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FLEXURAL BEHAVIOR OF ALIGNED STEEL REINFORCED CONCRETE BEAMS

Fatima Aboud Kareem [1*], Saad F. Resan [2]

[1]Department of Civil Engineering, College of Engineering, University of Misan, Maysan, 62001, Iraq
[2] Department of Civil Engineering, College of Engineering, University of Misan, Maysan, 62001, Iraq
**Corresponding author E-mail*: fatimaaboud982@gmail.com

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Abstract: The configuration of the steel reinforcement is investigated in this work in connection to the flexural behavior of reinforced concrete beams(RC beams).Employing unique steel reinforcement configurations allowed for the investigation of the influence that the shape of the steel has on the parameters of the concrete beam, such as the cracking load, ultimate load, load-deflection curve , ductility, and energy absorption. Seven beams were manufactured in all, and they were divided in to two groups: those that supported the concrete beams with curved steel bars, and those that used triangular steel reinforcement. Several bars of curved and triangle reinforcement were employed, with two, three, and five bars being utilized.The flexural behavior of reinforced concrete beams was found to be affected by the presence of curved and triangular steel reinforcement, according to research. The curved steel reinforcement not only increased the flexural strength but also significantly enhanced the ultimate load-bearing capacity. Additionally , the cracking strength was marginally increased as a result of the reinforcement. On the other hand, the cracking strength was significantly lower and the final flexural strength was significantly higher for steel bars that were organized in a triangle . In contrast to the triangular form, which showed a decrease in the cracking load of 4.2%-7.1% and an increase in the ultimate load of 7.8%-8.15%, the cracking load increased from 5.7% to 8%, and the ultimate load climbed from 11.4% to 32%. Both of these changes were accomplished by increasing the ultimate load. The ductility of the steel as well as its capacity to absorb energy were both enhanced by the modification of its configuration.

Keywords: steel reinforcement configuration, flexural behavior, curved steel bars, triangular reinforcement, and ductility.

1. Introduction

In recent years, there has been a growing recognition of the necessity of a rational and cost-effective design strategy for structures, which takes into consideration the non-elastic deformation of structural materials. An increasing number of people have accepted this necessity. This deformation results in a redistribution of internal moments and forces inside the structure, which ultimately leads to a significant increase in the structure's strength that is more than what would be achieved by merely taking into consideration elastic deformation. Nevertheless, reinforced concrete is unable to undergo inelastic deformation to the same extent as other types of concrete because of its brittle construction. It is possible that, as a consequence of this, there will be instances in which the capacity of certain important components to bear deformation will be exhausted before the redistribution of internal moments is completely established across the structural entirety. Therefore, it is of the utmost importance to establish thresholds for deformation capability that are commonly acknowledged. [1]. An extensive amount of research, both

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experimental and analytical, has been conducted to incorporate inelastic deformations into the design approaches of concrete structures.The actions of concrete structures that are subjected to non-elastic deformation have been the subject of a significant amount of time and effort spent by scientists to comprehend and measure these actions. These studies are being conducted to develop design methodologies that will guarantee adequate strength and performance while taking into account the limitations imposed by the restricted ability of concrete to deform without causing irreversible damage. Through the incorporation of inelastic deformations into the design process, engineers can generate designs for statically indeterminate structures that are both more efficient and financially advantageous.

By taking this method, it is possible to make better use of the strength of the structural material, and it provides a more accurate portrayal of how the structure behaves under a variety of load and strength conditions [2]. To improve the design procedures and standards for concrete structures, it is necessary to conduct experimental and analytical investigations. This will ensure that the structures are constructed in a manner that is safe, long-lasting, and effective overall. Several different analytical design techniques, which are frequently referred to as limit design theories, were proposed. Using an understanding of the load-deformation characteristics of the structure's sections, the theories work towards the goal of obtaining a solution by satisfying the equilibrium and deformation compatibility requirements of the structure at its ultimate state. This is accomplished by ensuring that the deformation compatibility requirements are met. These ideas are founded on either an understanding of the link between moment and curvature, as proposed by A.L.L. Baker and Gartner [3], or on the intersection of the two. The paragraphs that follow will explain both of these different kinds of comprehension. It has been unambiguously established that the use of the moment-curvature relationship, which was gained in the crucial section, as an appropriate picture of the overall behavior of the structural element is insufficient. This was demonstrated by the data that was gathered from the trials that were carried out. The relevance of developing a solution to the problem based on a knowledge of the connection between moment and rotation was brought to light as a result of this deficit. The European Concrete Committee [4] asserts that the ultimate load theory of design is the most all-encompassing approach to design and that it is founded on the concept of moment rotation.

Because the theory has reached such a more advanced stage of development, it is now conceivable to consider it to be more fit for practical application. This is because the theory has developed to such a stage. [5] The potential of structural elements to undergo considerable deformations after the yielding of tensile reinforcement is referred to as "ductility," and the term "ductility" is used to denote this capacity. This has the potential to save lives because it not only prevents a complete collapse but also provides a warning as to when something is going to fail. Throughout the entirety of the experiment, the ratio of longitudinal steel reinforcement was maintained at a constant value. With the aspect ratio of shear steel plates restricted to the ranges of 4.5 to 8, it was found that the ductility of the material was increased by 36%. This was accomplished without the utilization of bubbles. Lee [6] investigated how the strength, stiffness, and ductility of typical reinforced concrete beams changed. This investigation was carried out through the utilization of moment-curvature diagrams of the beams. When the fraction of tension steel is increased, it was found that the moment and curvature of the concrete strain are increasing, but that they are reducing. This was discovered through the process of analysis. The flexural ductility of lap-spliced reinforced concrete was explored by Wamer [7], who used 24 reinforced concrete beams as the test structure to determine its properties. The research results suggested that the key parameters that determine ductility are the quantity of transverse reinforcement that is placed above the splice as well as the strength of the concrete. However, even though the facilities that are in place to estimate the bond strength of lap-spliced concrete beams are adequate, likely, they will likely not achieve a decent performance because they are ductile. It is essential to increase the yield and ultimate load capacities of beams as well as slabs that are supported by a single direction. Even though increasing the longitudinal reinforcement ratio leads to a decrease in the ductility index, this is the case. To manage the crack width in reinforced concrete members, Smejkal and Proch´azka [8] developed a mathematical equation that possesses the capability to control the crack width. In the research that Fantilli and his colleagues [9] conducted, they realized that the width of the crack is directly proportional to the reinforcement ratio for beams that are constructed out of lightly reinforced concrete. When it comes to the fundamental characteristics of structural elements, ductility is of utmost significance for buildings that are intended to withstand the effects of seismic activity. For this reason, one of the most essential needs of these projects is to guarantee a minimum reinforcement ratio to prevent unexpected failure. This helps to ensure that the constructions are built effectively. On the other hand, concerning the subject of violation, the calculation of the minimum reinforcement ratio for exterior members is the subject of discussion. This is because different design codes have varying requirements for the determination of the minimum reinforcement ratio. This is the reason why this is the current situation. To add insult to injury, researchers favor several formulae of minimal reinforcement ratio, which in turn depend on a variety of features of reinforced concrete. On the other hand, one of the successful qualities that have a considerable influence on the limit is the section size of the members, which is also referred to as depth [9]. Within the context of this particular scenario, there exists a relationship that is inversely proportional between the minimum reinforcement and the depth of the beams. An additional effective parameter in the minimal reinforcement ratio of flexural members, according to Fantilli et al. [9], is the diameter of the reinforcement bars. This is the verdict that their study yields. This is so since concrete and steel exhibit bonding behavior. The rationale behind this is that concrete and steel have distinct bonding tendencies. There is a noticeable difference in the bonding tendency of concrete and steel. In addition, the effect of the concrete-steel bond on small reinforcement was determined to be satisfactory by Ozbolt and Bruckner [10]. The researchers could confirm this data. The minimal reinforcement ratio in beams can be determined by utilizing the modulus of elasticity of concrete and steel, as mentioned by Gerstle et al. [11]. The researchers came up with this suggestion. At least this ratio calls for a certain amount of reinforcement. Because of this, there is a chance that the plastic rotation ability simulation could work. Reinforced concrete (RC) beams' ultimate deformation characteristics were studied parametrically by Kheyroddin and Naderpour [12] to determine the effect of the tension reinforcement index and the bending moment distribution (loading type). To determine the impact of these specific elements, this analysis was conducted. Analytical data for fifteen simply supported beams with varying tension reinforcement ratios made up the published research outcomes. The investigation's findings were symbolized by these beams. These beams were subjected to three separate loading circumstances to evaluate their performance. In addition to comparing these outcomes to the predictions offered by the different formulations, the experimental data was also thought about. The results of an experiment to find the plastic rotation capacity of reinforced high-strength concrete beams are reported by Ko et al. [13]. The results of this investigation are discussed in their publication. A total of thirty-six beams were subjected to a variety of compressive strengths of concrete, tensile reinforcement ratios, and loading types for the researchers to evaluate the plastic rotation capacity. The findings from the experiment were then compared with the results of the numerical analysis. The effect parameters that affect the plastic rotation capacity are potential subjects for a great number of investigations that can be carried out. Steel ratios and size impacts are two examples of the characteristics that fall within this category. For instance, Hilierbogr [14] has argued that the rotation capacity of plastic hinges is dependent on the size of the member and that it is approximately inversely related to the height of the beam. This is an example of a hypothesis that has been brought forward. Researchers such as Mattock [15], Corley [16], Cederwall and Sobko [17], and Bosco et al. [18] are examples of those who have carried out experiments in this field in the past. These scholars have seen a pattern that is comparable to the one that is presented here. To study the impact that size has on the rotation capacity of plastic hinges, the researchers Bigaj and Walraven [19] carried out a series of tests on thin beams that were simply supported.

In addition to that, they went for the rotation capacity. To explore the ductile behavior and plastic rotation of reinforced high-strength concrete beams, a large number of investigations, both experimental and theoretical, have been carried out. These investigations have been carried out to obtain information. Some researchers, including Arslan and Cihanli [20], Bernardo and Lopes [21], and Carmo and Lopes [22], have contributed to these scientific investigations. According to the findings of the investigations, high-strength concrete members have a level of ductility that is sufficient to ensure that they are structurally safe. This is made possible on the condition that an appropriate decision is made concerning the quantity and location of the reinforcement and that the general guidelines that are established for normal-strength concrete structures can also be applied to high-strength concrete structures. Comparing the efficiency of the new technique of reinforcing with the traditional ones was effective according to the previous studies. Regarding the cost and implementation didn't need superior skills.

The main aim of this experimental study was to enhance understanding of how steel reinforcement configurations influence the ultimate strength and structural behavior of reinforced concrete beams. This was achieved through the design and testing of seven beams experimentally. Moreover, the brittleness of the concrete significantly restricts the steel reinforcing designs applicable to these elements which re-configures the steel reinforcement in a new form expected to improve the ductility of the beam. This capacity can be significantly improved by providing appropriate strength by making various configurations of steel reinforcement. The research was undertaken to examine the effects of substantial reinforcement on the deformation capacity and plastic behavior of concrete beams. A central point load was given to three sets of seven simply supported beams, which were reinforced with differing configurations of longitudinal reinforcement.

2. Concrete Mixes and Materials Properties

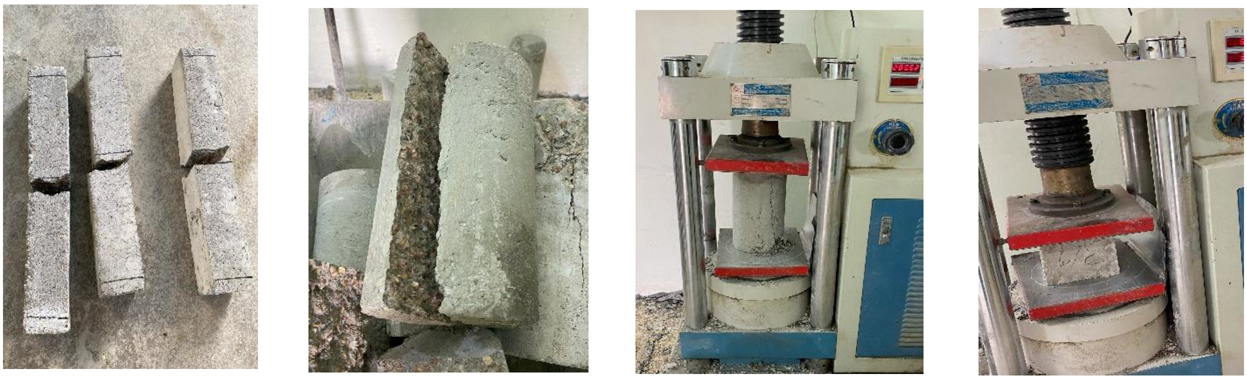
The quantities of the mix that are used in the production of concrete, as well as the elements that are utilized, are presented in Table 1 and Figure 1. The aggregates, cement, sand, water, silica fume, and superplasticizer that were included in the concrete mixture were those that were used. It is required to carry out a physical and chemical analysis of the material before beginning the process of mixing the components of the concrete. In the course of the material inspection, cement was analyzed following the standards that are required in Iraq. Additional tests, including sieve analysis, grading, and compressive strength, were carried out following the requirements of ASTM C109 [24], ASTM C-136 [25], ASTM C191 [26], and Iraqi standards No. 45/1984 [27], respectively. In the combinations, standard cement with the same chemical makeup was used. There were two different kinds of fine aggregates (sand) that were utilized, and their particle sizes ranged from 0.3 to 0.6 millimeters. In line with Iraqi Standard No. 45/1984[27], the selection of coarse aggregates was determined by the sieve analysis that was given in Table 1. The Superplasticizer (PC260), which is also known as the High Range Water Reducing Agent (HRWRA), was incorporated into the combination to fulfill the requirements that are described in ASTM C494 [28]. [29] The combinations were made with potable water that complied with the regulations that were described in the IQS 1703/1992. The steel bars that were utilized had nominal widths of ϕ12 and ϕ8 mm, and their yield strengths were 539 and 441 MPa, respectively. The standard of ASTM A615 was satisfied by the results of the tests conducted on these bars [30]. The experimental investigations that were carried out in the laboratory to evaluate the mechanical properties of concrete are depicted in Figure 2.

Table 1. Concrete Mixes details.

Material /(kg/m3)	NC
Cement.	480
Coarse Aggregate kg/m$^{3.}$ kg/m^3	1082
Super PS. Kf/m^3	3.26
Fine Aggregate	635
Density	2415
w/c.	0.318
fcu (28 days)	45
$f_{t.}$	5.12
$f_{r.}$	7.3

3. Beams Details and Casting Procedure

There were a total of seven molds utilized for this creation. Table 4 demonstrates that the dimensions of these molds are equal to the measurements of the beams that were created, which were 200 mm in length, 350 mm in width, and 1850 mm in height, with an effective depth of 310 mm. Utilizing a scraper and a steel brush, the molds were cleaned and lubricated to facilitate the removal of the objects that were set into the molds. To ensure that the beam specimens had accurate vertical sides and 90-degree corners, the panels of plywood measuring 20 millimeters were precisely cut and assembled throughout the fabrication process. It can be seen in Figure 3 that the plywood was used to construct the bottom of the experiments. Seven different molds were utilized to see this task through to completion. These molds have dimensions that are identical to those of the beams that were created, which were (200 x 350 x 1850) mm in length and had an effective depth of 310 mm. This is shown in Figure 2, which shows that the dimensions of these molds are identical. The molds were cleaned and lubricated with a scraper and a steel brush to make the process of



(a) (b) (c) (d)

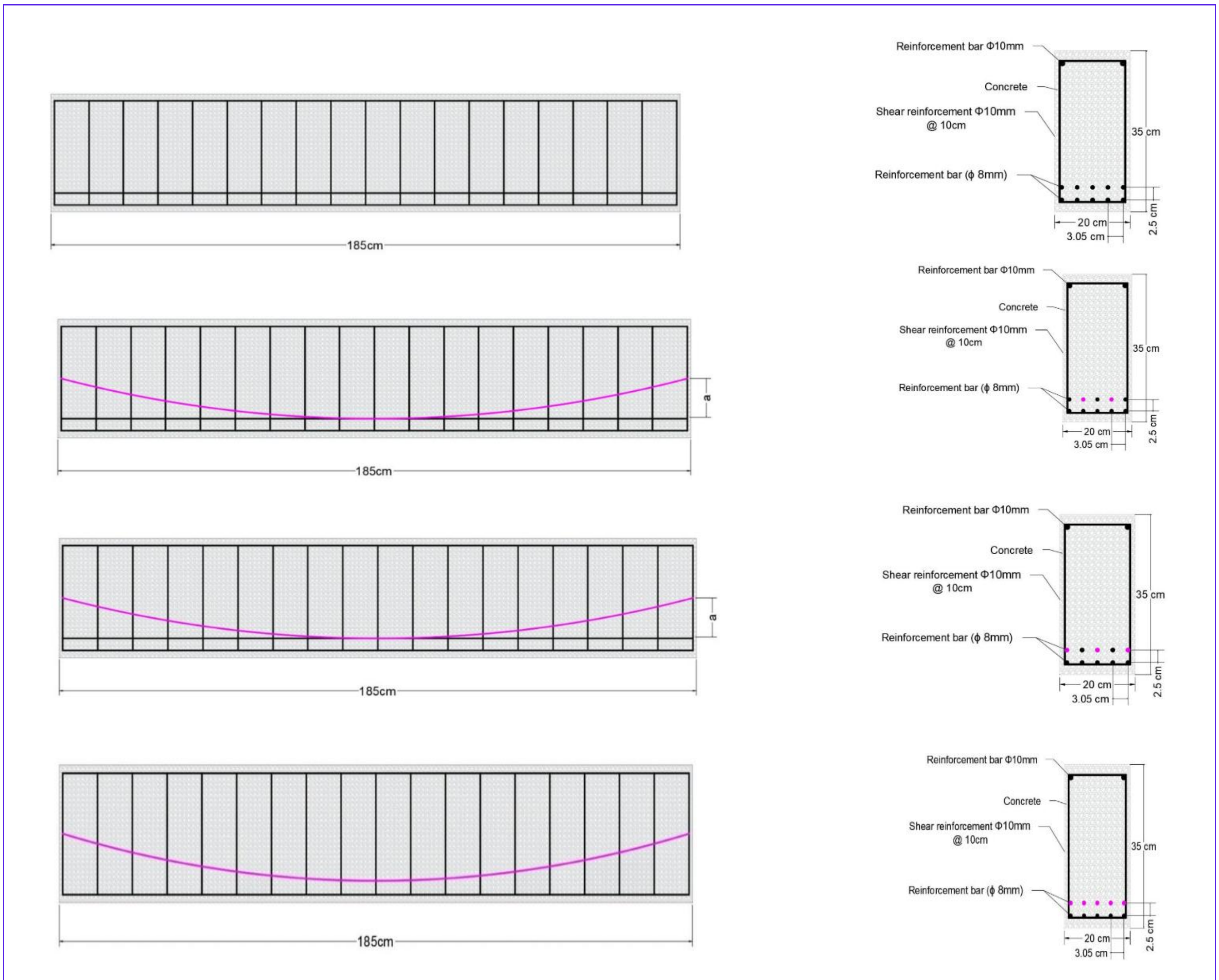
Fig. 1. Laboratory test specimens:(a) flexural test,(b) shear test,(c) cylinder compression test. (d) cube compression test.

demolding relatively simple. This was done to make the process more straightforward. Forms for the beam specimens were created by cutting pieces of plywood with a thickness of twenty millimeters and then constructing them with a great deal of attention to detail. This was done to ensure that the vertical sides were accurate and to provide corners that were at a right angle of ninety degrees. Plywood was used to create the bottom piece, as can be seen in Figure 3. To mix the concrete, mixers weighing one hundred kilograms were utilized. Before the reinforcement, cage, or casting control specimens were inserted into the molds, oil was applied to the control molds and forms. This was done before the testing was performed. Steel bars were placed into the forms, and then they were fixed in place. This was done to ensure that the necessary cover was maintained continuously. Before beginning the process of mixing, each of the components was weighed and then placed in a robust metal container that had been carefully cleaned. As part of the process of casting the concrete, plywood forms were utilized for the molds, and steel forms were utilized for the casting process itself. After twenty-four hours, the forms were taken from the mixture, and thirty-eight days later, the specimens were submerged in water. This occurred after the mixing and casting processes had successfully been completed. Samples were gathered and then poured into concrete cubes and cylinders as part of the process of establishing the concrete attributes of the cast samples. This was done to determine the composition of the concrete. To ensure that the beams were in good condition, a two-point load that was separated by 450 millimeters was applied to them, as can be seen in Figure 3. After reaching the point where the first crack began to appear, the load was gradually applied until it reached its highest conceivable level. This continued until the fracture stopped developing. As can be seen in Figure 3, linear variable differential transformers (LVDTs) were employed throughout the entirety of the testing procedure to carry out accurate measurements of vertical deflection to guarantee the best possible outcomes. Additionally, a thorough documentation procedure was carried out throughout the entirety of the inspection.

This was done in tandem with the examination. There are a lot of important pieces of information that were included in this datasheet. These include the initial fracture load, the ultimate load, deflections, crack modes, and failure modes.

Table 2. Description of Main Specimens.

Variable	Beam Remark	*f'c* (MP)	Dimensions (mm) Width	height	Length	Reinforcement Description
Ref.	BCFS0	45	200	350	1850	Ordinary reinforcement
Partial one-layer curved bars	BCF22	45	200	350	1850	Curvature two bars above
	BCF23	45	200	350	1850	Curvature three bars above
Partial layer Triangular bars	BTF22	45	200	350	1850	Triangles two bars above
	BTF23	45	200	350	1850	Triangles three bars above
alignment of full layer	BCF15	45	200	350	1850	the curvature of all the below bars
	BCF#25	30	200	350	1850	curvature of all the above bars
Partial two-layer aligned bars	BTF1222	45	200	350	1850	triangles four bars in multi-layer



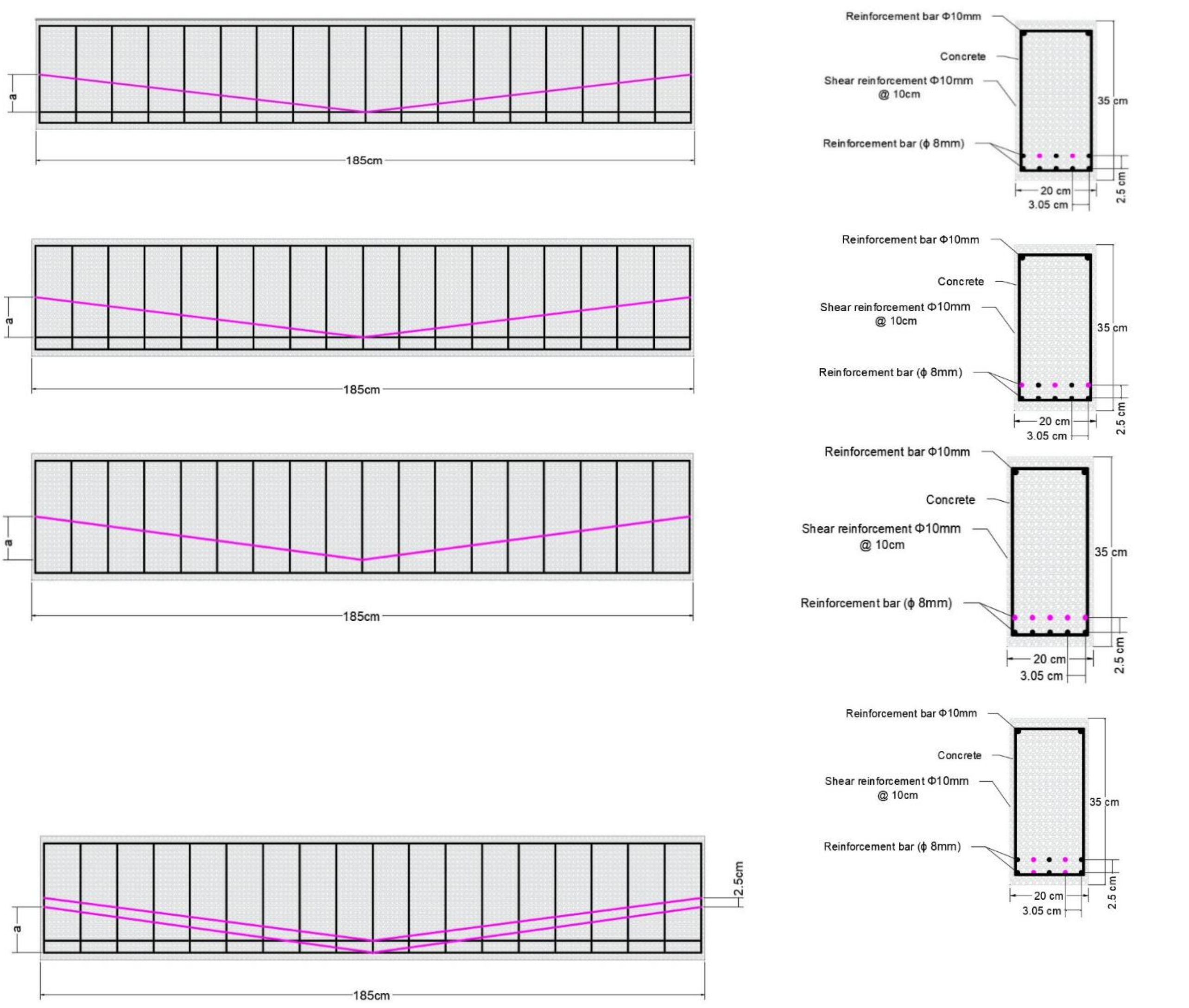


Fig. 2. Details of the tested beam

(a) (b)

Fig. 3. (a) Concrete pouring ,(b) Concrete beam testing.

4 Results and Discussion

The results of the specimens are depicted and summarised in this part. The results are discussed in connection to the cracking load, ultimate load, load-deflection curves, ductility index, stiffness, energy absorption, and failure mechanism.

TABLE 3: Test Result Load Deflection Carve.

Beam remark	Cracking Load (kN)	Ultimate load (kN)	Deflection (mm)	Ductility index	Energy absorption (kN.mm)
BCFS0	55.27	184	20.48	3.33	1892
BCF22	58.46	205	22.72	3.51	2505.01
BCF23	61.54	231	23.36	3.75	3046.12
BTF22	52.41	185	23.12	3.56	2376.35
BTF23	50.96	192	23.62	3.77	2896.65
BTF25	51.36	199	25.64	3.87	3246.67
BCF15	59.14	244.4	28.61	4.94	3068.82
BCF#25	45.97	222.4	34.88	5.20	4063.13
BTF1222	67.21	231.7	23.92	3.97	2732.05

4.1 Aligning the steel Reinforcement in a Curved Form

This section presents the impact of the configuration of the steel reinforcement. The curvature of the steel rebar in a novel configuration influenced the performance of the reinforced concrete beams, resulting in enhancements in cracking, ultimate load capacity, deflection, ductility index, and energy absorption. The control beam demonstrated a cracking load of 55.27 kN and an ultimate load of 184 kN, which dramatically improved when straight steel reinforcement was substituted with curved reinforcement. The BCF22 model, which incorporates the curvature of two steel rebars, demonstrated increases of 5.7% in cracking load and 11.4% in ultimate load, indicating a significant improvement in the structural behavior of reinforced concrete beams. Augmenting the number of curved rebar from two to three demonstrated a greater improvement in both the ultimate and cracking loads when juxtaposed with the control beam, exhibiting a marginal percentage increase of 11.3% in comparison. The comparison of the ultimate load revealed a significant enhancement of 25.5, as illustrated in Fig. 4. Augmenting the curved rebar to five in the second layer of the bottom longitudinal reinforcement resulted in an 8% increase in the cracking load, while the ultimate strength rose to 243 kN, reflecting a 32% enhancement. This represents the most significant increase in ultimate strength, serving as an indicator of the improved plastic limit behavior of the concrete beam with the same reinforcement ratio. The deflection was greatly increased by curving the steel rebar, with enhancements of 10.9% and 16.4% observed for the curving of two and three rebars, respectively, as illustrated in Fig. 4. The maximum deflection was seen in model BCF25, which incorporated the curvature of five rebars, demonstrating an increase of 27.9%, as illustrated in Fig. 4. Curved longitudinal bars exhibit increased deflection compared to straight bars due to several interrelated factors that impact their structural behavior. The primary reason lies in the geometry of the bars, which alters how loads are distributed along their length. When a curved bar is subjected to bending forces, its moment of inertia, which is a measure of an object's resistance to bending, is generally reduced in the direction of the applied load. This reduction means that the bar is less able to resist deflection, resulting in greater displacement under the same load compared to a straight bar of similar cross-section. Moreover, the curvature changes the load path, leading to non-uniform stress distributions. This can create localized stress concentrations that exacerbate deflection. Additionally, the curvature can influence the internal forces within the bar. As the bar bends, the outer fibers experience tension while the inner fibers are subjected to compression. This differential stress can lead to greater overall deformation, particularly when the curvature is pronounced.

4.2 Aligning the steel Reinforcement in a Triangular Form

Putting the steel rebar in three triangles changed how the RC beams behaved, which made their cracking, maximum load, deflection, ductility index, and energy absorption better. First, there is the control beam, which had a breaking load of 55.27 kN before triangle reinforcements were added instead of straight ones. When triangular bars were used instead of two steel rebars in Model BTF22, the cracking load went down by 4.2%, but the final load strength was almost the same as in Control Beam BCFS0. When three bars were added to the triangle, the ultimate load went up and the breaking load went down compared to the control beam and by only 7.8% compared to the model with two angled triangle rebar. There was a 4.3% improvement in the final load, as shown in Figure 5. In concrete beams reinforced with the same ratio, adding five inclined rebars to the second layer of bottom longitudinal reinforcement lowered the cracking load by 7.1% and raised the ultimate strength by 8.15%, reaching 199 kN. This shows that the plastic limit behavior got better. As you can see in Figure 5, when the steel rebar was tilted, the displacement was 12.9% higher in the model with two inclined rebars and 15.3% higher in the model with three inclined rebars. Figure 5 displays that the model BCF25, which has five rebars bent, had the most movement, 25.2% more than the other models. The decrease in the cracking load in this type of beam was due to the triangular weakest connection point at the midspan of the beam which the first crack initiated at this point.

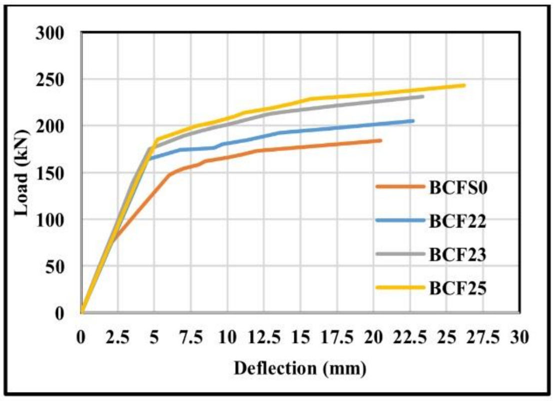


Fig. 4 Load deflection curve of curved steel reinforcement beams

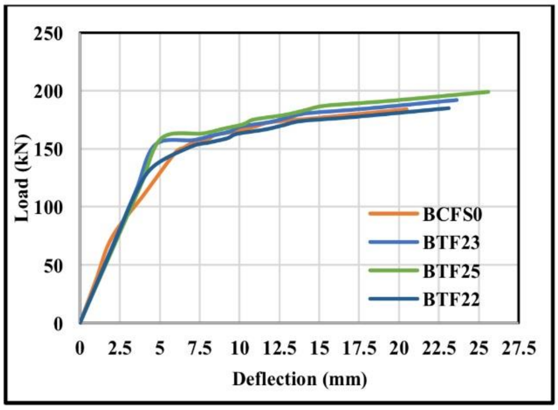
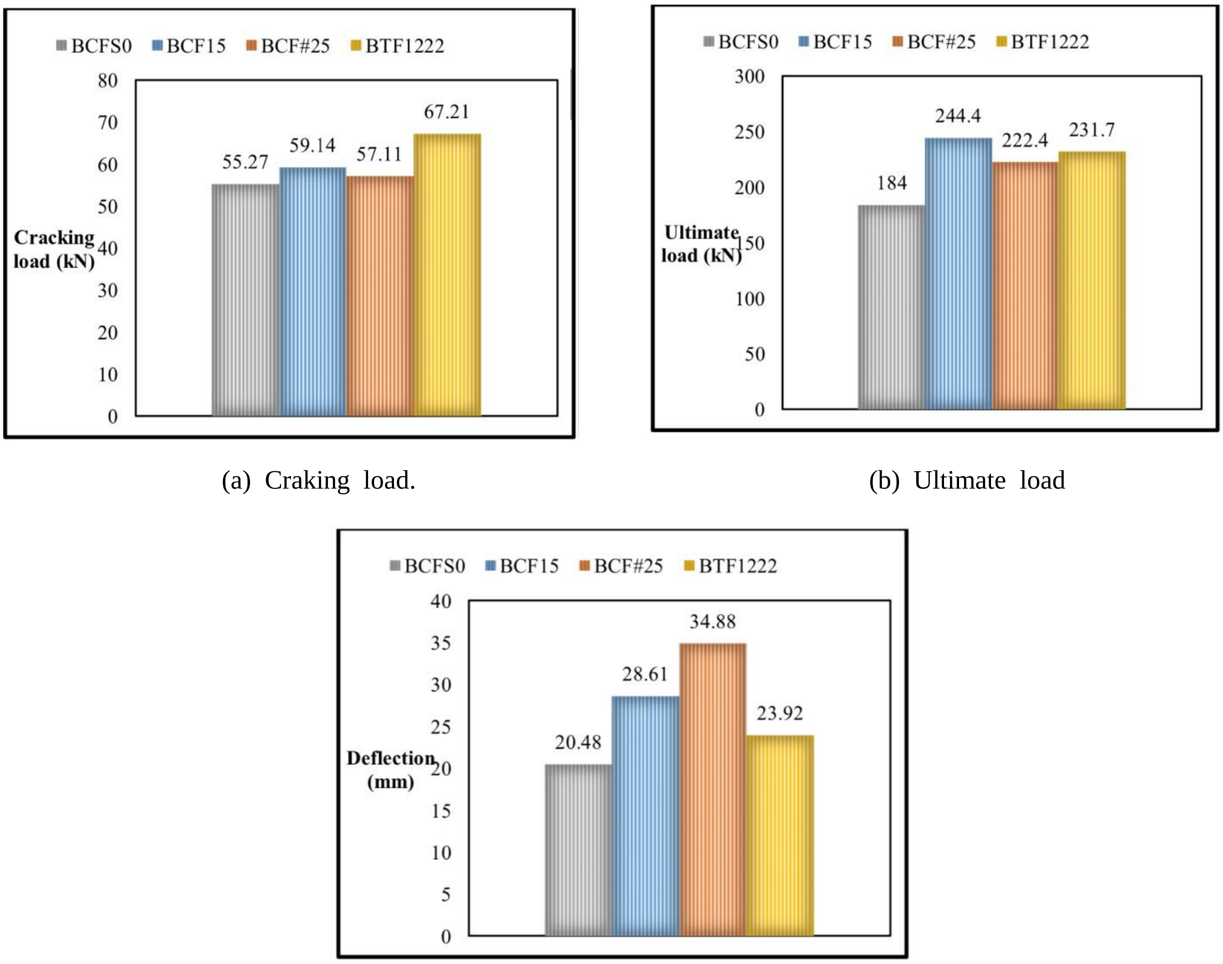


Fig.5. Load deflection curve of triangular steel reinforcement beams

4.3 Effect of alignment of full layer Reinforcement

Putting the aligned steel rebar made the RC beams behave differently, which made their cracking, maximum load, deflection, ductility index, and energy absorption distinct. First, there is the control beam, which had a breaking load of 55.27 kN before the reinforcement's replacement was added instead of straight ones. When curved bars were used in a full layer instead of partially curved steel rebars as in Models BCF15 and BCF#25, the cracking load increased to 59.14 kN and 57.11 kN with percentages of 7% and 3.3% as seen in Fig. 6 a. The ultimate load for the same beams enhanced by 32.8% and 20.9% respectively. The reinforcing with curved bars with a full layer as a second layer improved the strength more the first layer and the curving of the bottom layer completely increased the deflection by 70.3% as revealed in the Figure below. Regarding the triangular form alignment, hybridization of the two layers with four aligned bars (two bars for each layer) enhanced the cracking and ultimate load by 21.6% and 25.9% respectively as seen in Figure below. The deflection was changed by 16.8%.



(a) Craking load.

(b) Ultimate load

(c) Maximum deflection.

Fig. 6. Result of beams (BCF15, BCF#25, and BTF1222).

4.4 Ductility Index and Energy Absorption of RC Beams

According to the Concrete Ductility Index, a material can change shape a lot of times without breaking suddenly. Structures made of ductile concrete can change shape in clear ways, like cracking and twisting when they are put under flexural loads. Many things can change the ductility of concrete, but adding curved and triangular steel support can make it much more flexible. Those things help control and spread cracks, making things stronger and avoiding sudden failure. To find the ductility, you need to find the ratio of the ultimate deflection (Φu) to the yield deflection (Φy) [5]. While the area under the load-displacement curve [30] can be used to measure the energy absorption. The flexibility index and energy absorption of RC beams are shown in Table 5 and Fig. 7. The strength of the control beam BCFS0 was 3.33, but it got stronger when two bars were switched out for bent steel rebar. It went up to 3.51, which is a 5.4% improvement. When the number of bent beams was increased from two to three, as it was in the model (BCF23), the ductility got better by 12.6%. The ductility index went up to 4.07, which is equal to 22.2% for the beam with more bent rebars (BCF25), as shown in Fig. 7. When steel bars were shaped like rectangles, they made the ductility index better by 6.9%, 13.2%, and 16.2% for beams reinforced with two, three, and five triangle-shaped bars, respectively (Fig. 7). For the fully layers aligned reinforcement the ductility improved with 48.3% and 56.2% for beams with full aligned first and second layers (BCF15 and

BCF#25). Regarding the triangular form alignment, hybridization of the two layers with four aligned bars (two bars for each layer) enhanced the ductility by 19.2% respectively as seen in Figure below. When it came to energy absorption, it was the property that changed the most in the structure's behavior, and curving the steel reinforcement made it much better at absorbing energy. This beam, called BCFS0, had an energy absorption of 1892 kN.mm. This went up to 2505 kN.mm when two bars were changed with curved steel rebar, which is a 32.4% increase. When the number of bent beams was increased from two to three, as it was in the model (BCF23), the energy absorption got better, by 61%. Figure 7 shows that the energy absorption went up to 3492.63 kN.mm for the higher curved rebar number beam (BCF25), which is equal to 84.6%. It was better at absorbing energy when the steel bars were arranged in a rectangular shape. This was true for beams with two, three, or five triangle-shaped bars, as shown in Fig. 7. The energy absorption increased by 62.2% and 114.8% for beams with perfectly aligned first and second layers (BCF15 and BCF#25). Regarding the triangle form alignment, the hybridization of the two layers with four aligned bars (two bars for each layer) increased energy absorption by 44.4%, as seen in the figure below.

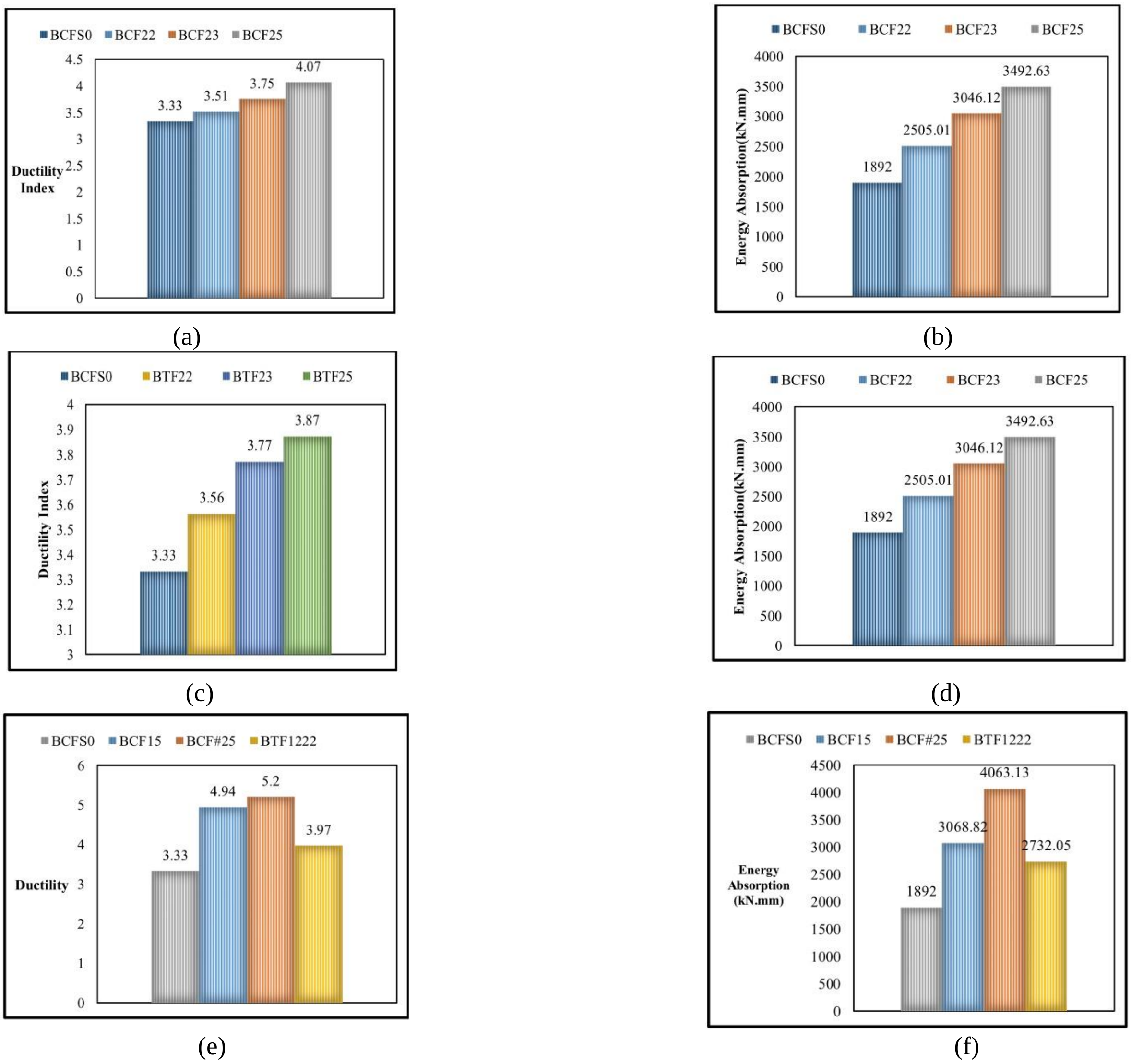


Fig. 7. Result of ductility index and energy absorption.

4.5 Cracking and Failure Mode

The Curved Steel Reinforcement Beams (CSRBs) exhibited the first cracking at the beam's midspan, in the tension fiber. The cracks in the CSRBs were observed to broaden and spread towards the applied load, indicating a more distributed cracking pattern. Compared to the regular reinforced beams, the CSRBs displayed more severe cracking, and the cracks spread over wider areas. The beams with two or three curved steel rebars (BCF22 and BCF23) showed a cracking pattern similar to the reference beam (BCSF0), with the crack diameter being around half that of the CSRBs. This suggests that the increase in the number of curved steel rebars (from two to three) did not significantly alter the cracking pattern compared to the reference beam. The beam with the highest degree of steel bar bending (BCF25) exhibited more deformation than the control beam when the cracks spread to the compression area. The previous beams (with fewer bent steel bars) had wider cracks than this beam, indicating that the increased bending of the steel bars may have influenced the crack propagation. The beams reinforced with triangle steel rebar showed a larger deformation area compared to the conventional beams. The cracks in these beams were wider than the control beam but narrower than the cracks observed in the CSRB specimens. Overall, the observed differences in crack patterns and failure mechanisms can be attributed to the influence of the curved and bent steel reinforcement configurations. The CSRBs exhibited a more distributed cracking pattern, likely due to the curvature of the reinforcement, which can enhance the load transfer and crack distribution within the beam. The beams with a higher number of curved steel rebars or increased bending of the reinforcement showed variations in the cracking behavior, suggesting that the degree of reinforcement curvature and bending can impact the failure mechanisms. The comparison to the control beam and the differences observed between the various reinforcement configurations provide insights into the structural performance and crack development characteristics of these beams. Understanding these failure patterns is crucial for optimizing the design and application of curved or bent steel reinforcement in structural elements. The use of curved bars in reinforced concrete structures significantly impacts crack patterns and failure modes due to their influence on load distribution and stress concentrations. Unlike straight bars, curved bars alter the path of loads within the concrete, which can lead to uneven stress distribution and increased deflection under load. This can result in flexural cracks developing at unexpected locations, often following the curvature of the bars rather than a linear path. Additionally, the curvature can create points of stress concentration, particularly at bends or anchorage points, which may lead to localized cracking. In terms of failure modes, structures with curved bars may experience premature flexural failure, where the concrete crushes before the reinforcement yields, due to the combined effects of increased deflection and altered stress distribution. Furthermore, if the design does not adequately address these factors, shear cracks may occur, particularly in regions with insufficient transverse reinforcement.

Fig. 8. Cracks pattern for beams.

5. Conclusions

This study explored the flexural performance of concrete beams incorporating inclined steel reinforcement. The findings reveal several significant insights into the behavior and performance of these beams, leading to important conclusions. The inclusion of curved steel reinforcement markedly enhanced both the cracking and ultimate load capacities of reinforced concrete (RC) beams. This improvement underscores the positive impact of curved reinforcements on structural performance. When straight steel reinforcement was replaced with curved rebars, notable enhancements were observed, with cracking loads increasing by up to 8% and ultimate loads rising by as much as 32%. These results highlight the effectiveness of curved reinforcement in optimizing structural behavior. As the number of curved rebars increased from two to five, a progressive enhancement in ultimate load capacity was recorded, culminating in a 32% increase for the configuration with five curved rebars. However, this increase in capacity was accompanied by greater deflection, particularly in configurations with more curved bars. This suggests a trade-off between strength and deflection characteristics, which must be carefully considered in design. The addition of curved reinforcement also improved the ductility index of the RC beams, signifying that these designs can accommodate greater deformation without experiencing sudden failure. This characteristic enhances overall safety, with both curved and triangular rebar configurations contributing to improved ductility. Notably, the beam reinforced with five curved rebars demonstrated a 22.2% increase in ductility. Furthermore, curved steel reinforcement significantly boosted the energy absorption capacity of the RC beams, with increases of up to 84.6%. This improvement indicates potential benefits under dynamic loads, making these beams suitable for applications requiring enhanced energy dissipation. In contrast, transitioning to triangular configurations for steel reinforcement did not yield similar improvements. The cracking load slightly decreased, suggesting that triangular arrangements may not be as effective as their curved counterparts. Distinct failure mechanisms were observed in beams reinforced with curved steel, characterized by larger crack widths and unique deformation patterns compared to traditional beams. The differences in crack patterns and failure mechanisms between the curved and triangular rebar configurations were notable. Curved rebar beams exhibited more extensive cracking, while triangular rebar beams showed a larger deformation area with cracks that were wider than those in traditional beams but narrower than those in curved steel reinforcement beams. In conclusion, the findings of this study emphasize the advantages of using curved steel reinforcement in hybrid concrete beams. The enhanced load capacities, improved ductility, and greater energy absorption potential make these beams a promising alternative in structural applications. However, the trade-offs regarding deflection and the varying effectiveness of triangular reinforcements highlight the need for thoughtful design considerations. Future research could further investigate the implications of these reinforcement configurations under different loading conditions and explore additional hybrid materials to optimize performance. The reinforcing with a full layer enhanced the flexural performance with a significant increase in the deflection which the aligning of the steel reinforcement, especially in the first layer decreased the resistance to the deflection.

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