Three-Dimensional Finite Element Analysis of Externally Strengthened RC Beams in Flexure with SWR

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Abstract A method of strengthening that is considered to be highly effective is the utilization of external steel wire rope (SWR). Predicting the flexural performance of reinforced concrete (RC) beams strengthened with external SWR is the objective of this study. An analysis using finite element (FE) method is presented and the results are verified by comparing them to laboratory tests conducted on five beams. Despite having identical rectangular cross-section geometries and being subjected to four-point bending, the SWR configurations of the beams varied. An assessment was conducted to evaluate the efficacy of three different constitutive laws, namely smeared crack, bilinear, and elastic-linear, in accurately describing the behaviors of concrete, steel, and SWR materials, respectively. The findings demonstrated a strong correlation with the experimental data, specifically regarding the load–displacement behavior, ultimate load, and failure modes.

Keywords Finite element analysis · Beam · Steel wire rope · Strengthening

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1 Introduction

Civil engineers around the world are confronted with the formidable problem of strengthening current structures. Several factors have had a significant impact on the safety of reinforced concrete (RC) buildings built in earlier times. These include higher live loads, updated design codes and specifications, as well as the adverse effects of carbonation, corrosion or chloride attack, and earthquakes [1–9]. Steel wire rope (SWR) shows great potential in regard to strengthening RC members, in particular due to its excellent strength, low weight, and high flexibility [10]. Recently, many studies have investigated the performance of SWR-strengthened RC members [11–14].

However, there is a significant scarcity of numerical investigations that examine the potential of external SWR strengthening method for improving the behavior of RC beams. In order to accurately replicate the respose of specimens with external SWR strengthening system, this research intends to generate finite element (FE) models. The study also seeks to fill current knowledge gaps and expand upon previous research by Haryanto et al. [15]. In this investigation, five models were created using the FE software package ATENA [16], utilizing material constitutive laws for concrete (smeared crack model), steel (bilinear model), and SWR (elastic-linear model). The validation of these models was carried out by matching the simulated responses to the data obtained from experiments.

2 Experimental Tests

The study involved constructing five beams, and the dimensions and quantities of the SWRs used in the experiments are shown in Table 1 and Fig. 1.

For the steel rods, measurements recorded a yield strength of 236.74 MPa and an ultimate strength of 369.40 MPa. In this investigation, Dynabolts with a diameter of 6 mm and a shear capacity of 10.3 kN, were employed as end anchors. In addition, a steel plate with a thickness of 2 mm was utilized. Dimensions of 50 × 100 mm were used for the single plate arrangement, and 25 × 100 mm were used for the

Table 1 Tested beams description

Beam	L (mm)	b (mm)	h (mm)	Longitudinal reinforcement		Stirrups	SWR
				Tension	Compression		
B00	1000	100	150	2Ø6	2Ø6	Ø6–50	–
B26	1000	100	150	2Ø6	2Ø6	Ø6–50	2Ø6
B28	1000	100	150	2Ø6	2Ø6	Ø6–50	2Ø8
B46	1000	100	150	2Ø6	2Ø6	Ø6–50	4Ø6
B48	1000	100	150	2Ø6	2Ø6	Ø6–50	4Ø8

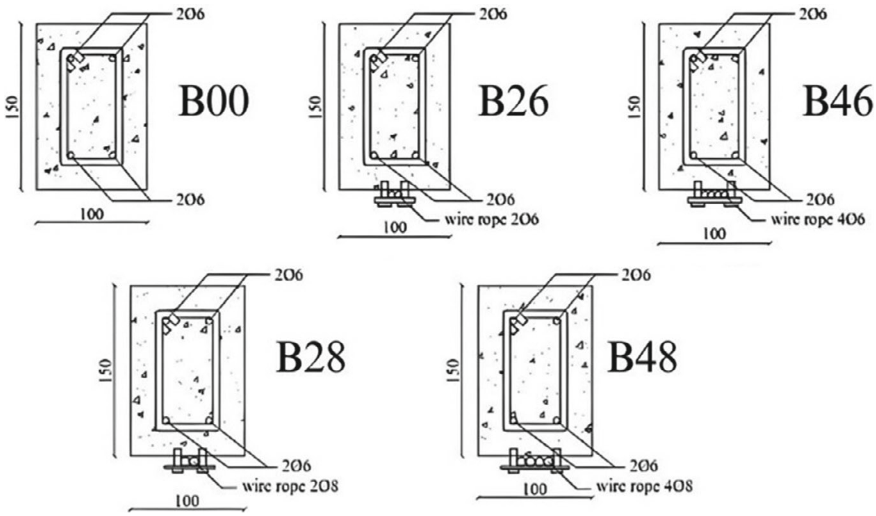


Fig. 1 Details of specimens

double plate arrangement. Tensile strength measurements were taken from 6 mm SWRs and found to be 599.48 MPa, while 8 mm SWRs showed a tensile strength of 755.92 MPa. Using a four-point bending setup, all specimens were tested and loaded in the same procedure.

3 Formulation of the 3D FE Model

3.1 Geometry of the Model and Description of Elements

Figure 2 illustrates a model of an unstrengthened beam, with strengthened beams omitted due to space constraints. This model accurately represents the geometric and material properties, as well as the boundary conditions, of the tested beams. To maintain consistency, a fractional representation (half of a beam) was utilized for modeling. It is assumed that a perfect bond exists within each material. Concrete and mortar were modeled using CC3DnonLinCementitious2, an eight-node solid element, ideal for creep measurements due to the assumption of hardening conditions prior to reaching compressive strength. Longitudinal reinforcements and SWRs were modeled with two-node CCReinforcement elements, which can deactivate the compression response, making them effective for simulating materials with lower bending stiffness. Additionally, CC3DElastIsotrope, an eight-node solid material, was used to model the load and support plates in the 3D simulation of linear isotropic materials. The eight-node CCCombinedMaterial element was employed to model

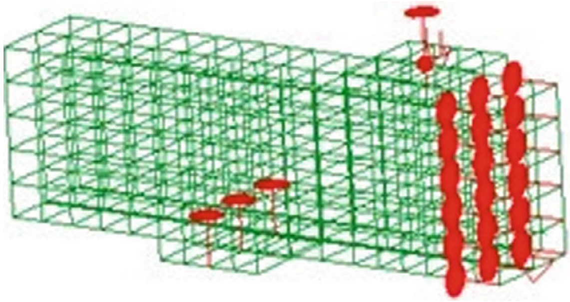


Fig. 2 Loading and boundary conditions

concrete with stirrups, allowing for complex combinations of concrete and smeared reinforcement in multiple directions.

3.2 Modeling of Materials

When subjected to tensile loading, the SWR material shows a linear elastic constitutive model, as demonstrated in Fig. 3. The steel reinforcement onstitutive model, however, was based on a bilinear stress–strain law. For concrete, which has a nonlinear and heterogeneous structure, the smeared crack properties and fracture mechanics approach were used to develop its constitutive models within the ATENA software. This approach relies on the uniaxial stress–strain relationship to describe the primary stress response, indicating that monotonic loading results in concrete fracture. In line with Kupfer et al. [17], the peak stress in uniaxial behavior was approximated using the biaxial failure surface. A simulated crack model was then employed to evaluate the stress response in concrete [18, 19].

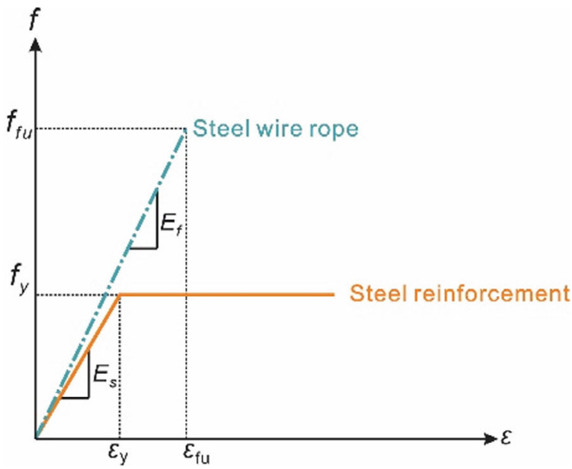


Fig. 3 Stress–strain law for steel reinforcement and SWR

4 Results and Discussion

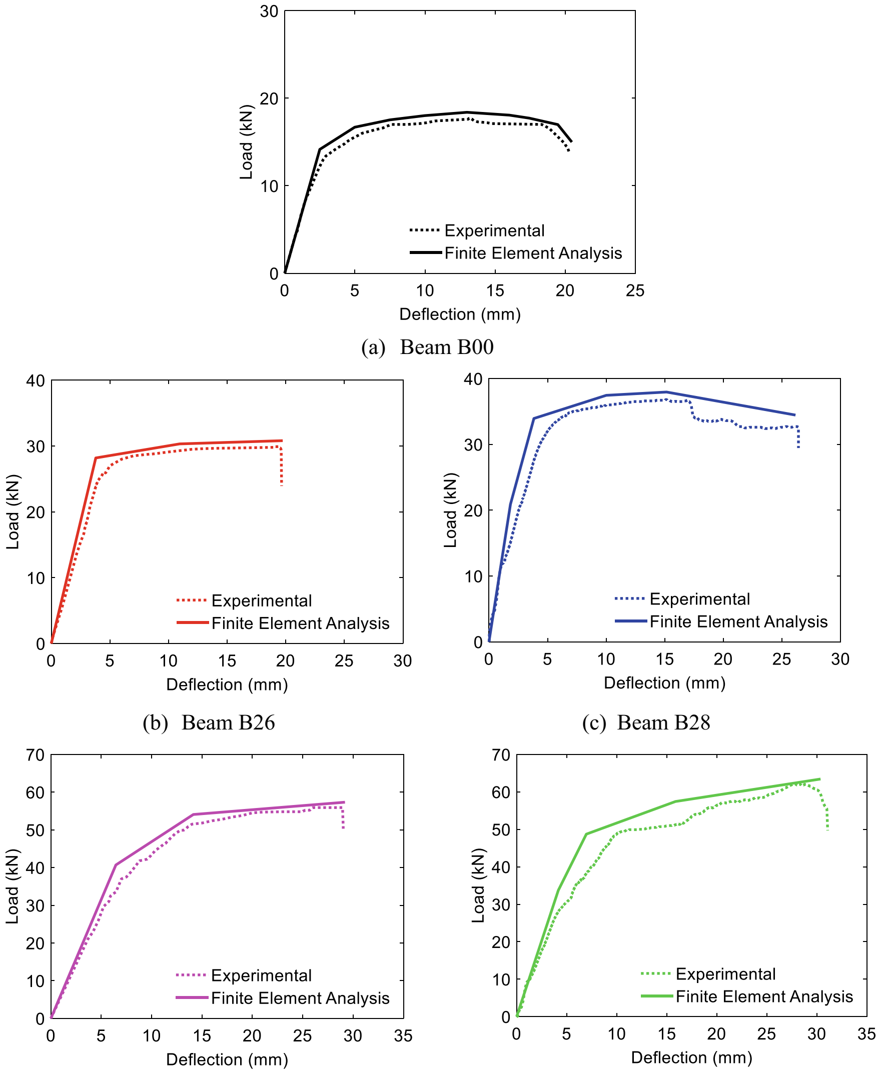
4.1 Model Validation

The load–deflection curves that were predicted for each of the five examined beams are shown in Fig. 4. Furthermore, Table 2 provides the ultimate load capacities and corresponding mid-span deflections as determined by both experimental tests and FE models. From Fig. 4 and Table 2, it is evident that the numerical and experimental results align well at all loading stages. The model predicts the load capacity and corresponding deflection with average discrepancies of 2.95% and 2.50%, respectively.

The FE results exhibited higher stiffness, particularly during the nonlinear stage of the beams. This suggests that the assumptions regarding the bond between steel and concrete, which did not account for bond-slip relationships, led to increased beam stiffness and overestimated strain concentrations in the steel at crack locations. Nevertheless, the findings validate the precision of the generated FE models in simulating the response of RC beams strengthened with external SWR.

4.2 Behavior of the Model

As shown in Fig. 5, the beam strengthened with external SWRs demonstrated a significant improvement in flexural strength. The unstrengthened beam (B00) had an ultimate load capacity of 18.39 kN and a corresponding deflection of 12.99 mm. The beam B26 had an ultimate load of 30.81 kN and a corresponding deflection of 19.74 mm, indicating a 67.55% increase in strength compared to the beam B00. The beam B28 achieved an ultimate load of 37.95 kN, representing a 106.38% improvement over the beam B00, with a corresponding deflection of 15.15 mm. The beam B46 achieved an ultimate load of 57.33 kN and a deflection of 29.19 mm, reflecting a 211.77% increase in strength compared to the beam B00. The beam B48 reached an ultimate load of 63.42 kN, representing a 244.90% increase in load capacity over the beam B00, with a corresponding deflection of 30.36 mm. Figure 6 depicts the crack configurations revealed at the point of failure, as determined by the FE simulations. The FE analysis results corresponded well with the test data, showing that the crack patterns and propagation from the bottom to the top indicated that all models experienced flexural failure.



(a) Beam B00

(b) Beam B26

(c) Beam B28

(d) Beam B46

(e) Beam B48

Fig. 4 Load-deflection curve comparisons between FE models and experiments

5 Conclusions

This study has introduced a nonlinear 3D FE model for assessing and predicting the behavior of five tested specimens, building upon a previous work [15]. By comparing the FE-simulated responses with experimental data, the models were generated and verified. The following are the findings of this investigation:

Table 2 FE models in comparison to the results of experiments

Beam	$P_{u\ (FE)}$ (kN)	$\delta_{u\ (FE)}$ (mm)	$P_{u\ (Exp)}$ (kN)	$\delta_{u\ (Exp)}$ (mm)	% Difference	
					P_u	δ_u
B00	18.39	12.99	17.70	13.12	3.89	−1.01
B26	30.81	19.74	29.90	19.45	3.04	1.52
B28	37.95	15.15	36.80	15.18	3.12	−0.19
B46	57.33	29.19	55.90	28.95	2.56	0.84
B48	63.42	30.36	62.10	27.87	2.13	8.94

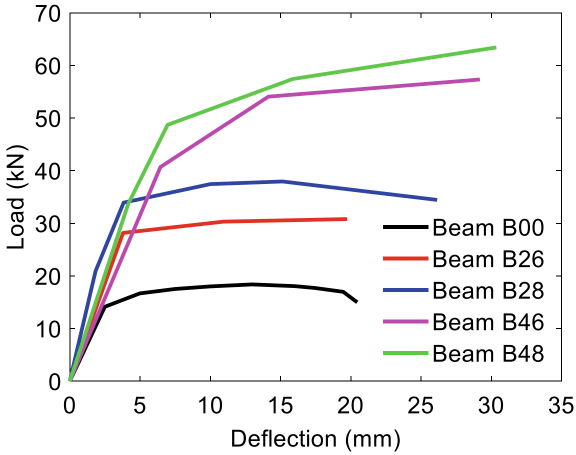
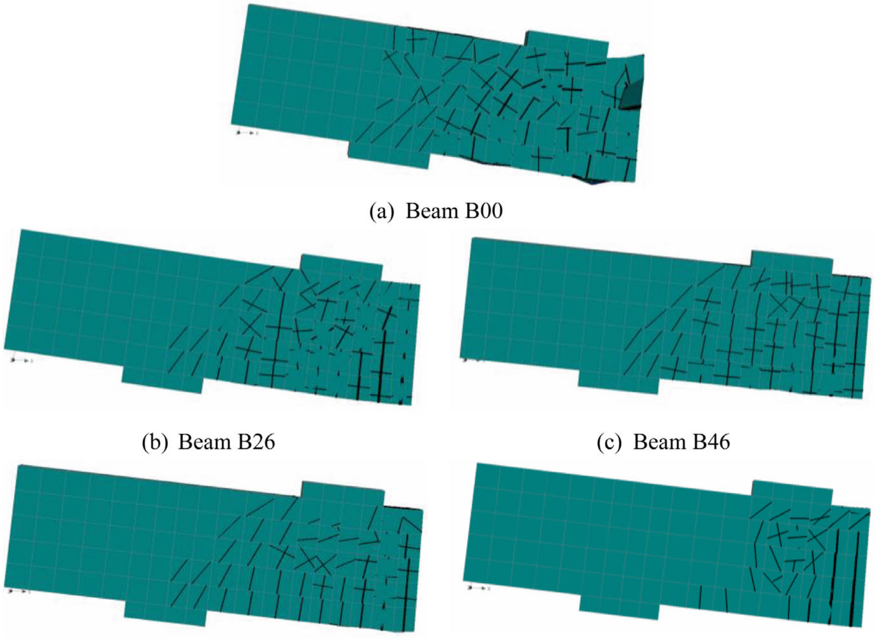


Fig. 5 Load-deflection curves for the generated FE models

- The load–deflection responses of the generated FE models exhibit a high degree of agreement with the experimental data.
- Beams strengthened with two external SWRs of 6 mm and 8 mm diameters showed increases in ultimate load of 67.55% and 106.38%, respectively, compared to the unstrengthened beam.
- The addition of four external SWRs with 6 mm and 8 mm diameters increased the ultimate load of the beams by 211.77% and 244.90%, respectively, relative to the control beam.
- The crack patterns observed in the FE simulations and their propagation from bottom to top indicate that all models experienced flexural failure.
- The validated FE models developed in this study can serve as a numerical platform for investigating and predicting the performance of RC beams externally strengthened in flexure with SWRs.
- Future research should include a parametric study with various prestressing levels to develop strategies that provide desirable ductile properties.



(a) Beam B00

(b) Beam B26

(c) Beam B46

(d) Beam B28

(e) Beam B48

Fig. 6 Modeled crack patterns at the failure

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