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Non-Linear Finite Element Analysis of Punching Shear Behaviour of RC Slab-Column Connections Strengthened Using FRP

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ABSTRACT: Punching shear failure is a significant concern for flat plate structures due to accumulation of localized stresses at the junction of slab-column. Strengthening is crucial to prevent these failures. External strengthening, like using FRP sheets, effectively addresses this vulnerability. This study involves NLFEA conducted to investigate the effects of strengthening against punching shear using externally bonded CFRP and BFRP strips. Nine slabs were simulated using ANSYS Workbench, varying FRP types and layers. CFRP enhanced shear resistance by up to 40%, increasing stiffness and reducing deflections. Additional BFRP layers improved strength by 18% compared to a single layer. The most efficient and cost-effective approach appeared to be using a single layer of CFRP strips in skew orientation. Analytical results were well-aligned with experimental findings, showing a very low COV of 1.8 to 2.3 percent.

KEYWORDS:NLFEA, Basalt fibre reinforced polymer, Carbon fibre reinforced polymer, Punching shear, External-Bonded strengthening.

I. INTRODUCTION

A revolutionary concept for flat slab construction has developed due to their effectiveness as a suspended flooring solution that enables simpler the shuttering and quicker site operations, flat slabs are being used to construct lot of commercial and residential buildings. Structural integrity of flat slabs is crucial for construction safety and lifespan. The phenomena of punching shear, usually appears at the slab-column junction due to concentrated stresses from columns, is a pivotal component that must be addressed. The requirement to improve flat slab punching shear resistance has resulted in the evolution of numerous strengthening techniques. These strategies aim to improve these structural element's load-carrying capacity, ductility, along with overall efficiency. As structures expand to meet greater weights and design demands, the requirement for strong and efficient strengthening techniques becomes increasingly important. Shear bolts, shear studs, externally bonded fiber-reinforced polymer (FRP) sheets, plates, rods, and grids are among the techniques used in strengthening (Haider K. Ammash, Zhen Huang). These methods have been shown to be effective in increasing punching shear capability of flat slab by adding additional flexural and shear reinforcement to the key locations. This reinforcement modifies the stress distribution and fracture propagation patterns, increasing the slab's load-carrying capability and post-cracking behavior.

Studies onto fan-shaped CFRP threads and steel stiffeners by Khaled F. El-Kashifet al. (2019) and Ashraf Mohamed Mahmoud(2015), respectively, showcasing increased punching shear capacity and improved behavior of strengthened flat slabs. Ahmed Ismail El-kassaset al. (2022)examine high-strength self-compacting concrete slabs with steel and basalt fibers, revealing the compatibility of experimental and analytical outcomes. Haider K. Ammash et al.(2022)investigate retrofitting with steel stiffeners, demonstrating improved deformation characteristics and substantial strength enhancements. Further investigations by Zhen Huang et al.(2020) explore CFRP grid-reinforced concrete slabs' punching shear behavior, while M.A.L. Silva et al.(2019) and Haider Hamad Ghayeb et al.(2023) highlight skewed CFRP placement and CFRP strengthening's benefits in terms of load-carrying capacity and behavior under stress. The work by H.S. Mahmoud et al.(2021) focuses on the effect of CFRP on slabs' load-bearing capacity and ductility. Additionally, Mohamed H. Sharaf et al.(2006) assess the performance of externally bonded CFRP strips in preventing punching shear failure. Lastly, Bowen Zheng et al. (2023)employ nonlinear finite element analysis to study punching behavior and slab-column connection influences. Strengthening of flat slab-column connections with stud shear heads, shear bolts and steel FRP, significantly decreased the stress due to shear at failure, resulting in far larger punching failure loads. but for the installation of shear studs and shear bolts the holes need to be driven in the slab column connection, this process will damage the structure, and the steel FRP is susceptible to corrosion when used as strengthening reinforcement.

The list of materials for reinforcing RC structures has lately moved up to include fiber reinforced polymers (FRPs). Fibers and a polymer matrix are combined to create the composite material known as Fiber Reinforced Polymer (FRP) such as CFRP and BFRP. These materials have garnered widespread application in structural strengthening due to their exceptional mechanical qualities. CFRP is excellent for extensively verity of applications due to its high strength-to-weight ratio, which is also corrosion resistance, and flexibility. It is used externally to bond CFRP sheets or strips to strengthen beams, columns, and slabs. BFRP is used in various types of building applications. Its modest weight makes it ideal for architectural aspects. The eco-friendly characteristics of BFRP are compatible with sustainable construction. Its resistance to corrosion, high tensile strength, and longevity help to support robust and creative building methods.

Numerical analysis is critical within structural engineering field for understanding the performance of complex structures under varying loads and situations. It enables precise structural response prediction, which aids in design optimization, safety assessment, and code compliance. Numerical simulations allow researchers to investigate real-world problems that would be impossible to test physically. They make it possible to create unique designs, find cost-effective solutions, and make informed decisions. Furthermore, numerical analysis improves understanding of failure processes, dynamic behavior, and seismic reactions, ensuring that structures are durable and safe. Overall, it speeds up the engineering process, minimizes risk, and advances structural construction and design techniques.Therefore, this study presents the outcomes of NLFEA conducted to investigate the effects of strengthening the flat slabs against punching shear through the employment of Carbon Fiber Reinforced Polymer (CFRP) and Basalt Fiber Reinforced Polymer (BFRP) strips bonding externally.

II. EXPERIMENTAL PROGRAM

For the current experimental study, M20 grade concrete and Fe 550 grade steel, 8mm bars at 100mm c/c (steel percentage 0.87%), were used. Nine slabs designed in accordance with the code IS 456 - 2000 were casted and tested, one serving as the control slab. RCC Flat slabs of size 1300 X 1300 X 80mm were casted.One of total nine slabs is an unstrengthened slab, which is referred to as control specimen. Remaining eight slabs were strengthened with unidirectional CFRP and BFRP fibres.Two specimens were wrapped in orthogonal and skew pattern with CFRP and other two specimens were wrapped in orthogonal and skew pattern with BFRP fabric.Two specimens were wrapped in double layers in skew pattern, each one with CFRP and BFRP and other two specimens were wrapped in double layers in skew pattern with alternate layers of BFRP and CFRP fabric. The outcomes of the experimental study are compared with Analytical results and discussed below.

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Fig 1: Experimental study

Table 1. Designation of specimens used for Analysis

Designation	Description
CS	Control slab
SOC	Strengthened in orthogonal pattern with CFRP fabric
SSC	Strengthened in skew pattern with CFRP fabric
SOB	Strengthened in orthogonal pattern with BFRP fabric
SSB	Strengthened in skew pattern with BFRP fabric
SS2C	Strengthened in skew pattern with 2 layers of CFRP fabric
SS2B	Strengthened in skew pattern with 2 layers of BFRP fabric
SSCB	Strengthened in skew pattern with 1^{st} layer CFRP and 2^{nd} layer BFRP
SSBC	Strengthened in skew pattern with 1^{st} layer BFRP and 2^{nd} layer CFRP

III. FINITE ELEMENT MODELLING

Following are the elements used for the modeling of Flat slabs in ANSYS workbench.

SOLID65

SOLID65 has been used to simulate solids in three dimensions, with or without reinforced bars (rebar). It is a 3-D element that lacks bending (out-of-plane) stiffness but has membrane stiffness in-plane. It is designed for shell structures wherein element bending plays a little role.

In tension, the solid can fracture, and in compression, it can crush. The element's solid capacity, for instance, can be employed to simulate concrete in applications involving concrete, whilst the rebar capability can simulate reinforcing behavior. Additionally, reinforced composites (like fiberglass) and geological materials (like rock) would fall under the umbrella of this element's applicability. Eight nodes that have translation in the node x, y, and z axes at each node make up the element. Rebar requirements may be established in a maximum of three different ways.

The concrete component resembles the 3-D structural solid yet also has unique cracking and crushing properties. The consideration of nonlinear properties of materials is the most crucial part of this component. The concrete can creep, crush, deform plastically, and crack in three orthogonal directions. Rebar can only be stretched or compressed; it cannot be sheared. Additionally, they have the ability to creep and deform plastically.

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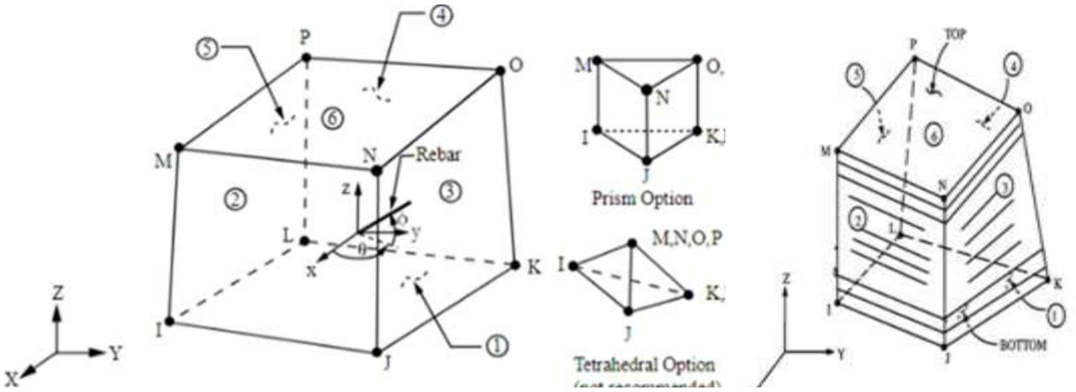
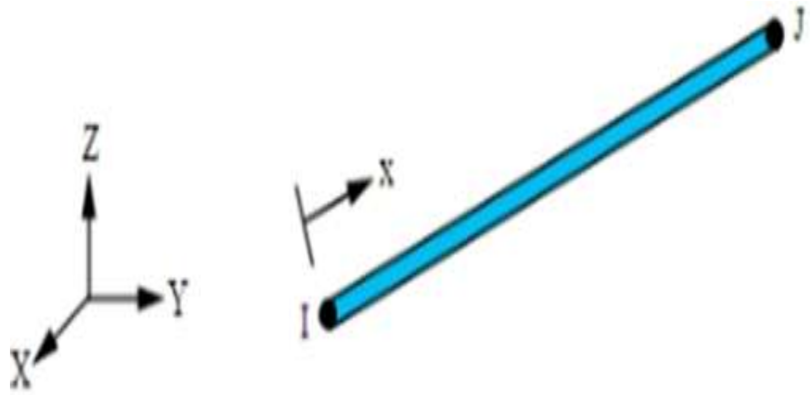


SOLID65 SOLID46



LINK8

Fig 2. Elements used for modelling

LINK8

The Link 8 element has 2 nodes with 3 degrees of freedom each, allowing for translation in the nodal x, y, and z directions. This element is a three-dimensional spar element. Plastic deformation is another property of this substance. Ability to deflect widely also plasticity, creep, swelling, and stress stiffening are included. It takes a nonlinear iterate solution approach to model tension-/compression-only possibilities.

SOLID46

The SOLID46 element is an eight noded element with three degrees of freedom, or translations in the nodal x, y, and z directions, at each of its nodes. Up to 100 distinct material layers with various orientations and orthotropic material qualities are supported by the Solid46 element.

Concrete constitutive model

A built-in concrete model is frequently used to replicate concrete. Williams and Warnke derived this material model. The non-linear behavior of concrete material in relation to tension cracking, compression crushing, and any internal reinforcing plasticity development is taken into consideration by Williams and Warnke's model. Concrete's behavior in the initial case, and prior to the start of the first crack, can be assumed to be linear elastic. After then, and as cracks appear, concrete softens and becomes nonlinear. In the concrete material model, a multi-nonlinear stress-strain curve is frequently created to take this plasticity effect into consideration. The formulas shown below are used to plot such stress-strain graphs.

The ultimate concrete compressive and tensile strengths for each slab model were derived from the elastic modulus obtained by the pulse velocity approach using Equations 1 and 2, respectively.

$$E_c = 5000\sqrt{f_{CK}} \quad \textbf{(1)}$$

$$f_{cr} = 0.7\sqrt{f_{ck}} \quad \textbf{(2)}$$

Where f_{ck}, f_{cr} and E_c are in N/mm2

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The crack face's conditions are represented by the shear transfer coefficient (βt). The value of βt can be between 0.0 and 1.0, with 0.0 indicating a clean fracture (complete loss of shear transfer) and 1.0 indicating a rough fracture (no loss of shear transfer). While most research of reinforced concrete structures used a value of βt between 0.05 and 0.25, this range of values was used in other studies. Convergence problems arose at low loads with βt less than 0.2 in this work's early studies employing a variety of shear transfer coefficient values. Consequently, 0.2 was selected for this study's shear transfer coefficient.

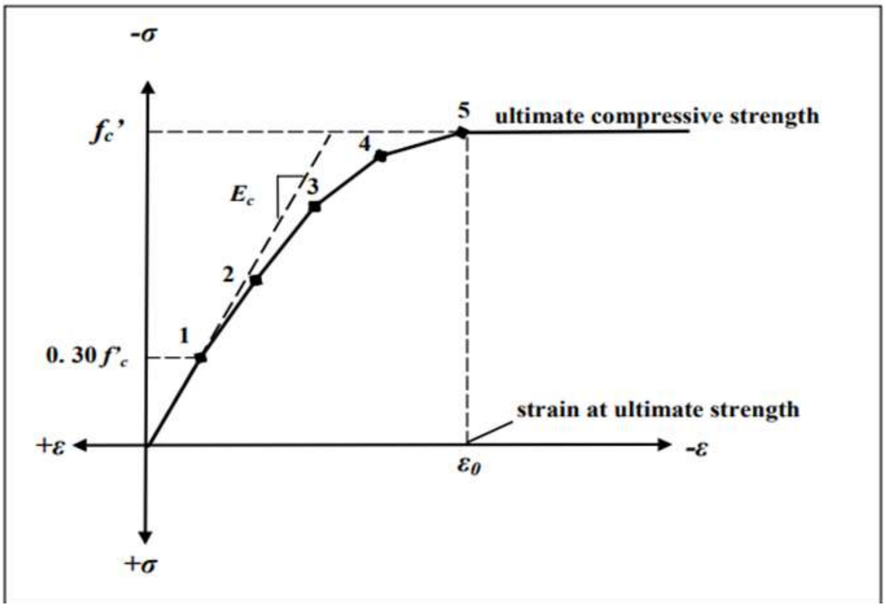

Fig 3. Uniaxial stress-strain curve for concrete (Gere and Timoshenko 1997)

$$f = \frac{E\,\varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon 0}\right)^2} \quad \textbf{(3)}$$

$$\varepsilon_0 = \frac{2f_{ck}}{E_c} \quad \textbf{(4)}$$

$$E_c = \frac{f}{\varepsilon} \quad \textbf{(5)}$$

where: f = stress at any strain ε, N/mm2

ε = strain at stress f

ε_0= strain at the ultimate compressive strength f_{ck}

The condensed stress-strain curve for each slab model consists of six points connected by straight lines. The curve starts at zero stress and strain. Equation 4 is used to calculate Point 1, which has a value of 0.30 fc'. Equation 2 is used to compute Points 2, 3, and 4, and Equation 3 is used to calculate ε_0 as well. The stress for each strain was determined after the selection of the strains. Point 5 is determined at fc' and ε=0.0035, expressing conventional crushing strain for unconfined concrete.

IV. METHODOLOGY

Slab Prototype

The sample specimen illustrating the internal slab-column connections of a flat plate construction was modelled and tested under gravity loadings with the aim of understanding outcomes of the testing phenomena and ultimate load bearing capacity of sample slab. A prototype building plan which is 6 m C/C on both directions was considered. So as to conduct the analysis, flat slabs of (1300 X 1300 X 80) mm dimensions are employed. The slab is reinforced with steel bars of 8 mm diameter spaced 100 mm C/C (Pt=0.87%).

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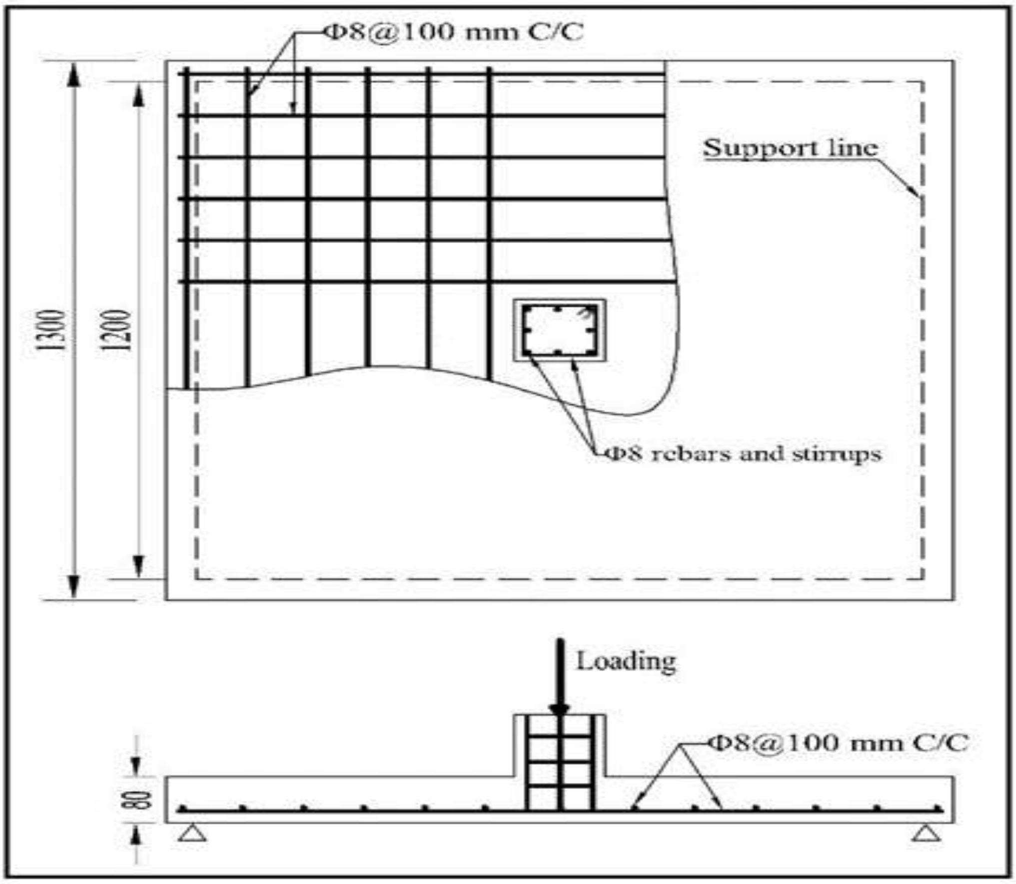
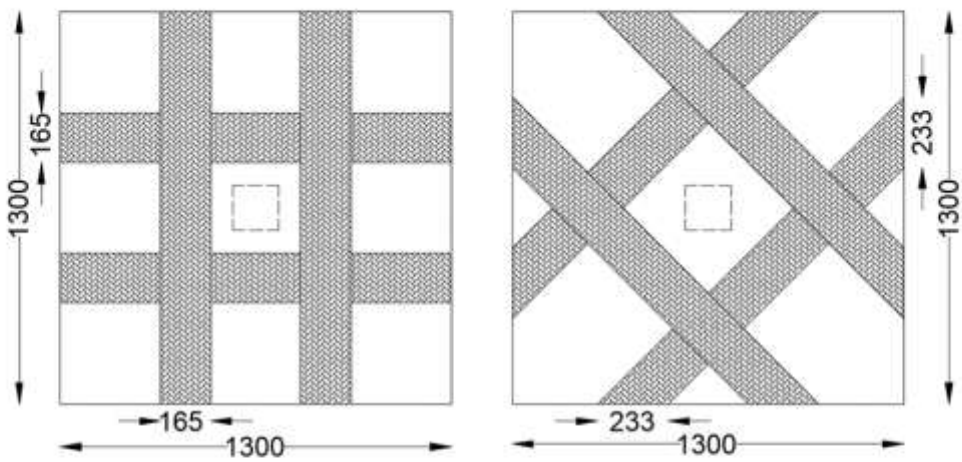


Fig 4. Reinforcement Details of slab-column

Strengthening Orientation

For the Non-linear finite element analysis 9 samples of flat slabs were considered, one of them is control specimen and the remaining specimens are strengthened with various strengthening reinforcement with different orientations. The designation for the proposed flat-slabs are described in Table 1.



(a) (b)

Fig 5. Strengthening orientation; a) Orthogonal; b) Skew

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Materials used

Concrete

M20 grade of concrete is used in current study. SOLID65 element has been used in ANSYS Workbench for defining the concrete material. For the plasticity effect, a multi-nonlinear stress strain curve shown in the Fig 3. is plotted and assigned for concrete material. The properties assigned for concrete material are listed in Table 2.

Table 2. Concrete properties

Properties	
Density (kg/m^3)	2400
Elastic modulus (MPa)	25000
Poisson's ratio	0.18
Ultimate flexural strength (MPa)	3
Ultimate compressive strength (MPa)	20

Table 3. Steel properties

Properties	
Density (kg/m^3)	7850
Elastic modulus (MPa)	210000
Poisson's ratio	0.3
Ultimate tensile strength (MPa)	585
Ultimate yield strength (MPa)	550

Steel

Steel of grade Fe550 is adopted in this study. Steel reinforcing bars with diameter of 8 mm are employing for slab in addition to column stub. The element LINK8 is employed to model the reinforcing steel bars in ANSYS (Fig 2) The properties assigned for the material, steel is listed in Table 3.

CFRP and BFRP fabric

For the modelling of CFRP and BFRP the SOLID46 element is used, since it represents layered element with 3 degrees of freedom (Fig 2).

Adhesive

As a primary coat to make the surface smooth for application of epoxy Nitowrap 30 primer was used. As for epoxy Nitowrap 410 is used for wrapping CFRP fabric. For the modelling of adhesive, the SOLID46 element is used, since it represents layered element with 3 degrees of freedom (Fig 2).

Table 4. CFRP and BFRP Properties

Parameters	BFRP	CFRP
Width of fabric (mm)	500	500
Fabric Thickness (mm)	0.22	0.43
Density (g/cc)	1.9	1.6
Tensile strength (MPa)	2100	4900
Tensile modulus (GPa)	105	250
Elongation (%)	2.6	1.7

Table 5. Adhesive Properties

Nitowrap 30, primer	
Density	1.14 g/cc
Pot life	25 min. @ 27^{0}c
Full cure	7 days
Nitowrap 410, saturant	
Colour	Pale yellow to amber
Application temp	15^{0}c – 40^{0}c
Viscosity	Thixotropic
Density	1.25 – 1.26 g/cc
Pot life	2 hours @ 27^{0}c
Cure time	5 days @ 30^{0}c

V. ANALYSIS OF PROPOSED FLAT SLABS

After defining the material properties, the geometry of proposed flat slab is created in the ANSYS drawing tool, such as space claim and design modeler. The Modelling is carried out in ANSYS Mechanical. Here the geometry is imported and the materials has been assigned, concrete for solid body and steel for reinforcement. The default tetrahedral meshing, coarse size, is provided and the bonded contact, i.e., no moment in normal and tangential directions, between reinforcement and solid body is created. the total load was applied in steps each step being increased by 5kN load. The simple support condition on all four sides is assigned.

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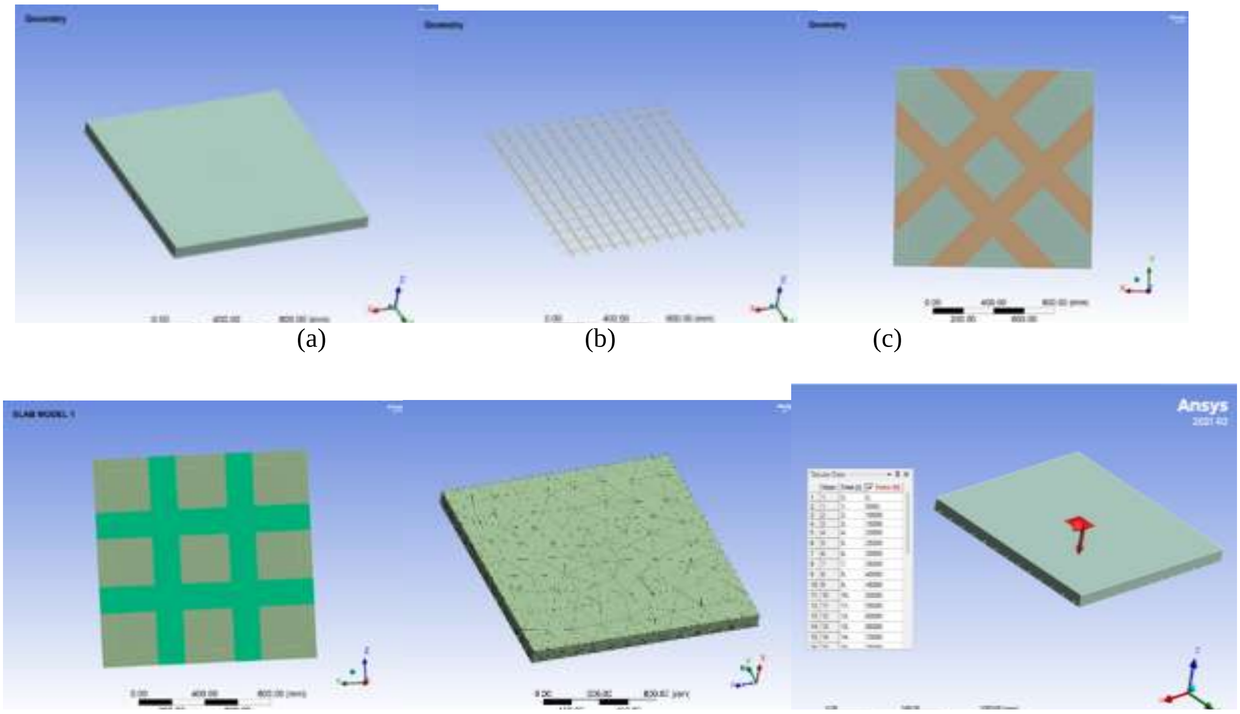

(a) (b) (c)

(d) (e) (f)

Fig 6. Geometry; (a) solid body, (b) Reinforcement, (c) skew wrap, (d) orthogonal wrap, (e) Meshing, (f) load setup

VI. RESULTS

First crack load

The "first crack load" on a load-deflection curve refers to the point on the curve when the structural element encounters its first visible crack or deformation. The onset of structural degradation is indicated by an abrupt change in the slope of the curve. Engineers may precisely detect this first crack load by evaluating the load-deflection curve, which is a critical characteristic for assessing structural integrity and calculating the load-carrying capacity of the element.

Table 6. First crack load data

Slab Designation	First crack load (kN)		V_{exp}/V_{NLFEA}
	Experimental V_{exp}	Analytical V_{NLFEA}	
CS	49	50	0.98
SOC	54	55	0.98
SSC	51	50	1.02
SOB	50	50	1
SSB	45	46	0.97
SS2C	62	60	1.03
SS2B	46	48	0.96
SSCB	43	45	0.95
SSBC	46	47	0.97
COV			0.0274

The load-deflection curve was obtained by analytical study. where there is a sudden change in the slope of the curve, the load corresponds to that point is obtained as the first crack load. From above details it is noticed that, from both experimental and analytical results, the appearance of the initial crack was postponed only by about 5kN in the slabs strengthened by CFRP and BFRP. Therefore, it can be inferred that, use of FRP as strengthening material externally is not much efficient in delaying occurrence of first crack. The analytical outcomes align with the experimental findings with the COV 2.74 percent.

Ultimate load

A non-linear simulation is commonly employed in ANSYS for determining the ultimate load. NLFEA takes into account plastic nature of material, significant deformations, and other elements that may create structural instability as load increases. ANSYS applies load increments progressively during the analysis, and the model's response is computed at each stage.

In ANSYS, force convergence is achieved through iterative calculations. ANSYS begins with an estimate of the displacements and iteratively modifies the nodal position to minimize the difference between the applied loads and reactions. Iterations are repeated until the difference between the imposed loads and the internal reactions becomes small, indicating that the forces have been balanced and force convergence has been accomplished.

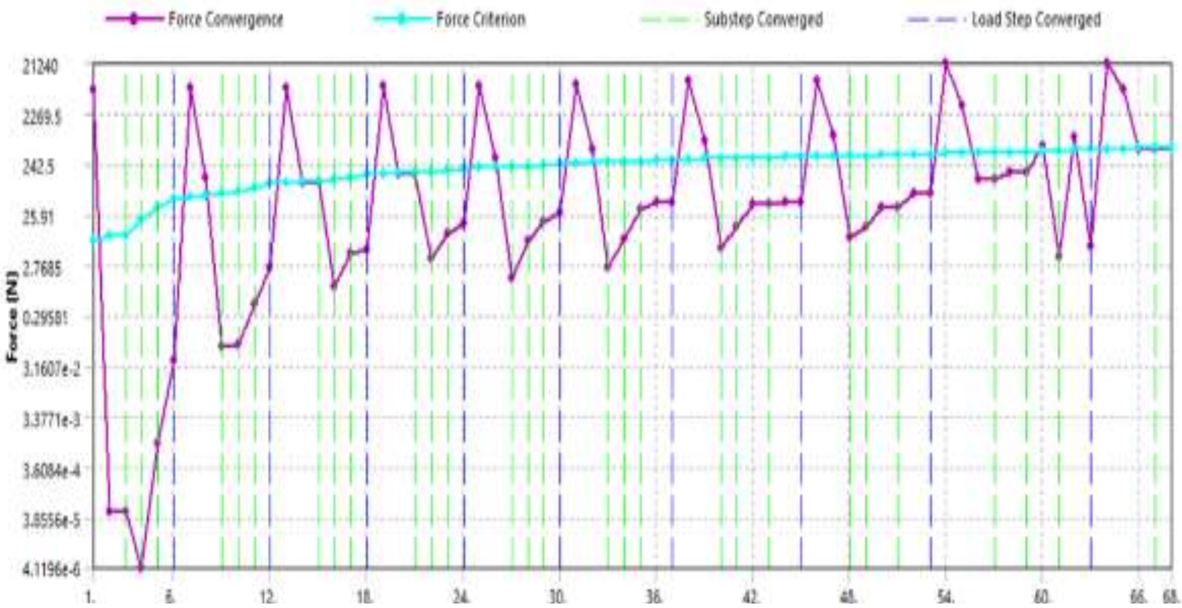

Fig 7. Force convergence

In finite element models, failure or ultimate load is obtained when the solution for a 5kN load increment fails to converge.

Table 7. Ultimate load data

Slab Designation	Ultimate load (kN)		Pu_{exp}/Pu_{NLFEA}
	Experimental Pu_{exp}	Analytical Pu_{NLFEA}	
CS	124	130	0.95
SOC	166	175	0.948
SSC	183	195	0.938
SOB	153	160	0.95
SSB	153	163	0.927
SS2C	198	200	0.99
SS2B	188	195	0.964

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SSCB	165	169	0.976
SSBC	171	176	0.97
COV			0.0181

Load-DeflectionBehavior
The deformation profile of control slab and all strengthened slabs from NLFEA are shown in fig.8

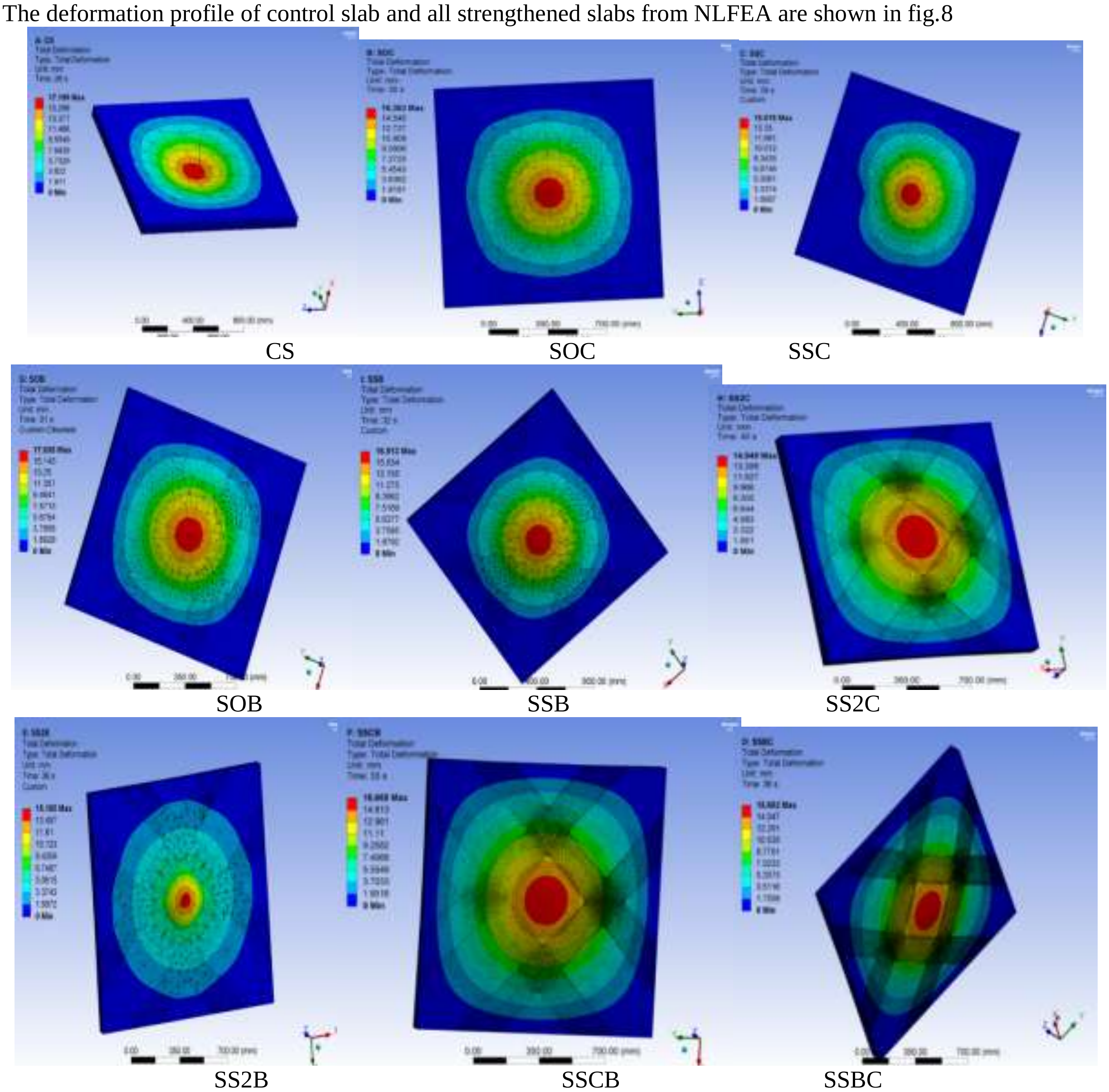

Fig 8. Deformation profile of flat slabs

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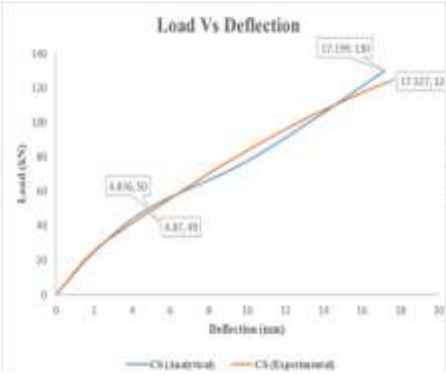
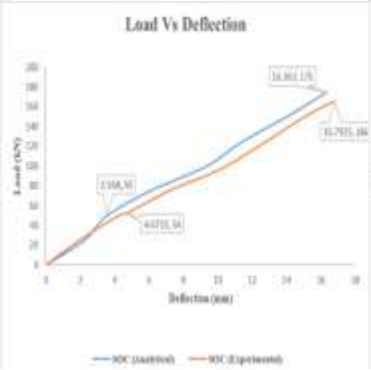
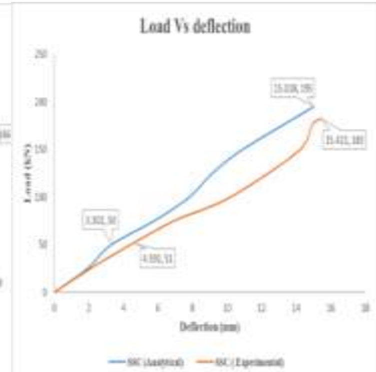


CS

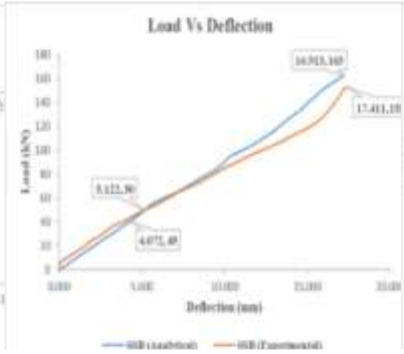


SOC

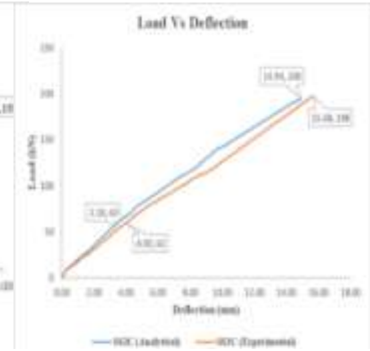


SSC

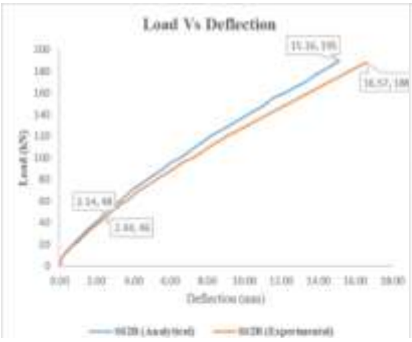
SOB



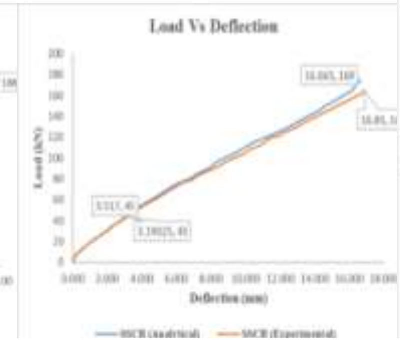
SSB



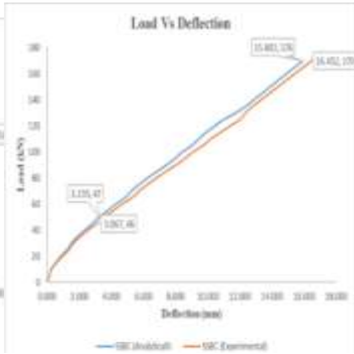
SS2C



SS2B



SSCB



SSBC

Fig 9. Load-Deflection curves

Load-Deflection comparison

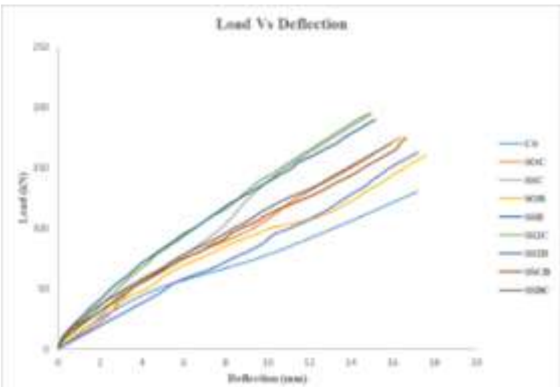


Fig. 10. Comparison of Deflection

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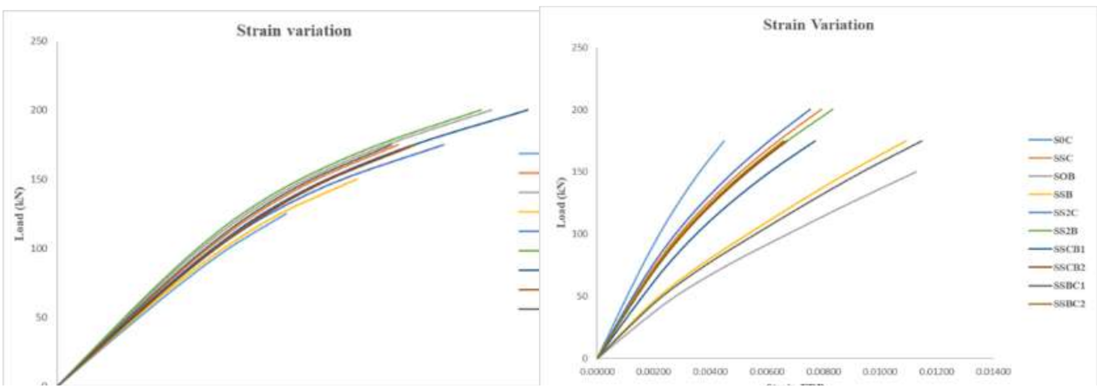
Table 8. Deflection at ultimate load data

Slab designation	Experimental		Analytical		$\Delta_{Exp}/\Delta_{NLFEA}$
	Ultimate load (kN)	Deflection (mm)	Ultimate load (kN)	Deflection (mm)	
CS	124	17.527	130	17.199	1.02
SOC	166	16.792	175	16.363	1.03
SSC	183	15.421	195	15.018	1.03
SOB	153	17.425	160	17.035	1.02
SSB	153	17.411	163	16.913	1.03
SS2C	198	15.68	200	14.94	1.05
SS2B	188	16.57	195	15.185	1.09
SSCB	165	16.85	169	16.665	1.01
SSBC	170	16.452	176	15.802	1.04
COV					0.023

From fig. 10, it is concluded that slabs strengthened with CFRP shows minimum deflection at higher loads. Hence, the application of CFRP strengthening resulted in an increased ultimate load-carrying capacity of the slabs. The specimen SS2C is stiffer in the cracked portion of the curve than other specimens. Therefore, it can be inferred that using double layers of CFRP enhanced the post cracking stiffness. Based on the aforementioned results, it becomes evident that when comparing the experimental and analytical outcomes, both the control and strengthened slabs exhibit a consistent deflection rate per applied load but The ultimate load derived from the NLFEA results is notably higher than that obtained from the experimental data, accompanied by minimal deflection. The correlation/coefficient of variation (COV) between NLFEA results and experimental results was 2.3 percent.

Steel and FRP strain variation in strengthened slabs

The comparison of strain in steel and FRP at applied loads in strengthened slabs and control slab is described in the fig. 11; Here in control slab the strain in steel is more at lower loads but in strengthened slabs the strain in steel is reduced at the same load. This change is occurred due to; the stresses are partially resisted by FRP's used for strengthening. The strain in CFRP is less at ultimate loads compared to that of BFRPbecause the CFRP has the high tensile strength and modulus of elasticity, the strain in steel is greatly reduced compared to BFRP. From the strain profile in figure 11(a), it is evident that in none of the specimens yielding of flexural reinforcement is observed, that shows specimens failed in brittle punching mode. From the strain profile in figure 11(b), it is evident that in none of specimens FRP's reaching their failure strain is observed, that shows specimen's failed in brittle punching mode.



(a) (b)

Fig. 11. Strain variation with strengthening configuration; (a) steel, (b) FRP

VII. CONCLUSIONS

The results of NLFEA of flat slabs strengthened in flexure for punching shear with CFRP and BFRP strips were presented. Total nine slabs were modelled and non-linear simulation is carried out in ANSYS workbench under axial load. Two slabs with CFRP strips, two slabs with BFRP strips, two slabs with double layer of CFRP and BFRP strips and two slabs with alternate layers of CFRP and BFRP strips externally bonded in tension side and one control slab without CFRP/BFRP strips. The test parameters considered were orientation and various types of FRP strips. Namely, Carbon and Basalt fiber reinforced polymer.

The findings of this study can be concluded as follows:

- The enhancement in punching shear strength was there in the strengthened slabs. The enhancement in punching strength was up to 40% by strengthening with CFRP strips.
- The strengthened slabs show more stiffness and lower deflections than that of control slab.
- Increasing number of layers of CFRP did not improve the strength significantly but there was up to 18% strength enhancement in the slab with double layers of BFRP than the single layer of BFRP.
- There was same amount of punching shear strength enhancement was in both strengthened slabs with single layer of CFRP wrapped in skew pattern (SSC) and double layer of BFRP wrapped in skew pattern (SS2B), but SSC is producing minimum deflection at same ultimate load.
- The most efficient and economical configuration for strengthening of flat slab appeared to be single layer CFRP wrapping in skew orientation.
- The strain in steel is reduced when CFRP is used as strengthening reinforcement due to its favourable mechanical properties such as high tensile strength and modulus of elasticity.
- The obtained analytical results were agreeable with experimental results with coefficient of variation of 1.8 to 2.3 percent.

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