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Numerical Investigation of the Behavior of Concrete Beams Reinforced with FRP Polymer Stirrups in the Form of Straps

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ABSTRACT

In reinforced concrete structures that are in corrosive environmental conditions, there is always a discussion of reinforcement corrosion. Therefore, because of the smaller diameter compared to longitudinal rebars and closer to the surface and consequently closer to the corrosive factors, stirrups are more affected by this corrosion. One of the most effective ways to prevent corrosion of stirrups is to use FRP rebars in structures exposed to corrosion. One of the disadvantages of using FRP rebar is that it is brittle, which makes it impossible to bend these rebars in a workshop environment. Therefore, a group of researchers suggested the use of straps made of FRP plates as stirrups and concluded some laboratory studies in this field. Now, the main goal of this study is to numerically investigate the behavior of beams made with this type of stirrups. For this purpose, 13 beams were modeled in Abaqus software and subjected to three-point bending loading. Also, things such as the type of FRP used, the width of the stirrups, the number of layers of the stirrups and the installation location of these stirrups were investigated and studied. The results of this study showed FRP stirrups with a cross-section equal to steel stirrups have a higher load capacity than beams with steel stirrups. Also, in terms of the beam's ductility, the beam with FRP stirrups has less ductility than the beam with steel stirrups. Regarding the effect of the number of FRP stirrup layers, the results showed that in stirrups with fixed width and variable number of layers, increasing the number of FRP stirrup layers will increase the bearing capacity and reduce ductility.

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1. Introduction

Traditionally, reinforced concrete structures have been utilized in proximity to water and in marine environments. The use of reinforced concrete in marine structures dates back nearly 130 years, starting in1896[1]. In many of these structures, corrosion and the reduction of structural capacity are critical issues. The loss of part of the structural capacity to withstand gravitational and lateral loads due to the corrosion of both longitudinal and transverse reinforcements is a serious concern. Therefore, finding methods to prevent the reduction of structural capacity is considered crucial. Transverse reinforcements are more susceptible to corrosion due to their closer proximity to the surface and smaller diameter compared to longitudinal bars[2,3]. The introduction of FRP (Fiber Reinforced Polymer) fibers and, consequently, FRP bars has somewhat alleviated this problem. These fibers can be carbon, glass, aramid, etc., resulting in composites known as AFRP (Aramid Fiber Reinforced Polymer), GFRP (Glass Fiber

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Reinforced Polymer), and CFRP (Carbon Fiber Reinforced Polymer). Composites consist of a binding material, usually epoxy, combined with an appropriate amount of fibers[4]. The most significant advantage of FRP materials is their excellent resistance to corrosion; thus, their application in reinforced concrete instead of steel rebar in corrosive environments has gained considerable attention[5] . However, the use of FRP materials imposes high costs on projects due to their inherent disadvantages, which has led some researchers to advocate for the simultaneous use of steel bars as longitudinal reinforcements and FRP as transverse reinforcements. This approach helps prevent corrosion in transverse reinforcements while also reducing costs.On the other hand, using FRP bars as transverse reinforcements can create challenges due to their brittle behavior during bending at corners. Therefore, this study aims to utilize FRP sheets that do not present such issues as strips and numerically investigate the behavior of such structures. Numerous studies have been conducted on the behavior of reinforced concrete structures utilizing FRP materials. Research by Chatoupadze in 2018[6], Liang et al in 2023[7], Kohi et al. in 2022[8], and Sharbatdar et al. in 2014[9] are among those indicating improved performance across various parameters for these structures.

The idea proposed by Sharbatdar et al., regarding using strips made from FRP sheets as stirrups serves as a foundation for this study; it aims to further explore this concept and gather more detailed information about this system.To achieve this goal, 13 beams were modeled in Abaqus software and subjected to three-point bending loads while examining various factors including stirrup material type, width, layer count, and installation locations. The results indicate that FRP stirrups with a cross-section equivalent to steel stirrups provide greater load-bearing capacity compared to beams with steel stirrups. Additionally, in terms of ductility, beams with FRP stirrups exhibit lower ductility than those with steel stirrups. Regarding the effect of the number of layers of FRP stirrups, results showed that increasing the number of layers with a fixed width leads to increased load-bearing capacity and reduced ductility.

2. Research Methodology

2.1. Modeling

To investigate the behavior of beams with FRP stirrups, a beam measuring 150 cm x 20 cm x 25 cm was modeled with steel longitudinal rebar and FRP stirrups (as shown in Figure 1) using finite element software Abaqus and subjected to three-point bending tests. For modeling purposes:

- Concrete Beam: Solid elements were used.
- Loading Plate & Supports: Wire elements were utilized for modeling steel rebars.
- FRP Strips: Shell elements were employed.

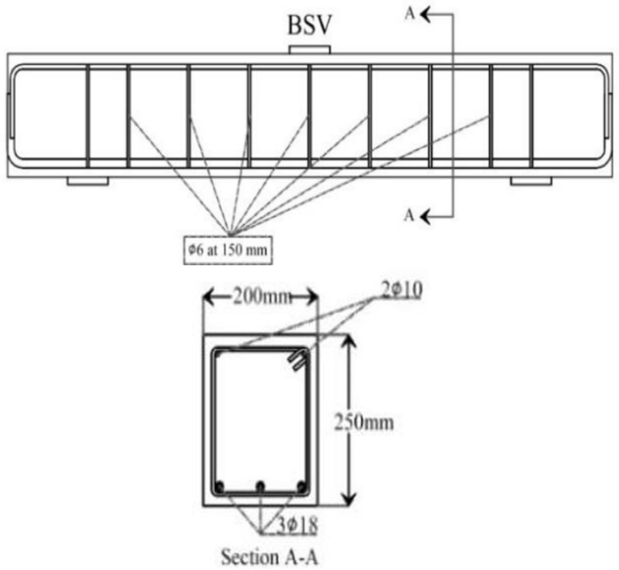

Figure 1. Details of the Modeled Beam[9]

The concrete was introduced into the software using the Concrete Damage Plasticity (CDP) model due to its suitability for simulating brittle materials like concrete. This model incorporates two mechanisms for tensile cracking and compressive crushing damage.The stress-strain curve for the concrete used in this study (37 MPa compressive strength) is illustrated in Figure 2

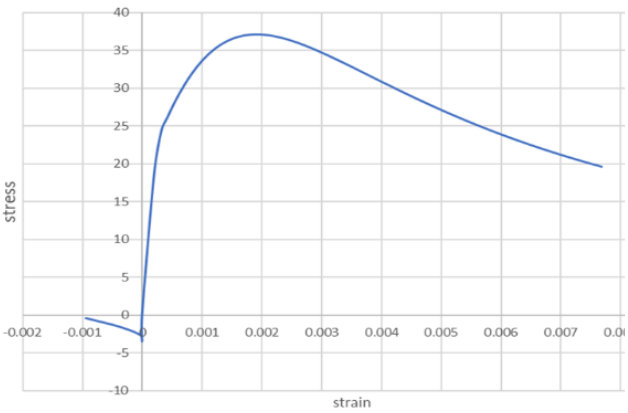

Figure 2. Stress-Strain Diagram of Concrete Modeled in Software[10]

The steel was considered as an elastic-plastic material with a bilinear model; its stress-strain curve is shown in Figure 3.

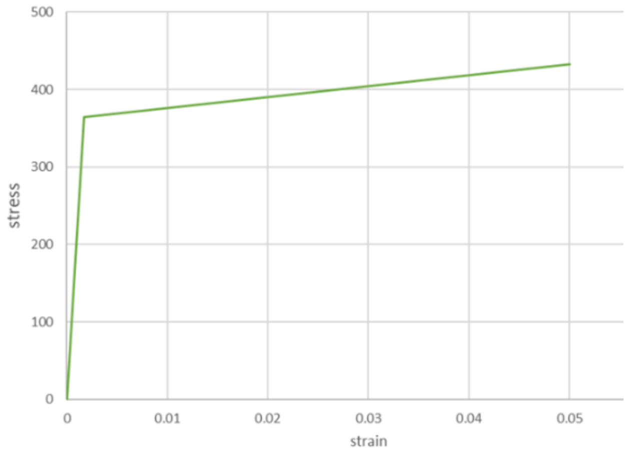

Figure 3. Stress-Strain Diagram of the Steel Used[10]

For modeling the properties of FRP materials, Composite Layup was utilized; elastic and plastic characteristics are listed in Table 1 along with fiber orientation illustrated in Figure 4.

Table 1.
Elastic and Plastic Properties of FRP Materials Entered into the Software[10]

	Yield Stress	Plastic Strain	Young's Modulus	Poisson's Ratio
gfrp	1825	0	80000	0.3
	1830	0.023		
cfrp	3680	0	242000	0.3
	3690	0.012		
afrp	2200	0	150000	0.3
	2250	0.02		

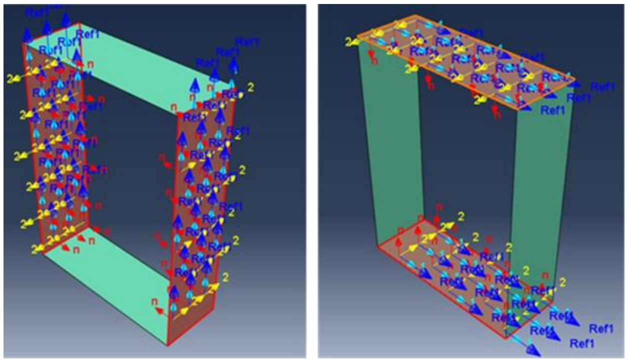

Figure 4. Orientation of the FRP Fiber Alignment

To conduct the analysis without encountering software convergence issues, Dynamic Explicit analysis was employed; displacement at each loading step is calculated based on node acceleration without forming a global stiffness matrix for faster computation.In this modeling approach:

- Surface-to-Surface Interaction was used for contact between pressure plates and beam surfaces.
- Rigid Body Constraints were applied for modeling pressure plates and supports.
- Embedded Region Constraints were applied for longitudinal rebar and FRP stirrups.

Boundary conditions similar to laboratory setups for three-point bending tests were established: two fixed points served as supports without displacement allowance while a third point applied pressure via hydraulic jacks allowing vertical movement only (as shown in Figure 5).

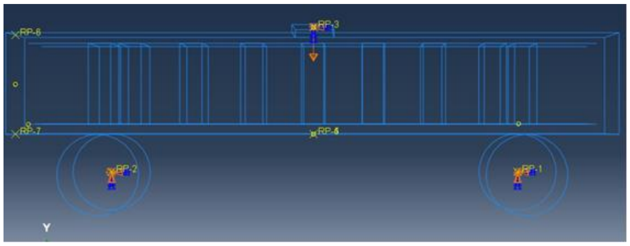

Figure 5. Application of Boundary Conditions to the Beam

Mesh generation was performed separately for each component with a mesh size of 20 mm extending from edges inward (illustrated in Figure 6).

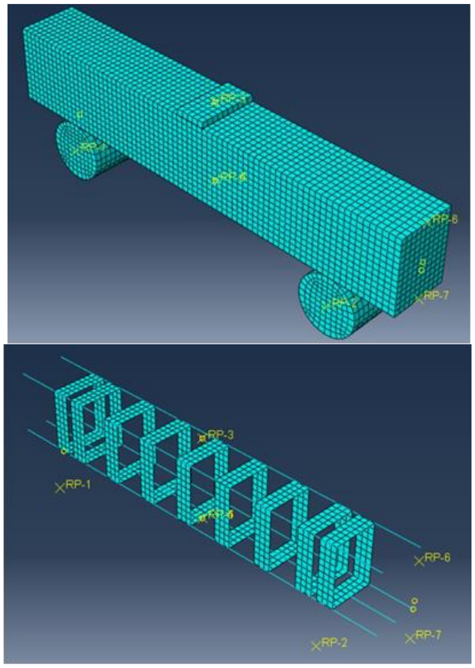

Figure 6. Mesh Representation of Model Components

2.2. Validation

For validation purposes in this study, laboratory results from Sharbatdar et al. were utilized; validation can be assessed through graphical representation comparing force-displacement curves obtained from experimental data (shown in Figure 7).

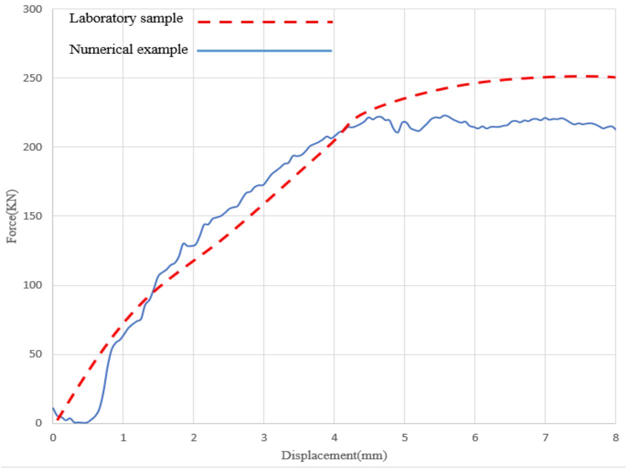

Figure 7. Force-Displacement Diagram of the BFV Sample

The results indicate a 10% difference between laboratory sample results and modeled samples within the software; this discrepancy can be attributed to variations in mesh generation between metallic stirrups and FRP stirrups along with other factors affecting data recording methods during experiments.Graphically assessing initial crack formation and failure paths allows comparison between laboratory samples and numerical models (illustrated in Figures 8 and 9).

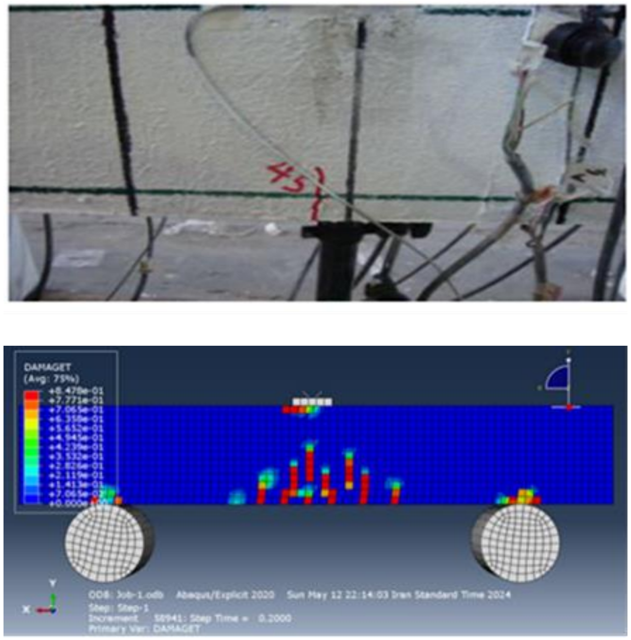

Figure 8. Path of Initial Crack in Laboratory and Modeled Sample[9]

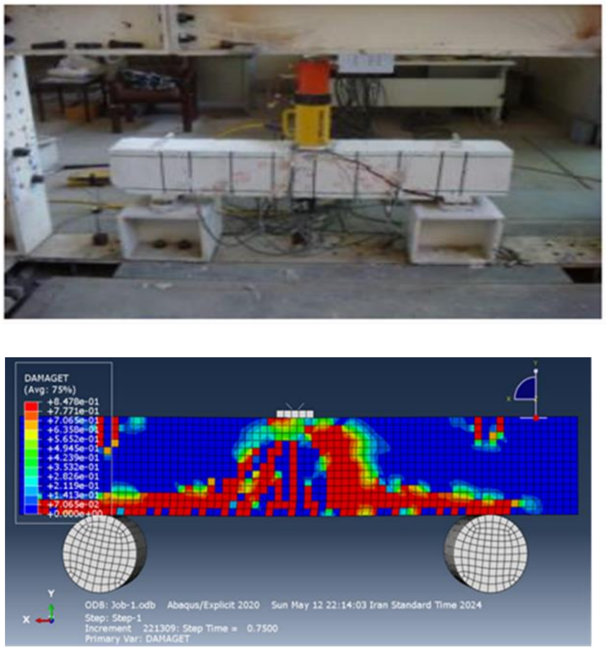

Figure 9. Failure Path of the Beam in Laboratory and Modeled Sample[9]

As illustrated in the graphical representations, the initial cracks appear in the middle of the beam, and the failure path aligns in both the laboratory and numerical models, validating the results of this study.

2.3. Introduction of Study Models

In this study, 10 beams were examined, all of which had fixed dimensions and longitudinal reinforcement bars, with only the FRP stirrups differing among the beams. Table 2 presents the types of stirrups modeled in the beams under consideration. These stirrups vary in terms of material, number of layers, and width.

Table 2.
Specifications for Various Types of FRP Stirrups

type	width (mm)	Number of layers
GFRP	54.9	3
CFRP	54.6	2
(Diagonal)CFRP	54.6	2
CFRP	54.9	3
AFRP	54.9	3
GFRP	82.5	2
GFRP	41.58	4
GFRP	54.9	2
GFRP	54.9	4
GFRP	54.9	5

All constructed beams were compared in terms of capacity and ductility across three aspects: the effect of stirrup material, the effect of stirrup layer count, and stirrup width.

3. Results and Discussion

3.1. Examination of Stirrup Material Impact on Beam Behavior

This section investigates the behavior of beams with various types of FRP stirrups compared to those with steel stirrups. The FRP stirrups were three layers thick with a width of 54.9 mm, forming a cross-section equivalent to a #6 steel stirrup. The resulting graph from this analysis is shown in Figure 10.

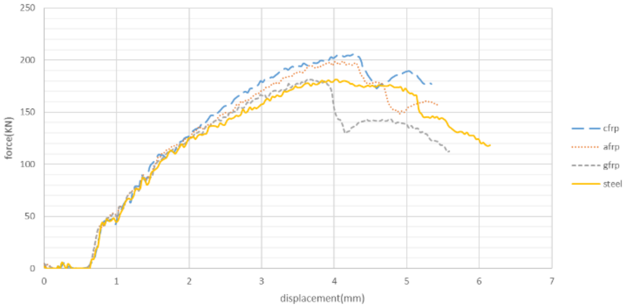

Figure 10. Force-Displacement Diagram for Beams with Steel, CFRP, GFRP, and AFRP Stirrups

Table 3 displays the maximum load-bearing capacity for each of the four models .Additionally, Table 4 illustrates the ductility characteristics of the examined beams

Table 3.
Load-Carrying Capacity of Beams with Steel, CFRP, GFRP, and AFRP Stirrups

percentage of additional capacity compared to steel stirrups	maximum load-bearing (KN)	type
-	181/558	steel
13	205/058	CFRP
0	181/345	GFRP
9	198/269	AFRP

Table 4.
Ductility of Beams with Steel, CFRP, GFRP, and AFRP Stirrups

Percentage of reduction in ductility compared to steel stirrups	ductility	type
-	1/5315	steel
18	1/2482	CFRP
2	1/50	GFRP
11	1/3540	AFRP

Due to the behavior of FRP materials, beams with FRP stirrups exhibit higher capacity but lower ductility compared to those with steel stirrups. Given that the objective of this study is to prevent corrosion in stirrups, an increase in cross-sectional capacity is not deemed significant. Moreover, considering that the behavior of beams with GFRP stirrups closely resembles that of those with steel stirrups, GFRP can be regarded as a viable alternative to steel stirrups.

3.2. Examination of Stirrup Width Impact on Beam Behavior

To investigate the impact of stirrup width on beam performance, three beams were studied. The stirrups used in these three beams had identical cross-sectional areas of 28.27 mm² but differed in width and layer count. Figure 11 schematically displays the cross-sections of these stirrups without scale.

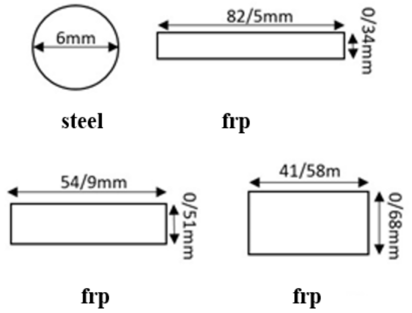

Figure 11. Schematic Cross-Sections of Modeled Stirrups (Not to Scale)

The results obtained are illustrated in Figure 12 and summarized in Table 5

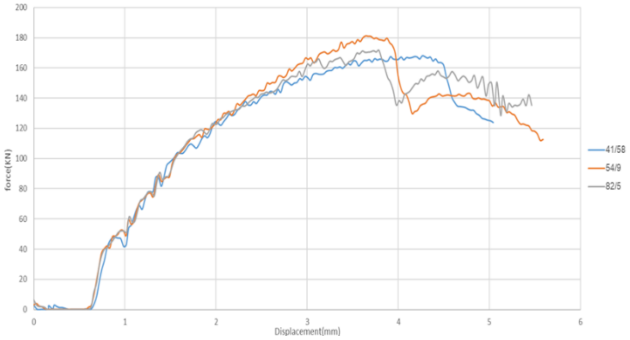

Figure 12. Force-Displacement Diagram for Three Models with Wide, Medium, and Narrow Stirrups

As shown in Figure 12 and Table 5, the highest load-bearing capacity belongs to the sample with a stirrup width of 54.9 mm, while the other two samples exhibit lower capacities. The reduced capacity observed in the sample with a width of 58.5 mm may be due to the close proximity of wider stirrups to each other, resulting in a separation between the core and outer layers of the beam, effectively creating two internal and external layers. This dual-layer configuration can lead to a reduction in capacity as the outer layer may fail before reaching peak performance.

Table 5.
Specifications for Various Types of FRP Stirrups

bearing capacity	width
168/041	41/58
181/345	54/9
171/614	82/5

3.3. *Examination of Stirrup Layer Count Impact on Beam Behavior*

[To this end, four beams were modeled with equal-width stirrups but varying layer counts. All stirrups had a width of 54.9 mm and were categorized into four types: two-layered, three-layered, four-layered, and five-layered configurations. The force-displacement curves for all four modeled beams are visible in Figure 12.As depicted in Figure 12 and Table 6, increasing the number of layers in the FRP stirrups leads to an increase in beam capacity without compromising design integrity.

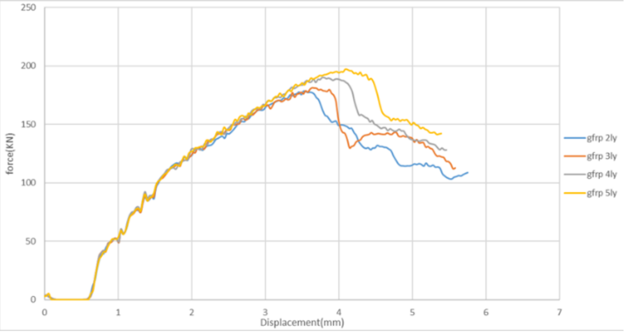

Figure 13. Force-Displacement Diagram for Beams with Varying Layers of Stirrups

Table 6.
Load-Carrying Capacity of Beams with Different Layer Counts of Stirrups

Number of layers	bearing capacity
2	176.364
3	181.345
4	189/438
5	196.901

Moreover, as indicated in Table 7, ductility values decrease by approximately seven to eight percent with each additional layer added.

Table 7.
Ductility of Beams with Different Layer Counts of Stirrups

Number of layers	ductility
2	1.634
3	1.534
4	1.414
5	1.319

4. Conclusion

Based on this study's findings, the following conclusions can be drawn:

Stirrup strips made from GFRP can be a suitable alternative to steel stirrups in corrosive environments.

Beams with CFRP stirrups having a cross-section equivalent to steel stirrups show a 13% increase in capacity and an 18% reduction in ductility compared to those with steel stirrups.

Beams with AFRP stirrups having a cross-section equivalent to steel stirrups exhibit a 9% increase in capacity and an 11% reduction in ductility compared to those with steel stirrups.

Beams with GFRP stirrups having a cross-section equivalent to steel stirrups demonstrate nearly equal capacity but a reduction in ductility by approximately 2% compared to those with steel stirrups.

A reduction of 25% in GFRP stirrup width while maintaining constant cross-sectional area results in a decrease of about 7% in capacity and a reduction of approximately 20% in ductility.

Increasing GFRP layer counts can lead to an approximate increase in capacity by about 3-5% per added layer while reducing ductility by about 7-8%.

An increase of 33% in GFRP stirrup width while keeping cross-sectional area constant results in a decrease of about 5% in capacity and about 29% reduction in ductility.

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