Shear Strengthening of Deep Beams Using Polymer-Based CFRP Bars via the Near-Surface Mounting (NSM) Technique

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Abstract: Near-surface-mounted strengthening with polymer-based carbon fiber-reinforced polymer (CFRP) bars has been proved as one of the efficient techniques in enhancing the shear capacity of reinforced concrete RC deep beams. This paper presents an experimental investigation on the shear behavior of RC deep beams strengthened with NSM CFRP bars. Five identical RC deep beam specimens with the same geometry and internal steel reinforcement were tested under two-point loading. One specimen was left un-strengthened as a control beam; while four specimens have been strengthened by CFRP bars embedded in the shear zone with two orientations, 0°/90° and 45°/135°, and two spacing configurations, 100 and 150 mm. Response parameters of prime interest included first shear cracking load, ultimate shear capacity, crack pattern, and mid-span deflection. The findings of the experiment demonstrated that NSM CFRP strengthening improved the shear performance of deep beams; depending on the orientation and spacing of the CFRP bars, shear capacity augmentation ranged from about 14% to 47% in comparison to the control specimen. Additionally, at similar load levels, strengthened beams demonstrated a 10% to 40% decrease in mid-span deflections and fracture widths. The test results demonstrate how well polymer-based CFRP bars inserted using the NSM technology improve the stiffness and shear strength of RC deep beams.

Keywords: Polymer, carbon fiber-reinforced polymer, Optimization, reinforcement concret.

1. INTRODUCTION

Because of their tunable characteristics, lightweight nature, corrosion resistance, and versatility in a variety of industries, including but not limited to the construction, transportation, energy, and environmental management sectors, advanced polymeric materials have become essential in modern engineering applications. Within the field of advanced polymer composites, carbon fiber reinforced polymer material is a class of high-performance functional polymers whose remarkable durability, stiffness-to-weight ratio, and tensile strength have made them widely used in infrastructure rehabilitation and strengthening. Through material efficiency and lower maintenance needs, these polymer composites are essential for prolonging the life of buildings in the housing and construction industries while promoting sustainable development objectives.

In buildings, bridges, transfer girders, pile caps, and industrial structures, RC deep beams are essential structural components where compression strut action—rather than flexural behavior dominates internal load transfer. Deep beams are particularly susceptible to brittle shear failures due to their low shear span-to-effective-depth ratio. A number of current constructions may have an inadequate shear capacity due to outdated design specifications, higher service loads, poor construction, or deterioration of the steel reinforcing brought on by corrosion and harsh conditions. Therefore, there is a genuine need for sophisticated polymer-based strengthening methods that may efficiently increase shear resistance while guaranteeing long-term durability [7-9]. Conventional shear strengthening techniques, such externally bonded reinforcement and steel jacketing, frequently experience premature debonding, increased self-weight, and corrosion susceptibility [10-12]. On the other hand, when properly attached to concrete substrates, polymer-based CFRP composites provide significantly superior resistance to environmental deterioration and enable effective stress transmission [13-15]. Therefore, a lot of research has been done on externally bonded CFRP sheets and laminates; however, their performance may be weakened by surface debonding, fire exposure, and mechanical damage, limiting their dependability under demanding service circumstances.

For the manufacturing and installation of polymer composite reinforcement in concrete structures, the NSM technology has shown great promise. The NSM method offers better confinement, better bond properties, and shielding of the polymer composite from external exposure by embedding CFRP bars in grooves carved into the concrete cover and bonding them using polymeric epoxy adhesives. From a materials science perspective, the interfacial behavior of polymer-concrete interfaces, elastic modulus compatibility, and the effectiveness of stress transmission inside the CFRP bars all of which have a direct bearing on structural performance control the performance of NSM systems [16-18].

Despite notable progress in polymer composite strengthening systems, existing research has largely focused on slender beams or vertical CFRP configurations, with limited experimental data available for RC deep beams strengthened using polymer-based CFRP bars. In respect to deep-beam systems, the

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feature of bar orientation and spacing which is crucial for stress transmission and fracture interception as well as the type of polymer and concrete interaction remains largely unexplored. Advances in the interdisciplinary field of polymer science and civil engineering, as well as in the optimum applications of polymer composites in structural engineering, depend heavily on a good knowledge of these difficulties.

This study will experimentally examine the shear strengthening of reinforced concrete deep beams employing near-surface mounting techniques and CFRP bars constructed of polymers in order to close this research gap. For reinforced concrete beams strengthened in shear with CFRP bars, including beams strengthened in shear with CFRP bars oriented at 0°/90° and 45°/135°, the study will examine the impacts of bar orientation and spacing. New avenues for the use of polymers in building will be made possible by the research's connection between the material characteristics of polymers and their structural engineering applications.

2. MATERIALS AND METHODS

The study's objective was to objectively examine the impact of polymer-based CFRPBars with near-surface mounting (NSM) on the shear strength of deep beams made of reinforced concrete. Everything in this study, including the materials, arrangement, and testing, has been chosen to represent contemporary building methods while allowing for an examination of important polymer-related topics. Important factors pertaining to the polymers under investigation include the orientation, spacing, and interfacial connection between polymer-based CFRPBars.

Ordinary Portland cement that met a number of criteria was used to prepare the concrete, with crushed stones serving as the coarse aggregates and natural river sand serving as the fine aggregates. At 28 days, the concrete's goal strength was around 30 MPa, which is a typical strength utilized in the construction of buildings including homes and infrastructure. To guarantee that the cement paste and aggregates were distributed properly, concrete was weighed and mixed using a mechanical mixer. In order to decrease air trapped in the concrete and avoid aggregate separation, the concrete was poured in formwork and compacted using mechanical vibration.

To give the compressive and tensile strength of the 28-day specimens, normal concrete cube/cylinder specimens have been produced alongside the specimens from the beam testing. Figure **1** depicts the specimens' geometry in the research that is being presented. Figure **1** shows the direction and spacing of the applied NSM CFRP. These include the distances between the spliced areas (100 mm and 150 mm) and the angles (0°/90° and 45°/135°).

Deformed high yield steel bars were used to strengthen the deep beams in order to meet the standard mechanical specifications for reinforced concrete constructions.

Flexural capacity was greater than shear capacity due to longitudinal tensile reinforcement in the bottom part of the beams. Therefore, it was anticipated that the control specimen would acquire a shear-dominated failure mode. To keep the structure stable throughout testing, further longitudinal reinforcement was added in the compression zone. To determine just the impacts of

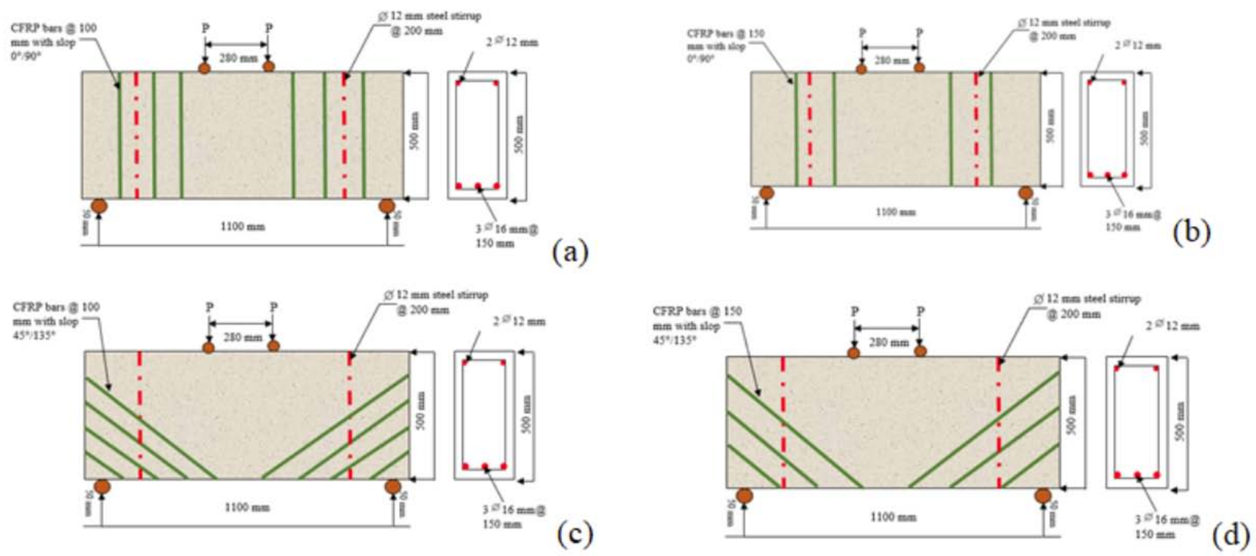

Figure 1: Details of reinforced concrete deep beam specimens strengthened with polymer-based CFRP bars using the near-surface mounting (NSM) technique: (**a**) CFRP bars at 0°/90° orientation with 100 mm spacing, (**b**) CFRP bars at 0°/90° orientation with 150 mm spacing, (**c**) CFRP bars at 45°/135° orientation with 100 mm spacing, and (**d**) CFRP bars at 45°/135° orientation with 150 mm spacing. All specimens have identical geometry, internal steel reinforcement, and loading configuration.

Table 1: Mechanical Properties of Reinforcing Steel Bars used in the Experimental Program

Bar Size (mm)	Modulus of Elasticity (Mpa)	Yield Stress (Mpa)	Ultimate Strength	Elongation %
ø16	200000	580	710	13.25
ø12	200000	338	498	14.35

the polymer-based CFRP strengthening parameters, all specimens had the identical reinforcement details. Prior to concrete casting with the proper concrete transparent cover, reinforcing steel bars were meticulously cut, bent, and readied as reinforcement cages. Table **1** reports the mechanical characteristics of the steel bars utilized as shear and longitudinal reinforcement. The elastic modulus of the 16 mm and 12 mm bars was 200 GPa, which is normal for structural steel. Bars of both sizes showed adequate ductility, as evidenced by an elongation more than 13%, and bars of 16 mm had better yield and ultimate strength than those of 12 mm. These characteristics ensured consistent performance of the reinforcement across all evaluated deep beam specimens.

Commercially available CFRP bars made via a pultrusion method served as the reinforcement of the polymer composite employed in this work. These bars belong to a family of high-performance functional polymers that are often used in transportation and construction. These CFRP bars were chosen due to their high tensile strength, corrosion resistance, linear elastic behavior up to failure, and compatibility with adhesives based on epoxy. Important material characteristics, such as nominal diameter, cross-sectional area, tensile strength, elastic modulus, and ultimate strain, were gathered from pertinent literature and manufacturer specifications. These polymer characteristics were crucial to the study because, when combined with concrete using the NSM approach, the stiffness and tensile capacity of CFRP bars directly affect stress transfer mechanisms, crack-control effectiveness, and overall shear resistance. In order to make it easier to attach polymer-based CFRP bars using the NSM technique, grooves were meticulously carved into the concrete cover in the shear zones after curing, as seen in Figure **2**. As shown in Figure **3**, polymer-based CFRP bars were inserted into the NSM grooves after the grooves were prepared, instrumented with strain gauges, and then completely sealed with epoxy glue.

To achieve meaningful comparison, five geometrically identical reinforced concrete deep beam specimens with steel internal reinforcement were constructed. The beams' dimensions were 1200 mm in length, 150 mm in width, and 500 mm in depth. This results in an approximate shear span-to-effective depth ratio of 0.9, which is typical of deep-beam behavior controlled by compression-strut action. Four specimens were repaired with the NSM CFRP bars laid in the shear zone in both sides of the beams, while the specimen without strengthening was used as the unstrengthened control beam. The strengthening design was developed to study the effects of the CFRP bar orientation and spacing, which are tightly related to the crack interception efficiency and polymer–concrete interaction.

Figure 2: Preparation of near-surface mounting (NSM) grooves cut into the concrete cover of a deep beam specimen prior to installation of polymer-based CFRP bars. The inclined grooves were formed to accommodate CFRP bar placement and ensure effective bonding with the epoxy adhesive.

Using a precision cutting tool, continuous grooves were cut into the concrete cover of the cured beam specimens as part of the near-surface mounting process. The grooves were made sufficiently deep and of adequate width to accommodate the CFRP bars with adequate epoxy cover for effective bonding.

In order to achieve dependable polymer-concrete adhesion, the surfaces were cleaned using pressured water and air after the grooves were prepared. This was a crucial step. As advised by the manufacturer, a two-part epoxy glue that is indicative of frequently used polymer binders in NSM applications was combined and partially placed into the grooves. To ensure complete contact and proper alignment, the CFRP bars were subsequently inserted into the epoxy-filled grooves and a slight compression applied. Additional epoxy was poured to completely fill the grooves and attain a flat surface finish. Strengthened specimens were cured for a pre-determined time period under ambient laboratory conditions to ensure the full

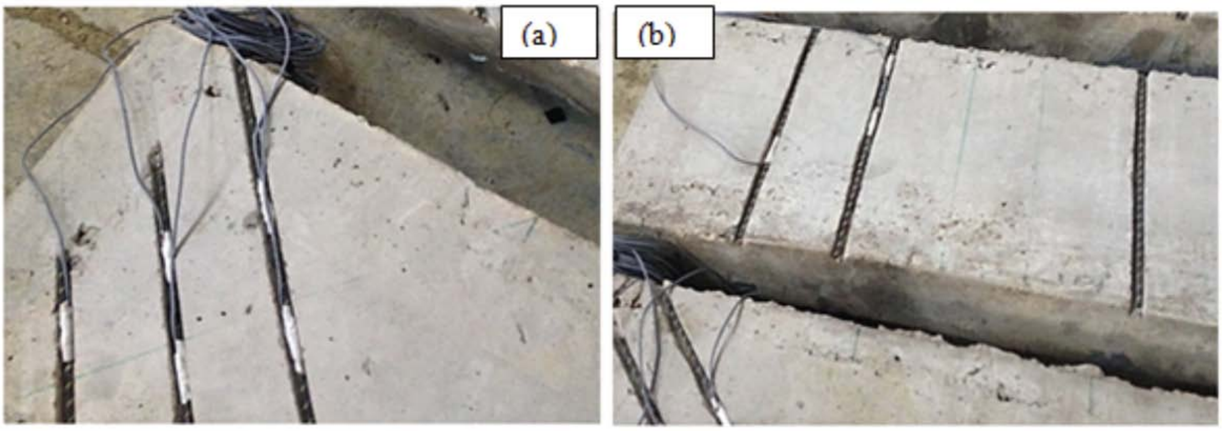

Figure 3: Installation of polymer-based CFRP bars in near-surface mounted (NSM) grooves of the reinforced concrete deep beam specimens: (**a**) placement of CFRP bars and strain gauges prior to epoxy filling, and (**b**) CFRP bars positioned within the grooves before complete encapsulation with epoxy adhesive.

polymerization of the epoxy and attainment of adequate bond strength.

Figure 4: Near-surface mounted (NSM) polymer-based CFRP bars after complete filling of grooves with epoxy adhesive. The epoxy encapsulation ensures effective polymer–concrete bonding, protection of CFRP bars, and reliable stress transfer within the shear zone of the deep beam specimen.

Each specimen was subjected to four-point loading using a hydraulic loading system in order to develop a constant shear area between the applied stresses. To replicate common boundary circumstances found in many structural applications, the beams were given a basic support at both ends. To record the process of fracture formation, stiffness deterioration, and the final failure behavior of the beams, the load was increased at a regulated pace. A calibrated load cell was used to record load levels during the test, while dial gauges with proven accuracy were used to quantify mid-span deflections. Before testing to improve crack visibility, the start and spread of cracks were properly tracked and noted on the white-painted beams' surface. By stopping the force at predefined intervals, deflection and fracture patterns were regularly observed.

The purpose of this study's experimental design was to demonstrate how polymer-based CFRP bars improve the process of stress transfer and fracture management, hence boosting shear resistance. By methodically changing solely CFRP orientation and spacing while maintaining the same concrete and steel reinforcing characteristics, this study isolates the impact of the polymer composite factors on the behavior of deep beams. A solid foundation for connecting the observed increases in shear capacity, stiffness, and modes of failure with the intrinsic characteristics of the polymer material is provided by the material characterisation, controlled specimen preparation, and thorough structural testing. The results are applicable to structural engineers as well as polymer scientists and materials researchers who are interested in the real-world use of innovative composite materials in construction thanks to this combined materials-and-methods approach.

3. RESULTS AND DISCUSSION

This section presents and discusses the experimental results obtained from the control and polymer-based CFRP-strengthened reinforced concrete (RC) deep beams, with particular emphasis on the influence of CFRP bar orientation and spacing on shear behavior. The discussion is framed to highlight the interaction between polymer composite material properties and structural response, thereby aligning the findings with polymer science–driven interpretations.

3.1. Compressive and Tensile Strength of Concrete

3.1.1. Strength Evaluation of the Polymer-Based Strengthening System

The mechanical properties of the concrete is the basis for evaluating the contribution of the polymer-based strengthening system. The mean compressive strength evaluated by standard cube and

Table 2: Compressive Strength Results of Concrete Cubes and Cylinders Tested at 28 Days

No of Cubes and Cylinders	Ultimate Compressive Strength fc´(Mpa)	Ultimate Compressive Strength fcu´(Mpa)
1	24.7	28.7
2	24.2	28.47
3	23.65	27.5
4	25.9	30.83
5	28.75	32.67
6	31.5	34.6
Average	26.45	30.46

cylinder tests at 28 days was close to the target value of 30 MPa. The cylinder strength ranged between 84 and 85 percent of the cube strength, which is typical for standard concrete. The differences in the structural response observed in the test are mainly due to the presence and arrangement of the CFRP strengthening system rather than to concrete quality, since all beam specimens were cast from the same lot of concrete and cured under the same conditions. Table **2** presents the compressive strength of the concrete at 28 days evaluated by routine cube and cylinder tests. Concrete cubes had an average compressive strength of 30.46 MPa, whereas cylinders had an average strength of 26.45 MPa. According to actual data documented in the concrete design rules, the strength of cylinders makes up approximately 84.4% of the strength of cubes. These findings demonstrate that the concrete mixture met the desired strength and offered a solid foundation for accurately evaluating the shear performance of the deep beams under test.

3.2. Crack Initiation and Failure Modes

The unretrofitted control deep beam developed a diagonal fracture that started close to the support and moved upward toward the loading point, exhibiting typical shear-dominated behavior. The brittle nature of deep-beam shear mechanisms in the absence of further reinforcement was demonstrated by the quick development of this fracture and the abrupt shear failure that followed. On the other hand, all polymer-based CFRP bar-retrofitted beams showed altered crack propagation behavior and delayed diagonal fracture onset. Through crack plane bridging and stress dispersion throughout the shear zone, the presence of CFRP bars actually prevented diagonal cracks from emerging and growing.

Shear-compression mechanisms were the main cause of failure for beams reinforced with vertically and horizontally oriented CFRP bars (0°/90°). This showed that while vertical CFRP bars increased shear resistance, their ability to intercept diagonal cracks was more constrained than with inclined configurations. Tests of specimens reinforced with 45°/135° inclined CFRP bars revealed more dispersed cracking and occasionally a change in the failure mode toward flexural behavior. This latter change illustrates how inclined CFRP bars are more effective in withstanding major tensile stresses and enhancing the compression strut's integrity.

The ultimate load capabilities of the control and CFRP-strengthened deep beams are displayed in Figure **5**. All of the reinforced beams showed a notable increase in ultimate load when compared to the control specimen (C), demonstrating the efficacy of the NSM CFRP strengthening technique. The inclined CFRP bars behaved better (St-45-15 and St-45-10) than the statistically equivalent beams strengthened with vertical CFRP bars (St-90-15 and St-90-10). The St-45-10 specimen achieved the highest ultimate load of 710 kN, demonstrating that RC deep beams' shear resistance and load-carrying capacity are improved by tighter spacing and an inclined orientation of CFRP.

3.3. Shear Capacity and CFRP Contribution

The experimental results demonstrated a significant enhancement in shear capacity for all CFRP-strengthened specimens relative to the control beam. The direction and spacing of CFRP determine the shear capacity improvements, which range from around 14% to 47%. Because there is better stress transmission between the polymer composite and the surrounding concrete, beams with closely spaced CFRP bars are more resistant to shear. CFRP's strong tensile strength and linear elastic nature, which bridge cracks and reallocate load once diagonal cracking begins, are the main reasons it contributes to shear resistance.

For all of the previously indicated characteristics, the designs with inclined CFRP bars performed better than the equivalent configurations with vertical bars, further demonstrating that the polymer reinforcement aligned with the primary tensile stress channels improves structural efficiency. Materialistically, CFRP

Table 3: Experimental Results of Samples

Model Code	CFRP Orientation (º)	CFRP location	Experimental results					
			First crack load[1] (kN)	Failure load[2] (kN)	Shear Load[3] (kN)	CFRP Contribution to shear[4] (kN)	Enhancement of shear[5] (%)	Failure Modes
C	-	-	120	490	245	-	-	Shear Failure
St-90-15	0/90	10 cm c/c	130	560	280	35	+14.3%	Shear - Compression
St-90-10	0/90	15 cm c/c	145	610	305	55	+24.5%	Shear -Compression
St-45-15	45/135	10 cm c/c	140	615	307.5	62.5	+25.5%	Shear -Compression
St-45-10	45/135	15 cm c/c	160	720	360	115	+47%	Flexural

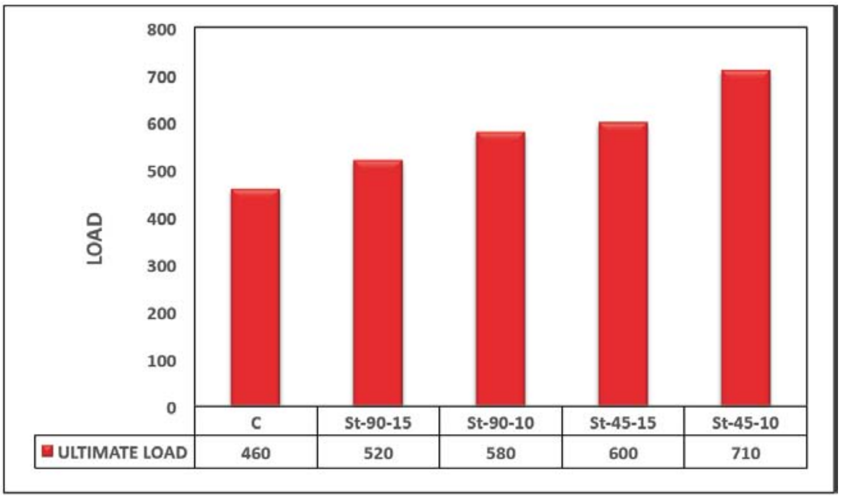

Figure 5: Comparison of ultimate load capacity for the control deep beam and CFRP-strengthened deep beams with different CFRP bar orientations and spacings. The results show a progressive increase in ultimate load with the use of NSM CFRP bars, with the highest capacity recorded for the beam strengthened with 45°/135° oriented CFRP bars at 100 mm spacing.

can withstand high tensile loads at large elastic moduli with little deformation, delaying the beginning of shear failure as well as the deepening of fractures. The CFRP bars' tensile capacity may be mobilized since the epoxy-bonded NSM system guarantees sufficient load transmission at the polymer-concrete contact without early debonding.

3.4. Load–Deflection Behavior and Stiffness Response

During the first elastic phase, the load-deflection curves of the reinforced and control specimens show the same rhythmic pattern; the CFRP wrapping has no influence before fractures appear. However, the CFRP-reinforced beams show more rigidity than the control specimen once the cracks appear. Depending on the wrapping pattern, the CFRP-reinforced specimens can reduce the deflection under the mid-span by as much as 10% to 40% for equal loads.

The nature of the CFRP bars, which include a polymer that maintains them rigid and firmly bound to concrete via an epoxy matrix, is directly responsible for this decrease in deflection.

Reduced deformation and improved post-cracking stiffness were the outcomes of the NSM CFRP bars' efficient sharing of tensile stresses with the internal steel reinforcement. The greatest improvement in stiffness was seen in specimens reinforced with inclined and closely spaced CFRP bars, highlighting the significance of polymer reinforcing distribution and orientation. Figure **6** shows the load-midspan deflection response of the control and CFRP-strengthened deep beams. All specimens exhibited a nonlinear response after a comparable linear response during the first elastic stage, until breaking. After the control beam reached a peak load, a steep load drop occurred, due to a brittle shear failure. On the other hand, CFRP-strengthened beams restrained larger load values with smaller midspan deflection, suggesting they can absorb more energy and are stiffer. The inclined CFRP bars reinforced beams exhibited a better postcracking performance, supporting the

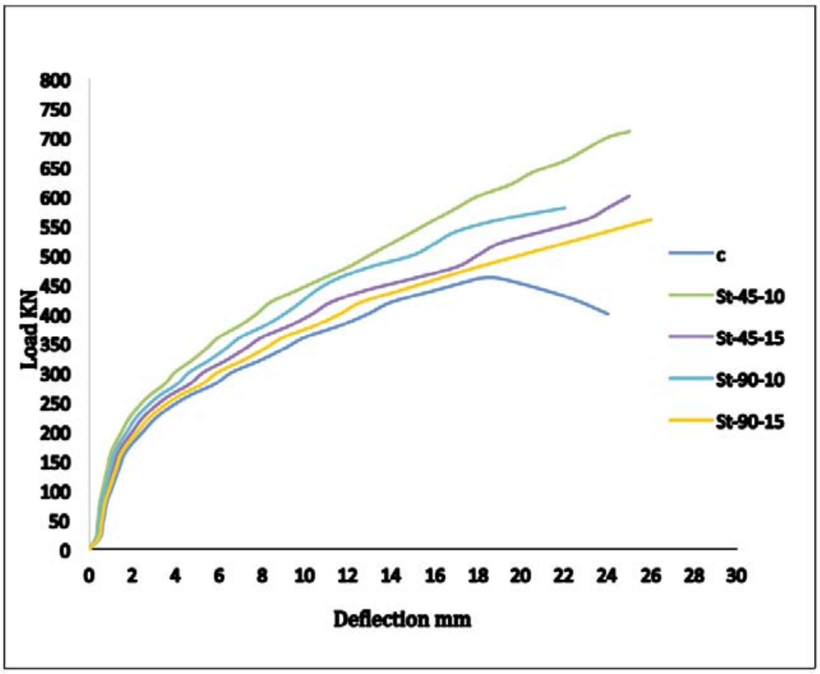

Figure 6: Load–midspan deflection curves of the control and CFRP-strengthened RC deep beams. The strengthened specimens exhibit higher load-carrying capacity and reduced deflection compared to the control beam, with inclined CFRP bar configurations showing improved stiffness and post-cracking performance.

preferred position of CFRP reinforcement to enhance shear resistance and reduce deflection.

3.5. Polymer–Concrete Interaction Mechanisms

The improved shear behavior and deformation control ability of the CFRP have been attributed to the bonding process between the polymer-based CFRP and the concrete matrix. A greater bonding power is induced by the resisting force of the surrounding concrete coverings, and the epoxy glue ensures the stress transfer from the fractured concrete parts to the CFRP. The NSM bonding is preferable to the external bonding, because it protects the polymer and avoids debonding from environmental factors to fully utilize the stresses of CFRP.

When diagonal fractures formed, tensile stresses were more likely to transfer to the CFRP bars, acting as crack arrestors that reduced the concentration of stresses in the concrete. In these cases, the orientation of the CFRP bars became important; diagonal bars were most effective because they were better aligned with the directions and planes of the primary stresses and fractures. This combination of concrete and polymer materials produced enhanced shear resistance and more distributed loading.

3.6. CFRP Angle and Spacing Effects CFRP Orientation

The results show a clear trend that the spacing and orientation of the CFRP bars are important to the effectiveness of the polymer-based shear strengthening. Tighter spacing results in greater overlap of the polymer reinforcing bars with potential fracture paths, resulting in more consistent stress distribution and greater shear resistance. Inclined layouts offer additional benefits by providing a larger angle for the bars to intersect with diagonal fractures. These results illustrate the importance of properly matching the reinforcing pattern in polymer science to take advantage of characteristics such as strength, stiffness and bonding capacity. With the CFRP bars close to the surface and a certain distance apart, this experiment shows that the bars can withstand higher loads inside the concrete. The close alignment of brittle and sudden shear failure in deep beams to controlled and ductile behavior confirms that near-surface-mounted CFRP bars are highly efficient in strengthening reinforced concrete deep beams in shear loading conditions. The improvements in shear resistance, reduced deflection, and changed failure characteristics of reinforced concrete deep beams clearly emphasize how the properties of polymer composites can be utilized in making CFRP systems more promising in sustainable high-performance structures.

4. CONCLUSION

Shear strengthening of reinforced concrete deep beams utilizing polymer-based NSM CFRP bars was the aim of this study and experiment. While the CFRP-strengthened beams showed significant increases in shear resistance, the unstrengthened beam suffered a brittle shear fracture. In comparison to the control beam, the shear resistance rose by 14% to 47% when the direction and spacing of the CFRP bars were changed. The CFRP bar orientation with an inclination of 45°/135° performed better than vertical and horizontal orientations due to better alignment with the diagonal shear cracks and increased stress transfer. The CFRP bars' closer spacing was further helpful in controlling cracks and transferring loads. The mid-span deflection of the beams reduced by 10%–40% for the strengthened beams, showing the high stiffness and linear elasticity of the strengthened beams and their better bonding with the concrete. The results confirm that the NSM CFRP bars made of polymers provide a reliable and practical solution for the increased shear resistance and elasticity of RC deep beams in construction.

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