. Majewski [9] also proposed the experimental relationships of strain ε_{c1} at the average concrete compressive strength and ultimate strain ε_{cu1} given by Eq. (3) and (4).

$$\varepsilon_{cu1} = 0.004 - 0.0011[1 - e^{-0.0215 f_{cm}}] \qquad (3)$$

$$\varepsilon_{c1} = 0.0014[2 - e^{-0.024 f_{cm}} - e^{-0.140 f_{cm}}] \qquad (4)$$

In current research structural nonlinear behavior is defined by Eq. (5) given by Euro Code [10] for a stress-strain relationship of concrete.

$$\sigma_c = f_{cm} \frac{k\eta - \eta^2}{1 + (k-2)\eta} \qquad (5)$$

Desayi and Krishnan [11] have given the stress-strain relationship given by Eq. (6) where compressive strain at peak loads is denoted by ε_{co} and according to Mander et al. [12], its value is 0.002.

$$\sigma_c = \frac{E_o \varepsilon}{1 + (\frac{\varepsilon}{\varepsilon_{co}})^2} \qquad (6)$$

Simulation of FEA using stress-strain relationship and tensile behavior of concrete used at the condition of post-failure. Fig 4 shows the modified tension stiffening model used in current research where the stress-strain curve in tensile behavior at critical strain ε_{cr} is used from ultimate stress σ_{to} to $0.77\sigma_{to}$. Using Eq. (8) proposed by Wang and Vecchio [13] and Genikomsou and Polak [14] was used for concrete ultimate tensile strength.

$$f_t' = 0.33\sqrt{f_c'} \text{ (MPa)} \qquad (8)$$

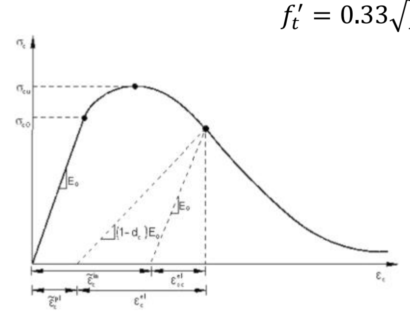

Figure 2. The CDP (Concrete Damaged Plasticity) model

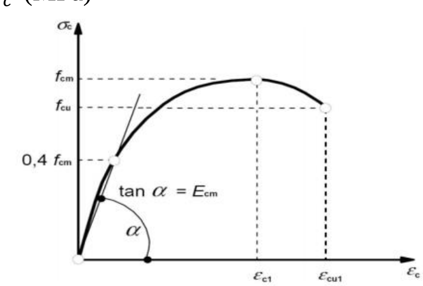

Figure 3. Eurocode 2 of Stress-strain diagram for structure(Under Compression)

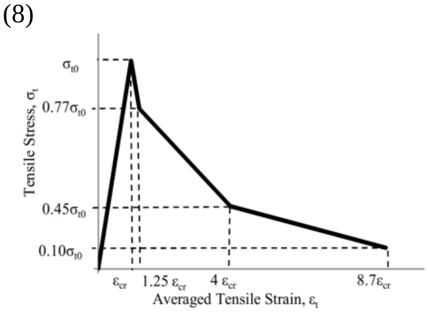

Figure 4. Eurocode 2 of Stress-strain diagram for structures (Under Tension)

3 Research Methodology

The foremost purpose of this research was to investigate and monitor the behavior of the two-way flat plate slabs which are reinforced with GFRP barriers facing increasing loading and compare their behavior with that of an iron rod. All the results have been obtained by numerical simulation on different Two Ways Glass fiber reinforced polymer concrete slabs samples using a commercial-based software Abaqus. All the simulations have been done on the specimens using CDP modeling. Samples were calibrated using various dilation angle parameters, different element types, varying mesh sizes, and different viscosity parameters along with boundary conditions and embedded regions/area constraints. The concrete and GFRP material properties were also discussed during these simulations process to achieve better results of punching shear response through the Computer.

4 Results

Various types of tests have been performed in Abaqus Simulia software for the prototype samples to monitor the action of punching shear in two-way flat plate slabs using GFRP bars. Different types of Two-noded element types GFRP & Steel (T3D2, T3D3, T3D2H, and T3D3H), Dilation angle parameter, mesh sizes, and viscosity parameters deformed truss elements which have three DOF at each node of reinforced bars were utilized in Abaqus for the simulations. Parameters needed for reinforcing bars modeling were discussed deliberately which are Poisson's ratio (ν) which has a value of 0.2 and the Modulus of elasticity including yield strength and zero plastic strain. GFRP and Steel bar physical properties utilized in this research as Young's Modulus (48.1 GPa, 48.2 GPa, and 200 GPa), Yield Strength (673 MPa, 699 MPa, and 470 MPa) respectively.

4.1 Discussions of Load Deflection Curves

Investigation of dilation angle parameter in Abaqus Simulia provided the response of load-deflection curves at an angle of 30° accurately and maximum load applied 367 kN in comparison with experimental results as 360 kN at 25 mm displacement as given in Fig 5. Similarly, Concrete Element types give better results at the C3D8R element type in line with experimental results as shown in Fig 6. Fig 7 shows excellent results with a slight difference of 6 kN only at T3D2, T3D3H, and T3D3H of GFRP element type. 50 mm mesh size (A finer mesh size) gives excellent results of load-deflection curves at 361 KN axial load-deformation in comparison with experimental value as shown in Fig 8. The exact Graphical value of the viscosity parameter of 0.003 also showed greater results for the experimental result as shown in Fig 9. It has been observed from the peak load curves that GFRP concrete progresses positively for the post-elastic effect of structures.

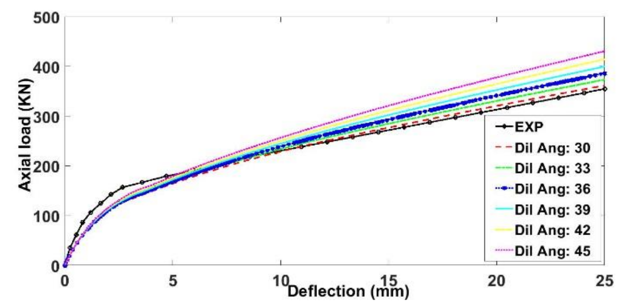

Figure 5. Dilation Angle Parameter

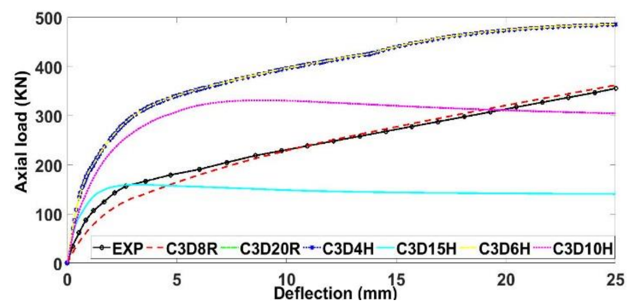

Figure 6. Concrete Element Types

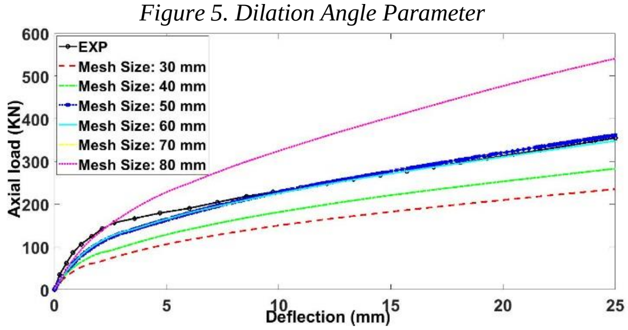

Figure 8. Mesh Sizes

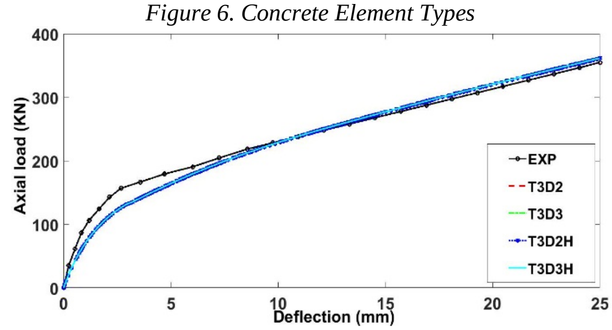

Figure 7. GFRP Element Types

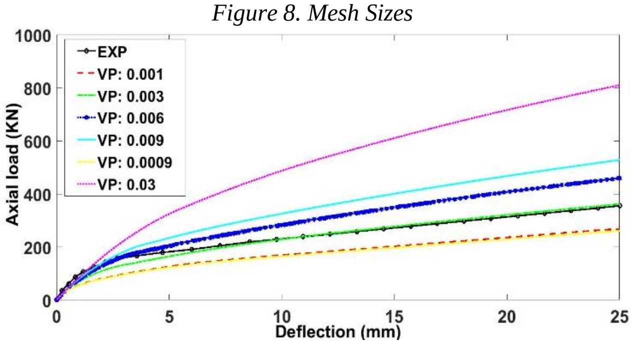

Figure 9. Viscosity Parameter

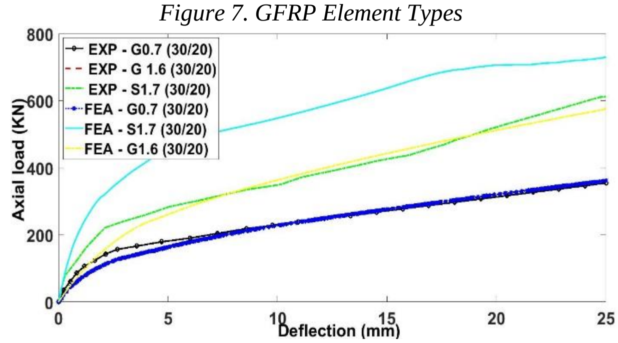

Figure 10. Experimental and FEA Results

4.2 Crack Patterns Discussion

As per experimental results, the cracks produced on the tension side of concrete slabs due to loading phenomena. Many software can predict the process and produce the FEA results. In current study, cracks propagation and punching shear response of GFRP reinforced concrete two-way flat plate slabs has been monitored by Abaqus Simulia software. FEA of these slabs are shown in Fig 11 (a, b, c & d) after loading increments of 1000 at a rate of 10^{-10} on top of square column stub resulting maximum optimistic principal plastic strains. A good agreement was achieved between FEA and experimental results to check Punching shear behavior of two-way flat plate slabs.

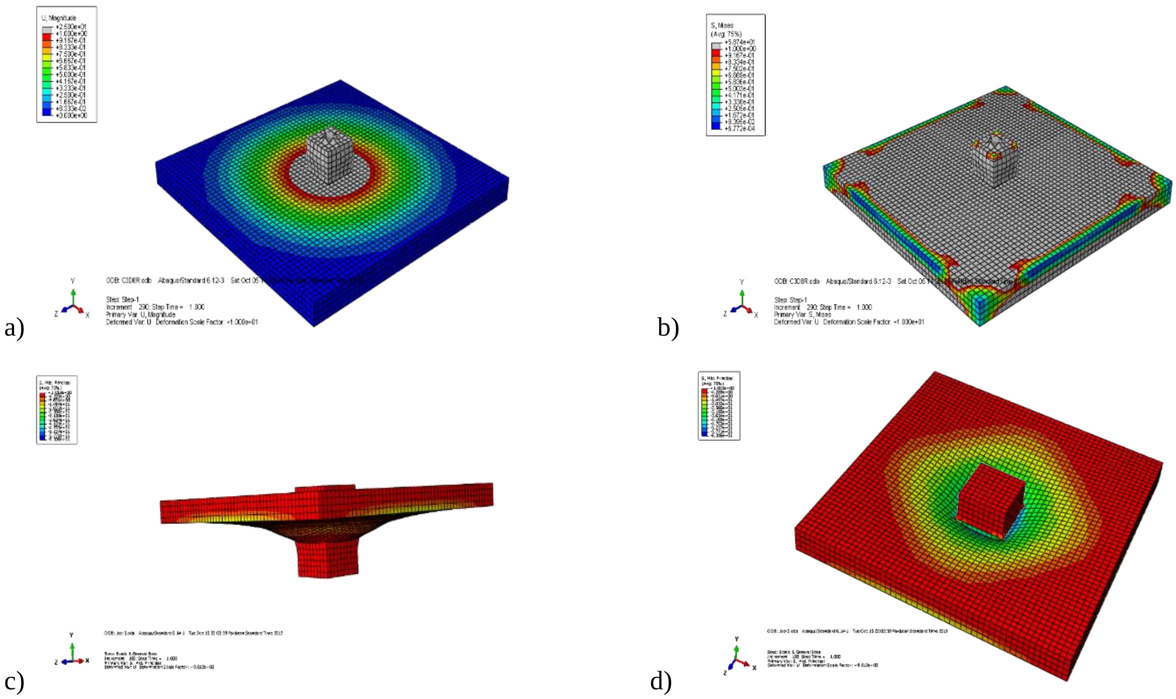

Figure 11: Punching Shear Results in ABAQUS (a)Load Increments (b) Deformed shape of 2 Way Slab (c) Deformation of Slab after load increments (d) Top View of Deflection Patterns during load increments

5 Conclusion

The planned FEA model of 3D solid homogeneous sections also presented a better relationship of parametric & geometric results. The following are the key findings obtained from the conducted simulation-based on NLFEA:

1. Two-way GFRP-reinforced flat plate slabs with top/bottom column stubs gave the most accurate results predicted by using the viscosity parameter 0.003, dilation angle 30°, concrete element type at C3D8R, GFRP element type T3D2, and 50 mm mesh sizes.
2. When the reinforcement ratio of prototype $G_{0.7}30/20$ increased from 0.71% to ratio 1.56%, and average punching shear stress improved by 39%. This increment in ratios enhanced the depth of the concrete contribution which describes as punching shear capacity that can be increased with the increase of reinforcement ratio. Similarly, when a higher effective reinforcement ratio was used (Ratio 0.17% to ratio 1.66%), the punching shear stress was enhanced.
3. The samples reinforced with steel bars yielded higher deflection at an equivalent load and demonstrated lesser punching shear stress compared with GFRP reinforced samples when the failure occurred. Exact value of $E_f/E_s = 0.25$ approx. which shows lower modulus of elasticity of GFRP reinforcing bars.
4. All the two-way flat plate slab samples along with column stub displayed the same punching shear failure and parallel crack patterns irrespective of the reinforcement ratio and type. Although, the thickness of the slab affects the punching shear measurements.
5. Punching shear behavior is slightly affected by the axial stiffness of the reinforcement. Also, Punching shear capacity increased with the increase of reinforcement axial stiffness which results in the decrease in crack width,

reinforcement strains, and deflections. The deflection of the two-way slabs was not reduced with a higher ratio of reinforcement, which shows the flexural cracks were fewer, and their widths were smaller.

Appendix

None.

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