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Numerical Investigation and Topology Optimization of Reinforcement Bars Using Finite Element Analysis

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Abstract

Modern software systems often suffer from poor readability, high complexity, and increased technical debt Reinforcement bars are critical structural components that govern the strength, stiffness, and durability of reinforced concrete structures. Conventional solid reinforcement bars, although widely used, often result in excessive material consumption and increased construction cost. In the present study, a numerical investigation combined with topology optimization is carried out to improve material efficiency of reinforcement bars while maintaining structural performance. Tensile behavior of conventional solid reinforcement bars made of Fe500 steel, Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and Titanium is analyzed using SolidWorks Simulation under an applied tensile load of 10 kN. Topology optimization is subsequently performed with constraints on maximum displacement and material reduction. Based on the optimization results, an optimized hollow reinforcement bar geometry is developed and subjected to tensile analysis. Furthermore, the flexural behavior of reinforced concrete beams using conventional solid and optimized hollow reinforcement bars is evaluated numerically using ANSYS. Stress distribution, deformation behavior, and material cost are compared. The results demonstrate that optimized hollow reinforcement bars exhibit comparable tensile and flexural performance to solid bars while achieving significant material and cost savings, highlighting their suitability for sustainable construction applications.

Keywords: *Reinforcement Bar, Finite Element Analysis, Topology Optimization, Tensile Analysis, Flexural Behavior, Sustainable Construction*

1. Introduction

Reinforced concrete (RC) structures are widely used in civil infrastructure due to their strength, durability, and versatility. The tensile capacity of RC members is primarily provided by reinforcement bars, which are conventionally designed as solid steel elements. Although current design codes ensure safety, they often result in conservative reinforcement layouts and inefficient material utilization, leading to increased cost and environmental impact. Recent advancements in finite element analysis (FEA) have enabled accurate numerical evaluation of reinforced concrete behavior, including stress distribution and deformation under loading. Several studies have demonstrated the reliability of FEA in predicting the flexural response of RC beams reinforced with alternative materials such as glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) bars (Huang, 2011; Ahmed & Khattab, 2016; Balamuralikrishnan & Saravanan, 2023) [1], [2], [8]. These materials offer advantages such as high strength-to-weight ratios and corrosion resistance, making them attractive alternatives to conventional steel reinforcement. Topology optimization has emerged as a powerful computational technique for improving material efficiency by eliminating low-stress regions while satisfying structural performance constraints. Its application in concrete structures has demonstrated significant potential for reducing material consumption without compromising strength or serviceability (Luo et al., 2015) [3]. Comprehensive reviews and experimental studies have further confirmed the feasibility of topology-optimized concrete members in practical applications (Stoiber & Kromoser, 2021; Flores-Vivian et al., 2019) [4], [5]. Optimization-based design approaches have also been applied to advanced reinforcement

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systems, including CFRP strengthening configurations, resulting in improved flexural performance and reduced material usage (Bekdaş et al., 2025; Alsuhaibani, 2024) [6], [9]. However, limited research has focused on applying topology optimization directly to reinforcement bars themselves, particularly for developing material-efficient hollow geometries. Addressing this gap, the present study conducts a numerical investigation of conventional and topology-optimized reinforcement bars made of Fe500 steel, CFRP, GFRP, and titanium [7], [10]. Tensile behavior and topology optimization are evaluated, followed by flexural analysis of reinforced concrete beams, to assess structural performance, material efficiency, and cost-effectiveness.

2. Objectives of the Study

The objectives of this research are:

- To numerically analyse the tensile behaviour of conventional solid reinforcement bars made of Fe500 steel, CFRP, GFRP, and Titanium.
- To apply topology optimization to reinforcement bars with defined displacement and material reduction constraints.
- To develop an optimized hollow reinforcement bar geometry based on topology optimization results.
- To evaluate the tensile behaviour of optimized hollow reinforcement bars.
- To study the flexural performance of reinforced concrete beams using solid and optimized hollow reinforcement bars.
- To compare structural performance and material cost between conventional and optimized reinforcement systems.

3. Numerical Modelling and Methodology

3.1. Tensile Analysis of Conventional Solid Reinforcement Bars

A conventional reinforcement bar with a length of 450 mm and a diameter of 20 mm is modelled using SolidWorks. Four different materials are assigned to the bar:

- Fe500 steel
- Carbon Fiber Reinforced Polymer (CFRP)
- Glass Fiber Reinforced Polymer (GFRP)
- Titanium (Table 1)

Table 1 Material Parameters of Reinforcement Bars

Property	Fe500 Steel Rebar	CFRP Rebar	GFRP Rebar	Titanium Rebar (Ti-6Al-4V)
Elastic Modulus, E (Pa)	**2.00×10^{11}**	**1.50×10^{11}**	**5.00×10^{10}**	**1.10×10^{11}**
Poisson's Ratio, ν	**0.30**	**0.25**	**0.25**	**0.34**
Shear Modulus, G (Pa)	**7.90×10^{10}**	**6.00×10^{10}**	**2.00×10^{10}**	**4.10×10^{10}**
Density (kg/m³)	**7850**	**1600**	**2000**	**4430**
Ultimate Tensile Strength, UTS (Pa)	**5.45×10^{8}**	**1.80×10^{9}**	**1.00×10^{9}**	**9.50×10^{8}**
Yield Strength (Pa)	**5.00×10^{8}**	**(No yield, brittle)**	**(No yield, brittle)**	**8.80×10^{8}**
Compressive Strength (Pa)	**5.45×10^{8}**	**8.00×10^{8}***	**5.00×10^{8}***	**9.50×10^{8}**
Thermal Expansion Coefficient (/K)	**1.20×10^{-5}**	**-1.0×10^{-6}**	**8.0×10^{-6}**	**8.6×10^{-6}**
Thermal Conductivity	**43**	**6**	**0.35**	**6.7**

(W/m·K)				
Specific Heat (J/kg·K)	**440**	**900**	**800**	**560**
Material Damping Ratio (–)	**0.01**	**0.03**	**0.04**	**0.01**
Failure Criterion	**von Mises**	**Max Principal Stress**	**Max Principal Stress**	**von Mises**

An axial tensile load of 10 kN is applied at one end of the bar while the other end is fixed. Linear static analysis is performed to obtain stress distribution and deformation behaviour. Figure 1 The figure presented in this study illustrates the finite element analysis (FEA) of a solid reinforcement bar subjected to axial tensile loading. The analysis aims to assess the stress distribution and deformation behaviour of the bar under a 10 kN tensile load, with one end fixed and the other subjected to the force. The bar has a length of 450 mm and a diameter of 20 mm, and the stress distribution is depicted through von Mises stress plots. The first part of the figure (a) shows the finite element model and boundary conditions applied to the bar. Parts (b), (c), (d), and (e) illustrate the results of FEA for different materials used in the reinforcement bar. Specifically, part (b) shows the FEA results for Fe500 rebar, part (c) for CFRP (Carbon Fiber Reinforced Polymer) rebar, part (d) for GFRP (Glass Fiber Reinforced Polymer) rebar, and part (e) for Titanium rebar. Each stress distribution map includes a color-coded scale representing the von Mises stress values, which are crucial for determining the material's yielding strength. The arrows pointing to the yield strength indicate the critical stress level for each material. This study provides insight into the mechanical performance of different reinforcement materials under tensile loading, contributing to selecting suitable materials for structural reinforcement.

3.2.Topology Optimization of Reinforcement Bars

Topology optimization is carried out in SolidWorks Simulation to identify regions of low stress suitable for material removal. The optimization parameters are defined as follows:

- Maximum allowable displacement: 0.5 mm
- Target material reduction: 20% of original volume

The objective is to minimize material volume while satisfying displacement constraints. The topology optimization is performed separately for all four materials.

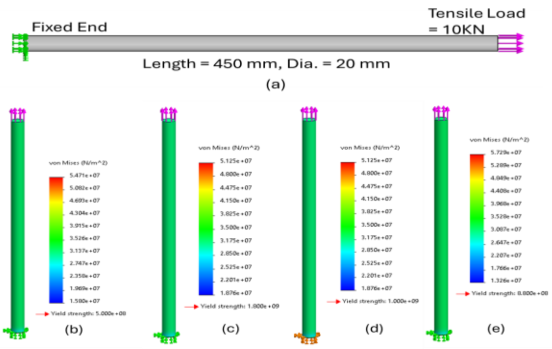

Figure 1. **(a) Finite Element Model and Boundary Conditions for Tensile Analysis of Solid Reinforcement Bar. (b)FEA of Fe500 Rebar (c)FEA of CFRP Rebar (d)FEA of GFRP Rebar (e)FEA of Titanium Rebar**

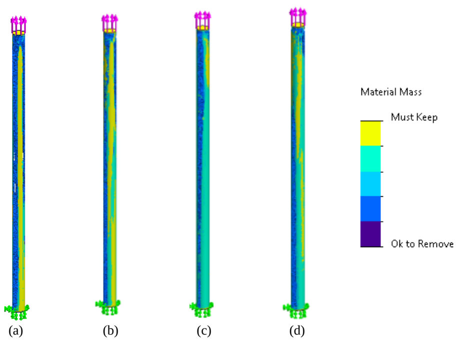

Figure 2 **Topology Optimization Results Showing Low-Stress Regions Suitable for Material Removal. (a) Fe500 Rebar (b) CFRP rebar (c) GFRP Rebar (d) Titanium Rebar**

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Figure 2 demonstrates the results of the topology optimization for four different materials (shown in parts a, b, c, and d), with the color gradient indicating the stress distribution throughout the bar. The regions where material can be removed are marked in blue and light green (indicating "Ok to Remove"), while the areas that need to remain intact for structural integrity are represented in yellow and purple ("Must Keep"). From the simulation, it is evident that the central portion of the reinforcement bar experiences significantly lower stress compared to the ends, which are subjected to higher tensile forces. This finding suggests that it is structurally safe to hollow out the middle section of the bar, as this region does not significantly contribute to the load-bearing capacity. By removing material from this low-stress area, the mass of the reinforcement bar can be reduced, leading to an efficient use of material without compromising the overall performance. This optimization strategy is highly effective in reducing material waste while ensuring that the critical regions of the bar, particularly the ends, remain sufficiently reinforced.

3.3. Design of Optimized Hollow Reinforcement Bar

Based on topology optimization outcomes, an optimized hollow reinforcement bar is designed. The geometry parameters are:

- Length: 450 mm
- Outer diameter: 20 mm
- Inner diameter: 10 mm

The optimized geometry is adopted uniformly for all four materials to ensure consistency in comparison (Figure 3).

Figure 3 Geometry of Optimized Hollow Reinforcement Bar Developed From Topology Optimization.

3.4.Tensile Analysis of Optimized Hollow Reinforcement Bars

The optimized hollow reinforcement bars are subjected to the same tensile loading conditions as the solid bars. Stress concentration and deformation behaviour are obtained and compared to evaluate the effect of material removal. Figure 4 illustrates the stress distribution in optimized hollow reinforcement bars subjected to tensile loading, with results for four different reinforcement materials: Fe500 rebar (a), CFRP rebar (b), GFRP rebar (c), and Titanium rebar (d). The analysis highlights the von Mises stress distribution, color-coded to indicate stress intensity, with red and yellow areas representing high-stress concentrations near the fixed ends, where the tensile load is applied. The central hollow region, where material removal was previously optimized, experiences significantly lower stress in all cases.

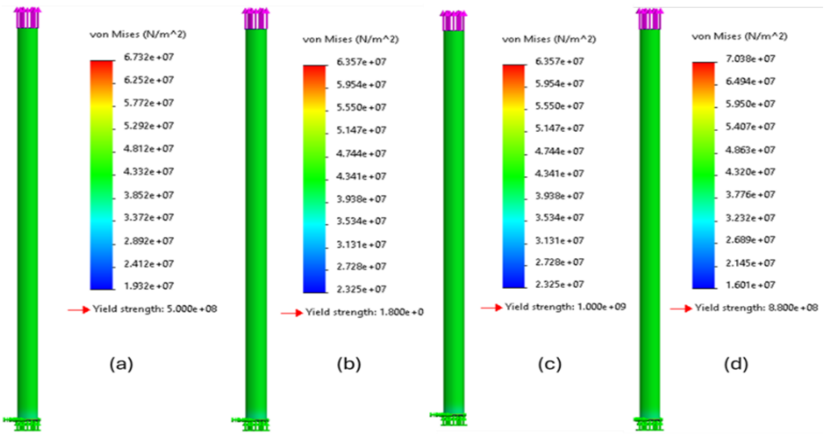

Figure 4. Stress Distribution in Optimized Hollow Reinforcement Bar Under Tensile Load. (a) Fe500 Rebar (b) CFRP Rebar (c) GFRP Rebar (d) Titanium Rebar

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The results demonstrate that hollowing the central region of the reinforcement bar does not compromise its structural integrity. This optimization approach allows for material reduction while maintaining performance, showcasing an efficient solution for lightweight structural applications.

3.5.Flexural Analysis of Reinforced Concrete Beams

Flexural behaviour is evaluated using ANSYS for two beam configurations.

3.5.1. Beam with Solid Reinforcement Bar

- Beam dimensions: 1500 mm × 150 mm × 200 mm
- Reinforcement: solid bar of 20 mm diameter
- Effective span: 1300 mm
- Loading condition: mid-span load of 100 kN

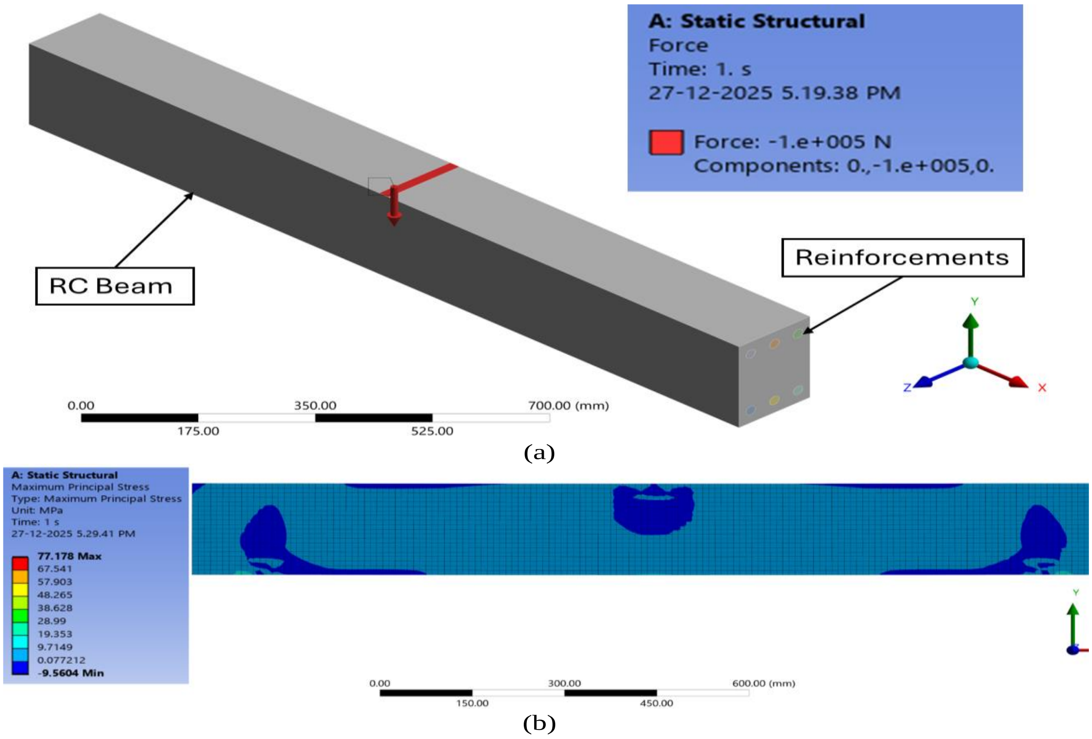

Figure 5. **(a) Model and Loading Setup for Conventional Bar Reinforcement. (b) FEA Model of a Concrete Beam With Solid Reinforcement Bars**

Figure 5 illustrates the finite element modelling and static structural analysis of a conventionally reinforced concrete (RC) beam. The beam geometry is defined with overall dimensions of 1500 mm×150 mm×200 mm and an effective span of 1300 mm. As depicted in Figure 5(a), the reinforcement is modelled as discrete solid bars with a 20 mm diameter, embedded longitudinally within the concrete matrix to resist tensile forces. The loading and boundary conditions replicate a standard three-point bending test. A downward mid-span concentrated load of 100 kN is applied along the negative Y-axis at t=1 s, as indicated by the force definition panel. Figure 5(b) presents the meshed finite element model and the resulting Maximum Principal Stress distribution. The stress contour reveals a maximum tensile stress of approximately 77.18 MPa, with significant stress concentrations observed near the loading point and support regions.

3.5.2. Beam With Optimized Hollow Reinforcement Bar

The same beam geometry and loading conditions are used, replacing the solid bar with the optimized hollow reinforcement bar (Figure 6).

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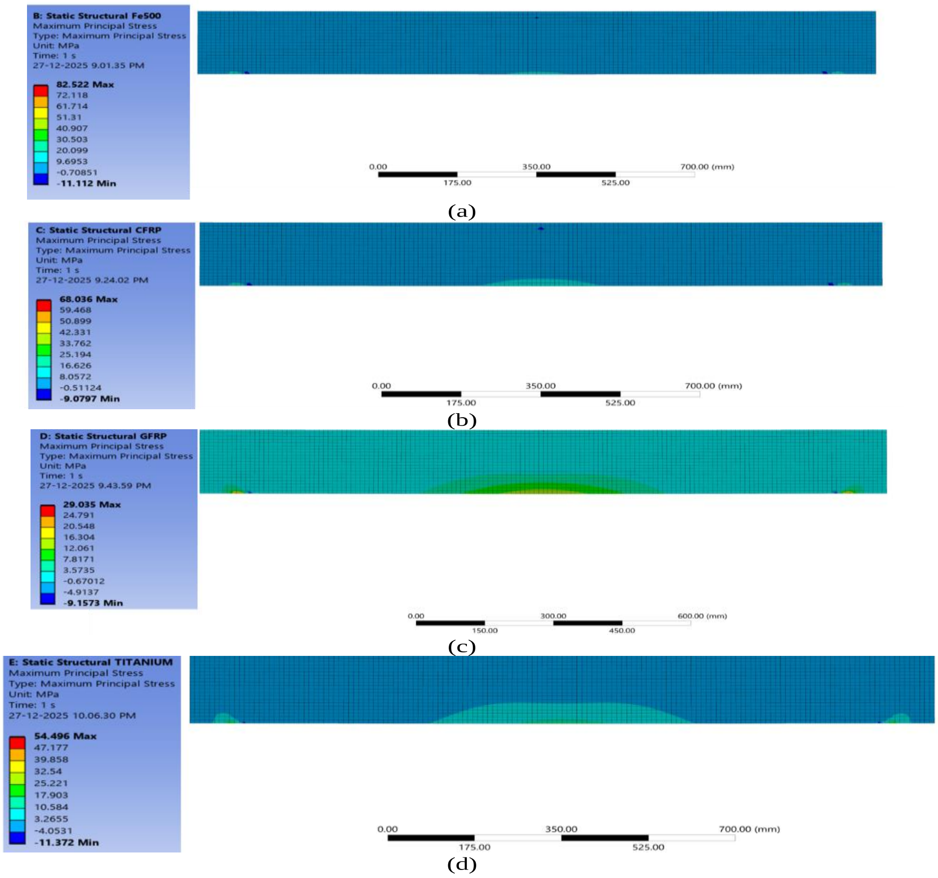

Figure 6. Finite Element Model of Reinforced Concrete Beam With Optimized Hollow Reinforcement Bar. (a) Fe500 Rebar (b) CFRP Rebar (c) GFRP Rebar (d) Titanium Rebar

4. Results and Discussion

4.1.Tensile Analysis Results of Solid Reinforcement Bars

The tensile analysis results indicate that stress distribution varies with material properties. Fe500 steel and Titanium show uniform stress distribution, while CFRP and GFRP exhibit higher stress gradients due to their anisotropic nature. Table 2 summarizes the maximum von Mises stress and deformation values obtained for solid reinforcement bars.

Table 2 Tensile Analysis Results of Solid Reinforcement Bars

Material	Max Stress (MPa)	Max Deformation (mm)
Fe500 Steel	54	0.07
CFRP	51	0.09
GFRP	51	0.28
Titanium	57	0.13

4.2.Topology Optimization Results

Topology optimization results confirm that approximately 20% of material can be removed from the central region of the bar while maintaining displacement below 0.5 mm for all materials.

4.3.Tensile Performance of Optimized Hollow Bars

Optimized hollow bars exhibit slightly increased stress concentration near the ends but remain within acceptable limits. Overall deformation remains comparable to that of solid bars. Table 3 compares tensile results of solid and optimized hollow reinforcement bars.

4.4.Flexural Performance of Reinforced Concrete Beams

Flexural analysis results indicate similar stress distribution patterns for reinforced beams with solid and optimized hollow bars. Maximum stress values remain within acceptable limits. Table 4 summarizes

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the flexural analysis results.

Table 3 Comparison of Tensile Performance Between Solid and Optimized Hollow Reinforcement Bars

Material	Stress - Solid (MPa)	Stress - Hollow (MPa)	Deformation - Solid (mm)	Deformation - Hollow (mm)
Fe500 Steel	54	67	0.07	0.09
CFRP	51	63	0.09	0.12
GFRP	51	63	0.28	0.38
Titanium	57	70	0.13	0.17

Table 4 Flexural Analysis Results of Reinforced Concrete Beams

Reinforcement Type	Max Stress (MPa)
Solid Bar (Conventional)	77.178
Optimized Hollow Bar (Fe500)	82.522
Optimized Hollow Bar (CFRP)	68.036
Optimized Hollow Bar (GFRP)	29.035
Optimized Hollow Bar (Titanium)	54.496

1.1.Cost Comparison

Material reduction achieved through topology optimization results in cost savings. Hollow reinforcement bars reduce material volume by approximately 20%, leading to significant cost reduction, particularly for expensive materials such as Titanium and CFRP. Table 5 presents a comparative cost analysis.

Table 5 Cost Analysis Results of Reinforced Concrete Beams

Material	Cost - Solid Bar (₹/m)	Cost - Hollow Bar (₹/m)	Cost Reduction (%)
Fe500 Steel	₹ 135.30	₹ 81.18	40.0%
CFRP	₹ 502.40	₹ 301.44	40.0%
FRP	₹ 179.10	₹ 107.46	40.0%
Titanium	₹ 2,826.00	₹ 1,695.60	40.0%

Conclusions

This study presents a detailed numerical investigation of reinforcement bars using finite element analysis and topology optimization. The results demonstrate that optimized hollow reinforcement bars can achieve comparable tensile and flexural performance to conventional solid bars while significantly reducing material usage and cost. The findings highlight the potential of topology optimization as an effective tool for sustainable reinforcement design in reinforced concrete structures. Future studies may include experimental validation, fatigue analysis, and long-term durability assessment of optimized reinforcement systems.

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