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Numerical insights into punching shear of reinforced concrete slabs under concentric uni-axial tensile forces

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Abstract
Punching shear failure in flat slabs is a critical failure mode due to its brittle nature, which can lead to loss of the slab-column connection. However, tensile stresses developed within flat slabs, caused by thermal effect or concrete shrinkage, may influence the punching shear capacity.
The study offers first a literature review on previous experimental studies carried out, showing the different methodologies used in the experimental tests, which have significant effects on the results. Afterwards, a numerical nonlinear finite element model was carried out and validated using ATENA 3D which matches existing experimental data available in the previous studies. The model was used to further investigate the influence of concrete compressive strength on the shear behavior of flat slabs.

Keywords: Punching shear, concrete slabs, flat slabs, axial tension, finite element analysis

1. Introduction

Flat slabs are commonly used in construction as they allow flexible partitioning and maximize the clear height, which is often preferred from an architectural standpoint, depending on the building's purpose. While flat slabs are simple to construct, they are prone to punching shear failure at the slab-column connection, which is a local, brittle failure that redistributes load paths to nearby columns, and potentially may lead to the collapse of the entire structure [1, 2]. As a result, punching shear behavior is a key consideration when designing flat slabs [3, 4].
In some cases, reinforced concrete flat slabs may experience axial stresses due to various reasons. In post-tensioned slabs, the axial compressive stresses arise from the prestressing force, which enhances the punching shear capacity of the slabs [5]. Conversely, the presence of axial tensile stresses due to concrete shrinkage or temperature changes further induces the formation of cracks, leading to a significant reduction in the slab's punching capacity [6]. While being one of the critical failure modes, limited studies investigated the combined effect of punching shear with concentric axial tensile. The design codes also vary in how they consider these axial stresses when calculating the slabs' punching capacity [7, 8, 9].
This study initially examines the impact of axial stresses-both compressive and tensile-on the one-way shear capacity and punching shear strength of concrete slabs, based on existing experimental data from the literature.
Secondly, the study numerically examines the combined impact of axial tensile stresses and punching shear in slabs using ATENA 3D [10], calibrated against Zakaria *et al.* [11] experimental database. After validating the model, the influence of concrete strength on punching shear under uni-axial tensile stresses is analyzed, and the results are presented alongside the conclusions.

2. Literature Review

Over the past several decades, many catastrophic punching shear failures have been documented in the literature as part of efforts to understand the root causes of these sudden collapses. One significant case occurred in January 1971, when two-thirds of a 16-story apartment building under construction collapsed. Investigations revealed that the failure originated from the punching shear of the main roof slab [1]. Another incident took place in March 1997 at the top floor of the Piper's Row car park in Wolverhampton, where an investigation determined that the collapse was caused by punching shear failure at a slab-column connection [2].

More recently, in 2020, a progressive collapse occurred in a parking garage in Santander, Spain. Investigations suggested that the primary cause of the failure was punching shear [12].

When subjected to axial compressive stresses, reinforced concrete elements show a higher one-way shear capacity associated with the delay in cracking caused by axial compressive forces [13]. A relatively high level of compressive stress can lead to brittle crushing in concrete at the compressive zones, so researchers focused on investigating the one-way shear behavior of concrete elements under axial compressive forces.

Gupta and Collins [13] experimentally studied the root cause of that failure with respect to the available design provisions. The study included a comparison between twenty-four reinforced concrete elements with varying axial compressive stress levels against the ACI 318-99 [14] provisions for shear design of reinforced concrete members under combined shear and axial compression. The results revealed deficiencies in the ACI 318-99 [14] provisions for elements subjected to high axial compressive stress levels, which can lead to an unconservative design. Xie *et al.* [15] tested six identical reinforced concrete panels that represent the web regions of concrete walls and girders to investigate the influence of longitudinal reinforcement ratio on the one-way shear strength. The results revealed that the ACI 318-08 [16] simple expression for shear strength calculation of elements subjected to axial compressive stresses showed a good agreement against the experimental results; however, the ACI 318-08 [14] simplified approach showed unconservative results for the specimens under axial tensile stresses.

The partial collapse of the AMC warehouse in August 1955 sparked concerns about assessing the one-way shear behavior of reinforced concrete elements under axial tensile stresses [17]. Many studies investigated the presence of axial tensile stresses which reduces the one-way shear strength of reinforced concrete [15, 17, 18, 19, 20]. Elstner & Hognestad investigated one-way shear strength of concrete beams which experienced 50% reduction under an axial tensile stress of 1.4 MPa. Meanwhile, Jørgensen *et al.* [18] indicated through his experimental study that under low tensile force levels, below 40% of the reinforcement's yield strength, the shear strength remained largely unaffected. However, when the tensile force exceeded 40% of the yield strength, a reduction in shear capacity was observed. Overall, the findings aligned well with the design predictions of Eurocode 2.

Fernàndez-Montes *et al.* [19] carried out an experimental campaign on reinforced concrete T-shaped beams under combined shear forces and axial tension without shear reinforcement. The findings revealed that when the applied tension exceeded 25% of the concrete's tensile strength, the shear capacity decreased by up to 30% compared to the control specimen. Pham *et al.* [20] examined the shear capacity of 15 reinforced concrete beams lacking shear reinforcement while subjected to axial tensile forces. The test results indicated a slight decrease in shear capacity as axial tensile loading increased till 2.5 MPa. This reduction was primarily linked to whether the beam section had fully cracked or remained partially intact.

Although aforementioned studies investigated how axial tensile stresses affect the one-way shear strength of reinforced concrete elements, limited studies focused on axial tensile stresses impact on two-way shear strength (i.e. punching shear). Major international design codes, including EC 2 [7], ACI 318-25 [8], and ECP 203-2020 [9], account for axial stresses in their one-way shear strength provisions. However, only EC 2 [7] considers the effect of axial tensile stress on punching shear strength. Research on punching shear in concrete slabs, with or without shear reinforcement, has mainly focused on prestressed slabs, where axial compressive stresses are introduced through prestressing forces [5].

Ramos *et al.* [6] investigated the influence of compressive membrane forces on the punching shear strength of five prestressed reinforced concrete slabs, using a non-prestressed slab as a reference specimen. The results were compared with the predictions of FIB Model Code 90 [21] and Eurocode 2 [7], revealing that the presence of axial compressive stresses resulted in reduced vertical deflections and lower top reinforcement strain values compared to the reference specimen. The axial compressive forces also delayed the initiation of inclined cracks through the slab thickness. In the reference slab, the first crack appeared at approximately 40% of the ultimate load, whereas in the prestressed slabs, it occurred at 60-70% of their peak load. The observed failure surface angles for the slabs under axial compression ranged between 30° and 35°.

Clément *et al.* [22] conducted tests on 15 specimens measuring 3000 × 3000 mm in plan with a thickness of 250 mm. The specimens were categorized into three series to separately assess the effects of axial forces (N-series), bending moments resulting from prestressing (M-series), and tendon arrangement (P-series). The findings highlighted the substantial influence of prestressing on the punching shear capacity of slabs. Axial compressive forces were found to delay crack formation, resulting in increased capacity compared to the control specimen. However, the most notable enhancement in punching capacity was attributed to the external moment generated by eccentric tendon placement.

Ragab *et al.* [23] experimentally investigated six post-tensioned slabs, two made with normal-strength concrete and four with high-strength concrete, to examine the effect of strand distribution on punching shear behavior. The results indicated an increase in punching capacity by 17% for distributed strand arrangements and by 30% for banded-distributed arrangements. When compared to predictions from various design codes, Eurocode [7] provided good agreement with the experimental outcomes. The study concluded that adjusting the critical punching perimeter from 0.5d to 0.75d (where d is the slab's effective depth) in the ACI 318-08 [16] calculations yields results more consistent with the experimental findings.

Einpaul *et al.* [24] developed a numerical model to investigate the effects of moment redistribution and compressive membrane action on the punching shear strength of continuous reinforced concrete flat slabs around interior columns. The model was validated using selected experimental punching test data from the literature. The results demonstrated that the proposed model provided a closer match to experimental findings compared to the predictions of existing design codes.

Kang *et al.* [25] conducted a study on the two-way shear strength of post-tensioned slabs by applying concentric compressive stresses to specimens with small shear span-to-depth ratios, aiming to quantitatively assess the flexural-shear interaction. The investigated parameters included the quantity and arrangement of post-tensioning reinforcement. The findings revealed a significant increase in punching shear capacity, ranging from 53% to 87% compared to conventionally reinforced concrete slabs, with the concentrated tendon layout resulting in higher capacities than the distributed configuration.

When concrete undergoes volumetric changes in the presence of relatively stiff vertical elements such as stiff columns and retaining walls that offer lateral restraint, concrete slabs can experience axial tensile stresses that simultaneously act with vertical loading. While most of the studies available in the literature were directed to the case where axial compressive stresses act on the slabs to simulate the post-tensioned slabs case, only a few studies tackled the case where concentric axial tensile forces act on the concrete slabs, causing a significant reduction in the punching shear strength of the examined slabs.

These studies were categorized based on the test procedures adopted in experimental investigations. A non-simultaneous loading test is when reinforced concrete slabs are first subjected to axial loading until the targeted concentric tensile force was achieved; afterward, the axial forces were released, and only vertical punching loads were applied till failure. This non-simultaneous loading technique produced inconclusive results, often showing little to no variation in the punching shear strength of the tested specimens [26, 27, 28, 29].

On the other hand, the simultaneous technique of concentric axial tensile forces and vertical loads, where the slabs are first subjected to the targeted concentric axial tensile forces, then kept at the same tension level while subjected to the vertical loading till the punching shear failure occurs [11], [30, 31, 32]. showed a significant reduction in the punching strength of the tested specimens.

J. H. Abrams [26] examined the impact of bi-axial tensile forces on the strength of reinforced concrete slabs by experimentally testing 26 square slabs measuring 1220 × 1220 mm in plan and 150 mm in thickness. The applied concentric axial tensile stresses ranged from 0 to 0.85 f_y, where f_y is the yield strength of the reinforcement used. The study employed a non-simultaneous loading sequence, in which concentric axial tensile forces were applied first to reach the targeted stress level, then released before applying vertical loads until failure. The results indicated a reduction in stiffness due to the presence of bi-axial tensile forces, although no significant decrease was observed at lower tension levels. Johnson and Arnaouti [27] tested three reinforced concrete slabs with a thickness of 90 mm under bi-axial tensile forces, applying tension levels of 0.43 f_y and 0.86 f_y using a non-simultaneous loading procedure. The results showed no significant reduction in the punching shear strength of the specimens under bi-axial tensile stresses. Only a slight decrease in strength was observed in the slab under the higher tension level of 0.86 f_y. White and Gergely investigated the effect of bi-axial tensile forces on the punching shear strength of reinforced concrete slabs using a non-simultaneous loading approach. The study also explored the influence of several parameters, including flexural reinforcement ratio, shear span, and column size. The research aimed to evaluate the punching shear capacity of a reinforced concrete containment vessel wall under internal pressure. The specimens were divided into three groups to isolate the effects of each parameter, with one slab not subjected to concentric axial tension serving as the reference. The findings revealed that punching shear strength increased with higher reinforcement ratios, greater shear spans, and larger column sizes. Moreover, the influence of bi-axial tensile stresses on punching shear strength was found to be dependent on the tension level, becoming significant only when the applied tension approached 0.85 f_y. Ramos *et al.* [6] conducted an experimental study to evaluate the effects of uni-axial and bi-axial tensile and compressive forces on the punching shear strength of thirteen reinforced concrete slabs. The specimens were organized into two series: the AR and BD series. The AR series (AR2 to AR7), with dimensions of 2300 × 2300 mm and a thickness of 100 mm, investigated the influence of axial compressive forces applied either in one direction (AR3 and AR4) or both directions (AR5 to AR7), using AR2 as the control slab. The BD series, with dimensions of 1500 × 1500 mm and a thickness of 125 mm, focused on the effects of uni-axial compressive forces (BD1-BD4) and uni-axial tensile forces (BD5-BD8), applied in a non-simultaneous loading sequence. The uni-axial tensile stresses in the BD series ranged from 0 to 3.95 MPa. The experimental punching shear capacities were compared with predictions from Eurocode 2 (2004), ACI 318-08, and the FIP (1998) recommendations for designing post-tensioned slabs and foundation rafts. The results showed that ACI 318-08 underestimated the punching strength, while Eurocode 2 provided good agreement with the experimental data. The FIP recommendations yielded more consistent predictions but involved greater complexity due to the need to assess the decompression punching force. Hoang [29] studied the punching behavior of concrete slabs under concentric axial tensile forces, focusing on the effect of initial cracking. The slabs were first exposed to uniaxial and biaxial tensile forces using mechanical tensioning until surface cracks developed, reaching widths up to 0.55 mm. After achieving the targeted crack width, the tensile forces were released, and vertical loading was subsequently applied to induce punching failure, following a non-simultaneous loading procedure. The results showed no significant reduction in the punching strength compared with the reference slab.

More recent studies followed the simultaneous loading test of concentric axial tensile forces and vertical load. Fernández *et al.* [30] conducted both experimental and numerical investigations on the punching behavior of five reinforced concrete slabs under concentric uniaxial tensile forces. The specimens measured 1650 × 1650 mm in plan and had a thickness of 120 mm. The study employed a simultaneous loading procedure, in which the slabs were exposed to uniaxial tensile forces and vertical punching loads at the same time. All specimens had a reinforcement ratio of 1.1% (Type A), except for one specimen with a higher reinforcement ratio of 1.9% (Type B), which was included to evaluate the influence of reinforcement ratio on punching shear performance. The applied uniaxial tensile forces in the study ranged from 0 to 1.26 T_{cr}, where

$T_{cr} = A_c\, f_{ct}$ represents the cracking axial load at which the first visible crack appears in the slab. Here, A_c is the cross-sectional area of the slab, and f_{ct} is the concrete's modulus of rupture. Table 1 presents the tested specimens, the corresponding levels of applied axial tension, and the resulting outcomes, which demonstrate a significant reduction in punching strength as the axial tensile force increases. This reduction follows an almost linear trend, reaching a maximum decrease of 28% at an axial tension level of 1.26 T_{cr}, compared to the reference slab. This decrease in punching capacity is also accompanied by a reduction in stiffness. Additionally, the results indicated that increasing the flexural reinforcement ratio in the direction parallel to the applied tensile force (Type B specimen) had no notable effect on enhancing punching strength.

Table 1: Experimental test results, Fernández *et al.* [30].

Test number	Specimen type	T/T_{cr}	Failure load P_u (kN)	$P_u/P_{control}$
1	A	0	249.13	1.00
2	B	0.44	240.4	0.911
3	A	0.69	215.2	0.864
4	A	1.02	198.4	0.796
5	A	1.26	179.4	0.720

Hossam *et al.* [31] tested four reinforced concrete slabs, each with a clear span of 1500 mm in both directions and a thickness of 150 mm. One specimen served as a control slab, while the remaining three were subjected to simultaneous application of concentric axial tensile forces and punching loads. The applied axial tensile stresses ranged from 0 to 3.56 MPa, remaining below the concrete's modulus of rupture ($f_{ct} = 3.78$ MPa). The results showed that when the applied axial tensile stresses remained below the concrete's modulus of rupture, there was no significant reduction in the punching shear capacity of the slabs. Minor variations in capacity were attributed to slight differences in the concrete compressive strengths among the specimens. However, notable differences were observed in the punching shear crack angles. In the direction parallel to the applied axial tensile forces, the crack angles for specimens S1, S2, S3, and S4 were 34°, 29°, 26°, and 24°, respectively. In contrast, the crack angles in the perpendicular direction were 32°, 35°, 38°, and 41°, indicating a clear influence of the axial tensile forces on the failure surface geometry.

Zakaria *et al.* [11] conducted an experimental study to assess the punching behavior of three reinforced concrete slabs under the combined effect of concentric uniaxial tensile forces and vertical punching loads applied simultaneously, along with a fourth specimen serving as a control slab. The specimens were labeled based on the magnitude of the applied axial tension: ST-0 for the control slab, and ST-720, ST-1100, and ST-1300 for slabs under axial tensile forces of 720 kN, 1100 kN, and 1300 kN, respectively. The test procedure involved two stages: first, applying concentric axial tensile forces until the slab cracked at the targeted axial load level; second, maintaining these tensile forces while applying vertical loading until failure. All slabs had plan dimensions of 1500 × 1500 mm and a thickness of 150 mm as shown in Figure I.2.

A significant reduction in flexural stiffness was observed among the tested specimens, ranging from 12% to 57%. Additionally, the maximum decrease in punching shear strength reached 29% in the specimen subjected to an axial tensile force equal to three times the cracking load of the slab cross-section. This highlights the considerable impact of sustained axial tension on both the stiffness and punching capacity of reinforced concrete slabs.

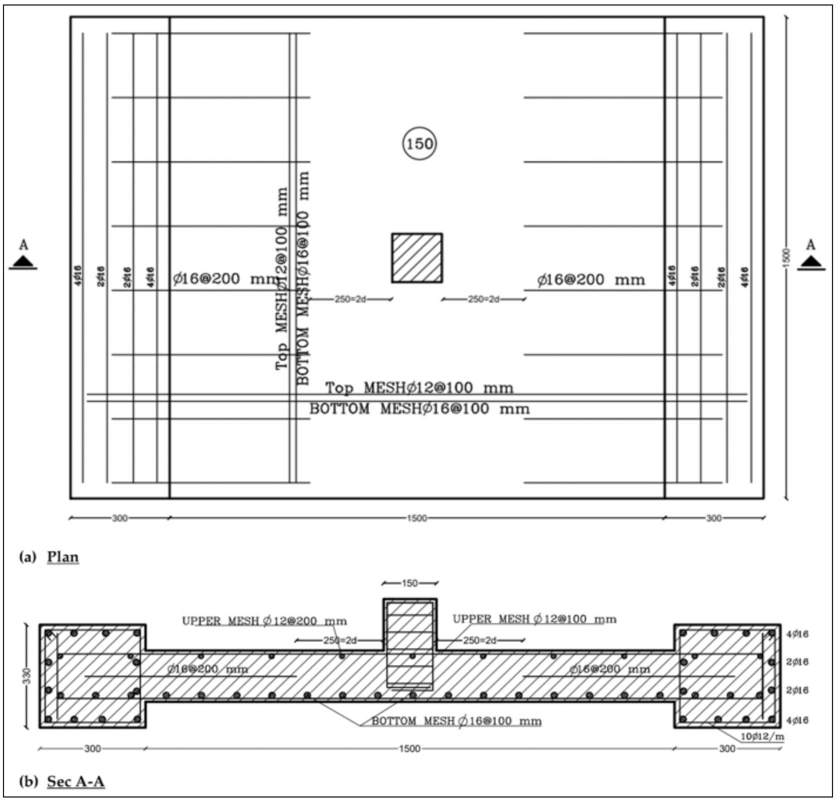


Fig 1: Details of specimens tested by Zakaria et.al [11].

A comprehensive review of the available experimental studies reveals a lack of consensus among researchers regarding the influence of concentric axial tensile stresses on the punching shear strength of reinforced concrete slabs. These inconsistencies are often attributed to differences in the experimental methodologies, particularly the procedure used to apply concentric axial tensile forces during testing. Based on the loading sequence, previous studies can generally be classified into two main categories: non-simultaneous loading and simultaneous loading.

In the non-simultaneous loading approach, the slabs are first subjected to concentric axial tensile forces until a predefined stress level or cracking condition is reached. Following this, the axial tensile forces are released, and only vertical loading is applied to induce punching shear failure. This method simulates scenarios where tensile forces are transient or act independently from the punching load. However, results obtained using this procedure often show little to no reduction in punching shear capacity, leading to ambiguity regarding the true effect of axial tension. Such outcomes may be influenced by the release of tensile forces prior to failure, which does not accurately represent conditions where tensile stresses persist under service or extreme loading.

In contrast, the simultaneous loading procedure involves applying concentric axial tensile forces and vertical punching loads concurrently, with the axial tension maintained throughout the loading process until failure occurs. This method is considered to better reflect real structural behavior, particularly in situations where slabs are subjected to sustained or gradually increasing axial tensile stresses, such as from temperature effects or shrinkage restraint. Studies adopting this approach have more consistently reported reductions in punching shear strength and stiffness, especially as the level of axial tension increases.

Overall, the observed discrepancies in experimental results across the literature underscore the importance of the loading method in accurately assessing the influence of concentric axial tensile forces on punching shear behavior. These findings highlight the need for standardized testing protocols and further research to clarify the role of axial tension in punching shear failure mechanisms.

Although previous studies have demonstrated a notable reduction in the punching shear strength of concrete slabs subjected to concentric axial tensile forces, the scope of experimental findings remains limited due to challenges in applying high levels of tension in laboratory settings. Non-linear finite element analysis (NLFEA) has emerged as a reliable tool for accurately predicting the behavior and strength of reinforced concrete elements under various loading conditions. Given this, there is a clear need to further investigate the punching shear behavior of concrete slabs across a broader range of concentric axial tensile forces.

However, existing experimental studies are confined to relatively low-tension levels. For instance, the highest recorded axial tensile stress reached only 3.25 times the concrete's tensile rupture strength equivalent to 1300 kN in the specimens tested by Zakaria *et al.* [11]. With the growing use of advanced NLFEA techniques, the prediction of punching shear capacity has become increasingly precise, often showing strong agreement with experimental results. Therefore, in the present study, non-linear finite element modeling is employed to both validate and extend the experimental findings of Zakaria *et al.* [11].

3. Non-Linear Finite Element Modeling

A non-linear finite element analysis software ATENA, Cervenka [33] is used to develop a model that simulates the punching shear behvaior and crack development in slab column joints under concentric axial tensile forces. The model was validated against the experimental results reported by Zakaria *et al.* [11], which included a reinforced concrete slab subjected to combined uni-axial tensile forces of 720 kN in addition to the vertical loading, tested in simultaneous loading technique. The specimen size is 1500 × 1500 mm in plan, and a uniform thickness of 150 mm. The model has demonstrated its capability to predict not only the ultimate punching shear capacity but also the evolution of cracking patterns under combined axial and vertical loading conditions.

a. Model Geometry

In this model, the concrete components, including both the slabs and thickened edges, are represented using three-dimensional, 20-node quadratic solid brick elements. These high-order elements are well-suited for capturing the non-linear behavior of concrete, especially in terms of crack initiation, propagation, and post-cracking response.

The reinforcing steel bars are modeled using two-node truss elements, which are embedded within the solid brick elements of the concrete. This embedded reinforcement modeling technique enables the bars to interact directly with the surrounding concrete, effectively transferring forces between the two materials without the need for additional interface elements [33]. To ensure an accurate representation of the reinforcement layout and its interaction with the concrete mesh, the steel bars are automatically subdivided based on their intersection points with the solid concrete elements. This subdivision improves the mesh quality and ensures a more precise simulation of stress transfer and bond behavior along the steel-concrete interface [33].

b. Material Model

In ATENA, concrete is modeled as a 3D non-linear cementitious material, capable of simulating the complex behavior of reinforced concrete under both tensile and compressive stresses [33]. The concrete parameters used in this study, such as compressive strength, tensile strength, and modulus of elasticity, are estimated based on the provisions of ACI 318 [8]. The material model adopted in ATENA characterizes the concrete response through four continuous states that describe its behavior under different loading conditions, as illustrated in Figure 2.

Under tensile loading, the concrete initially follows a linear stress-strain relationship until it reaches its tensile strength, at which point cracking occurs. After cracking, the response transitions into a softening phase, represented by a descending stress-strain curve governed by the crack-opening law, which depends on the concrete's fracture energy [33].

In compression, the model assumes a non-linear hardening branch leading up to the peak compressive strength, reflecting the gradual increase in stiffness and strength due to internal microstructural changes. Beyond this peak, the behavior transitions into a strain-softening phase, simulating the concrete material's post-peak degradation due to crushing. This comprehensive material model allows ATENA to realistically capture the punching shear behavior and cracking evolution of reinforced concrete slabs under the combined action of axial tension and vertical loading.

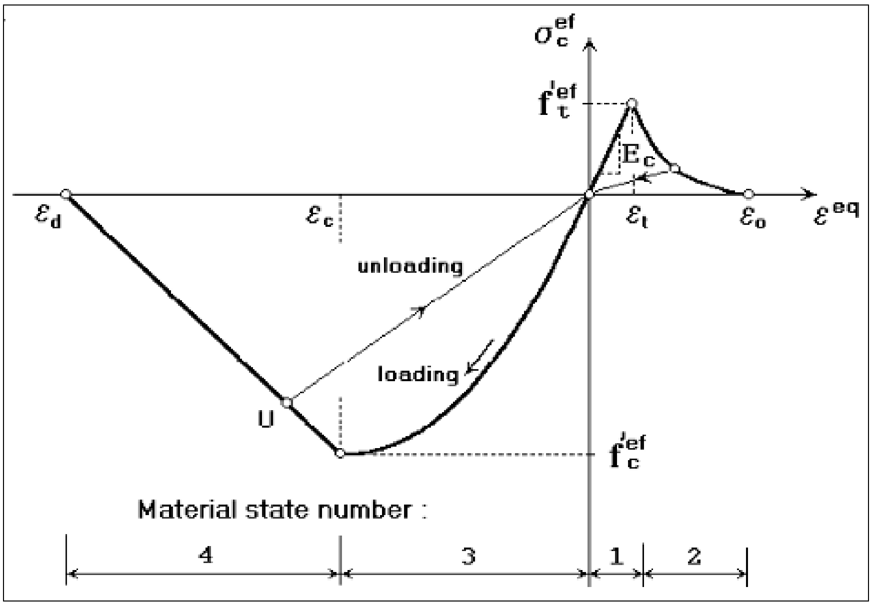


Fig 2: Concrete material uniaxial stress-strain relationship adopted in ATENA 3D [33].

The non-linear finite element concrete material parameters adopted in the presented study are given using the following equations:

$$f_c' = 0.8 f_{cu} \quad (1)$$

$$f_t = 0.56\sqrt{f_c'} \quad (2)$$

$$E_c = 4700\sqrt{f_c'} \quad (3)$$

$$f_{cm} = f_c' + 8\ Mpa \quad (4)$$

$$G_f = 73 f_{cm}^{\ 0.18} \quad (5)$$

Where:

f_c' : is the concrete compressive cylindrical strength at 28 days (MPa).

f_t : is the concrete tensile strength (MPa).

f_{cm} : is the concrete mean compressive strength as per CEB-FIB 2010 [34] (MPa).

E_c : is the Concrete young's modulus before cracking (MPa).

G_f : is fracture energy of concrete used in crack opening law as per CEB-FIP 2010 [34] (N/m).

As for reinforcement bars, they are represented as discrete elements using 2-node truss elements with "CC Reinforcement" material [33]. The reinforcement material behavior is modeled using a bilinear stress-strain relationship with strain hardening, as illustrated in Figure 4, to accurately reflect the mechanical properties of the B500DWR steel bars used in the experimental specimens tested by Zakaria *et al.* [11]. This bilinear model captures the initial elastic response followed by a linear hardening branch beyond the yield point, allowing for a realistic simulation of reinforcement behavior under increasing tensile loads.

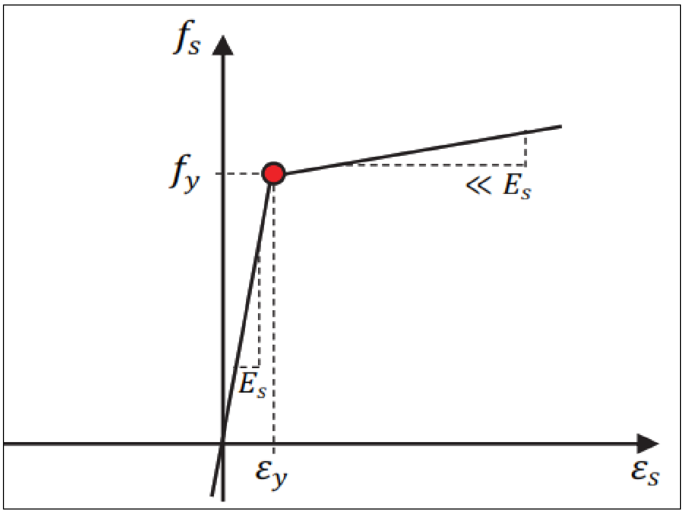


Fig 3: Reinforcement stress-strain law adopted in ATENA 3D [33].

The loading column and the steel support frame used to apply boundary and loading conditions to the concrete slabs are modeled in ATENA using a 3D elastic isotropic material. To accurately represent the mechanical properties of structural steel and eliminate any undesirable local deformation, a Young's modulus of 200,000 MPa and a Poisson's ratio of 0.3 are assigned. This idealization assumes purely elastic behavior for the steel components throughout the analysis, as their deformation is minimal compared to that of the concrete slabs and does not significantly influence the punching shear behavior being investigated.

In the numerical model, vertical loading is applied using a displacement-controlled approach with a predefined increment of 0.1 mm, applied at the center of the loading column. This method allows for controlled and stable simulation of the punching shear behavior, particularly near the peak and post-peak response.

The concentric tensile stresses are introduced by applying axial tensile forces directly to the reinforcement bars (T16 @ 200 mm) positioned at the mid-height of the slab, as shown in Figure 5. These bars are extended into the adjacent beams connected to the slab edges to ensure the development of uniform axial tensile stresses across the slab. This setup replicates the experimental configuration used by Zakaria *et al.* [11] enabling a realistic simulation of the combined effect of axial tension and punching shear on the structural response of the slab.

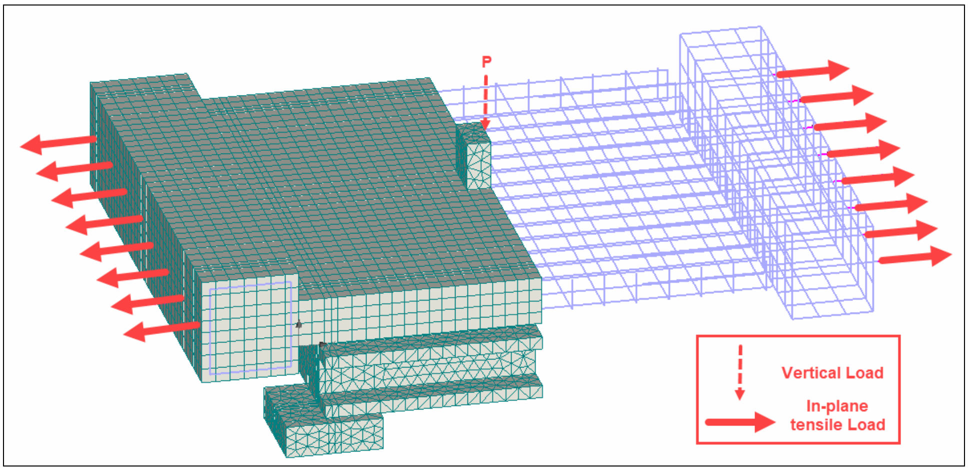


Fig 4: ATENA 3D numerical model.

The boundary conditions assigned in the finite element models are carefully defined to replicate the actual setup used in the experimental program conducted by Zakaria *et al.* [11]. In the numerical model, the steel supporting frame rests on four supporting pads, consistent with the experimental configuration.

To ensure structural stability and accurate representation of the experimental conditions, the bottom surfaces of all supporting pads are fully restrained against translation in the x, y, and z directions. This constraint prevents any undesired movement or rotation of the support system during loading and allows for a reliable simulation of the real boundary conditions imposed in the laboratory tests as shown in Figure 6.

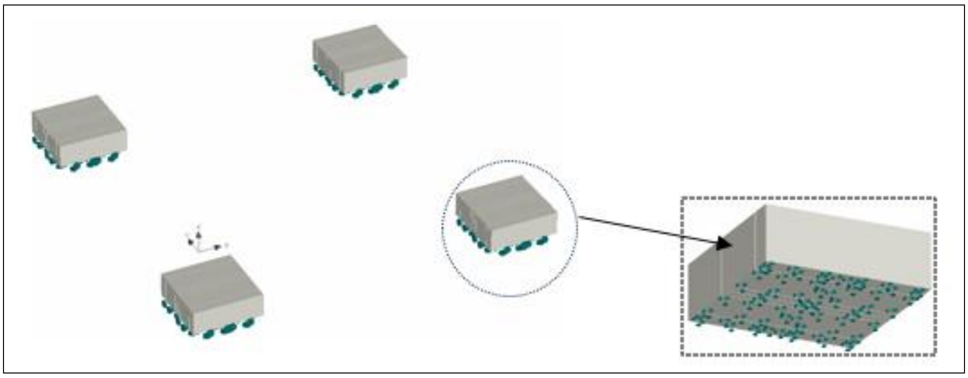


Fig 5: Boundary conditions in the ATENA 3D model.

4. Modeling Verification

In order to expand the experimental results and gain more understanding of the punching shear behavior of concrete slabs under concentric axial tensile forces, the developed non-linear finite element model is validated against the experimental specimen tested by Zakaria *et al.* [11] that was subjected to concentric axial tensile force of 720 kN "ST-720", using key response parameters including the failure load, mid-span deflections, and crack pattern observed in the experimental study. The comparison between the numerical and experimental results confirms the model's ability to accurately replicate the punching shear behavior of reinforced concrete slabs subjected to concentric axial tensile forces. This validation ensures that the model can be reliably used to investigate further the structural response under various levels of axial tension beyond those tested experimentally.

Figure 6 presents a comparison between the experimental and numerical load-displacement responses of the specimen ST-720. The experimental failure load was recorded as 315.5 kN [11], while the numerically predicted failure load using the ATENA model was 305.3 kN, indicating a small deviation of approximately 2%. In terms of vertical displacement at failure, the experimental and numerical values were 8.6 mm and 8.83 mm, respectively, with a deviation of around 7%.

Furthermore, as illustrated in Figure 7, there is a good agreement in the cracking pattern between the experimental observations and the ATENA simulation. The model accurately captured the crack propagation and distribution, particularly around the punching zone, demonstrating the reliability of the non-linear finite element approach in simulating both the strength and failure mechanisms of reinforced concrete slabs under axial tension and vertical loading.

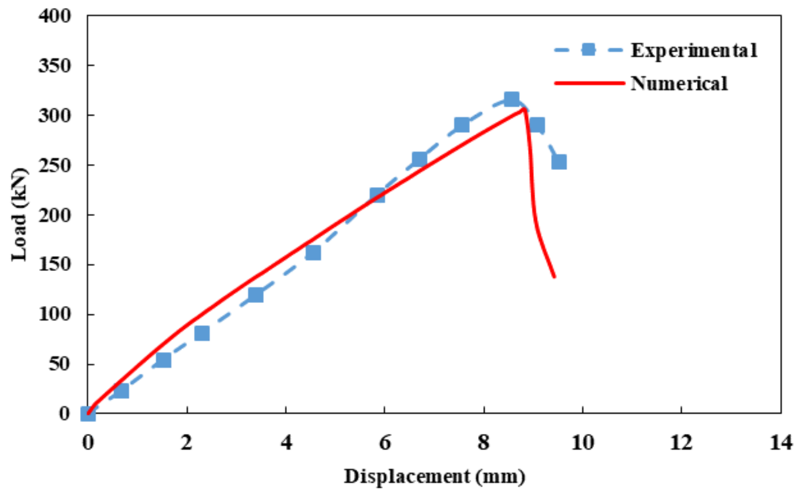


Fig 6: Load-displacement relationship comparison between experimental and numerical results for specimen ST-720.

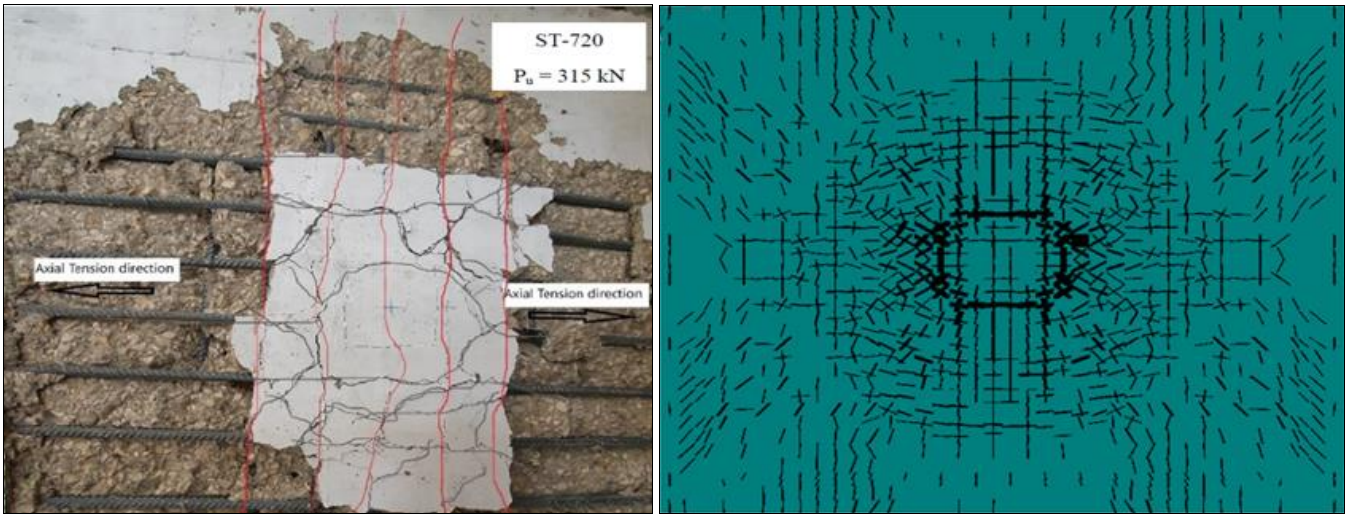


Fig 7: Crack pattern comparison between the experimental and numerical results for specimen ST-720.

The comparison between the experimental data and the results obtained from the non-linear finite element analysis demonstrates the strong predictive capability of the developed ATENA 3D numerical model, particularly in simulating the punching shear strength of the ST-720 specimen. With a deviation of only 2% between the predicted and experimentally observed failure loads, the model shows good accuracy in capturing the key response parameters of the reinforced concrete slab under the combined action of vertical loading and concentric axial tensile forces. This level of agreement validates the use of ATENA 3D as a reliable and robust tool for simulating the complex behavior of reinforced concrete elements subjected to such loading conditions.

5. Effect of Concrete Strength

The presented results of the induced non-linear finite element model using ATENA 3D shows an accurate prediction of the punching shear behavior of reinforced concrete slabs subjected to concentric uni-axial tensile forces. The comparison between the numerical results obtained using ATENA 3D and the experimental data provided by Zakaria et.al [11] In terms of the punching failure load and the cracking development showed that the proposed model can be used to investigate the non-addressed parameters in the experimental results.

Concrete compressive strength is pivotal in determining the punching shear capacity of reinforced concrete slabs. Increasing concrete strength generally enhances the slab's ability to resist punching failure due to its improved shear stress capacity around the column perimeter. However, this effect may diminish at higher strength levels, especially when interacting with other factors such as in-plane forces. This section examines the influence of concrete strength on punching behavior using calibrated numerical models.

Figure 7 shows the effect of increasing the concrete cubic characteristic strength on the punching capacity of concrete slabs subjected to in-plane tensile forces. This study compares how increasing the concrete compressive strength (f_{cu}) affects the punching shear capacity of reinforced concrete slabs subjected to different levels of axial tensile forces, represented by the Level of Tension (LoT), which represents the in-plane tensile stress acting on the slab as a percentage of the concrete modulus of rupture ($LoT = \frac{f_{in-plane}}{f_t}$). To make the comparison more straightforward, the punching capacity at $f_{cu} = 25\ MPa$ is used as a reference for each LoT level, and the percentage increases are calculated accordingly.

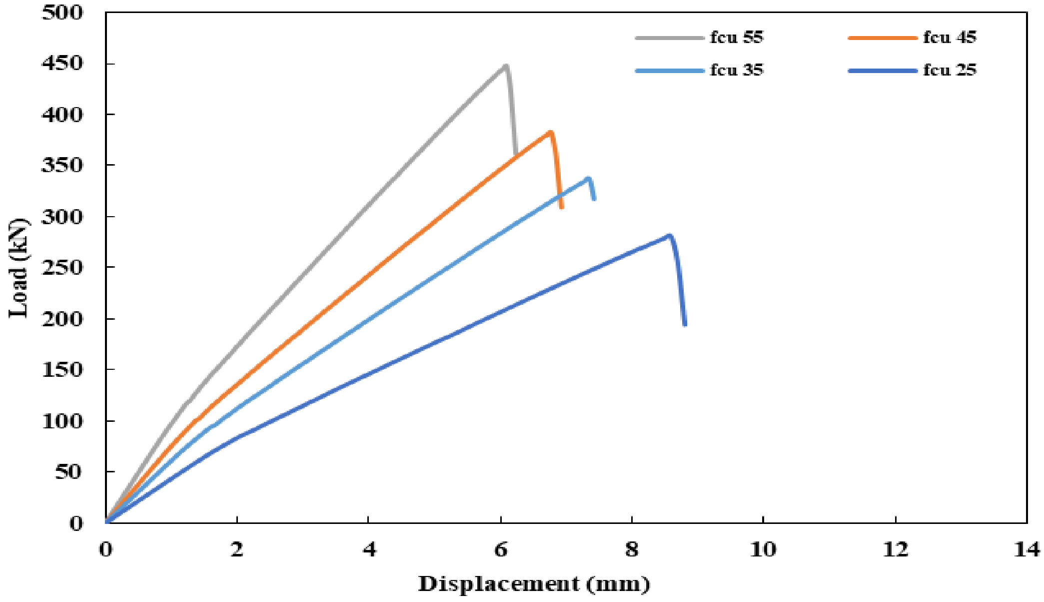
At LoT 1 (low axial tension), increasing fcu from 25 MPa to 55 MPa led to a 59.4% increase in punching capacity. At 35 MPa and 45 MPa, the increases were 20.1% and 36.2%, respectively, showing a strong positive effect of concrete strength under low tension.

For LoT 2, the increase reached 70.2% at 55 MPa, with intermediate gains of 28.3% and 54.5% at 35 MPa and 45 MPa. This confirms that higher concrete strength significantly improves resistance, even at moderate tension levels.

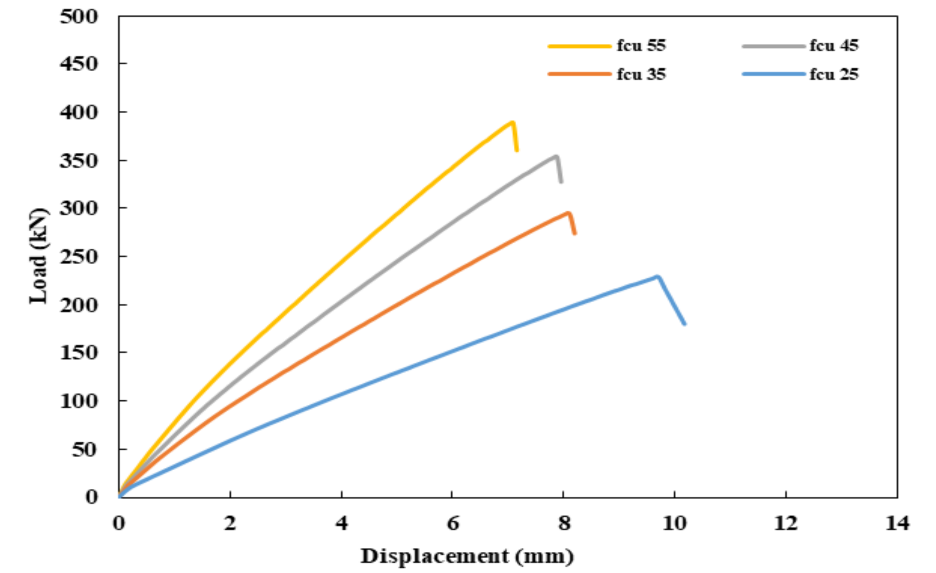
At LoT 3, the improvements were 16.1%, 36.1%, and 59.3%, respectively, indicating that the benefit of higher concrete strength continues under higher axial tension.

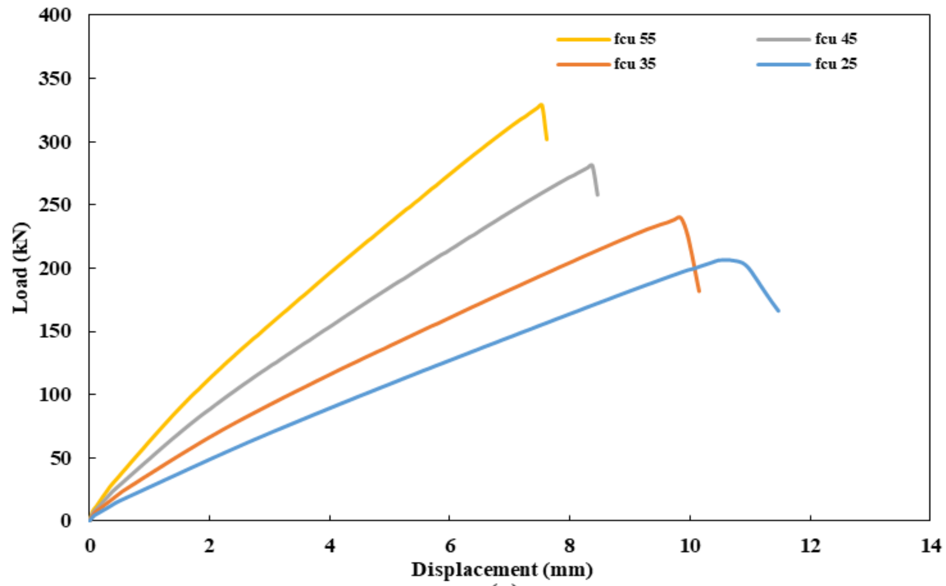
At higher tension levels (LoT 4 and LoT 5), although the overall punching capacities were lower due to the increased axial forces, the effect of increasing f_{cu} was still noticeable. For LoT 4, the gains were 14.3%, 26.6%, and 36.5%, and for LoT 5, they were 15.5%, 28.0%, and 47.3% at 35 MPa, 45 MPa, and 55 MPa, respectively.

These results clearly show that increasing concrete strength is an effective way to reduce the negative impact of axial tensile forces on punching shear performance, especially at low, and moderate levels of tension, however, at high levels of tension, the increase in the punching strength becomes less significant at higher concrete grades.



(a)


fcu 55
fcu 45
fcu 35
fcu 25
Load (kN)
Displacement (mm)
0
50
100
150
200
250
300
350
400
450
500
0
2
4
6
8
10
12
14
(b)


fcu 55
fcu 45
fcu 35
fcu 25
Load (kN)
Displacement (mm)
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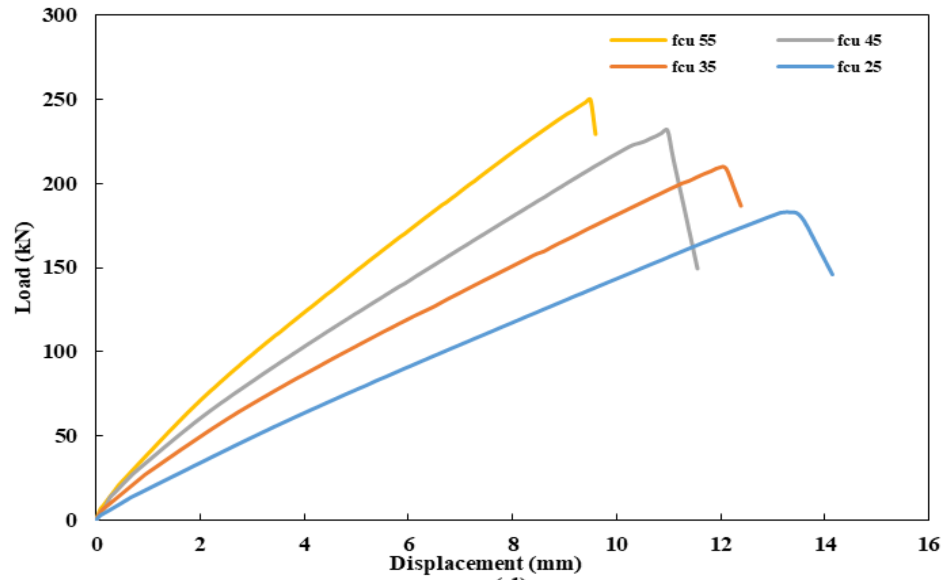
12
14
(c)


fcu 55
fcu 45
fcu 35
fcu 25
Load (kN)
Displacement (mm)
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50
100
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300
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2
4
6
8
10
12
14
16
(d)

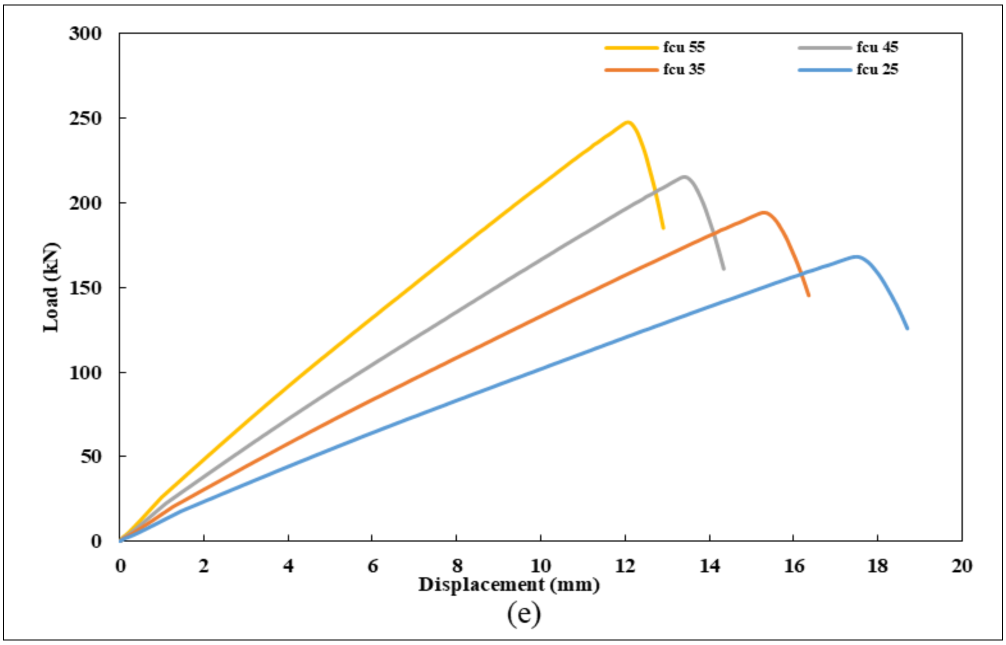

Fig 8: Load-displacement for specimens under: (a) LoT=1, (b) LoT=2, (c) LoT=3, (d) LoT=4, and (e) LoT=5.

6. Conclusion

A non-linear finite element model was developed using ATENA 3D and validated against experimental data from Zakaria *et al.* [11] for a slab subjected to 720 kN axial tension (ST-720), showing high accuracy with only 2% deviation in punching capacity. The model successfully predicted crack propagation, failure mode, and load-displacement behavior, confirming its reliability in capturing the complex interaction between axial tension and punching shear failure.

A parametric study showed that increasing the concrete compressive strength significantly enhances punching capacity, especially under low to moderate axial tension:

- At LoT 1, increasing strength from 25 MPa to 55 MPa resulted in a 59.4% increase in capacity.
- At LoT 2 and 3, similar enhancements were observed, confirming the positive impact of concrete strength.
- At LoT 4 and 5, the gains became less pronounced, indicating diminishing returns at higher tension levels.
- These results highlight the importance of considering both concrete strength and axial tensile force level when designing for punching shear in flat slabs.

Future work will include

- Investigating the numerical model capability against more experimental data.
- Studying the effects of other parameters (e.g., slab thickness, and column rectangularity ratio).
- Developing modified or simplified design equations for slabs under combined axial tension and vertical loads.
- Investigating serviceability behavior (e.g., crack width, stiffness degradation) under axial tension.

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