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Finite Element Modelling of Polypropylene Fibre Reinforced Concrete Beams Reinforced with Steel under Bending

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Abstract: Application of the fibre-reinforced concrete has manifested a wider acceptability over time for its contribution towards significantly improving the flexural performance of structural members. A lot of work has been done to understand the influence of fibres on the mechanical and structural behaviour of reinforced concrete. Towards this end, several researchers have experimentally investigated the residual flexural strength to characterize the fibre-reinforced concrete. The number of influencing parameters to be investigated through experiments is mostly limited because of the time and cost implications. Consequently, validation of the experimental investigations through analytical models and further utilizing these models to study the behaviour in greater detail is a viable option for researchers. As part of this work, an analytical investigation has been performed to investigate the performance of full-scale polypropylene fibre-reinforced concrete beams. The models have been validated through comparison with the observed performance during an experimental investigation where tests on twelve full-scale FRC beams were performed. Three-dimensional finite element models of the beams under 4-point loading were prepared and the post-cracking flexural performance of FRC beams has been investigated by varying the dosage of polypropylene fibres obtained from shredding medical face masks.

Keywords: Fibre reinforced polymers, Polypropylene, Residual flexural strength, Finite element, Constitutive model

Introduction

Various types of fibres used in concrete are known to have the ability to improve and modify the mechanical properties of a cementation matrix and the flexural toughness, as reported by experiments carried out previously by (Yoo et al., 2016; Xu et al., 2020; Al Marahla & Garcia-Taengua, 2021; Yousefi et al., 2022). Several researchers (Biolzi & Cattaneo, 2017; Fallah& Nematzadeh, 2017; Lee, 2017, Abbass et al., 2018, Jhatial et al., 2018, Belmokaddem et al., 2020) examined the influence of fibres on the residual flexural parameters considering different types of fibers, aspect ratio and volume fractions following the available standards (EN 14651, 2007a; ASTM C1609, 2012). Amin and Gilbert (2018) found in their study that the addition of steel fibers to concrete increased the tension carried by the concrete, as the fibers demonstrated the ability to transmit tensile stress across cracks while inhibiting the propagation of splitting cracks.

Fibres can substantially improve the post-cracking performance of structural members after the formation of the first crack, particularly in the steel fiber reinforced concrete, which can be used to replace conventional reinforcement partially or fully (Abbass et al., 2018). However, applications of non-steel fibres has mostly

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remained limited to restraining and controlling the plastic cracking. Biolzi and Cattaneo (2017) investigated the effect of steel fibres on the instantaneous deflection and confirmed that steel fibres improved the stiffness of RC beams, and consequently reduced the deflection.

Non-metallic fibres have lower tensile strength and modulus of elasticity but lower carbon footprint compared to steel fibres (Jhatial et al., 2022). However, research has focused on investigating the influence of steel fibres on the flexural behaviour of RC members and paid little attention to non-metallic fibres. Researchers have identified synthetic fibres (a form of non-metallic fibres) as a promising material due to their low environmental impact (Cadenazzi et al., 2020).

Modelling of structural members under bending using available software has focused on the plain concrete and steel FRC. The direct post-cracking tensile behavior of steel fibre reinforced concrete is utilized as a stress-crack opening response in the available guidelines. Finite-element computations model of FRC structural application is required to economize the experimental effort and to overcome the shortfalls in existing techniques for modeling and analyzing the flexural and post-cracking performance of non-metallic FRC elements with less time and effort. Therefore, this study investigates experimentally and numerically the influence of polypropylene fibres obtained from shredding medical face masks on the flexural performance of RC members.

In this study, an experimental campaign was conducted on FRC prismatic and full-scale beams. Normal strength concrete having a water to cement ratio of 0.45 was considered with varying the volume fraction of fibres obtained from face masks. Therefore, three groups of concrete mixes were categorized by the content of 0, 0.25% and 0.5%. Parametric study on full-scale beams under flexure has been carried out considering the experimental conditions. FE models using the constitutive models obtained experimentally for modelling the behaviour of materials using DIANA software are included.

Materials and Methodology

Background Experimental Program

In this research, the influance of the inclusion of randomly oriented polypropylene fibres in concrete was evaluated. Different concrete members containing varying volume fraction of fibre (0, 0.25%, and 0.5%) were investigated experimentally. Experimentl campain comprised nothced prisms produced and tested under three point bending test complying with EN 14651 standard, and full-scale conventionally reinforced beams tested under four point bending test. Residual flexural strength obtained experimentally were employed in the charactrisation of concrete properties in FEA models.

Materials

Concrete mixes having water /cement ratio of 0.45 was used. At age of 28 days, average compressive strength of reference mixes was 36 MPa. Medical face masks with 70 GSM density were used as fibres in concrete with three different volume fractions of 0, 0.25% and 0.5%. Special cutting machine was used to shred the masks to a regular size of 40 mm length and 5 mm width. Reference mixes with fibres were adjusted by varying the superplasticizer dosage to accommodate different fibre contents. A good level of workability was observed in fresh concrete, slump value was between 120 and 150 mm. For all cases, concrete mixes were produced following the same sequence, details on the mixing sequance and testing are available in (Al Marahla et al., 2023).

Table 1. Reference mix designs

Constituents	Quantity (kg/m^3)		
	Mix 1	Mix 2	Mix 3
Water	200	200	200
Cement	417	417	417
Coarse aggregate	928	928	928
Fine aggregate	801	801	801
Superplasticizer	4	6.2	7.8
Fibres content % (masks)	0	0.25	0.5

Specimens, Test Setup and Methodology for Three Point Bending Test

For each of the FRC mixes as per the combinations listed in Table 1, ten prismatic specimens were tested under flexure. Notched prisms complying to EN 14651 (2007b) standared were prepared, cast and tested under 3PBT flexure as depicted in Figure 1.

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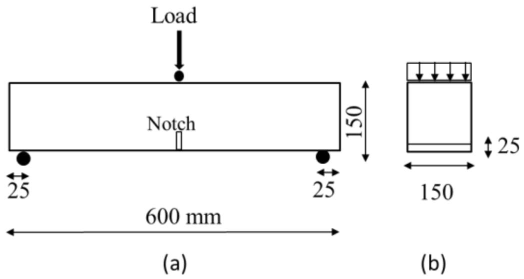


Figure 1. Specimen dimensions; (a) Elevation, (b) Cross section

Limit of proportionality (fL) and residual strength parameters f_{R1}, f_{R2}, $f_{R3,}$ and f_{R4} corresponding to fracture displacement values of 0.5, 1.5, 2.5, and 3.5 mm, respectively, were derived from this test. The load-displacement response for each case was used to define the constitutive curve in the modelling of FRC beams.

Specimens, Test Setup and Methodology for Four Point Bending Test

Full-scale beams had a dimension of 150 mm wide, 200 mm total depth and 2200 mm long with 2000 mm clear span as shown in Figure 2. In total, three different mix designs were considered in this study with the mix proportions listed in Table 1. Twelve beams were produced and tested, 4 typical beams for each concrete mix.

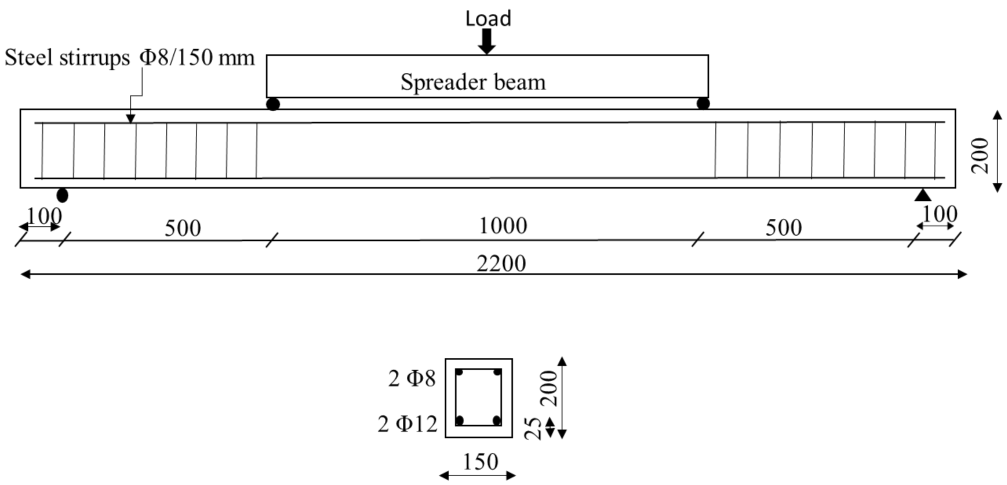


Figure 2. Beam geometry and typical cross sections

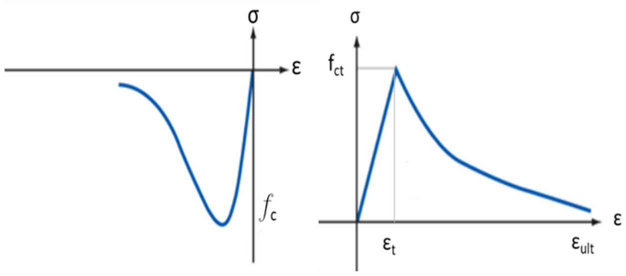
During each test, beam vertical deformations were monitored and recorded. The mid-span deflection was measured using linear variable differential transformers (LVDTs) that were connected to a data logger that recorded the mid-span deflection up to the failure load.

Finite-Element Modelling

In this investigation, a nonlinear finite element analysis was carried out to simulate the behavior of fiber-reinforced concrete beams subjected primarily to flexure. To accomplish this, the DIANA FEA software was utilized to predict the response of RC members with varying fiber contents. Three-dimensional finite element models of experimentally tested beams were created to evaluate the flexural behavior. The geometry, boundary conditions, and reinforcement details of the modelled beams were identical to those utilized in the experimental investigations. Comparing and discussing the results derived from nonlinear FE analysis and those obtained experimentally are presented in this section.

The mechanical properties of concrete were assigned in accordance with FIB Model Code 2010. To simulate the behavior of concrete, a total strain-based cracking model with rotating crack orientation was employed. Concrete was modelled using 3D solid elements (Diana, 2017), while steel reinforcement was modelled using bar elements with bond slip interface to the surrounding concrete.

In both instances (plain and FRC), the compressive behavior of concrete was modelled using the Parabolic model (Thorenfeldt, 1987). To model the tensile behavior of reinforced concrete beams without fibers, the nonlinear post-cracking softening of concrete Hordijk model was used (Hordijk, 1992). The smeared crack approach has been adopted to represent the behavior of the materials, with standard continuum elements representing concrete (Rashid, 1968). Figure 3 below depicts the models used to predict the behavior of concrete under compression and tension.



(a) (b)

Figure 3. Concrete behaviour models; (a) Torenfeldt model , (b) Hordijk model

On the basis of experiments on notched prisms, flexural parameters (residual flexural strength versus CMOD curves) were specified. In order to account for the effect of added fibers on the tensile behavior of FRC, the constitutive behavior in DIANA was modified with the parameters obtained from bending test on notched beams. The post-cracking response (stress-CMOD) were incorporated into the modeling as shown in Figure 4.

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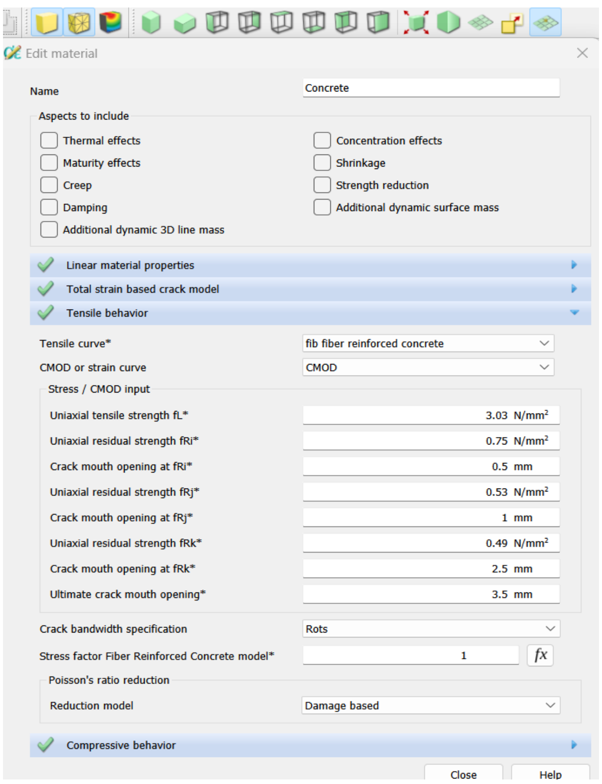

Figure 4. Tensile function of concrete using DIANA

After conducting a mesh sensitivity analysis, the 25mm mesh size was chosen to model the concrete elements considered in this study. Figure 5 shows the mesh used in this model.

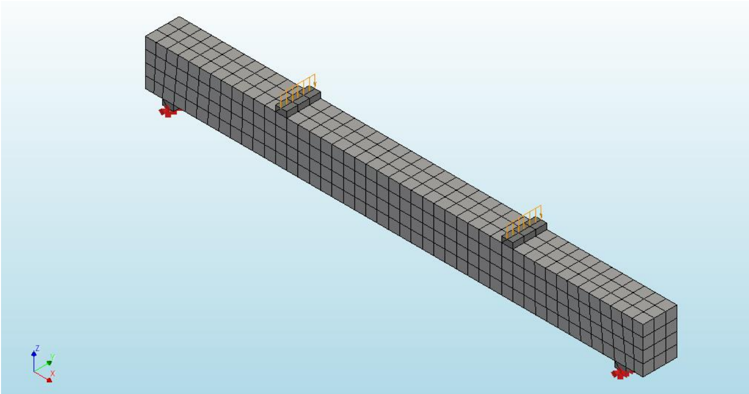

Figure 5. Mesh used in FEA for beams in DIANA

In terms of boundary conditions, beam modelled in this study was allocated simply supported conditions. Where the vertical and horizontal translations were restricted at one support, while only the vertical translation was restricted at the other support. Steel plates were used for loading and support and their linear elastic material properties were simulated. Due to the symmetry in geometry, reinforcement, boundary conditions, and loading, only one-half of the RC beam was modelled to save computational time. For obtaining capacity and post-peak behavior in DIANA FEA, the Modified Newton Raphson iterative scheme with the line search option was used, and the energy and displacement convergence norms were satisfied with a tolerance of 0.001 and 0.01, respectively.

Results and Discussion

Characterization Test (3PBT)

After the formation of a single crack at the notch's tip, prisms without fibres failed abruptly, resulting in the prisms' separation into two pieces. Whereas prisms with various volume fractions of face masks fibres demonstrated superior ductility compared to reference specimens without spontaneous splitting. Filure modes are shown in Figure 6.

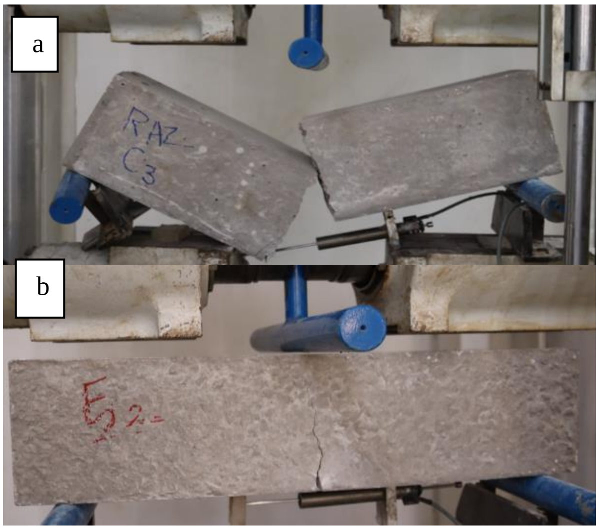

Figure 6. Failure of prisms (a) plain concrete, (b) with fibres

Residual flexural parameters obtained experimentally are presented in Table 2. Values present the average of ten different values.

Table 2. Residual flexural parameters

Fibre content (%)	f_{LOP}	f_{R1}	f_{R2}	f_{R3}	f_{R4}
0	2.46	0	0	0	0
0.25	2.69	0.42	0.38	0.37	0.36
0.50	3.03	0.75	0.53	0.49	0.46

Figure 7 presents the load-crack displacement associated with each fractional volume of fibres. Using the EN 14651 standard's proposed general formula, the vertical displacement (deflection) of a prism derived from a flexural bending test can be converted to an approximation of the CMOD. From the post-cracking behaviour of tested prisms, it was found that the limit of proportionality increased by up to 22.5% in FRC specimens exposed to the maximal dose considered in this study. This is due to the delay in crack coalescence induced by the addition of fibres to concrete mixes.

In addition, Figure 7 reveals that the addition of a higher volume fraction (0.5%) of fibers led to increase the residual parameters. At a crack width of 0.5 mm, the residual flexural ratio (f_{R1}/f_{LOP}) was 0.16 and 0.25 for fiber additions of 0.25% and 0. 5%, respectively. And (f_{R3}/f_{LOP}) values of 0.14 and 0.17, respectively, at a crack width of 2.5 mm.

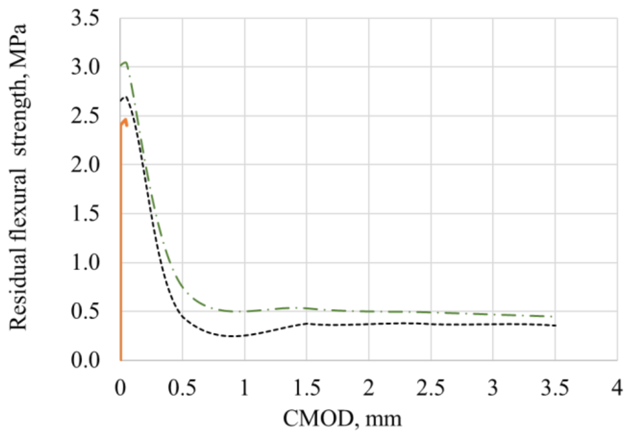

Figure 7. Load-CMOD for prisms with different dosages of polypropylene fibres

Flexural Tests (4PBT)

During the test carried out on the short-term deflection of beams, the midspan deflection of each beam was measured until failure. Table 3 presents the experimentally observed failure modes, maximal load (peak), midspan deflection, cracking loads, and number of cracks for each beam. It was observed that all beams failed in flexure under conditions of ultimate state.

Table 3. Beams results (mode of failure, deflection and cracking)

Beam	P_{max} (kN)	$\delta_{\text{at max load}}$	Ductility index (μ)
F01 (no fibres)	93.3	34.0	2.67
F02 (replicate)	96.4	35.1	2.54
F03 (replicate)	96.4	35.1	2.54
F04 (replicate)	97.7	38.3	2.44
F11 (with 0.25% fibres)	95.2	37.4	2.88
F12 (replicate)	96.2	31.1	4.50
F13 (replicate)	100.1	33.3	4.51
F14 (replicate)	100.9	33.2	4.32
F21 (with 0.5 fibres)	100.3	32.5	4.66
F22 (replicate)	103.7	28.7	5.58
F23 (replicate)	104.8	29.2	5.64
F24 (replicate)	106.5	30.1	5.35

However, beams made of plain concrete (F01, F02, F03, and F04) exhibited explosive concrete crushing, whereas fibre-reinforced beams with 0.25 and 0.5 percent fibres exhibited relatively ductile behavior, with the beams reaching the failure stage progressively. Previously conducted research (Shaaban et al., 2021; Hammad et al., 2022; Al Marahla et al., 2023) examined the flexural and cracking behaviour of reinforced concrete beams containing fibers. According to the authors, the addition of polypropylene fibres increased flexural fractures by up to 30% and increased stiffness.

FEA Analysis

To establish the validity of the FE models in comparison to the experimental behavior, the relationship between load and deflection and modes of failure of beams were compared. The relationship between load and deflection for experimentally measured beams and modelled beams is compared in this study. The experimentally obtained behaviour is contrasted to the behaviour obtained from models containing normal concrete (NC) and FRC.

Figure 8 illustrates the load-deflection profiles obtained experimentally and those from FEA. The results indicate a reasonable correlation between the experimental and finite element results, especially in the case of beams without fibers, where the FE model predicts a lower load at the time of failure than the experimentally determined value. The model of FRC beams indicates that the beams initially displayed a relatively stiffer behavior than reference beams. This may be due to the assumption of a perfect bond between reinforcement and concrete in the FEA.

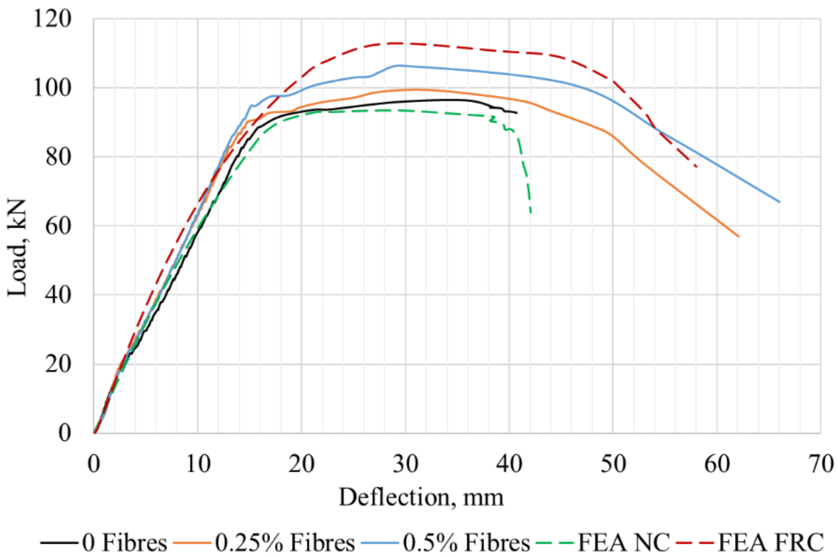

Figure 8. Comparison between mid-span deflection obtained experimentally and FEA results.

During the stage of crack formation and development, a plateau is observed where the deformation increased under a constant load prior to beam failure. While this is similar to the experimentally observed behavior, it occurred at a comparatively higher load in the FE model than in the tested beams. The experimentally determined average midspan deflection at the ultimate load for an FRC beam with a 0.5% fiber content was 29.4 mm associated with 106 kN, whereas the numerical values of midspan deflection were 28 mm associated with a vertically applied load of 114 kN. This variation in the load and deflection behaviour is attributable to the size of the fibres used, and their dispersion.

From the results of the FE models, it was observed that yielding of steel reinforcement was associated with extensive concrete cracking in the tension zone. In both modelled scenarios, this was followed by the cruching of the concrete in the compression zone, which is consistent with the experimental observations. Stresses developed in steel rebars as longitudinal reinforcement at ultimate condition is shown in (Figure 9) below.

For precise and reliable numerical modeling of the post-cracking behavior of FRC members, the results of FEA indicated that the efficacy of fibre in tension should be accounted for in concrete material properties (constitutive curve).

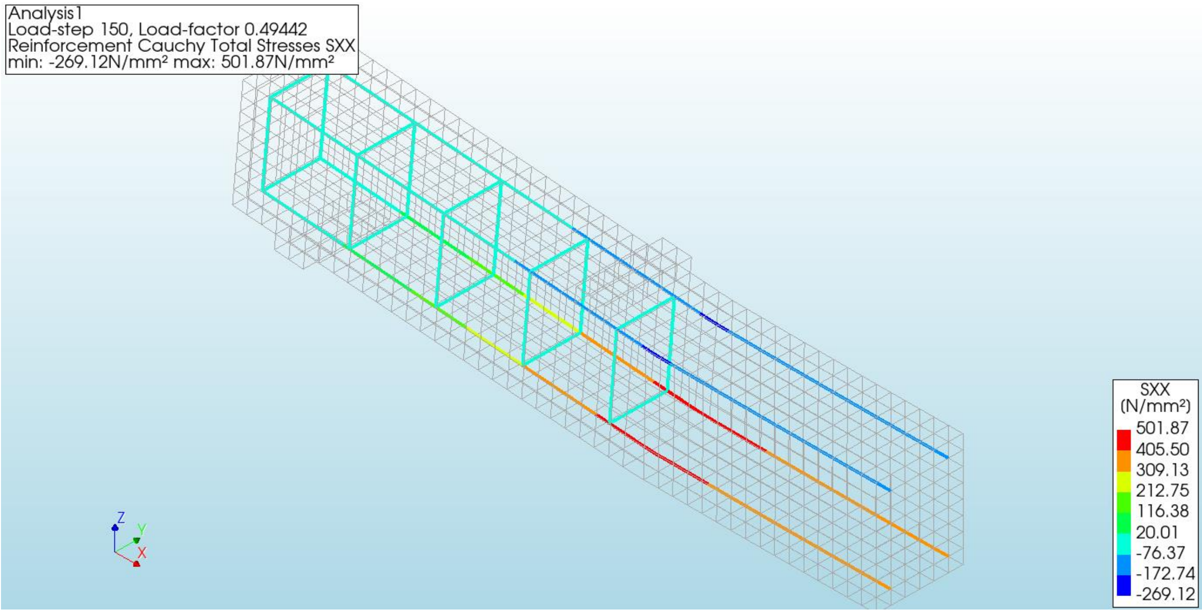

Figure 9. Stresses developed in steel reinforcement under ultimate condition.

Conclusion

In this investigation, a nonlinear finite element analysis was carried out to simulate the behavior of fiber-reinforced concrete beams under bending. DIANA FEA software was utilized to predict the response of RC members with varying fiber contents. Three-dimensional finite element models of experimentally tested beams were created, and a nonlinear static analysis was conducted to evaluate the flexural behavior. In numerical analysis, the geometry, boundary conditions, and reinforcement details of the modelled beams were identical to those utilized in the experimental investigations. Based upon the discussion and presented results, the following conclusions were drawn:

- Fibres considered in this study enhanced the post-peak ductility of the FRC prisms when compared to those prisms without fibers. Residual parameters were improved by up to 25% of peak strength due to the incorporation of fibres.
- The contribution of polypropylene fibres across the cracks can be illustrated by the residual tensile strength, and the behavior is identified as a function of the concrete's tensile strength in FEA.
- The addition of fibers to concrete mixtures substantially enhances the beams' flexural behavior, bending stiffness, and ductility. The mid-span deflections in FRC beams were lower by up to 19% when compared to the reference beams.
- The FEA results indicated that the efficacy of fibre in tension should be accounted for in concrete material properties (constitutive curve) for precise and reliable numerical modeling of the flexural and cracking behavior of FRC members.

Recommendations

Finite element (FE) analysis using available software is recommended to be incorporated in future research including the findings concluded from the experimental campaign. Moreover, the authenticity of the models in predicting the flexural behaviour and cracking performance of full scale FRC beams reinforced with steel bars can be evaluated and improved with less time and effort. The objective of FEA modelling should be to predict and investigate the influence of contributory parameters on the behaviour of members.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM.journal belongs to the authors.

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