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Finite Element-based Optimization of Shear-Strengthening Strategies for I-Shaped RC Beams using Hybrid Materials and Plate Reinforcement

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Abstract

This study investigates the shear-strengthening performance of I-shaped reinforced concrete (RC) beams using advanced materials and external steel plate configurations through nonlinear finite element modeling (FEM) in ANSYS. Three shear enhancement techniques were evaluated: high-strength concrete (HSC), steel fiber-reinforced concrete (SFRC), and externally bonded steel plates of different configurations (full-length, vertical, inclined). The FEM models were validated against experimental results with a deviation of less than 2%, demonstrating excellent predictive accuracy. Results reveal that inclined and full-length steel plates achieved the greatest improvement in shear capacity of up to 22% compared to control specimens. In comparison, SFRC provided a comparable 17.5% increase, while offering additional advantages such as improved durability and corrosion resistance. Additionally, the influence of web material replacement on crack propagation and load redistribution was examined. This study provides a comprehensive comparison of shear-strengthening methods and offers practical insights into effective retrofit strategies for existing RC structures under increased service demands.

INTRODUCTION

Long-span and prestressed concrete structures often use I-shaped beams. The broad flange not only enables the development of a strong compressive force but also optimizes the arm of the internally coupled by placing the product of the compressive stress close to the compressive surface [1]. By removing as little concrete as possible from the strain zone, where only steel reinforcement can effectively bear tension, less dead weight is created, allowing for the construction of smaller, lighter members [2,3]. The I-shaped cross's thin web also better carries shear stress [4–6].

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The maximum shear strength of beams without shear reinforcement (stirrups) can be significantly increased, according to experimental research, by incorporating steel fibers into the concrete [7–9]. The quantity of fibers (fiber volume fraction Vf), fiber aspect ratio (Lf/Df), and bond conditions for the steel fibers all affect the increase in shear strength owing to the fibers. After cracks develop, the fibers continue to bridge the cracks and sustain high stresses until they either fracture or are pulled out from the concrete matrix.

The mechanism behind the shear failure in beams is naturally complex to comprehend. Multiple methods and theories for the design of beams under shear stress have been developed and proposed by scholars over the past decade. However, these theories were still considered to be unable to fully explain the behavior and mechanism of shear failure [10]. Shear failures are generally sudden and brittle because internal forces are not distributed within the member, underscoring the need to ensure proper design of shear capacity in beams [11]. Moreover, Silva et al., [12] has concurred and discussed that shear cracking in general is more complex and relatively compared it with flexural cracking and noted that the complication of the shear cracking is due to the direction of the shear crack on the stirrups which is not perpendicular on the stirrups as a result of observing the impact of "compressive stress in concretes since longitudinal reinforcement proportion, kind of stirrup, side concrete's cover, stirrup proportion and pre-stress" on the cracking width by shear on I-Shaped beams. Furthermore, as mentioned previously, numerous experiments and studies have been published to enhance the performance of RC beams with various shapes. Adhikary et al., [13] explored the use of steel plates horizontally on Rectangular RC beams, bonding them to the web with epoxy-bonded cementitious material. The experiment included two control RC beams and 10 beams with bonded steel beams on their webs. The experiment utilized the finite element method (FEM) for the analysis. The beams shear strength with steel plates has increased significantly, reaching 84% of that of the RC beams with no plates. The plate's thickness and depth were primary factors that influenced the enhancement of the beams shear strength, with a proportional relationship. Another strengthening method of beams is to add Fiber Reinforced Polymer (FRP) sheets and wrap them around the structural member to increase its performance [14].

Buildings may be designed with fewer sections and longer spans using high-strength concrete, which also reduces dead weight [15]. Additionally, prior research demonstrates that steel fiber concrete and high-strength concrete could be utilized to enhance shear strength and bending moment capacity. Most experimental studies have recommended substituting the entire depth of RC beams with high-strength concrete or SFRC, with a focus on rectangular-section beams.

Mhanna et al., [11] investigated the possibility of increasing the T-beams and rectangular beams with Carbon Fiber Reinforced Polymer (CFRP) shear strength. Two methods of wrapping were considered: U-Wrapping and fully wrapping. It was concluded that ideally for the increment of beam shear strength is to fully wrap it with the CRFP sheets with an increase of maximum percentage of 201.63% depending on the profile of the beam, however in some situations the fully wrapping becomes impractical due to physical obstructions imposed from the existing structure, thus U-wrapping would be the only solution with a risk of the sheet being de-bonded as the tests demonstrated the fragility of sheets under the brittle mode of beams when it is not completely wrapped. Others have investigated shear strength and behavior enhancement in other shapes of reinforced beams, such as I-beams. Hasgul et al. [16] explored the use of steel fibers and their impact on the flexural and shear behavior of ultra-high-performance concrete I-shaped beams. A total of four beams were cast for the tests, with shear and flexural parameters including curvature ductility, deflection, failure mode, cracking pattern, and load–deflection response. Also, two of the beams were cast without fibers to observe the performance difference between them. The tests showed that steel fibers could substitute shear reinforcement in I-shaped beams, as observed in the transformation of shear failure into flexural failure. In general, there is a lack of literature on studies examining the influence of beam shapes beyond two on beam performance and the recommended enhancement methods for each shape.

High-strength steel (HSS) with a yield stress of 685 MPa or more and high-strength concrete (HSC) with a compressive strength of more than 70 MPa may be used to minimize member section size and concrete volume, and to reduce the number of steel bars, for the total building structure [17]. Because the HSC also has a reduced water-to-cementitious materials ratio, the durability of concrete may be increased [18]. Nevertheless, when concrete's compressive strength rises, it becomes more brittle, necessitating additional transverse reinforcement [18,19]. Concrete's ductile behavior may be improved by using short, discontinuous steel fibers as an alternate material [18,20]. According to earlier studies [21–23], adding steel fibers to concrete beams may improve shear resistance, toughness, encourage flexural failure, and increase ductility in addition to perhaps serving as a replacement for traditional shear reinforcement.

Additionally, the steel fibers are randomly oriented, which improves resistance to crack opening and bridges microcracks in the matrix [24]. A crucial factor in the bridging function and in the generation of higher tensile strength during fracture is the shear stress at the interface between the steel fibers and the surrounding matrix (the bond strength between steel fibers and matrix). Once the steel fibers in the concrete break or are removed entirely, the concrete collapses.

There are few research investigations on high-strength steel fiber-reinforced concrete (SFRC) beams with HSS longitudinal bars, despite the benefits of using steel fibers as reinforcement in concrete beams. To thoroughly characterize the factors influencing the maximum shear strength of the SFRC beams, the general behavior of SFRC beams is provided in a review of the literature.

The steel fibers serve a function comparable to shear reinforcement in transversally reinforced concrete beams, as stated by Dinh [25]. Steel fibers are useful for managing fractures, promoting the formation of numerous diagonal cracks, and redistributing tensile stress. They also limit the spread and opening of diagonal cracks. The steel fibers may also prevent early concrete cracking along the tensile reinforcing bar, like shear reinforcement. The shear strength calculations for an SFRC beam encounter several difficulties, as it is recognized that the orientation and distribution of steel fibers in concrete may not be adequately controlled due to potential segregation and fiber balling. The most significant problem with steel fiber reinforcement in an SFRC member is the optimal distribution of steel fibers to enhance mechanical characteristics. In contrast to typical concrete, the large diagonal fissures in an SFRC beam are caused by fiber withdrawal rather than shear reinforcement giving way.

Additionally, a difficult issue remains regarding the pullout behavior of steel fibers and the binding strength between steel fibers and concrete [25]. The beam cross-section (shape and size), ratio of shear span to effective depth, tensile reinforcement proportion, concrete's compressive strength, size of coarse aggregate, fiber volume fraction, and the bond stress between steel fibers and the surrounding matrix all have an impact on the shear behavior of a simply-supported SFRC beam subject to two-point concentrated and monotonic loads. The shear span/effective depth, the longitudinal tensile reinforcement proportion, the concrete's compressive strength, the fiber volume fraction, and the bond stress between the surrounding matrix and steel fibers appear to be the variables most frequently considered when calculating SFRC ultimate shear stress.

According to earlier research, the shear span/effective depth proportion significantly affects the final shear strength of the SFRC. When a beam with a short shear span forms an arch, the load is transferred directly from the loading point to the support via a compressive strut. Batson et al. suggested a crucial value of a shear span-to-effective depth ratio of 3 for the SFRC beams in 1972, according to Dinh [26].

Objectives

The shear behavior of hybrid-reinforcement I-beams is simulated using ANSYS finite-element models; however, the web is constructed of concrete that differs from the compression and tension flange concretes. The concrete has been modeled using 3D nonlinear brick elements (solid elements), whereas the steel reinforcement has been modeled using a discrete bar element. Parametric research was conducted to evaluate the impact of using external web steel plates on the shear behavior of hybrid-reinforced concrete I-beams by assessing the ultimate shear force and shear force-deflection graph using existing experimental data [27]. Along the shear span, three distinct kinds of beams with various configurations have been bonded to the sides of the beam webs.

FINITE ELEMENT MODEL

Element Types

The concretes SFRC, HSC, and NSC are modelled in ANSYS using a nonlinear 3D brick element (SOLID 65). There are eight nodes in the solid elements, each with three components and translations in the nodal z, y, and x directions. The steel reinforcing was modelled in ANSYS using a discrete axial element (LINK180). These elements require two nodes; each node has three degrees of freedom, like those of the brick elements. To minimize stress concentration issues and localized crush of concrete elements at the supporting points, and loading application sites, a (4 cm) thick steel plate modeled in ANSYS utilizing (SOLID 185) is placed at the support and under the loading positions. There are eight nodes in the element, each with three degrees of freedom and translation in the z, y, and x directions. [28]

Material Properties

Concrete

Table 1 demonstrates the numerical values for the concrete elements of the modelled beams. In the ANSYS program, the input data for the concrete properties are introduced as follows:

- Uniaxial crushing stress $f'c$: taken from experimental data.
- Uniaxial cracking stress f_t: can be calculated from the modulus of rupture test, $f_t = 0.7\sqrt{f'c}$ [29].
- Modulus of elasticity E_c: taken from experimental data.
- Poisson's ratio υ =0.2 for all modelled beams.
- Shear transfer coefficient $\beta_o = 0.1$ and β_c=0.4.
- Compressive stress-strain curve: it is based on the multilinear isotropic hardening model by using the following equations [30],

$$f'c = \frac{\varepsilon\, Ec}{1+\left(\varepsilon/\varepsilon_0\right)^2} \quad \text{for} \quad \varepsilon_1 \le \varepsilon \le \varepsilon_0 \tag{1}$$

$$E_c = \frac{\sigma}{\varepsilon} \quad \text{for} \quad 0 \le \varepsilon \le \varepsilon_1 \tag{2}$$

$$\varepsilon_0 = \frac{2 * f'c}{E_c} \tag{3}$$

$$\varepsilon_1 = \frac{0.3 * f'c}{E_c} \tag{4}$$

Where:

ε = strain

ε_0 = strain corresponding to $f'c$ ultimate compressive strength

σ = stress, MPa

ε_1=strain corresponding to (0.3 $f'c$)

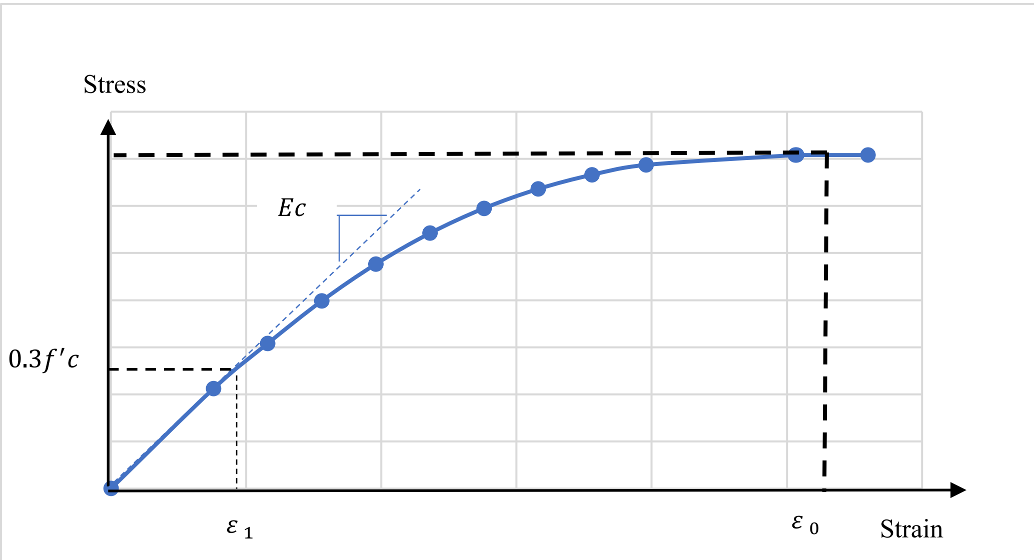

Figure 1. Simplified Compressive Uniaxial Stress–Strain Curve of Concretes in Tension, The Stress-Strain Curve has been Presumed to be Linear-Elastic up to Concrete Cracking [31]

Table 1. The Numerical Values for Concrete Element

	Concrete type: Lower and Upper Flange	Concrete type: Web	$f'c$ (MPa)	f_t (MPa)	E_c (MPa)
NSC	NSC	NSC	41	4.48	30094.7
HSC		HSC	71.2	5.9	34914.2
SFRC		SFRC	44.2	4.65	31793.7

Steel Reinforcement and Steel Plates

The plastic-elastic behavior with strain hardening was modeled as a bilinear curve using the Von Mises yield criterion for steel. As illustrated in Fig. 2, this relationship is expected to be similar in tension and compression. The strain hardening modulus (ET) has been estimated to be in this study (0.03 Es). This magnitude was used to prevent convergence issues during iteration. It is believed that the steel plates are linearly elastic. The plates and steel reinforcement have a Poisson's proportion of (0.3) and an elastic modulus of (200GPa). For all the modelled beams, the (Ø16mm) and (Ø10mm) longitudinal steel bar yield strengths are (596.8MPa) and (532.78MPa) respectively, and for (Ø3mm) and (Ø5mm) stirrups, the steel bar yield strength is (230MPa).

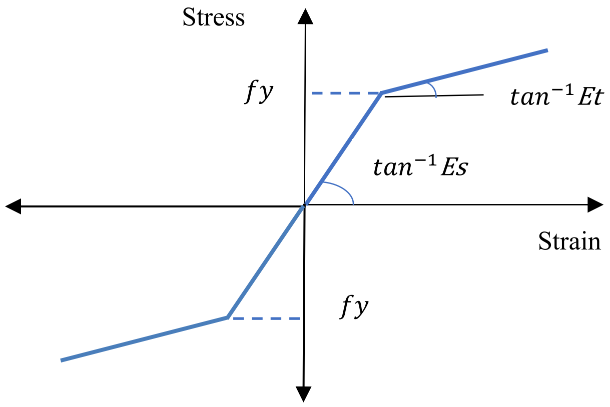

Figure 2. Modelling of Reinforcing Bars

Case Study

The beam specimens, tested in accordance with the procedure reported in [27], were simply supported over an effective span length of 1400 mm and subjected to a two-point loading configuration. The spacing between the applied loads was maintained at a constant distance of 260 mm to ensure a uniform bending moment region between the loading points. The geometric characteristics and actual dimensions of the tested beams are schematically illustrated in Figure 3.

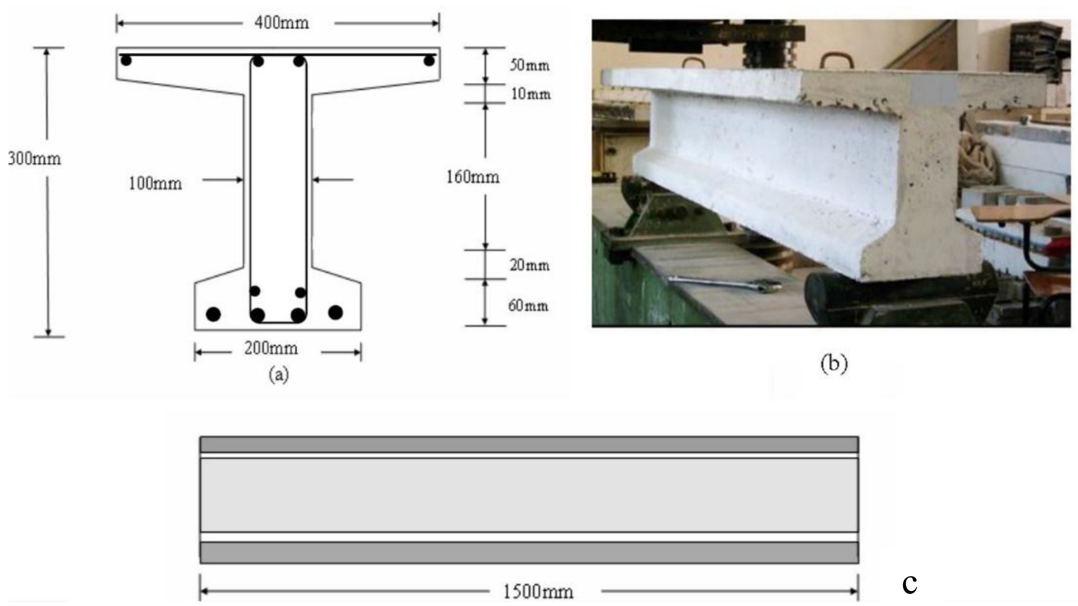

Figure 3. Details of Test Beams: a) Beam Cross-Section; (b) Isometric View; and (c) Side View [27]

Meshing, Boundary Conditions, and Loading

Half of the total beam model has been utilized for finite elements modeling, taking advantage of the symmetry of both geometries and loadings. Just one load plate and one support plate have been required due to symmetry. Volumes are used to represent the beams, plates, and supports (solid elements). The chosen model uses shear reinforcing (stirrups) and longitudinal reinforcing (tensile strengthening) as connection components. The mesh is built in such a way that rectangular or square components are produced (Figure 4).

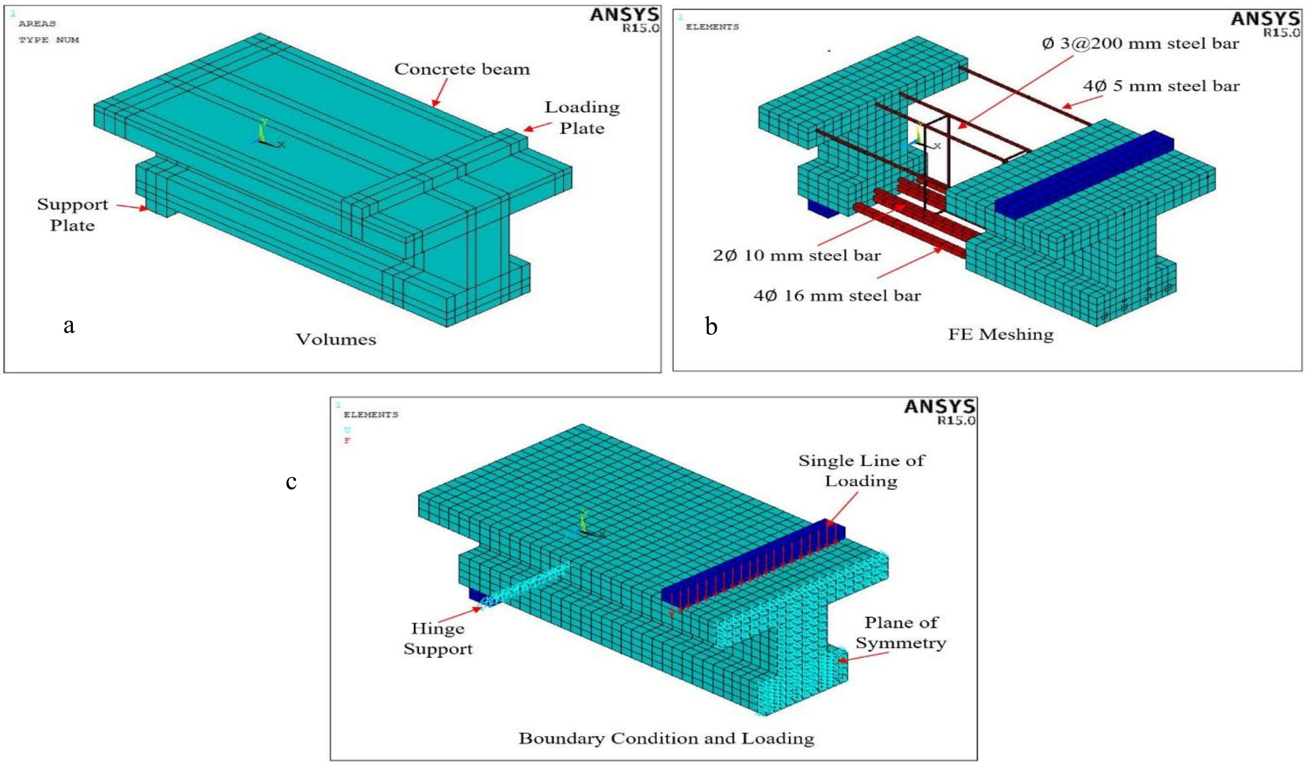

Figure 4. a) Modelling; b) FE Meshing; c) Boundary Conditions and Loading of the Modelled Beams

FINITE ELEMENT RESULTS

Load Deflection Curve

The shear force obtained by experimental work [27] and that forecasted by the finite element model are demonstrated in Table 2 and plotted in Figures 5-7. The finite element model is in good agreement with the experimental results over the entire range of behavior and shows that the maximum difference in ultimate shear force is 2%.

Table 2. The Difference between the Finite Element and the Experimental Ultimate Shear Force

Beams	Experimental Shear force $V_{u\,exp}$, kN	FE shear force $V_{u\,FE}$, kN	$\left\lvert\frac{V_u\,exp - V_u\,FE}{V_u\,exp}\right\rvert$
NSC	104	106	1.9%
HSC	119.5	122	2%
SFRC	130.5	130	0.38%

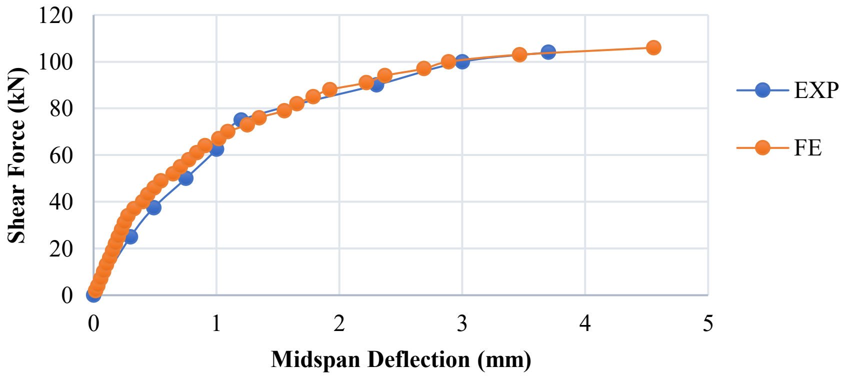

Figure 5. Experimental and Forecasted Shear Force-Deflection Curve for NSC Beams

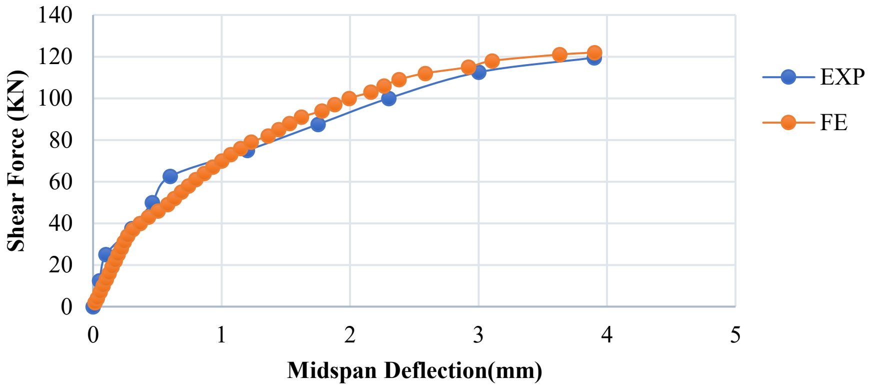

Figure 6. Experimental and Forecasted Shear Force-Deflection Curve for HSC Beams

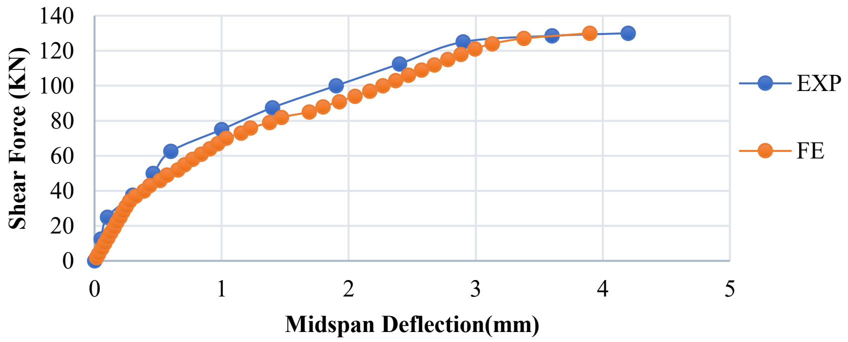

Figure 7. Experimental and Forecasted Shear Force-Deflection Curve for SFRC Beams

Parametric Study

In this study, the normal-strength concrete I beam has been used as a control beam to demonstrate the effect of using steel plates on the ultimate shear force and midspan deflection. The I beam was strengthened by modelling steel plates (shell63 element) [28] on both sides of the beam web with different shapes along the shear span. The thickness of all steel plates was 2 mm. The plate's geometry is demonstrated in Figure 8. Table 3 showed a difference in shear force between the control beam and the strengthening beam with steel plates.

The highest enhancement was observed in the inclined steel plate configuration, achieving a 22% increase in peak shear strength compared to the control, which was followed closely by the full-length plate configuration [32], with a 20.5% increase, and vertical plate reinforcement, with a 17.3% increase. In contrast, the SFRC-infilled beam recorded a 17.5% gain, nearly matching the performance of vertical plate strengthening, while the HSC-filled web exhibited a 12.8% improvement. These findings suggest that while plate-based strategies offer higher shear capacity, SFRC provides a competitive alternative with added durability and crack resistance benefits.

The ultimate shear strength of the reinforced beams was compared to that of the reference (controlling) beam (NSC), and the shear force at collapse (Vu) was listed in Table 3. The beams' shear strengths (B-F-P), (B-Sh-P), (B-2-P), (B-6-P), (B-P-O), and (B-Inc-P) increased (22%, 19%, 11%, 14%, 0.02% and 19%), respectively. The application of steel plates can also improve the beam's stiffness, as demonstrated in Figures 9-14. Up to the yielding point, the reinforced beam behaved similarly to the controlling beam; both beams reached yielding with almost the same stiffness and deformation under the same loading. Once steel plates have been utilized beyond their yielding points (for the same loading condition), deflection decreases, and this behavior becomes more apparent as the load level rises.

There is no tangible improvement in shear strength and stiffness for the beam strengthened with steel plates with openings (B-P-O), and the shear force-midspan deflection curve is almost identical to that of the control beam.

Beyond peak strength, the energy absorption capacity (area under the load–deflection curve) was assessed as a ductility indicator. SFRC-infilled beams exhibited the highest energy absorption, indicating superior post-peak behavior and crack-bridging ability, attributed to fiber interlock mechanisms. Full and inclined plate configurations, although offering higher initial shear strength, demonstrated a more brittle failure with limited post-peak deformation capacity. These findings are illustrated in Figure 9.

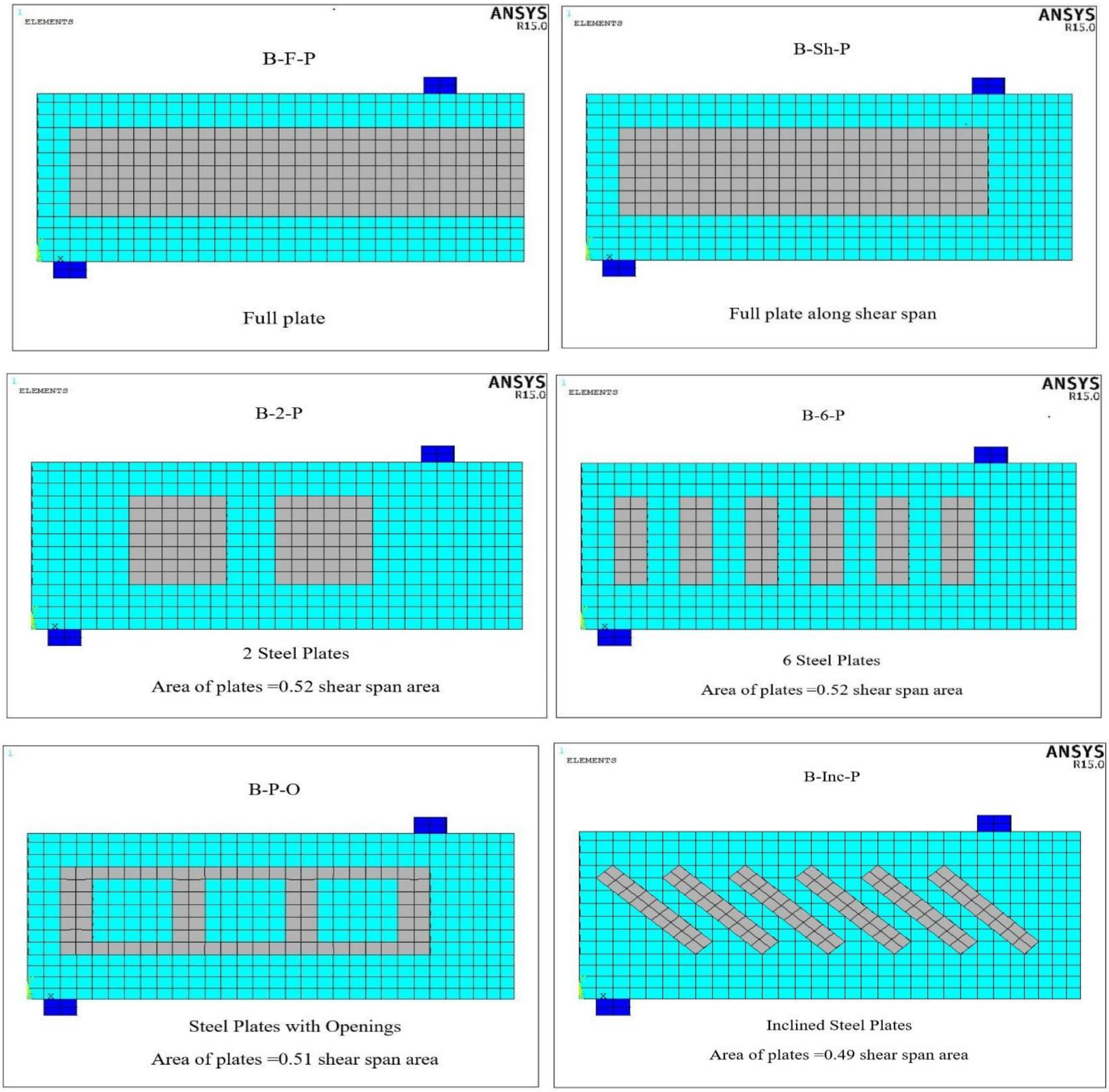

Figure 8. The Geometry of the Steel Plates is Modelled in ANSYS

Table 3. A Compression between the Shear Force of the Control Beam and the Strengthened Beam with Steel Plates

Beam	ID	V_u, KN	$\frac{V_u\ strengthening - V_u\ control}{V_u\ control}$
NSC (Control)	Control	106	
Beam-full steel plates	B-F-P	130	22%
Beam-shear span steel plates	B-Sh-P	127	19%
Beam-2 steel plates (Area=0.52 shear span area)	B-2-P	118	11%
Beam- 6 steel plates (Area=0.52 shear span area)	B-6-P	121	14%
Beam-steel plates with openings (Area=0.51 shear span area)	B-P-O	108	0.02%
Beam-inclined steel plates (Area=0.49 shear span area)	B-Inc-P	127	19%

As demonstrated in Figure 15, Strengthened beams (B-Sh-P), which had shear span steel plates, and (B-Inc-P), which had inclined steel plates, demonstrated approximately the same shear force-midspan deflection.

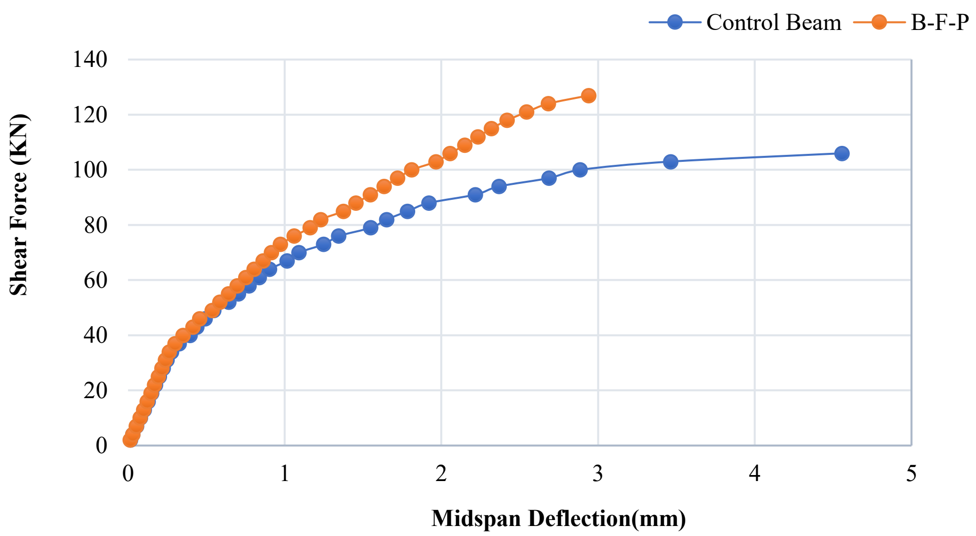

Figure 9. Shear Force-Midspan Deflection Curves for Concrete I Beams and a Strengthened Beam by a Full Plate

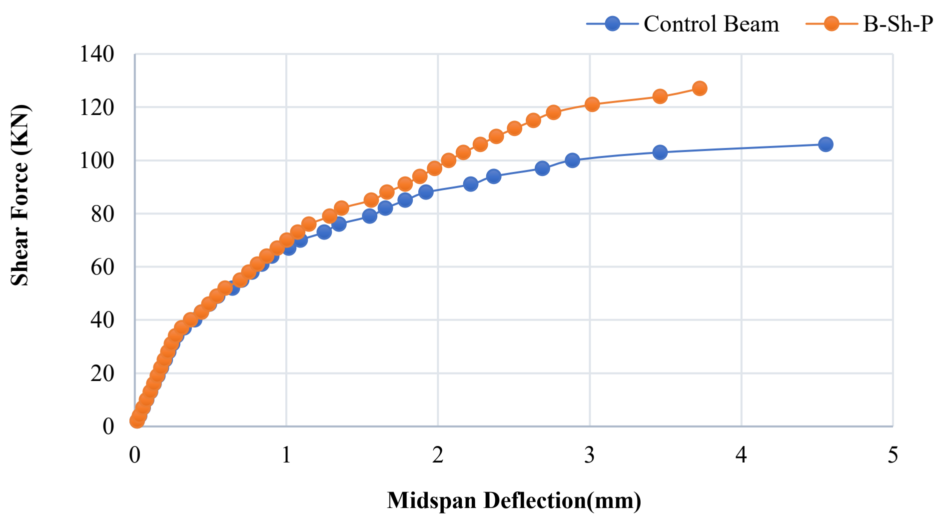

Figure 10. Shear Force-Midspan Deflection Curves for Concrete I Beams and a Strengthened Beam by a Full Plate along the Shear Span

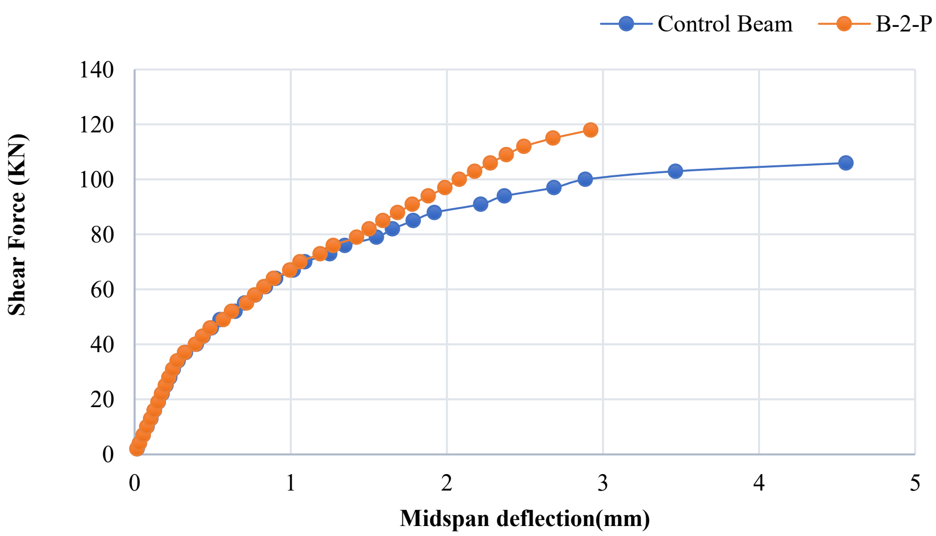

Figure 11. Shear Force-Midspan Deflection Curves for Concrete I Beams and a Strengthened Beam by Two Sheet Plates

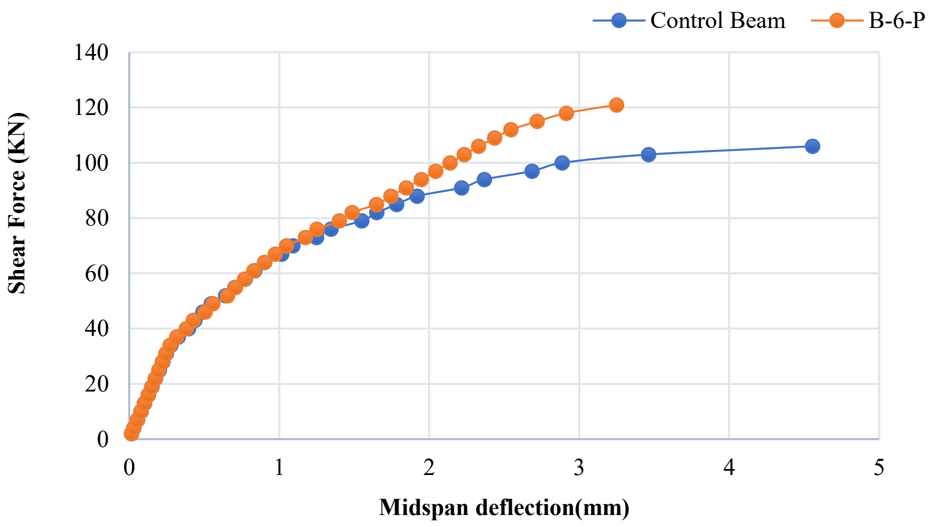

Figure 12. Shear Force-Midspan Deflection Curves for Concrete I Beams and a Strengthened Beam by Six Sheet Plates

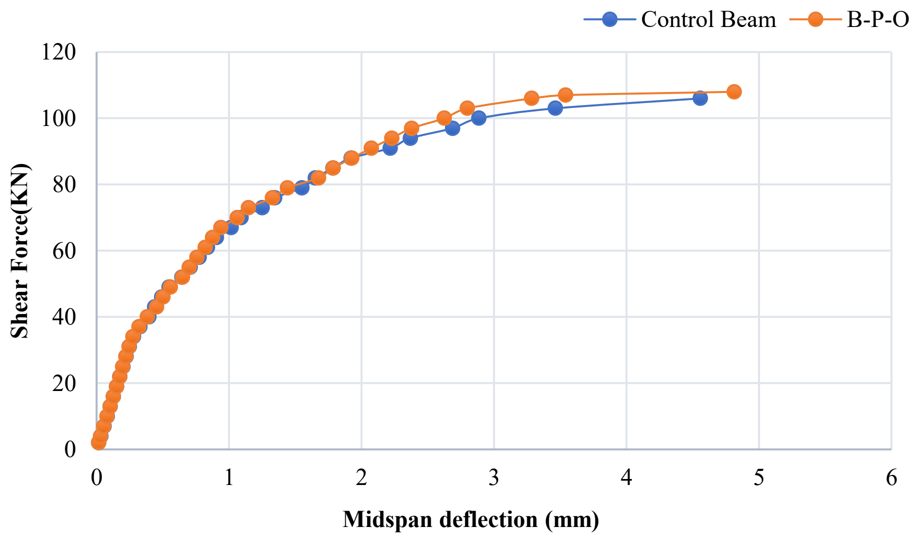

Figure 13. Shear Force-Midspan Deflection Curves for Concrete I Beams and a Strengthened Beam by Steel Plates with an Opening

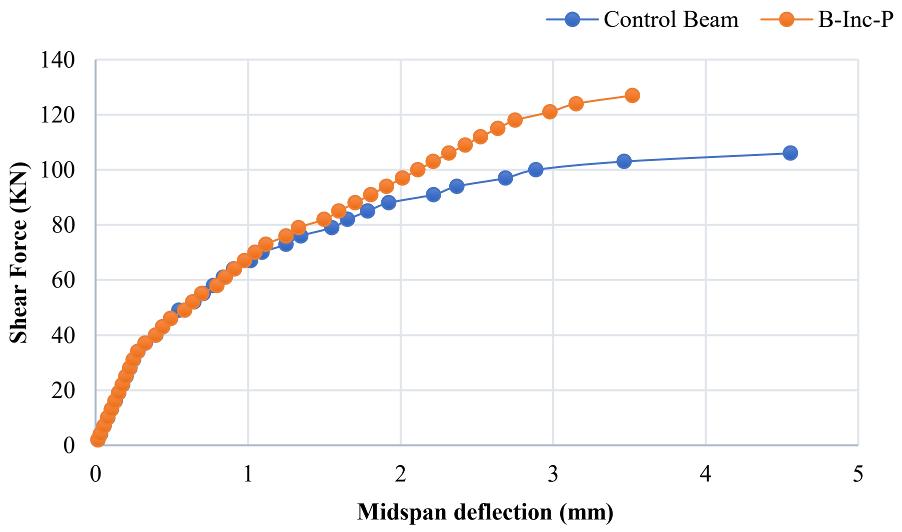

Figure 14. Shear Force-Midspan Deflection Curves for Concrete I Beams and Strengthened Beams by Inclined Steel Plates

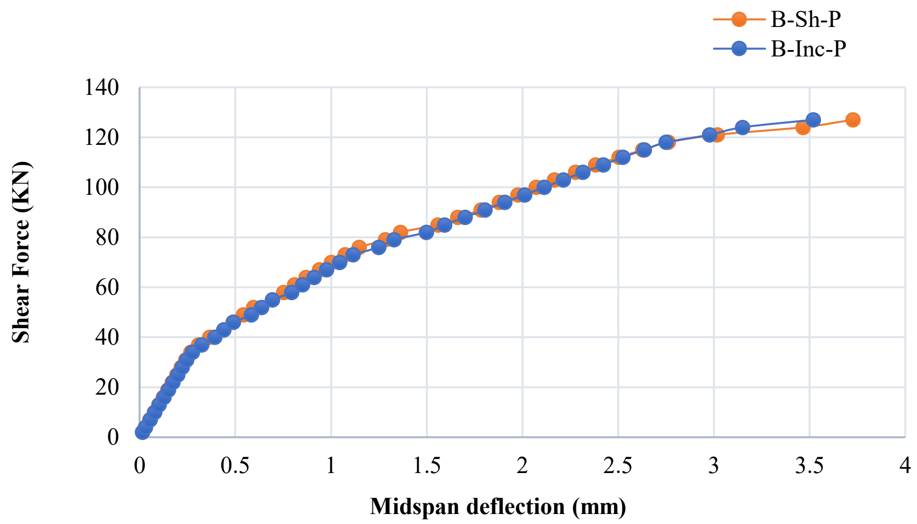

Figure 15. A Comparison of Shear Force Midspan Deflection Curves for (B-Sh-P) and (B-Inc-P)

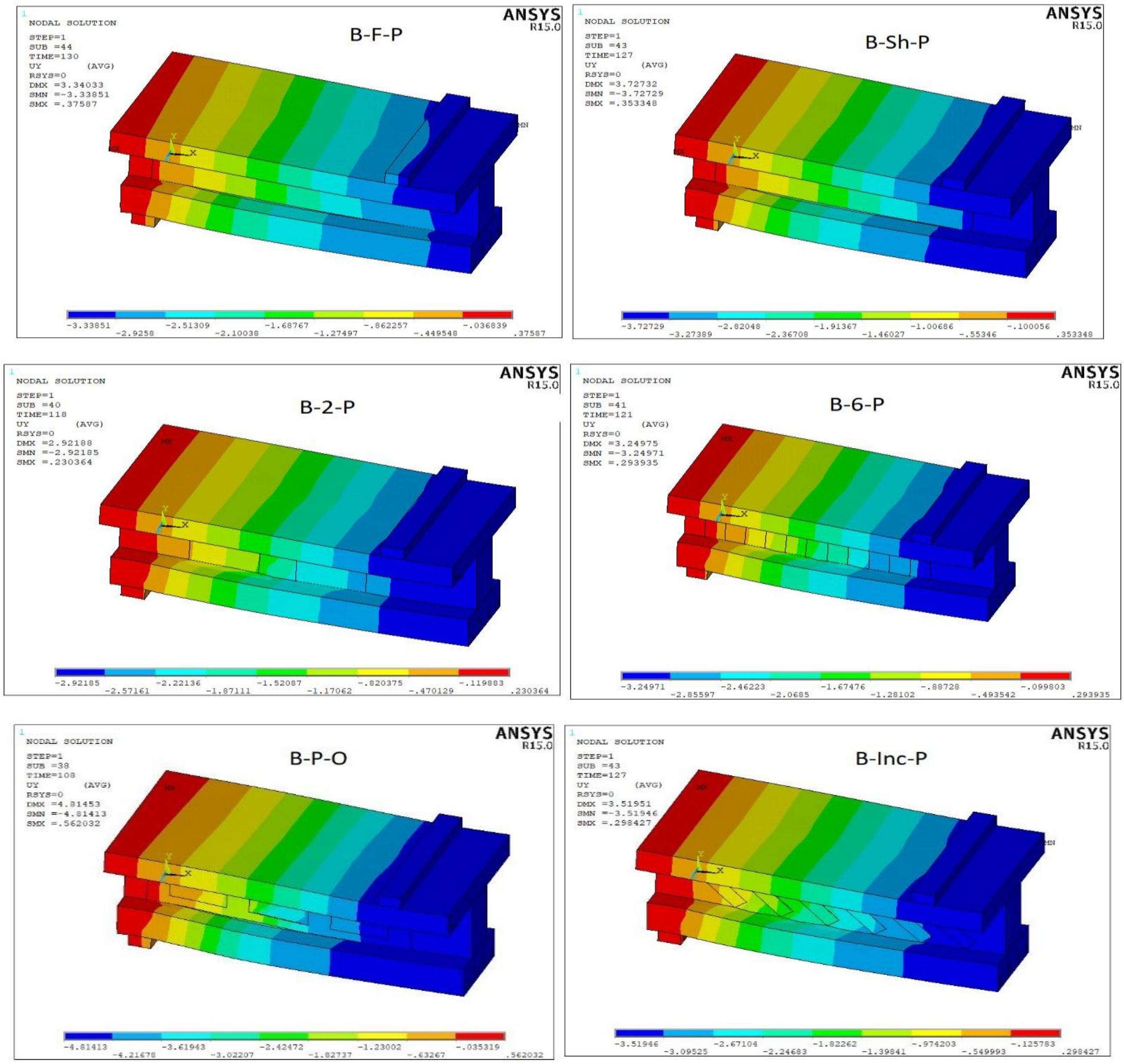

Figure 16. Deflection along the Strengthened Concrete I Beams at the Ultimate Shear Force, as Forecasted by the ANSYS Software Model

Figure 16 shows the deflection along the strengthening concrete I beams at the ultimate shear force as anticipated by the ANSYS software model; the blue color represents the maximum value of deflection, which occurs at midspan of the beams, and the red color represents the minimum value of deflection. In general, the vertical deflection decreases when using steel plates compared with the control beam, whose maximum deflection is 4.6 mm. There are no significant changes in deflections at ultimate shear force between the beams (B-Sh-P, B-2-P, B-6-P, B-Inc-P).Vertical deflection of 3.3 mm obtained in the beam with full plates (B-F-P) at the ultimate shear force equal to 130 KN, while vertical deflection of (3.7, 2.9, 3.2, 4.8, 3.5) mm obtained in the beam (B-Sh-P, B-2-P, B-6-P, B-P-O, B-Inc-P) at the ultimate shear force, respectively. Also, the maximum deflection in the beam (B-P-O) is 4.8 mm, which is almost equal to that of the control beam, as mentioned earlier.

Visual examination of simulated crack patterns revealed that inclined plates effectively redirected shear cracks, leading to a more evenly distributed cracking pattern. In SFRC and HSC beams, cracks were finer and less pronounced, reflecting the matrix's internal contribution to shear resistance. Conversely, the control beam exhibited dominant diagonal cracking with rapid propagation, confirming the benefit of the strengthening systems.

By comparing HSC and SFRC beams with beams strengthened with steel plates, HSC behaved similarly to (B-6-P), which had six steel plates. In contrast, SFRC showed behavior like (B-Sh-P and B-Inc-P), which had a shear span and inclined steel plates, as demonstrated in Figure 17.

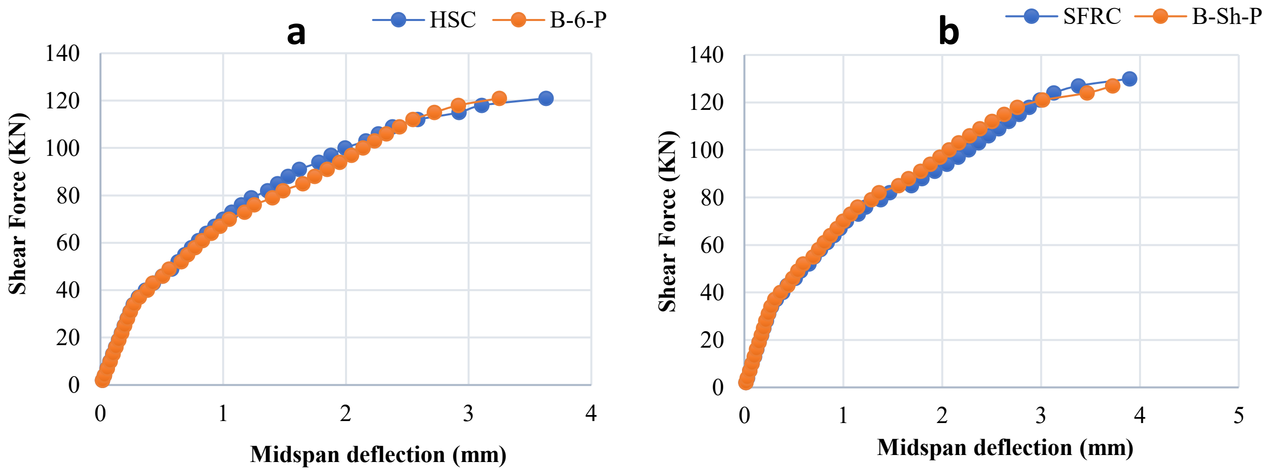

Figure 17. A Comparison of Shear Force Midspan Deflection Curves for: a) HSC and B-6-P; b) SFRC and B-Sh-P

CONCLUSIONS

The finite element (FE) models were successfully validated against previously reported experimental results, demonstrating excellent agreement. Therefore, ANSYS can be reliably used to analyze the shear behavior of hybrid-reinforced concrete (RC) I-beams.

- Strengthening the web of an RC I-beam with full-length steel plates bonded to both sides increased the shear strength by 22%.
- Strengthening the web with steel plates to both sides within the shear-span increased the shear strength by 19%.
- Using two steel plates bonded to both sides, with a total plate area equal to 0.52 times the shear span area, increased the shear strength by 11%.
- Using six steel plates bonded to both sides, with a total plate area equal to 0.52 times the shear span area, increased the shear strength by 14%.
- Steel plates containing openings did not produce a significant improvement in either shear strength or stiffeness.
- Inclined steel plates bonded to both sides, with a total plate area equal to 0.49 times the shear-span area, increased the shear strength by 22%.
- Beams strengthened with shear span steel plates and inclined steel plates exhibited similar shear force-midspan deflection responses.
- The behavior of beams constructed with high-strengn concrete (HSC) was comparable to that of beams strengthened with six plates, whereas steel fiber-reinforced concrete (SFRC) beams exhibited behavior similar to that of beams strengthened with shear-span and inclined steel plates.

REFERENCES

1. McCormac, J.C. and Brown, R.H., *Design of Reinforced Concrete*, John Wiley & Sons, 2015.
2. Zhang, G., Ali, Z.H., Aldlemy, M.S., Mussa, M.H., Salih, S.Q., Hameed, M.M., Al-Khafaji, Z., and Yaseen, Z.M., Reinforced Concrete Deep Beam Shear Strength Capacity Modelling using an Integrative Bio-Inspired Algorithm with an Artificial Intelligence Model, *Engineering with Computers*, 2020, pp. 1-14. https://doi.org/10.1007/s00366-020-01137-1
3. Abdallah, M.H., Thoeny, Z.A., Henedy, S.N., Al-Abdaly, N.M., Imran, H., Bernardo, L.F.A., and Al-Khafaji, Z., The Machine-Learning-based Prediction of the Punching Shear Capacity of Reinforced Concrete Flat Slabs using an Advanced M5P Model Tree Approach, *Applied Sciences*, 13(14), 2023, Article No. 8325. https://doi.org/10.3390/app13148325
4. Lin, T.Y. and Burns, N.H., *Design of Prestressed Concrete Structures,* John Wiley & Sons, 1981.
5. Jabbar, D.N., Al-Rifaie, A., Hussein, A.M., Shubbar, A.A., Nasr, M.S., and Al-Khafaji, Z.S., Shear Behaviour of Reinforced Concrete Beams with Small Web Openings, *Materials Today: Proceedings*, 42(5), 2021. https://doi.org/10.1016/j.matpr.2020.12.710
6. Ali, Y.A., Falah, M.W., Ali, A.H., Al-Mulali, M.Z., Al-Khafaji, Z., Mohammed, T., Al Sa'adi, A.H.M, and Al-Hashimi, O.A., Studying the Effect of Shear Stud Distribution on the Behavior of Steel-Reactive Powder Concrete Composite Beams using ABAQUS Software, *Journal of Mechanical Behavior of Materials*, 31(1), 2022, pp. 416-425. https://doi.org/10.1515/jmbm-2022-0046
7. Noghabai, K., Beams of Fibrous Concrete in Shear and Bending: Experiments and Model, *Journal of Structural Engineering (ASCE),* 126(2), 2000, pp. 243-251. https://doi.org/10.1061/(ASCE)0733-9445(2000)126:2(243)
8. Ali, A.M., Falah, M.W., Hafedh, A.A., and Al-Khafaji, Z.S., Evaluation of the Influence of Steel Fiber on Concrete Characteristics, *Periodicals of Engineering and Natural Sciences,* 10(5), 2022, pp. 368-379. https://doi.org/10.21533/pen.v10i3.3111
9. Al-Abdaly, N.M., Hussein, M.J., Imran, H., Henedy, S.N., Bernardo, L.F.A., and Al-Khafaji, Z., Shear Strength Prediction of Steel-Fiber-Reinforced Concrete Beams using the M5P Model, *Fibers,* 11(5), 2023, Article No. 37. https://doi.org/10.3390/fib11050037
10. Wei, W.W., Che, Y., and Gong, J.X., Shear Strength Prediction for Reinforced Concrete Beams without Stirrups, *Magazine of Concrete Research*, 63, 2011, pp. 433-440. https://doi.org/10.1680/macr.10.00054
11. Mhanna, H.H., Hawileh, R.A., and Abdalla, J.A., Shear Strengthening of Reinforced Concrete Beams using CFRP Wraps, *Procedia Structural Integrity*, 17(3), 2019, pp. 214-221. https://doi.org/10.1016/j.prostr.2019.08.029
12. De Silva, S., Mutsuyoshi, H., Witchukreangkrai, E., and Takagi, M., Experimental Study on Shear Cracking Behavior in I-Shaped Partially Prestressed Concrete Beams, *Proceedings of the Japan Concrete Institute,* 2006, pp. 817-822.
13. Adhikary, B.B., Mutsuyoshi, H., and Sano, M., Shear Strengthening of Reinforced Concrete Beams using Steel Plates Bonded on Beam Web: Experiments and Analysis, *Construction and Building Materials,* 14(5), 2000, pp. 237-244. https://doi.org/10.1016/S0950-0618(00)00023-4
14. Khalid, S.Z., Shinde, S.B., and Pathan, K.M., Civil Engineering Applications and Research of FRP in India as Compared to China, *Journal of Mechanical and Civil Engineering,* 1999, pp. 49-53.
15. Newman, J. and Choo, B.S., *Advanced Concrete Technology, Volume 4: Testing and Quality*, Elsevier, 2003.
16. Hasgul, U., Yavas, A., Birol, T., and Turker, K., Steel fiber Use as Shear Reinforcement on I-Shaped Reinforced Concrete Beams, *Applied Sciences,* 9(24), 2019. https://doi.org/10.3390/app9245526
17. Lee, H.J. and Chen, J.H., *Testing of Mechanical Splices for Grade 685 Steel Reinforcing Bars*, TTK Research Report, 2014, pp. 54-88.
18. Liao, W.C., Perceka, W., and Liu, E.J., Compressive Stress-Strain Relationship of High-Strength Steel Fiber Reinforced Concrete, *Journal of Advanced Concrete Technology*, 13(8), 2015, pp. 379-392. https://doi.org/10.3151/jact.13.379
19. American Concrete Institute (ACI), *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary,* American Concrete Institute, Farmington Hills, MI, 2019.
20. Perceka, W., Liao, W.C., and Wang, Y., High-Strength Concrete Columns under Axial Compression Load: Hybrid Confinement Efficiency of High-Strength Transverse Reinforcement and Steel Fibers, *Materials,* 9(4), 2016, Article No. 264. https://doi.org/10.3390/ma9040264
21. Parra-Montesinos, G.J., Shear Strength of Beams with Deformed Steel Fibers, *Concrete International,* 28, 2006, pp. 57-66.
22. Aoude, H., Belghiti, M., Cook, W.D., and Mitchell, D., Response of Steel Fiber-Reinforced Concrete Beams with and without Stirrups, *ACI Structural Journal*, 109(3), 2012, pp. 359-367. https://doi.org/10.14359/51683749

23. Voo, Y.L., Foster, S.J., and Gilbert, R.I., Shear Strength of Fiber Reinforced Reactive Powder Concrete Prestressed Girders without Stirrups, *Journal of Advanced Concrete Technology*, 4(1), 2006, pp. 123-132. https://doi.org/10.3151/jact.4.123
24. Thomas, J. and Ramaswamy, A., Mechanical Properties of Steel Fiber-Reinforced Concrete, *Journal of Materials in Civil Engineering (ASCE),* 19(5), 2007, pp.385-392. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(385)
25. Dinh, H.H., *Shear Behavior of Steel Fiber Reinforced Concrete Beams without Stirrup Reinforcement,* Ph.D. Thesis, University of Michigan, 2009.
26. Dinh, H.H., Parra-Montesinos, G.J., and Wight, J.K., Shear Behavior of Steel Fiber-Reinforced Concrete Beams without Stirrup Reinforcement, *ACI Structural Journal*, 107(5), 2010, pp. 597-606.
27. Husain, H.M., Al-Nu'man, B.S., and Aziz, D.A.H., Shear Behavior of Hybrid Reinforced Concrete I-Beams Containing Steel Fiber Reinforced Concrete and High-Strength Concrete, *Journal of Engineering Development,* 10(4), 2006, pp. 36-52.
28. ANSYS Inc., *ANSYS User Manual*, ANSYS Inc., 2015.
29. American Concrete Institute (ACI), *Building Code Requirements for Structural Concrete (ACI 318-14),* American Concrete Institute, Farmington Hills, MI, 2014.
30. Desayi, P., Iyengar, K.T.S.R., and Reddy, T.S., Equation for Stress-Strain Curve of Concrete Confined in Circular Steel Spiral, *Materials and Structures*, 11(65), 1978, pp. 339-345. https://doi.org/10.1007/BF02473875
31. Bangash, M.Y.H., *Concrete and Concrete Structures: Numerical Modelling and Applications*, Elsevier Applied Science, 1989.
32. Al-Khafaji, Z., Heddam, S., Kim, S., Denouwé, D., Bouaissi, A., Mohammad, R.S., et al., State-of-the-art: Artificial Intelligence Models Era in Modeling Beam Shear Strength, *Knowledge-Based Engineering and Sciences,* 3(3), 2022, pp. 1-63.