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Parametric Investigation of the Shear Behavior of PVA Fiber-Reinforced Concrete Beams

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Abstract: This study investigates the influence of five key parameters on the shear behavior of polyvinyl alcohol fiber-reinforced concrete (PVAFRC) beams using the general-purpose finite element software ANSYS. The examined parameters include the volume fraction of PVA fibers (Vf), the longitudinal steel reinforcement ratio (ρs), the yield strength of longitudinal reinforcement (fy), the transverse reinforcement ratio (ρv), and the yield strength of vertical stirrups (fyv). Due to the strong bond between PVA fibers and concrete, an increase in Vf is expected to enhance the shear capacity of PVAFRC beams. In reinforced concrete (RC) beams, PVA fibers mitigate premature shear crack formation and slow crack propagation by bridging microcracks. Increasing ρs significantly improves shear capacity while reducing strain ductility and deflection. A minor enhancement in shear capacity is observed with an increase in fy, whereas a slight reduction in deflection and a marginal improvement in shear failure load is noted with an increase in ρv. Furthermore, increasing ρv enhances both shear capacity and strain ductility. However, a substantial improvement in both shear capacity and ductility is observed when fyv is increased for PVAFRC beams with the same ρv

Keywords: Reinforced concrete beams; PVA fibers; Load-deflection curves; Finite element; ANSYS

1. INTRODUCTION

Due to its sudden and brittle nature, shear failure is considered one of the most critical challenges in the structural performance of reinforced concrete (RC) beams. Unlike flexural failure, which often exhibits ductile behavior with significant warning signs, shear failure occurs abruptly, leading to catastrophic structural collapse. To mitigate this abruptness and enhance the shear capacity, various reinforcement techniques have been explored, including the use of bent bars, vertical and horizontal stirrups, and advanced material modifications such as fiber reinforcement and chemical admixtures[1-3] .

Among the fiber reinforcement strategies, polyvinyl alcohol (PVA) fiber has garnered significant research interest due to its unique mechanical and chemical properties. PVA fibers exhibit a hydrophilic nature, enabling superior adhesion to cementitious matrices compared to other synthetic fibers. This strong bond enhances crack-bridging capability, effectively controlling microcrack propagation and delaying crack coalescence, thereby improving the overall shear resistance of concrete beams. Moreover, the integration of PVA fibers has been shown to enhance the ductility and energy absorption capacity of concrete, contributing to improved post-cracking behavior and toughness. Studies have investigated the influence of PVA fiber parameters on the shear behavior of RC beams, highlighting their role in improving shear strength, delaying crack initiation, and modifying failure modes [3-6].

This study aims to evaluate the shear performance of polyvinyl alcohol fiber-reinforced concrete (PVAFRC) beams through a parametric analysis conducted using the finite element software ANSYS [7]. A validated numerical model was developed to simulate the shear response of previously tested PVAFRC beams, providing a predictive framework for assessing shear behavior under various reinforcement conditions.

A total of eleven beam specimens were analyzed to investigate the influence of five key parameters on shear performance: (i) the volume fraction of PVA fibers (Vf), (ii) the longitudinal reinforcement ratio (ρs), (iii) the yield strength of longitudinal reinforcement (fy), (iv) the transverse reinforcement ratio (ρv), and (v) the yield strength of vertical stirrups (fyv). These parameters were systematically varied to examine their effects on shear strength, crack propagation, and failure mechanisms. The numerical results were compared with experimental data to validate the accuracy of the proposed model in predicting shear behavior and assessing the contribution of PVA fibers to shear resistance.

2.Modeling of PVAFRC Beams

2.1 Model Description of the Tested Beams

Finite element modeling (FEM) is employed to conduct a parametric investigation on an experimentally tested polyvinyl alcohol fiber-reinforced concrete (PVAFRC) beam, as studied by Shaaban et al. [3]. The numerical model is developed to replicate the structural response of PVAFRC beams under shear loading conditions, enabling a detailed assessment of the effects of various reinforcement parameters. Figure (1) illustrates the geometric configuration and reinforcement detailing of the analyzed PVAFRC beams. Figure (2) illustrates the load deflection relationship of the experimental test and the validated model.

Eleven PVAFRC beam specimens, designated as S1, S2, ..., and S11, are examined to evaluate the influence of key design parameters on shear performance. These parameters include variations in fiber volume fraction, longitudinal reinforcement ratio, transverse reinforcement ratio, and steel yield strength. The numerical analysis provides insight into the shear behavior, crack propagation mechanisms, and load-carrying capacity of PVAFRC beams, contributing to the optimization of fiber-reinforced concrete design for enhanced structural performance.

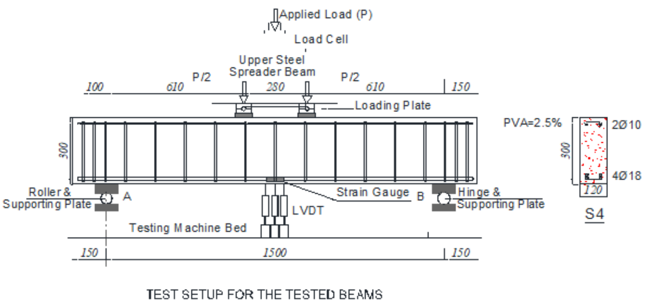


FIG 1. Beams Geometrical and Steel Reinforcement Details [3]

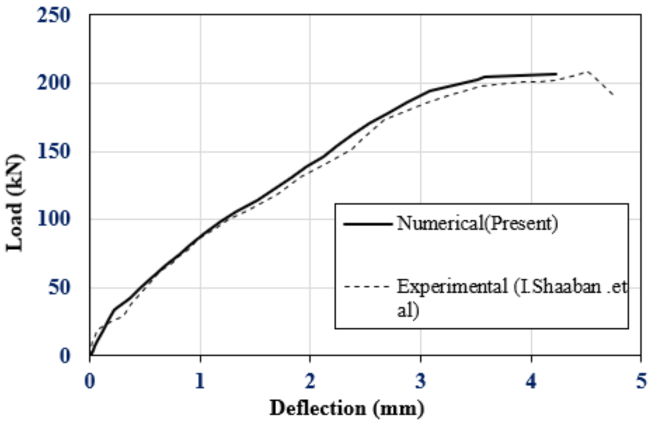


FIG 2. Load displacement relationship oof B4 [3]

2.2 Finite Element Geometric and Material Idealization

The finite element software ANSYS is utilized to perform nonlinear analysis and numerical modeling of PVAFRC beams according to ongoing research by authors. Table 1 details the structural element types used in the simulation to represent the distinct material properties accurately. Figure (3) presents the three-dimensional finite element model developed in ANSYS [7], along with the formulation of the essential modeling components.

In the numerical model, concrete behavior is characterized by a nonlinear constitutive relationship. A linear tension-softening model is adopted for concrete tension to simulate post-cracking behavior. At the same time, the Hognestad-Popovics stress-strain curve [8] is applied for concrete in compression to capture strain-hardening and softening effects. The concrete strength of beam S4 is equal to 58 MPa reinforced by PVA fiber with volume fraction equal to 2.5%. The steel reinforcement is modeled using a bilinear stress-strain relationship, accounting for both elastic and plastic behavior under tensile and compressive loading conditions. Table 2 presents the properties of PVA fiber used in the validated study, which can be classified as High-Strength PVA fiber [3]. To integrate the contribution of PVA fibers, modifications are incorporated into the concrete model using simulation procedures and suitable material specifications. Tensile strength and elastic modulus are defined in the material model using linear stress-strain relationships. Smeared reinforcement or discrete fiber elements can be used to simulate the fiber volume percentage and orientation angle. Enhancing crack-bridging effects and improving the ductility and shear resistance of the material according to ongoing research by authors. These adjustments ensure that the numerical simulation accurately reflects the experimental behavior of PVAFRC beams under shear loading.

TABLE 1: Structural Element Types Utilized to Discrete the Numerical Models

Material	Structural Element
Fibrous Concrete	SOLID 65
Non-fibrous Concrete	SOLID 65
Bearing and Loading Plates	SOLID 45
Steel bars	LINK 180

TABLE 2: PVA Fiber properties[3]

Length (mm)	Diameter (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (g/cm3)	Elongation (%)
12	0.039	1620	42.8	1.3	7

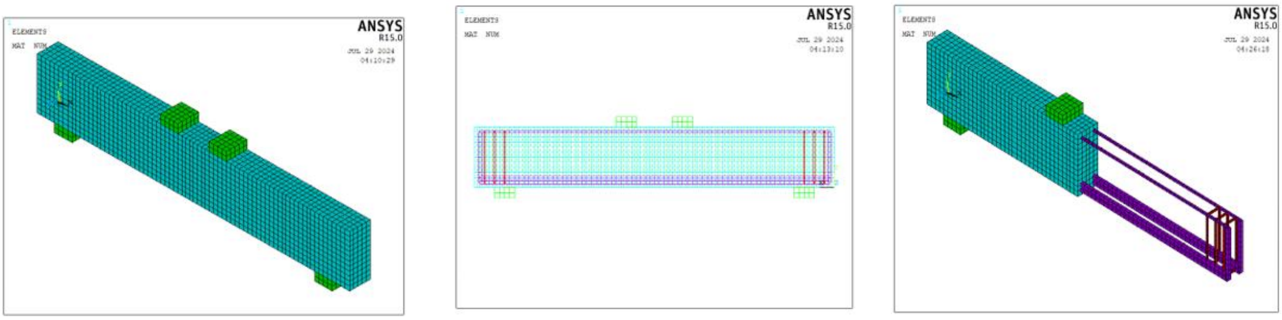


FIG 3. Idealization models of 3-D finite elements for the beams according to ongoing research by authors

TABLE 3: The Input Parameters for the Analyzed Specimens according to ongoing research by authors

Beam	V_f (%)	$\rho_s = \frac{A_s}{b.d}$ %	f_y (MPa)	$\rho_v = \frac{A_v}{b.S}$ %	f_{yv} (MPA)
S1	0	3.26%	400	---	240
S2	1	3.26%	400	---	240
S3	1.5	3.26%	400	---	240
S4	2.5	3.26%	400	---	240
S5	2.5	1.44%	400	---	240
S6	2.5	1.63%	400	---	240
S7	2.5	3.26%	350	---	240
S8	2.5	3.26%	500	---	240
S9	2.5	3.26%	400	0.42%	240
S10	2.5	3.26%	400	0.67%	240
S11	2.5	3.26%	400	0.42%	350

3.Parametric Studies

Four key parameters are considered in the numerical investigation to evaluate their influence on the shear behavior of polyvinyl alcohol fiber-reinforced concrete (PVAFRC) beams. These parameters are systematically varied to assess their impact on shear strength, crack propagation, and overall structural performance. Table 3 provides a detailed summary of the examined parameters, and their respective values used in the study.

3.1. Ratio of PVA fiber volume content (V_f)

Four PVAFRC beam specimens were analyzed to evaluate the effect of varying polyvinyl alcohol (PVA) fiber volume fractions (Vf) on shear performance. As mentioned in the validated research[3], the percentage is calculated based on the weight of the fiber with respect to the total weight of the concrete mix. The examined V_f values were 0%, 1%, 1.5%, and 2.5%, corresponding to beam specimens S1, S2, S3, and S4, respectively. Figure (4) illustrates the predicted shear response curves for the specimens S1, S2, S3, and S4 providing insight into the influence of fiber reinforcement on load-bearing capacity, crack propagation, and overall structural behavior. Figure (5) presents crack pattern of beams S3 and S4 .

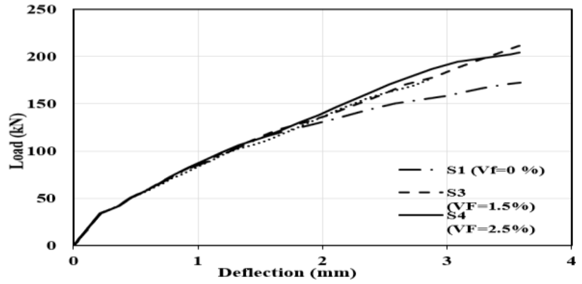
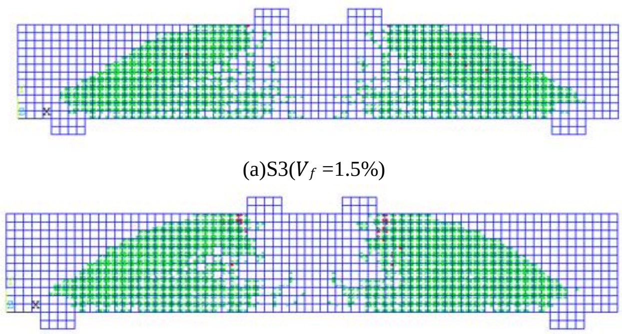


FIG 4. Predicted load-displacement relations for beams S1, S2, S3 and S4

The numerical analysis indicates that increasing the polyvinyl alcohol (PVA) fiber volume fraction (V_f) generally enhances the shear capacity (V_u) of PVAFRC beams. However, beyond a certain threshold, further increases in V_f may result in diminishing returns or even adverse effects on shear performance. The optimal fiber volume fraction was determined to be 1.5%, yielding the maximum observed shear capacity. A comparative evaluation of the beam specimens revealed that the shear capacity increased by 2.3%, 22.6%, and 18.6% for specimens S2, S3, and S4, respectively, relative to S1. A slight enhancement in toughness (I) was observed, with increases of 8.4% and 10.3% for specimens S3 and S4, respectively, compared to S1. Additionally, Stiffness (Ku) is improved by 18.8%,17.2% and 20.8% for specimens S3 and S4, respectively, compared to S1. These results highlight the effectiveness of fiber reinforcement in improving both shear strength and energy absorption characteristics while also emphasizing the importance of optimizing fiber dosage to avoid negative effects on performance.



(a)S3(V_f =1.5%)

(b)S4(V_f=2.5%)

FIG 5. Predicted Crack Patterns for beams S3 and S4

3.2. Ratio of Longitudinal Steel

Three PVAFRC beam specimens were analyzed to investigate the effect of varying longitudinal reinforcement ratios (ρ_s) on shear performance. The examined ρs values were 1.44%, 1.63%, and 3.26%, corresponding to beam specimens S4, S5 and S6, respectively. Figure (6) presents the predicted shear response curves for the specimens S4, S5 and S6 providing insight into the influence of longitudinal reinforcement on load-carrying capacity, crack propagation, and overall structural behavior. Figure (7) presents crack pattern of beams S4, S5 and S6

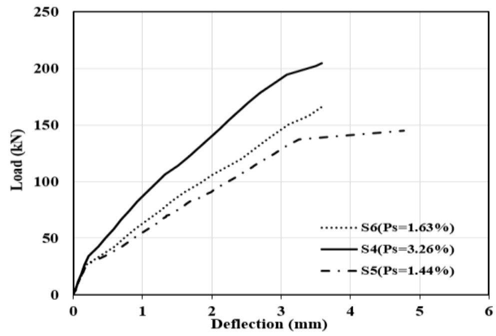
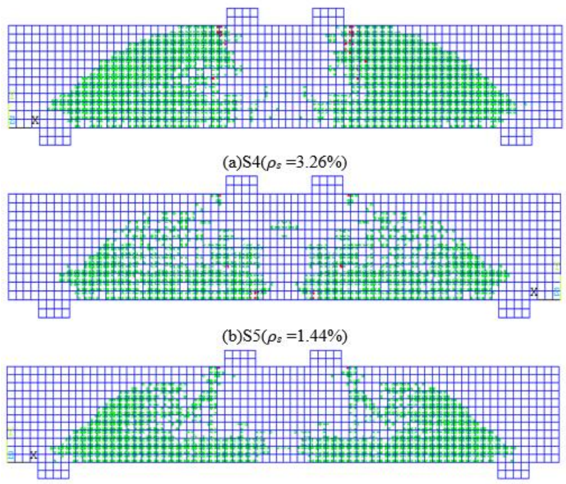


FIG 6. Predicted load-displacement relations for Beams S4, S5 and S6

The shear capacity (Vu) of specimens S4 and S6 increased by 40.8% and 14.7%, respectively, with an increase in the longitudinal reinforcement ratio (ρs) compared to specimen S5. Additionally, the corresponding mid-span deflection was reduced by 25% and 23% for specimens S4 and S6, respectively, relative to S5. Additionally, Stiffness (Ku) is improved by 24.9%and 62.2% S4 and S6, respectively, relative to S5. These results indicate that increasing ρs enhances shear strength while simultaneously reducing deformation, contributing to improved structural stiffness and load resistance. comparable outcomes were documented by M.M.Khalil[9].



(a)S4(ρ_s =3.26%)

(b)S5(ρ_s =1.44%)

(c)S6(ρ_s =1.63%)

FIG 7. Predicted Crack Patterns for beams S4, S5 & S6.

3.3. Yield Strength of the Longitudinal Steel

Three PVAFRC beam specimens were analyzed to examine the influence of varying longitudinal reinforcement yield strength (f_y) on shear performance. The considered f_y values were 350 MPa, 400 MPa, and 500 MPa, corresponding to specimens S7, S4, and S8, respectively. Figure (8) presents the predicted load-displacement relations for these specimens. The results indicate that increasing fy leads to a slight improvement in shear capacity (V_u), with increases of 0.3% and 11.7% for specimens S4 and S8, respectively, relative to S7. Additionally, a minor increase in mid-span deflection was observed, with values rising by 2.9% and 22.2% for specimens S4 and S8, respectively, compared to S7. However, a slight reduction in stiffness was observed as f_y increased by 4.9% and 4.1 for S4 and S8, respectively, relative to S7 and a notable reduction in ductility was observed as f_y increased, indicating a trade-off between higher reinforcement strength and the ductility of PVAFRC beams. comparable outcomes were documented by M.M.Khalil [9].

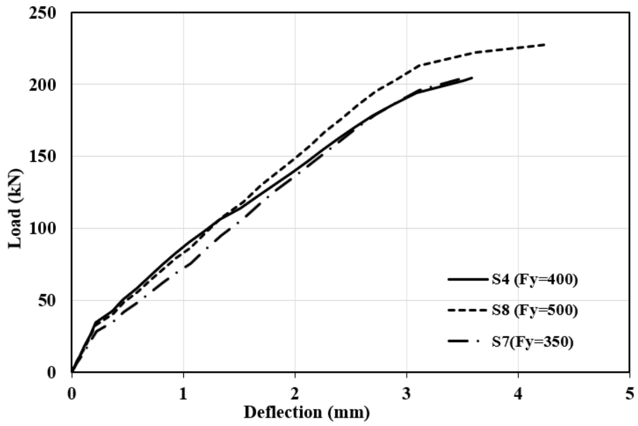


FIG 8. Predicted load-displacement relations for Beams S4, S7 and S8

3.4. Effect of the Vertical Stirrups Ratio

Three PVAFRC beam specimens were analyzed to evaluate the effect of varying vertical stirrup ratios (ρv) on shear performance. The examined ρv values were 0.0%, 0.42%, and 0.67%, corresponding to specimens S4, S9, and S10, respectively. Figure (9) presents the predicted load-displacement relations for thespecimenS4, S9, and S10, illustrating the influence of transverse reinforcement on shear strength, crack development, and overall structural behavior. Figure (10) presents crack pattern of beams S4, S9 and S10.comparable outcomes were documented by M. K. Ghali and J. Maheswaran [10],[11].

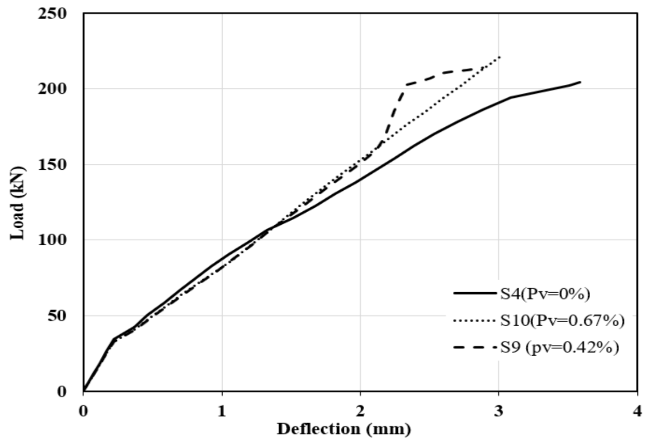


FIG 9. Predicted load-displacement relations for Beams S4, S19 and S10

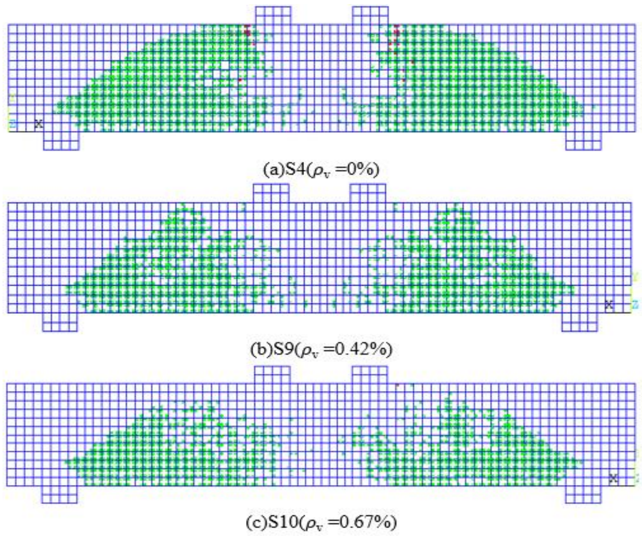


FIG 10. Predicted Response Crack Pattern for beams S4, S9& S10.

The results indicate that increasing the vertical stirrup ratio (ρv) enhances both shear capacity (Vu) and structural stiffness. Specifically, the shear capacity increased by 4.7% and 8% for specimens S9 and S10, respectively, compared to S4. the mid-span deflection (Δu) was reduced by 19.5% and 12.8% for specimens S9 and S10, respectively, relative to S4. Stiffness is increased by 31.5% for S9 relative to S4. These findings demonstrate the effectiveness of transverse reinforcement in improving shear resistance and limiting deformations, contributing to enhanced overall structural performance.

3.5. Yield Strength of the vertical Stirrups

Two PVAFRC beam specimens were analyzed to investigate the effect of varying the yield strength of vertical stirrups (f_{yv}) on shear performance. The considered f_{yv} values were 240 MPa and 350 MPa, corresponding to specimens S10 and

S11, respectively. Figure (11) presents the predicted shear response curves for these specimens. The results indicate that increasing fyv leads to a slight improvement in shear capacity (Vu), with an increase of 9.7% for specimen S11 compared to S10.Ductility is enhanced by 43.7% regards to S10. Additionally, stiffness is reduced slightly by 8.9% for specimen S11 compared to S10. This enhancement suggests that higher-yield-strength stirrups contribute to improved shear resistance, though the overall effect remains limited compared to other reinforcement parameters.

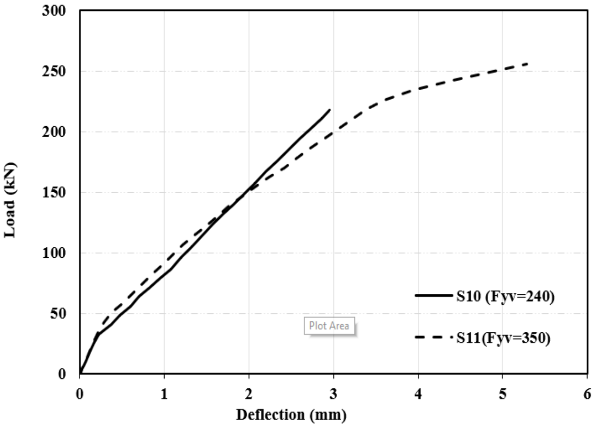


FIG 11. Predicted load-displacement relations for beams S10 and S11

4.CONCLUSIONS

Based on the numerical results obtained for the selected parameters, the following inferences can be drawn regarding the shear performance of PVAFRC beams:

1. The incorporation of PVA fibers enhances shear failure resistance and ductility. The optimal fiber volume fraction (Vf) was determined to be 1.5%, resulting in a 22.5% increase in shear capacity (Vu), improved ductility, and reduced deflection compared to non-fibrous beams.
2. Increasing the longitudinal reinforcement ratio improves shear capacity but reduces ductility. Compared to a beam with ρs=1.44%, increasing ρs to 1.63% and 3.26% resulted in shear capacity improvements of 14.6% and 40.8%, respectively, while reducing deflection by 23% and 25%.
3. Increasing the yield strength of the longitudinal reinforcement led to a marginal enhancement in shear capacity. Compared to a beam with fy=350 MPa, increasing fy to 400 MPa and 500 MPa resulted in shear capacity improvements of 0.3% and 11.7%, respectively, for the same ρs.
4. The presence of vertical stirrups significantly improved deflection performance. Compared to a beam without stirrups (ρv= 0.0%), beams with ρv=0.42% and 0.67% exhibited deflection reductions of 19.5% and 16.2%, respectively. Additionally, shear capacity increased slightly by 4.7% and 8.1%, respectively.
5. Increasing the yield strength of the vertical stirrups (fyv) contributed to improved shear resistance. A PVAFRC beam with fyv=350 MPa exhibited a 9.7% increase in shear capacity compared to a beam with fyv=240 MPa.

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