Available online at www.garmian.edu.krd

Passer Journal of Basic and Applied Sciences

Passer 7 (Issue 1) (2025) 416-434

Original Article

A Combined Numerical and Experimental Evaluation of the Flexural Performance of Wire Mesh-Strengthened RC Beam

[1]Nasih Habeeb Askandar *, [1], Ghafur H. Ahmed [2], Ghazi Bahroz Jumaa [3], Roshna Ahmed Hussein [1&4]

[1] *Civil Engineering Department, University of Halabja, Halabja 46018, Kurdistan Region, Iraq.*
[2] *Highway Engineering Department, Technical Engineering College, Erbil Polytechnic University, Erbil 44001, Kurdistan Region, Iraq.*
[3] *Civil Engineering Department, University of Garmian, Kalar 46021, Kurdistan Region, Iraq.*
[4] *Halabja Education General Directorate, Ministry of Education, Kurdistan Region, Iraq,*

Received 02 January 2025; revised 13 March 2025;
accepted 01 April 2025; available online 17 June 2025

DOI: 10.24271/psr.2025.497536.1881

ABSTRACT

The focus of this study is to determine how well stainless-steel wire mesh (SSWM), an externally bonded strengthening material, may improve the flexural performance of reinforced concrete (RC) beams. Evaluating the structural advantages of SSWM in terms of load-carrying capacity, deflection reduction, and crack management is the main goal. The use of SSWM as an affordable, long-lasting, and fire-resistant reinforcing method for RC beams is what makes this work novel. Finite element analysis (FEA) was carried out using Abaqus to validate the results of experimental testing on strengthened and control beams, as part of a combined experimental and numerical approach. The results show that, in comparison to control beams, SSWM greatly enhances flexural performance, increasing load capacities by 99% to 149%. Furthermore, mid-span deflections decreased from 53.7% to 53%, indicating improved structural stability. According to the crack study, reinforced beams had better damage control, fewer cracks, and the capacity to support loads after they first cracked. The accuracy of FEA in predicting the structural behavior of SSWM-strengthened beams was confirmed by the close match between the numerical models and experimental data. This study provides a promising and sustainable strengthening solution for RC structures, offering both economic and environmental benefits.

Keywords: SSWM; Flexural strengthening; Finite Element Method; ABACUS

1 Introduction

It is currently essential to identify appropriate strengthening techniques with simple and inexpensive installation due to unfavorable conditions that might damage reinforced concrete (RC) structures, especially in countries with limited resources. Since beams are the main structural components responsible for withstanding loads, effective strengthening techniques must be developed to ensure the structures' safety. The necessity for RC beams to be strengthened and upgraded arises from changes in the structural system and an increase in the applied load, design errors, construction-related issues, unforeseen damages, as well as modifications as a result of the steel reinforcement's reduction in stress, and deflection restrictions[1-7]. Externally bonded strengthening materials are one of the primary techniques utilized to strengthen RC structural elements along the tension face of the RC beams. Various materials, including longitudinal bars, FRP composites, SSWM, ferrocement, and fibrous materials, are commonly used to strengthen externally bonded systems [8-13]. SSWM has been recognized as an appealing approach for strengthening, rehabilitating, repairing, and even retrofitting RC elements when applied as an external strengthening material and incorporated within the additional larger section. This method can increase the ductility and the strengthened beams' load capacity. To create a regularly distributed mesh, the material known as SSWM comprises a series of regularly spaced, closely spaced rods that are welded together. Because of its relative simplicity of placement, high strength-to-weight ratio, and handling, SSWM has a wide range of advantages. Additionally, compared to other strengthening materials, it possesses desirable qualities such as being lightweight, durable, fire-resistant, and environmental stability. Compared to other materials, it reduces labor and waste parts, it also saves time and money [2]. Strength, durability, and simplicity of installation are all integrated at a low cost with SSWM's cost-effective strengthening solution. FRP is more expensive, less fire-resistant, and needs specialized labor, despite its increased strength. Although ferrocement is the least expensive, it performs worse structurally than FRP and SSWM.

* Corresponding author
E-mail address nasih.askandar@uoh.edu.iq (Instructor).
Peer-reviewed under the responsibility of the University of Garmian.

Even though stainless-steel wire mesh (SSWM) is beneficial for strengthening structures, little study has examined how it affects RC beams concerning flexural strengthening using both experimental and numerical methods. By assessing the load-carrying capability, deflection behavior, and cracking control for SSWM-strengthened RC beams, this work intends to address this gap. The innovation is in evaluating SSWM as a cost-effective, fire-resistant substitute for existing strengthening techniques. The results will improve the performance and durability of RC beams by offering insightful information about effective and sustainable strengthening methods.

Raiyani, S.D. and P.V. Patel explored strengthening hollow concrete RC beams using SSWM [14]. To compare the control and SSWM-strengthened arrangements, eight beams were evaluated. The results were in good agreement with a finite element model, including cracking and ultimate torque. For strengthening concrete torsionally, SSWM seems practical. In T-shaped reinforced concrete flanged beams, Raiyani, S.D., P.V. Patel, and S.D. Vora [15] evaluated the efficiency of externally bonded SSWM for improving shear strength. Numerical simulations validate the effectiveness of SSWM in shear strengthening through testing on SSWMs and trials on externally strengthened beams. The strengthening of concrete structures is covered by Makawana, R., P. Patel, and D. Joshi [16] while focusing on previous issues with FRP materials. Due to its ductility and bond with concrete, SSWM is regarded as an alternative. The study's employing SSWM to strengthen beam-column connections produced improved load resistance, ductility, and capacity, demonstrating that SSWM is a cost-effective option for strengthening concrete structures. Makawana, R., D. Joshi, and P. Patel [17] examined the use of SSWM for strengthening precast beam-column connections. On precast specimens enhanced using SSWM, monotonic loading tests reveal greater load capacity, improved ductility, and decreased concrete crushing. The efficacy of externally bonded SSWM for boosting shear strength in T-shaped reinforced concrete flanged beams is evaluated by Raiyani [15]. The effectiveness of SSWM in shear strengthening is demonstrated through stress and bond tests, trials, and experiments on externally strengthened beams, which are backed by numerical simulations.

Bhavsar, S.V., S.D. Raiyani, and P.V. Patel compare SSWM with carbon and glass fiber-reinforced polymers using experimental and finite element analysis [18] . According to the results, SSWM is just as efficient as CFRP and GFRP at enhancing torsional strength, damage patterns, and ultimate strain. Khan, M.A. and M. Venu [19] were used in numerous layers of SSWM, the flexural strength of strengthened RC beams is investigated. To increase flexural strength, several SSWM wrapping configurations on RC beams are put to the test. The results of the tests compare the strength gains for various wrapping configurations. Fang, S. examined the effectiveness of alkali-activated slag (AAS) ferrocement jackets in strengthening deteriorated corroded RC columns to address the issue of chloride-induced corrosion to RC structures [20]. Axial compressive experiments on corroded RC columns with AAS jackets and tensile testing on AAS ferrocement with layers of SSWM were performed. Loading capacity and ductility are strongly influenced by the SSWM percentage. Emara, M., et al [21] examined the application of steel mesh (SM) for the internal and external confinement of reinforced concrete (RC) columns, overcoming the drawbacks of conventional steel stirrups. It investigates how SM systems, wraps, positions, and stirrups affect performance. SM increases stiffness, load capacity, ductility, energy absorption, crack control, and spalling reduction. Partial internal confinement, which demonstrates a higher capacity and appropriate ductility than external confinement, is achieved by two SM wraps around steel ties. Xie, X., et al. [22] investigated the use of steel wire mesh (SWM) and polymer mortar to improve existing reinforced concrete (RC) shear walls. One as control and four strengthened RC shear wall specimens performed experimental testing utilizing various SWM ratios and wrapping procedures. By experimental and prior findings, a proposed theoretical expression based on the softened strut and tie model successfully predicted the reinforced shear wall capacity.

Tripathy, D. and V. Singhal used steel wire-reinforced cementitious matrix (SWRCM) overlays to study the flexural behavior of masonry [23]. Through experimental and finite-element analyses, factors impacting flexural capacity, such as reinforcement %, matrix strength, and masonry compressive strength, were examined. This work presented a new equation that takes these aspects into account and offers a step-by-step method for calculating effective tensile strain in SWRCM. Kumar, V. and P. Patel investigated the use of locally accessible SSWM to increase the axial strength of columns made of plain cement concrete of grades M15, M20, and M25 [24]. One or two SSWM wraps are applied to strengthen specimens of various heights, and the increased strength may exceed 86%. The bond and tensile strengths of SSWM support the viability of strengthening it. Kumar, V. and P. Patel explored employing SSWM instead of Fiber Reinforced Polymer (FRP) to strengthen structures [25]. Axial strength enhancement of SSWM-reinforced plain cement concrete and reinforced cement concrete columns is investigated using finite element (FE) analysis using the ABAQUS software. We look at different concrete grades, column heights, and SSWM wraps. The numerical results show significant axial capacity gains for both PCC and RCC columns. Choi, J.-H. investigated the seismic retrofit of circular columns with lap splice features utilizing SSWM composites [26]. When compared to unstrengthened columns, retrofitted columns showed better flexural strength and ductility. Kim, S.-H. and D.-K. Kim discussed seismic retrofit for RC columns that had not been seismically designed [27]. The work suggests a technique for the insufficient lap-splice region that uses permeable polymer mortar casing and SSWM. It was demonstrated through experimental testing on scaled specimens that seismic capacity is increased by retrofitting with an elliptical SSWM wrap and mortar casing. Kim, S.-H. and J.-H. Choi investigated the use of SSWM composites as a repair technique for concrete columns that were affected by earthquake damage and had insufficient lap splices [28]. Scaled columns were tested with cyclic loading, strengthened with SSWM wraps, and then put through another round of testing. The improved flexural strength, ductility, and energy dissipation of the repaired columns validated SSWM as a successful repair method for such columns. Zhang, M.J., et al explored the effectiveness of a laminate made of pre-stressed SSWM and mortar (M) for structural strengthening [29]. Pre-stress must be attained in SSWM, and jogging anchors must be used for anchoring. Flexural experiments on cracked RC beams reinforced with pre-stressed SSWM-M show that it performs better than smaller diameter SSWM-M at controlling crack growth and restoring capacity and stiffness.

Molkens, T., et al. stated that, apart from its corrosion resistance, stainless steel has outstanding mechanical properties. Maintaining its strength and rigidity for a longer period, it outperforms carbon steel in a fire [30]. According to Rabi, M., Cashell, K., and Shamass (2019), stainless steel offers many desirable qualities, such as superior mechanical strength, fire resistance, durability, and a longer life than carbon steel[31].

According to this review, little study has been done on the behavior of RC beams strengthened by SSWM. Even less research has been done on how to strengthen RC beams subjected to bending moment utilizing SSWM. This experimental and numerical investigation aimed to understand the impact of the SSWM strengthening technique on the cracking load, peak flexural strength, and failure modes of RC beams. Six RC beams were tested under flexural action to achieve this. Five RC beams were strengthened using various SSWM layers, whereas one RC beam was left unstrengthened and used as the control specimen. The flexural moment, deflection, and load-deflection behavior of the SSWM-enhanced samples were compared with those of control beams at the start of the crack and the final stage. SSWM-strengthened RC beams were numerically simulated under bending stress using the finite element program (Abaqus). Because SSWM is a common and economically viable option for strengthening RC elements, the current study will benefit professionals in structural strengthening.

Here are some more recent studies on SSWM in flexural strengthening: Li, Wei, and Zhu [32] studied reinforced concrete beams strengthened with Engineered Cementitious Composite (ECC) mesh reinforced with high-strength stainless steel wire rope (HSSSWR), demonstrating enhancements in flexural capacity, ductility, and crack management. In a different study by Fan, et al [33] looked into RC columns reinforced with HSSS wire-ECC, emphasizing improved ductility and load-carrying capacity. Furthermore, Shah, Raithatha, and Raiyani [34] investigated externally bonded SSWM for flexural strengthening and revealed that it was an efficient and affordable alternative for CFRP and GFRP.

In summary, the use of steel wire mesh for the flexural strengthening of RC specimens provides a substitute alternative for structural deficiencies and enhanced performance in general. Comprehensive knowledge of the efficacy, sustainability, and practicality of SSWM as a strengthening material will be gained through the combination of experimental research and numerical simulations performed using the Abaqus modeling program. In contrast to FRP sheets, SSWM is an economical and generally accessible alternative that doesn't have problems with stress concentration, especially in corners. Additionally, SSWM provides longer-term durability that is superior to ferrocement. Although composites are preferred for lightweight constructions, their corrosion resistance might not match that of SSWM. ferrocement may not be as durable or corrosion-resistant as SSWM. Various factors, including the project environment, material availability, cost considerations, and structural needs, affect whether SSWM, ferrocement, or composites are used [35]. Steel wire mesh outperforms ferrocement as a cost-effective, corrosion-resistant option for strengthening RC beams. By investigating its robustness and usefulness, this continuing study aims to improve its structural utility and maximize its use in the next engineering and building projects. The results of this investigation will advance our understanding of RC strengthening methods and help us make sound decisions for structural rehabilitation and retrofitting projects that are both environmentally friendly and economically practical.

2 Research Significance

The current study addresses the immediate demand for easily deployable, cost-effective strengthening techniques for reinforced concrete structures, especially in developing countries. The study's primary objective is to create efficient strengthening methods for beams since they are essential elements that carry loads that guarantee structural safety. The numerous advantages of SSWM, such as its low cost, simplicity of installation, durability, and fire resistance, are highlighted. A detailed analysis of the literature, which reveals research gaps in the context of RC beams strengthened using SSWM, represents the basis of this study. It aims to offer informative information to structural engineers and experts participating in structural rehabilitation and retrofitting projects by combining experimental testing and numerical simulations, with an emphasis on economical and ecologically suitable solutions.

3 Experimental Work

3. 1 Description of the experimental specimens

A laboratory experiment was conducted on six reinforced concrete beams made of grade M35 concrete. The ASTM C94/C94M concrete mix design for M35 has been finalized [36] . Table 1 illustrates the various constituent quantities needed for constructing concrete.

Table 1: Mix proportion for M30 concrete (ASTM C94/C94M).

Material	Quantity (kg/m^3)	Proportion
Cement	350	1
Fine aggregate	875	2.5
Coarse aggregate (9.5mm down)	1050	3.0
Water	157.5	0.45

According to ASTM C39/C39M [37], after 28 days, the compressive strength of three cubes was tested; the outcomes are presented in Table 2. The RC beams were reinforced longitudinally and transversely using GR60 rebar, or reinforcement steel. According to ASTM A615/A615M [38] guidelines, the longitudinal reinforcement bars' yielding strength,

ultimate strength under tensile load, and elongation have been evaluated, and the findings are displayed in Table 3. The transverse reinforcement had similar mechanical characteristics.
The external cross-sectional dimensions of the RC beam specimens were 100 mm x 200 mm, and their overall lengths were 1600 mm. The RC beams were designed per ACI318-19 [39] code requirements.
The longitudinal reinforcement for the RC beams consisted of four 10 mm diameter bars at each corner, and the transverse reinforcement consisted of stirrups with a 10 mm diameter at 125 mm (c/c) spacing. Figure 1 illustrates the details of the reinforcement. As illustrated in Figure 1 and Table 4, one RC beam remained unstrengthened (Control), whereas five RC beams were strengthened using various SSWM layers.

Table 2: Concrete Cube Compressive Strength Results.

	Compressive strength (MPa)
1st Cube	35.71
2nd Cube	36.30
3rd Cube	34.90
Mean	35.63
SD	0.57

Table 3: Mechanical and physical properties of Grade 60 reinforcing steel.

	1st Sample	2nd Sample	3rd Sample	Mean	SD
The bar diameter, mm	10	10	10		
Bar's length Before testing in millimeters.	60	60	60		
Bar's length after testing in millimeters.	70.5	69.1	70.3		
Yield strength (MPa)	536	456	446	451	4.55
Ultimate tensile strength (MPa)	635	642	671	649	15.58
Elongation (%)	17.5	15	17	16.5	1.08

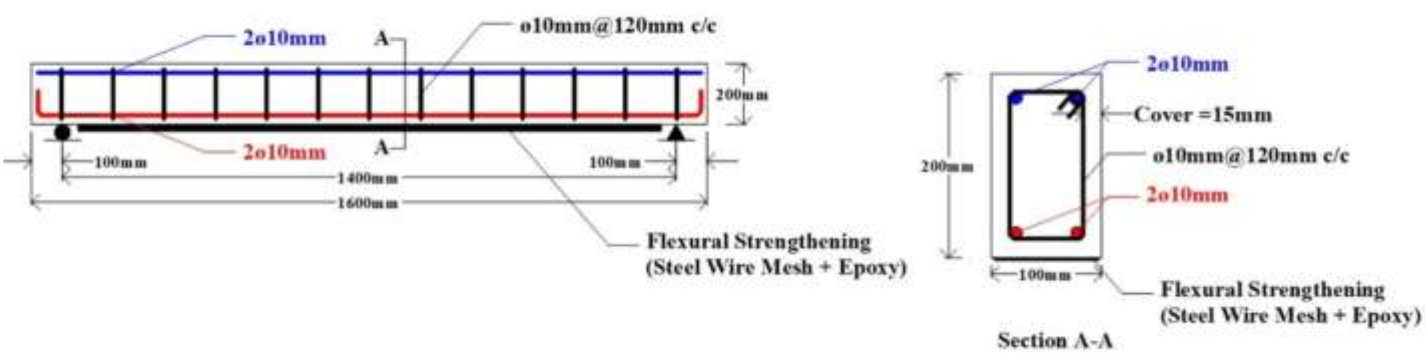


Figure 1: Reinforcement details of the RC beam.

Table 4: Description of RC beam specimens.

Specimen	Description of Strengthening	Thickness of the epoxy layers (mm)	Distance from the tension steel's centroid (mm)
Control	No strengthening	0	15
SB-1	Strengthening with one layer of (100mm strip) of SSWM	2	17
SB-2	Strengthening with [one layer of (100mm strip) + one layer of (50mm strip)] of SSWM	3	18
SB-3	Strengthening with two layers of (100mm strip) of SSWM	3	18.5
SB-4	Strengthening with [two layers of (100mm strip) + one layer of (50mm strip)] of SSWM	4	20
SB-5	Strengthening with three layers of (100mm strip) of SSWM	4	20.5

3. 2 Strengthening materials: epoxy-based adhesive materials and SSWM

Different kinds of SSWM with different wire diameters and mesh sizes can be found in regional marketplaces. These SSWMs perform important functions as strong, durable, and resistant materials that are frequently utilized as strainers, baskets, sieves, and barriers. Their suitability for these applications is increased by their resistance to corrosion. Depending on the kind of weave, wire meshes are divided into four categories: the weave patterns include plain, twilled, plain Dutch, and twilled Dutch [14]. The stainless-steel wire utilized in this experiment had a bidirectional type plain weave with a mesh count of three. Similar characteristics existed in the orthogonal directions for the SSWM (Figure 2). Stainless steel wires that were tied with 8 mm square apertures in both directions were used to create the mesh. The wire's nominal diameter was 1.6 mm. The steel wires have a major role in determining the SSWM's tensile strength and elastic characteristics. SSWM's mechanical characteristics were assessed per ASTM D3039/D3039M [40]. Two SSWM sections were cut into portions that measured 100 mm by 300 mm each, and they were sandwiched between two steel plates that measured 100 mm by 100 mm each. Sikadur-30 LP, epoxy-based adhesives, was used to join the steel plates and SSWM strips. A certain amount of stress was given to the steel plates at the two ends of the specimens to guarantee appropriate contact between the SSWM and the plates. The samples were cured for 7 days at room temperature. The specimen ready for tensile testing is shown in Figure 3(a), illustrating its plan and section. A universal testing machine (UTM) was used to test these coupons underneath a direct tensile force (Figure 3(b)). The UTM was used to hold the steel plates at the ends of the SSWM samples to provide direct tension. Figure 3(b) shows the use of dial gauges to measure the elongation as tensile stress increased[14].

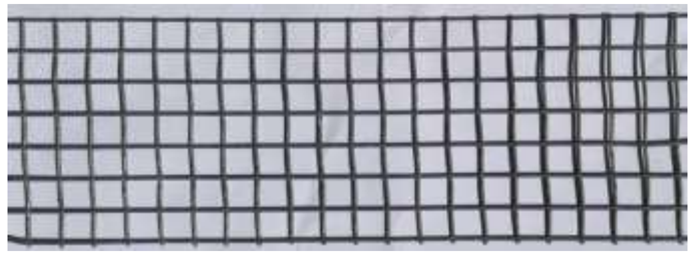


Figure 2: Stainless Steel Wire Mesh Sample Used for Strengthening.

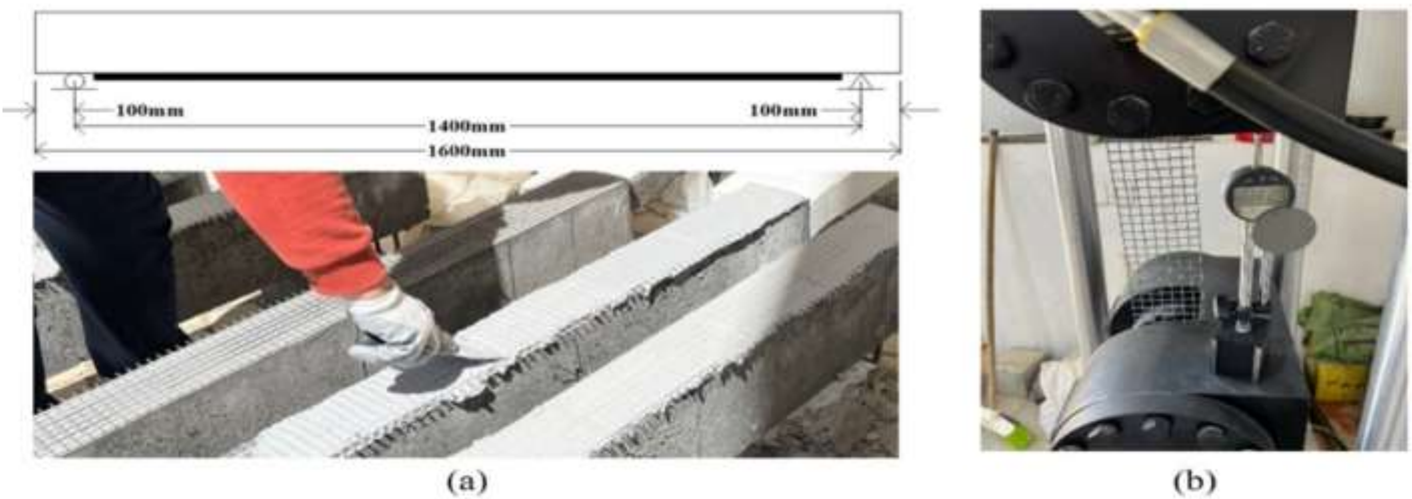


Figure 3: (a) SSWM specimen sample; (b) Testing of SSWM's tensile strength.

The stress-strain diagrams during tension testing using the SSWM sample are shown in Figure 4. The material properties used in the Abaqus numerical simulations have been determined using these curves. Even though both specimens were prepared simultaneously in comparable circumstances, the distinctive flexibility of SSWM indicates small shifts between the samples. Assume that there was a small amount of slippage at the grip end throughout the loading process, in that instance, inequalities in the initial stiffness may have occurred from some steel wires within the 100 mm width of the SSWM strip not experiencing uniform stress during loading.

The yield strength of SSWM, based on the results of the tension test, is lower than that of FRP, but due to its elastoplastic stress-strain behavior, it may withstand ductile failure in RC elements that have been strengthened with SSWM. According to Table 5, the average SSWM has a tensile strength of 513.5 MPa, rupture strain of 0.0330, and elastic modulus of 194 MPa. These values were obtained through tensile tests conducted according to standard methods. In particular, a uniaxial tensile load was applied to the SSWM samples for generating the stress-strain curves, and the highest stress recorded on the curve was used to determine the tensile strength. The first linear part of the stress-strain curve, whose slope indicates the stiffness of the material, was used to calculate the elastic modulus. The chosen adhesive, Sikadur-30 LP, has excellent SSWM-to-concrete adhesion, a long pot life, high-temperature resistance, and non-shrinkage. SSWM works better than MasterBrace 3500 priming and MasterBrace 4500 high strength epoxy for bonding SSWM to concrete [25]. Epoxy resin and hardener contribute to Sikadur-30 LP, and the specifications provided by the manufacturer are listed in Table 6. An author explored how strengthened beams behaved concerning the bond between the material used for strengthening and the concrete substrate[41] . Therefore, it was decided that performing bond tests between SSWM and the concrete surface was crucial before applying them to RC beams. Using a test for double-shear lap bonding, [15, 42, 43] reported on the bond behavior between SSWM and concrete. There were no instances of the SSWM debonding during these tests, and the failure that was seen was due to the wire mesh tearing.

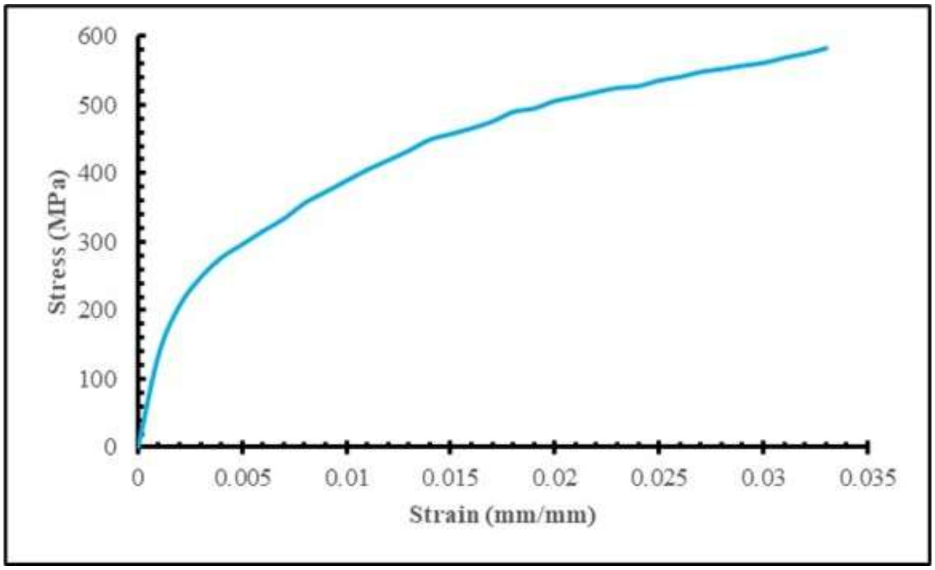


Figure 4: SSWM tension testing demonstrates stress-strain behavior.

Table 5: Mechanical and physical properties of the SSWM.

	1st Sample	2nd Sample	Mean	SD
Width in millimeters	100	100		
Thickness in millimeters	4.02	4.02		
No. of wires	8	8		
The sectional area of a single wire (mm^2)	3.17	3.17		
The total cross-section area of mesh (mm^2)	25.36	25.36		
Ultimate load (N)	8233	8279		
Ultimate tensile strength (MPa)	512	515	513.5	1.5
Rupture strain (mm/mm)	0.0552	0.0547	0.05495	0.00025
Modulus of elasticity (GPa)	190	194	192	2

Table 6: Sikadur®-30 LP (two-part epoxy impregnation resin).

Appearance and colours	Part A: white; Part B: black; Parts A+B: light grey
Density (at 23 °C)	~1.65 kg/lt (parts A+B)
Mixing ratio	Part A: B = 3:1 by weight or volume
Layer thickness	30 mm max
Open time	90 min (at +25 °C)
Viscosity	Pasty, not flowable
Service temperature	−40 °C to 45 °C (when cured at > 23 °C)
Tensile strength	15 MPa to 18 MPa (when cured for 7 days at 23 °C)
Shear strength	17 MPa to 21 MPa [40 °C to 55 °C (7 days)]

3. 3 Strengthening procedure

Using the specified adhesive and the proper SSWM widths and a number of layers, listed in Table 4, the RC beams were strengthened by applying SSWM on the tension face of the beam. This was done after the RC beams had been wet-cured for 28 days. As demonstrated in Figure 5a, the concrete surface was smoothed by grinding. The strengthening of the beam specimens was done in the following steps.

- To ensure that the surface is sufficiently roughened to improve the binding between the existing concrete substrate and the steel wire mesh, thoroughly grind the tension face of the RC beam with a grinder.

- Strips in the specified width (100 mm) have been cut from the SSWM roll. To apply the SSWM, the beam specimens were marked.

- Utilizing a mixing spindle and a slow-speed stirrer, the adhesive parts A (resin) and part B (hardening agent) were mixed in the proportion of 3:1 for 3 minutes, or until the adhesive was largely grey and had a smooth consistency.

- A thin layer of adhesive, around two millimeters in thickness, was applied to the beam's surface with a steel plate (Figure 5(b)).

- To ensure that the prepared SSWM strip had been properly positioned without any air spaces, it was placed over the recently applied adhesive and gently presses down (Figure 5(c)).

- A second coat of adhesive, approximately two millimeters thick, was applied to completely cover the SSWM strips and provide a level and smooth surface (Figure 5(d)).

Follow the manufacturer's instructions to let the epoxy cure, 15 days curing process. To guarantee consistency, the bond was cured for 15 days at a regulated temperature and humidity level. The bond strength and, in turn, the overall performance of the reinforced beams can be greatly impacted by these curing conditions.

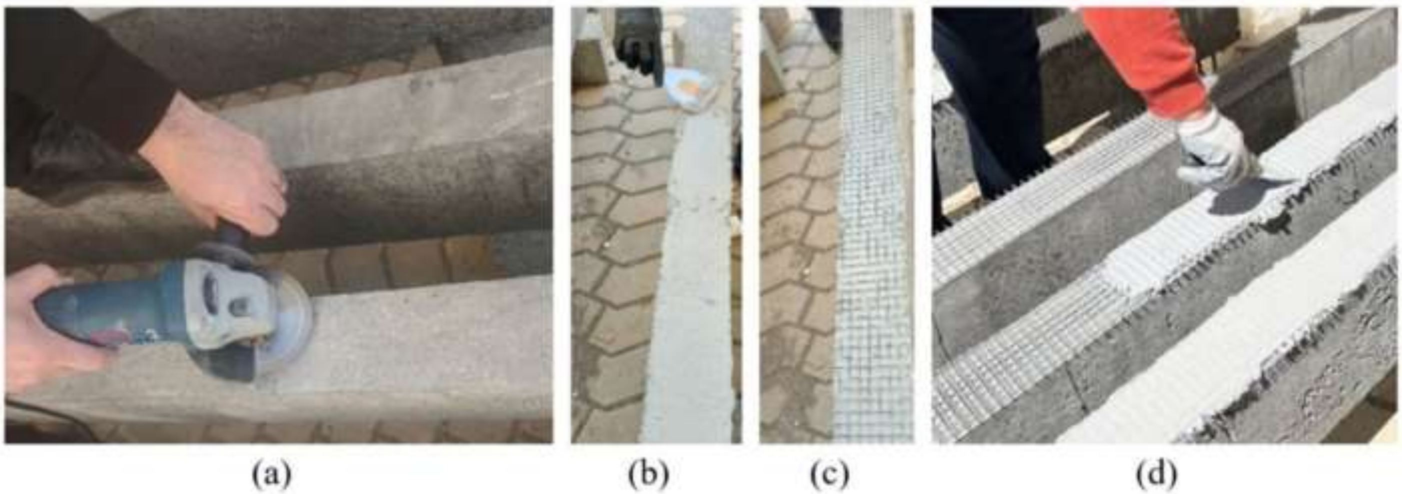


Figure 5: (a) Grinding of the beam sample; (b) Putting on the initial layer of adhesive; (c) Applying the SSWM in the appropriate position; (d) Applying the last layer of the adhesive.

3. 4 Instruments and testing setup

The reinforced concrete (RC) specimens are thoroughly bleached before the testing to improve the visibility of cracks while loading arises. After an appropriate curing period (28 days), aided by a hydraulic machine, all beams undergo a progressive loading rate that results in bending failure. For all beams, a uniform loading frame with a 600 kN capacity is used. As shown in Figure 6, the load is applied in 2.0 kN increments, with a beam supporting a single concentrated load. Using a laboratory loading machine, roller supports provide lateral support for the beams. A computerized pressure gauge inside the hydraulic system monitors the applied load. A dial displacement gauge is used to measure the deflection of the beam at its mid-span, where the load has been introduced during each increment of loading. The width of cracks at the mid-span is also measured utilizing a micro crack scope. These mid-span deflection readings and crack width measurements are thereafter carefully documented within a table. To efficiently monitor the responses of the test specimens, throughout the entire examination, all equipment is carefully organized. Each specimen's behavior is evaluated, taking into account characteristics such as deflection, failure mode, primary cracking appearance, and ultimate load.

Figure 6: Bending test configuration.

4 Numerical Study

A non-linear finite element analysis (FEA) approach was employed for modeling and analyzing the behavior of reinforced concrete (RC) beams that have been strengthened with SSWM under flexural stress. This analysis technique simulates the behavior of these specimens using the Abaqus scheme.

4. 1 Modeling layout and Geometry

4. 1. 1 Concrete

In addition to being brittle and irregular, concrete exhibits nonlinear characteristics. In finite element (FE) modeling, it is essential to properly represent its behavior. In the present study, we model concrete utilizing a solid brick element with eight nodes, this provides each of the nodes with three degrees of freedom (df). This substance can withstand crushing, three-way perpendicular cracking, and plastic deformation. The discretization of reinforced concrete (RC) beam samples using Abaqus is demonstrated in Figure 7(a).

4. 1. 2 Reinforcement steel

The longitudinal as well as transverse reinforced steel bars were modeled using embedded truss elements, also known as 2-node linear 3-dimensional (3D) truss elements, abbreviated T3-D2. In this approach, the steel bars are an integral component of the structure that hosts concrete elements. When a node of the embedded element corresponds with the host element, the translational *df* of the embedded element is limited to the interpolated values derived from the associated *df* of the host element. Figure 7(b) shows the representation of the Abaqus meshing of the steel reinforcing bars.

4. 1. 3 SSWM

An elastoplastic material was used to simulate the SSWM. An effective representation approach for the SSWM was a 4-node double curving thin shelled extrusion-type element, called S-4R, because of its extremely small thickness to its other dimensions. This decision was made in order to accurately convey the SSWM's behavior. Employing the Abaqus platform, the SSWM element meshing technique is illustrated visually in Figure 7(b).

4. 1. 4 Interaction

In the numerical study, perfect bonding in the outermost concrete and the reinforcement bars was presumed to be resulting in complete compatibility. This concrete-steel interaction was modeled with the use of an embedded region constraint.
Research by S.D. Raiyani and P.V. Patel show that no slippage of the SSWM along with the concrete substrate occurred during any of the bond tests in this regard. These investigations revealed just the tearing apart of the SSWM, indicating a strong bond that exists between the SSWM and the concrete substrate. A tie constraint was utilized in the modeling approach to replicate this perfect bond [14].
The reinforced concrete beams started to deform during the process of loading. The dilation reached the SSWM as a result of the link that formed between the concrete's outermost layer and the SSWM. To simulate this behavior within the Abaqus program, a conceptual framework was constructed in which the SSWM was identified as the slave face and the concrete surface as the master surface.
The complex interactions between SSWM, epoxy, and concrete under varying load conditions are not well captured by the FEA model utilized in this investigation. The overall accuracy of the predictions may be impacted by these restrictions, which include the simplification of material properties, assumptions about bond-slip behavior, and difficulties precisely simulating the post-peak reaction of the materials. To increase model reliability, future research needs to concentrate on improving these elements.

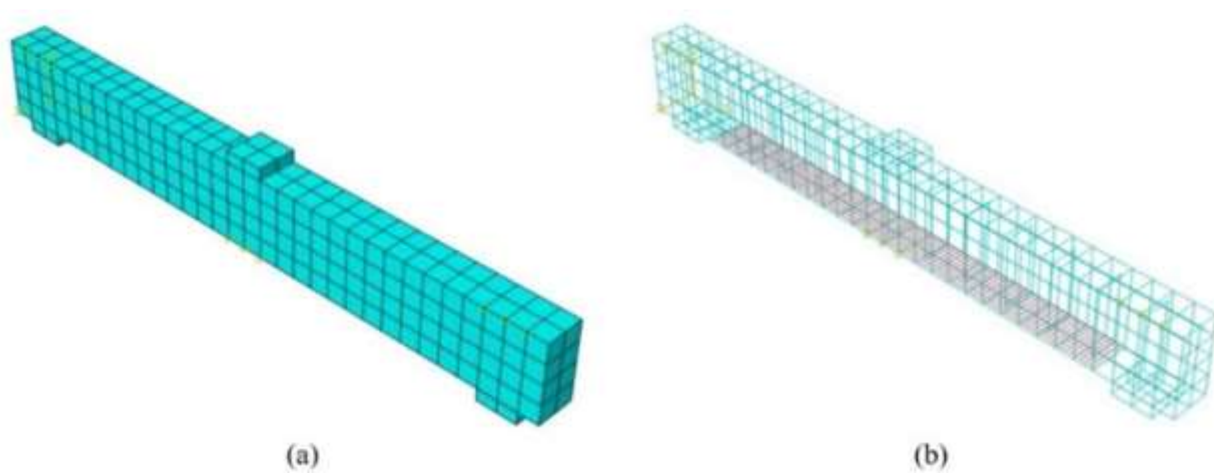


Figure 7: (a) An eight-noded solid brick element indicating RC beam; (b) 2-node 3D linear truss elements were used to represent the reinforcement steel, which was embedded in concrete. Four-node shell elements were used to simulate the SSWM.

4. 2 Materials modeling

A versatile method for examining an extensive spectrum of structures, including beams, solids, and shells, in varied conditions of the load is the Concrete Damaged Plasticity (CDP) model. Within the particular context of this investigation, the Abaqus system's CDP model effectively simulated the characteristics of concrete. This model effectively combines the characteristics of isotropic elasticity and non-associated multi-hardening plasticity, offering an in-depth representation of the irreversible degradation that takes place during the fracturing process [14].

This model takes into account two different failure modes, each of which is a crucial part of the Abaqus platform (DS, 2016). These mechanisms, which cover concrete's tensile cracking and compressive crushing, are systematically added to the model. The mechanical characteristics that control how well concrete behaves under tension and compression serve as a basis for the virtual simulation of these phenomena. As a result, the CDP model successfully represents the complex details of the uniaxial tensile and compressive behaviors revealed by concrete materials.

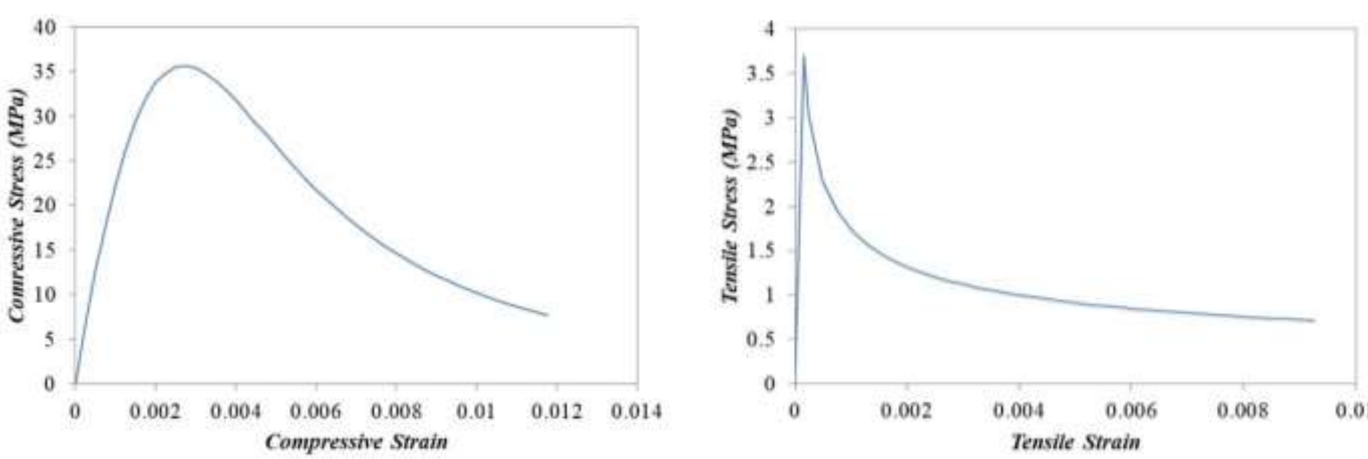
The CDP model applies to a wide variety of structural elements and loading conditions. Its ability to accurately simulate the complex material responses of concrete is further demonstrated by the incorporation of non-associated multi-hardening plasticity, isotropic elasticity, and accurate representation of failure mechanisms involving compressive crushing and tensile cracking. This integration shows how the model might improve our knowledge of how different mechanical pressures affect concrete structures.

4. 2. 1 Concrete

The concrete damaged plasticity model is present in the ABAQUS material library because it has an established record of success in similar applications and can be employed to simulate concrete behavior. This model is quite flexible and can predict concrete structures' responses to monotonic, cyclic, and dynamic loads with excellent accuracy. It is predicted that tensile cracking and compressive crushing are the primary sources of concrete failure. Damaged plasticity is used in this model to characterize the uniaxial tensile and compressive properties. The following assumptions have been adopted regarding the critical variables for describing concrete's plastic properties: fb/fc (indicating the ratio of biaxial compressive ultimate strength to uniaxial ultimate compressive strength) was set at 1.16, k (indicating the ratio of tension meridian plane to the second stress invariant of the compression meridian plane) was assumed to be 0.667, and μ (indicating the viscosity parameter) was set at 0.026. Ψ (representing the dilation angle) was set at 15° and ε (flow potential eccentricity) was set at 0.1. Those parameters that are relevant to the behavior of the concrete were specifically described for this model in Table 7. This thorough representation of the parameters offers a complete understanding of how the concrete responds to various stresses and strains, ultimately assisting in a more accurate and reliable simulation of its behavior under diverse loading conditions. [43]

Experimental testing was done to ascertain the mechanical properties of the concrete utilized in this investigation for all specimens, both under compression and tension. The results are shown in Table 2. Figure 7(a) demonstrates the discretization process of the reinforced concrete (RC) beam sample using the Abaqus scheme.

Linear elastic behavior, which can be explained through parameters like the elastic modulus and Poisson's ratio, first characterizes the mechanical response of concrete to both compression and tension. Different description is used to define the more complex nonlinear behavior of concrete, which includes inelastic strain and associated yield stress. Jeng and Hsu's stress-strain relation accurately reflects the stress-strain curves for the uniaxial compressive and tensile behavior of concrete [44]. Figures 8(a) and 8(b), which introduced these stress-strain relationships into the model, illustrated the concrete's stress-strain behaviors and served as a basis for the modeling procedure. Notably, the model's validity is supported by empirical data for these behaviors that were gathered through uniaxial compression and tension testing. However, several crucial criteria corresponding to failure mechanisms have to be taken into account to accurately represent the plasticity portion of the material's behavior. These characteristics include viscosity, eccentricities, the proportion of tensile to compressive meridians stress, and the bi-axial to uni-axial strength. These aspects are of utmost importance for understanding the complex failure mechanisms that concrete can experience.



(a) **(b)**

Figure 8: (a) Compressive strain of concrete (b) Concrete's tensile strain; [44].

Table 7: Concrete failure parameters.

Parameter	Value
Angle of dilation (deg.)	15
Eccentricity	0.1
Compressive strength ratio (biaxial to uniaxial)	1.16
Proportion of compressive to tensile meridian	0.667
Viscosity	0

4. 2. 2 Steel reinforcement

The tensile stress-strain properties of the reinforcing steel were simulated using the elastoplastic bi-linear stress-strain curve model (as shown in Figure 9). This particular model provides a systematic illustration of the behavior of the reinforcing steel under tensile loading conditions. The research ensures an accurate characterization of the reinforcing steel's performance and deformation when subjected to tensile stresses by using this model.

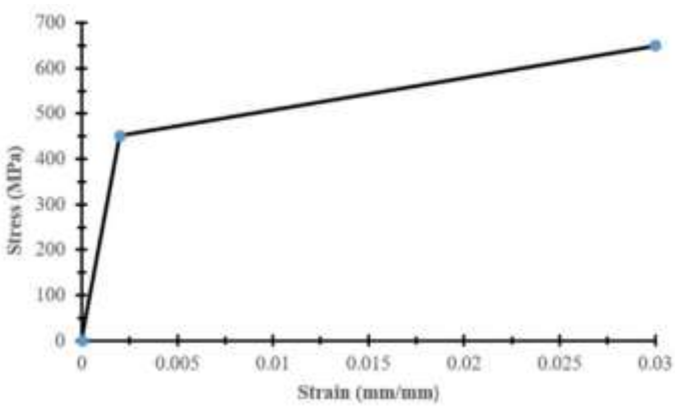


Figure 9: Steel reinforcement's stress-strain relations [44].

4. 2. 3 SSWM

The stress-strain relationship of the SSWM was modeled using the mean stress-strain values extrapolated from two SSWM samples (as illustrated in Figure 4). As part of the process, the mechanical behavior of the SSWM material was represented in the model. The research aims to accurately represent the SSWM's material properties and therefore enable a more accurate modeling of its performance under varied loading conditions by taking into account the typical stress-strain response of these specimens.

4. 3 Loading and boundary conditions

To accurately simulate the experimental settings, the numerical simulation carefully considers the boundary conditions and loading of the reinforced concrete (RC) beam specimens. This Finite Element (FE) model has detailed features. The nodes were selectively constrained both vertically and horizontally at one end of the beam, providing the appearance of a hinged connection. ll nodes were permitted to move on the opposite end, except for vertical displacement, replicating a roller connection. At half the length of the uppermost portion of the beam, a single-point load was applied to replicate the real bending effect observed during experimentation. The horizontal axis of the beam's cross-section was bent due to the impact of this load. The software Abaqus' explicit module was utilized to execute these simulations. It was essential to prove the validity of the numerical model before exploring the flexural characteristics of the RC beams. So, an assessment was carried out to ensure that the simulation was accurate and consistent with the reality. Numerical models were conducted using a displacement-controlled loading mechanism. The behavior of the RC beam specimens after yielding was properly predicted using this method. This addressed the full spectrum of post-yielding responses along with providing information about the structural integrity of the beam under various stress conditions.

5 Results and Discussion

During the experimental phase of the present investigation, we investigated the mid-span deflection of the specimens at different load intervals. After that, we created load-deflection graphs to observe how strengthened beams behave to bending. We recorded the load and deflection values at the first crack and the ultimate load for both the unstrengthened and SSWM-strengthened beams for the purpose of evaluating the effectiveness of the strengthening technique. We performed experiments and compared the average load and deflection readings for both the control and strengthened beams. To assess the impact of SSWM on RC beam flexural resistance, we also closely monitored and analyzed the failure modes of the unstrengthened (control) and strengthened samples throughout the testing process.

5. 1 Experimental Results load-deflection behavior

A full comparison of mid-span deflection measurements for both the unstrengthened and SSWM-strengthened RC beams taken at various load intervals is shown in Figure 10. The results demonstrate that the RC beams enhanced with SSWM performed significantly better under bending stresses than the unstrengthened control specimen. It further indicates that the SSWM strengthening greatly enhanced the beams' ability to resist bending loads and minimized mid-span deflection, two crucial indicators of structural strength and stability. The maximum load capacity of reinforced concrete (RC) beams is illustrated in Figure 11(a). The control beam, which served as a reference point, had the lowest maximum load capacity (26.5 kN). The load-bearing performance of succeeding beams, beam SB-1, beam SB-2, beam SB-3, beam SB-4, and beam SB-5, which had respective load capacities of 52.5 kN, 58.5 kN, 62.5 kN, 63.3 kN, and 66 kN, showed substantial enhancements. This information demonstrates the effectiveness of structural strengthening by highlighting a distinctive trend of improving load capacity. The mid-span maximum deflection of reinforced concrete (RC) beam specimens is depicted in Figure 11(b). The control beam exhibits the largest deflection at 35 mm, whereas the deflection values of the SB-1 and SB-2 beams are decreasing at 30 mm and 25 mm, respectively. Surprisingly, with values of 22 mm, 18 mm, and 16.5 mm, respectively, beams SB-3, SB-4, and SB-5 show significant declines in deflection. These results demonstrate that RC beams can be used in a variety of engineering applications by successfully minimizing their deflection through structural strengthening modifications.

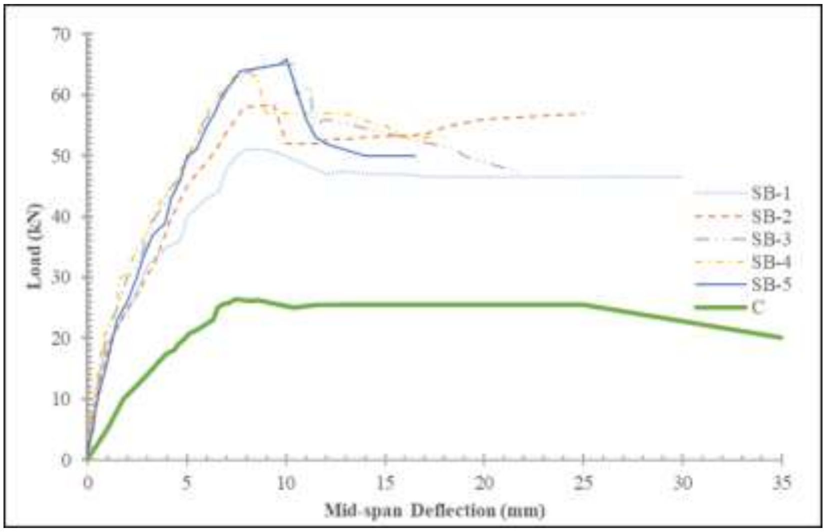
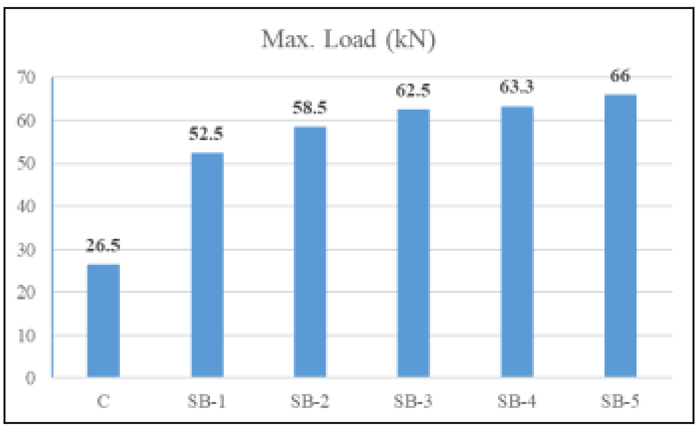
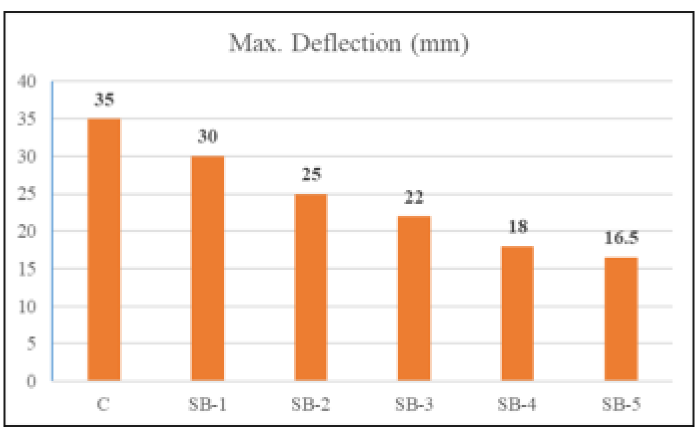


Figure 10: The experimental results of specimens' load-deflection behavior.



(a) Specimens max. load



(b) specimens max. mid-span deflection

Figure 11: Specimens max. load and max. mid-span deflection.

When progressively subjected to a bending force, control specimen C revealed an almost linear relationship between the applied load and deflection until the first crack developed. The control specimen's first crack was noticed at a load of 20 kN and a deflection of 5mm (Δcr). The deflection of specimen C climbed rapidly after the first crack appeared until the ultimate load (Pu) reached 26.5 kN. The mid-span deflection (Δu) for specimen C measured 35mm at the point of maximum load. When the maximum load had been attained, additional cracks began to appear, leading to the deflection to continue expanding while the load was decreased. As a result of extensive cracking, the specimen's loading was halted when it became unstable. Specimens SB-1 and SB-2 revealed the first crack alongside a load of 31 kN and an associated deflection of 4 mm. A relatively linear load-deflection characteristic was observed up until the first crack. The specimen's mid-span deflection developed non-linearly after the first crack, reaching Pu = 52.5 kN for SB-1 and 58.5 kN for SB-2 with corresponding Δu = 30 mm for SB-1 and 25 mm for SB-2. From then on, the deflection grew as the load decreased. In specimens, SB-3, SB-4, and SB-5, up to the first crack appearing at roughly Pcr=32 kN, the deflection increased linearly with increasing load. The deflection at the first crack for these specimens was about 3.5mm. For SB-3, SB-4, and SB-5, the maximum loads were 62.5 kN, 63.3 kN, and 66 kN, respectively, whereas the associated deflections were 22 mm, 18 mm, and 16.5 mm. Table 8 presents a complete list of the results. The SSWM-strengthened RC beam specimens all demonstrated larger ultimate and cracking load resistance than the control samples. Moreover, the beams with SSWM added to them had less deflection. All specimens in the initial phase exhibited similar flexural stiffness, demonstrating concrete's participation. Due to SSWM's contribution, the specimen revealed increased cracking load and decreased deflection. Compared to the control beams, each SSWM-strengthened RC beam exhibited a much higher energy absorption capability. For each RC beam strengthened employing SSWM, high flexural stiffness, and linear load-deflection behavior were seen before cracking. After the first cracking, stresses were transferred from the concrete to the reinforcement, which reduced deflection but didn't significantly improve load-bearing capacity. The load-deflection behavior altered after this, but before the peak load, the flexural stiffness increased. The ductile response in the post-cracking stages of the RC beams with SSWM strengthening was improved by the presence of both external and interior reinforcements. Compared to control beams, specimen SB-5's ultimate flexural strength increased by 2.49 times but its corresponding deflection decreased by 0.47 times, demonstrating higher stiffness but potentially decreased ductility. It proved that specimens with a higher SSWM ratio performed more effectively in increasing several significant structural characteristics. In particular, as compared to the other specimens, they demonstrated considerable improvements in cracking load, post-cracking stiffness, and ultimate flexural strength. This enhanced performance is a result of the external strengthening material, SSWM, being continuously and copiously present inside the specimens' flexural tension zone. These specimens are more effective at enhancing structural performance because of the continuous reinforcement in this vital location, which increases stiffness after cracking, increases ultimate flexural strength, and improves load-bearing capacity. Additionally, Table 8 demonstrated that when the number of SSWM layers increased RC beams' ultimate load capacity significantly increased. The load capacity of the control beam was 26.5 kN, while the beams strengthened with SSWM layers revealed significant enhancements. SB-1 attained 52.5 kN after being strengthened with one layer of SSWM. SB-2 reached 58.5 kN with one and a half layers. With two layers, SB-3 obtained 62.5 kN. With two and a half layers of strengthening, SB-4 scored 63.3 kN, while SB-5, with three layers, had the maximum capacity at 66 kN. The gradual enhancement in load-bearing capacity indicates an immediate association between increased structural strength and the number of SSWM layers. It highlights how effective SSWM is as a strengthening method for improving the load-bearing. Table 8 further supports the strengthening efficacy by showing a continuous increase in cracking load (P_{cr}) with an increase in SSWM layer number. This trend is similar to that observed for ultimate load. We compared our results with those of other studies that used comparable strengthening techniques, like SSWM and FRP, in order verify the findings and emphasize the special contributions of our investigation. This comparison highlights the unique features of our study and emphasizes its importance in the larger context of RC beam strengthening by demonstrating the cost-effectiveness, durability, and flexural performance advantages of SSWM.

Table 8: Summary of test results.

Beam	First crack					Ultimate				
	P_{cr} (kN)	$\frac{P_{cr}}{P_{cr,Control}}$	$\frac{P_{cr}}{SSWM_{layer}}$	Δ_{cr} (mm)	$\frac{\Delta_{cr}}{\Delta_{cr,Control}}$	P_u (kN)	$\frac{P_u}{P_{u,Control}}$	$\frac{P_u}{SSWM_{layer}}$	Δ_u (mm)	$\frac{\Delta_u}{\Delta_{u,Control}}$
C	20	1	----	5	1	26.5	1	---	35	1
SB-1	31	1.55	31	4	0.8	52.5	1.98	52.5	30	0.86
SB-2	31	1.55	20.66	4	0.8	58.5	2.21	39	25	0.71
SB-3	32	1.6	16	3.5	0.7	62.5	2.36	31.25	22	0.63
SB-4	32	1.6	12.8	3.5	0.7	63.3	2.39	25.32	18	0.51
SB-5	32	1.6	10.66	3.5	0.7	66	2.49	22	16.5	0.47

5. 1. 1 Maximum crack width

Figure 12 illustrates the maximum crack width in RC beams. The control beam has the largest cracks, as well extending 24 mm, indicating its vulnerability to structural degradation when not strengthened. The reduced crack widths in the strengthened beams (SB-1 through SB-5) are 20 mm, 15 mm, 12 mm, 5.5 mm, and 3.5 mm, respectively. This significant reduction in crack width in the strengthened beams emphasizes how effectively the flexural enhanced SSWM technique performs in enhancing the structural integrity of RC beams. The significance of SSWM reinforcement in preventing crack propagation and guaranteeing the long-term durability and safety of RC beams is highlighted by these outcomes, which have significant implications for the construction industry and structural engineering.

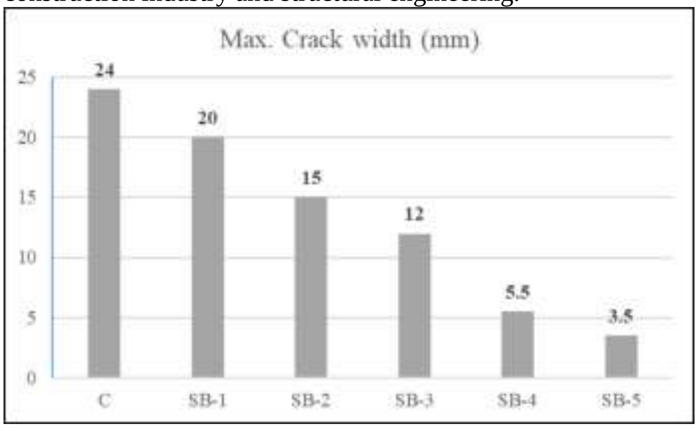
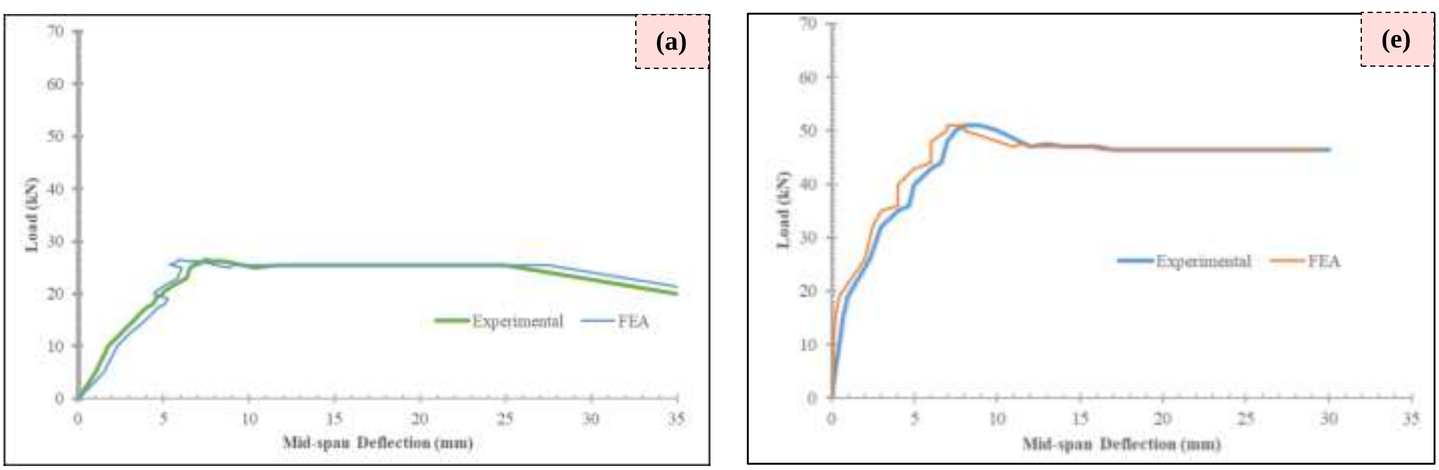


Figure 12: Specimens max. crack width.

5. 2 Analysis of FE and ACI318-19 code predicted results

A comparison between the results of finite element simulations and the experimental load-deflection response is presented in Figure 13. The results demonstrate a high degree of similarity. Although there were slight variations in the load-deflection behavior after attaining the peak load, the load-deflection patterns up to the ultimate load quite match the experimental data. The FE simulations accurately predicted the initial flexural stiffness for all beams. Then, when the load increased, the initial cracking deflection demonstrated a more rapid ascent. The sudden increase of deflection up to the maximum load point was caused by forces transferring from the reinforcement to the concrete. Beyond the first cracking stage, there was a variation between the predicted load-deflection based on FE and the actual experimental behavior. This disparity resulted from the presumption that the reinforcement and concrete had a perfect interaction or bond.



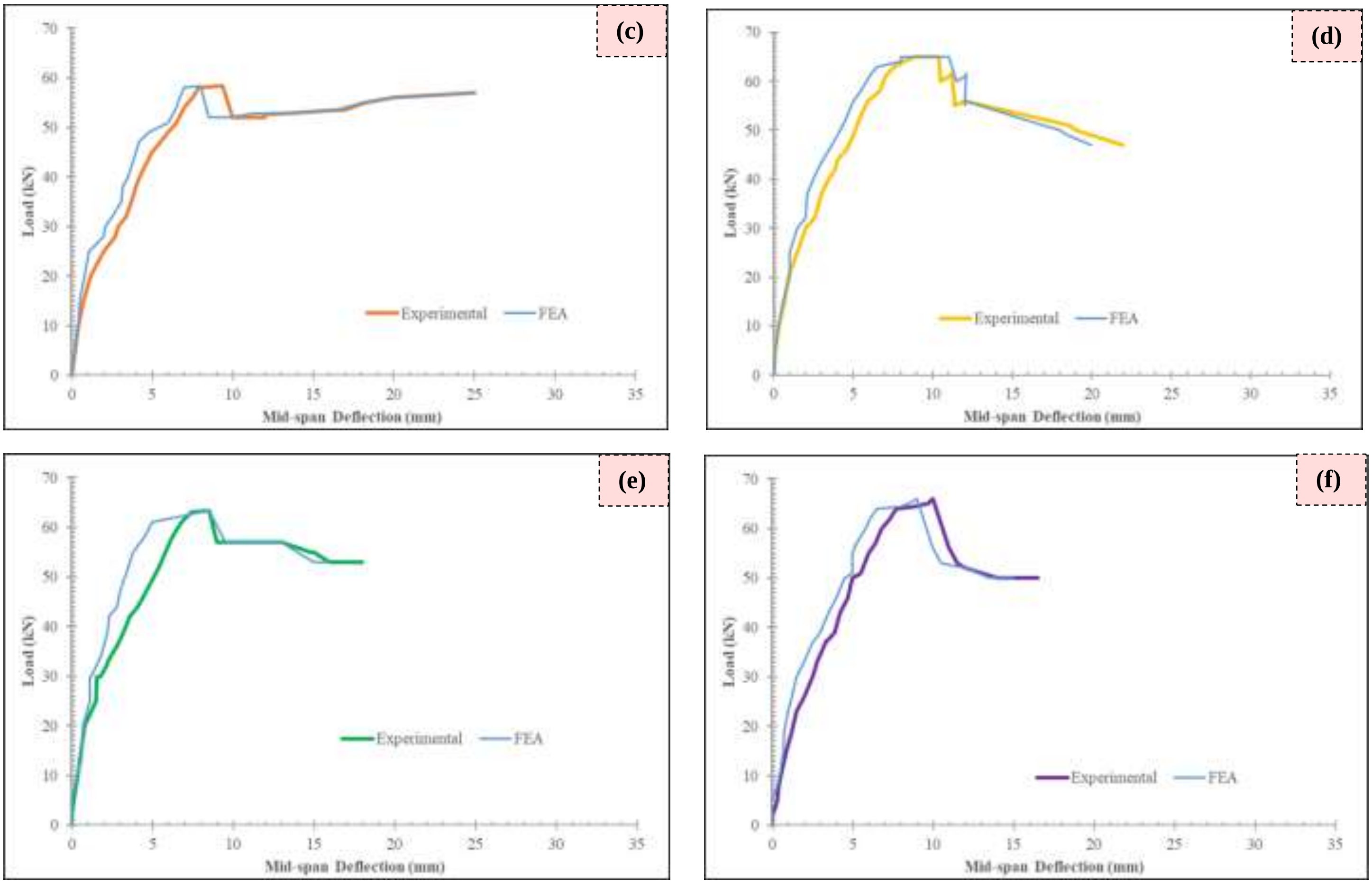


Figure 13: Comparing the load-deflection behavior experimentally as well as via FEA: (a) C; (b) SB-1; (c) SB-2; (d)SB-3; (e) SB-4; (f) SB-5.

Finite element analysis (FEA) results and experimental data have been combined to create Table 9, which contrasts the ultimate load and the corresponding deflection. The outcomes demonstrate that the numerical simulation performed satisfactorily in predicting the peak load of both unstrengthened and SSWM-strengthened RC beams with an accuracy of 2–9%. The FE simulation's prediction of the deflection associated with the ultimate load also quite replicated the experimental values, within a margin of 3-11%. The FEA further confirmed the significant improvement in flexural behavior resulting from the SSWM-strengthened RC beams' strong bond with the concrete surface had brought about.

As illustrated in Table 9, a significant consistency can be seen when comparing the experimental and predicted outcomes for the ultimate flexural capacity (Pu). For all specimens, predicted Pu values are consistently less than the experimental results. For beam C, for instance, the predicted value is roughly 14.7% higher than the experimental value; in contrast, the predicted values for SB-1, SB-2, SB-3, SB-4, and SB-5 are significantly lower, with the range being between approximately 20.5% and 26.1% less than the corresponding experimental values. The ACI 318-19 standard specifications for epoxy-strengthened RC beams (SB-1, SB-2, SB-3, SB-4, and SB-5) may not have included the significant epoxy flexural tensile strength (15–18 MPa), which might be the reason for the observed differences in results.

Comparing experimental load-deflection responses with finite element simulations frequently reveals important structural analysis insights. Differences in post-peak load in this case could indicate a number of reasons affecting behavior, including bond failures or complex material interactions. Complex phenomena such as force transfers between materials are difficult to portray using modern numerical models, even though they frequently accurately simulate beginning stiffness.

The combination of experimental and FEA data in Table 9 emphasizes how important precise predictions for ultimate loads and related deflections are for structural design and validation. Standard requirements have been brought to attention by persistent variations in expected ultimate flexural capacity (Pu). For reliable simulation results, structural engineers must take into account all relevant material qualities, such as epoxy flexural tensile strength, in their design codes and standards. Failure to do so may significantly reduce predicted accuracy.

Table 9: Comparison of experimental, FEA, and ACI318-19 predicted results for ultimate load and corresponding deflection.

Beam	P_u (kN)					Δ_u (mm)		
	FEA	Exp.	FEA/Exp.	Pred. ACI 318-19	Pred./Exp.	FEA	Exp.	FEA/Ex.
C	29.1	26.5	1.09	30.40	1.14	38.9	35	1.11
SB-1	56.5	52.5	1.07	40.10	0.77	32	30	1.06
SB-2	60.3	58.5	1.03	43.20	0.74	26.3	25	1.06
SB-3	61.3	62.5	0.98	46.30	0.74	21.35	22	0.97
SB-4	60	63.3	0.94	49.90	0.79	16.8	18	0.93
SB-5	61	66	0.92	53.10	0.80	15	16.5	0.90

5. 3 Failure modes analysis

The various failure patterns that the control RC beam and the SSWM-strengthened RC beams exhibit are depicted graphically in Figure 14. Characteristic behavior similar to traditional reinforced concrete beams emerged in the control beam. Additionally, the tension face had been dominated by a complex pattern of crack formation that ultimately led to structural failure. The failure to effectively control the spread of the cracks resulted in the formation of much bigger cracks, which seriously compromised the structural integrity of the beam. The control beam experienced a significant decrease in stiffness as these cracks spread, severely compromising its ability to support loads. These findings confirm the expected behavior of unstrengthened RC beams and highlight the critical function of strengthening in preventing crack progression and preserving structural integrity. By contrast to that, significant improvements in structural behavior were demonstrated by the strengthened beams, particularly SB-1 through SB-5. These beams not only demonstrated enhanced control over the initial appearance of cracks, but they also showed an apparent reduction in crack widths, especially when the number of SSWM layers was increased. Their structural performance was greatly enhanced by this strengthening technique, which successfully reduced the amount of crack propagation. Furthermore, because of the skillful restoration or potential enhancement of stiffness, these strengthened beams demonstrated an impressive ability to support large loads even after they had cracked. The overall strengthening effect persisted, even if adding more SSWM layers came with a trade-off of decreased load capacity. This demonstrated a significant increase in the beams' ability to support loads and clarified the general advantages of SSWM reinforcement in boosting structural integrity and load-bearing capacity. The highest crack widths observed in the specimens of RC beams are shown in Figure 12. Significant cracks measuring up to 24 mm were visible in the control beam, indicating its susceptibility to structural deterioration in the absence of strengthening. In contrast, the beams that were strengthened by SSWM (SB-1 through SB-5) demonstrated narrower cracks, ranging from 20 mm, 15 mm, 12 mm, 5.5 mm, and 3.5 mm, in that order. The strengthened beams' dramatic decrease in crack widths highlights how well the flexural-enhanced SSWM approach supports the structural integrity of RC beams. This decrease is essential for preventing the spread of cracks and guaranteeing the long-term stability and integrity of these structural components. The results of this investigation have important implications for structural engineering and the building sector, highlighting the vital role that SSWM reinforcement plays in enhancing the lifespan and strength of structures.

In summary, SB-4 and SB-5, two of the RC beams, demonstrated significant enhancements in structural performance relative to the typical behavior of the control beam. The utilization of a greater number of SSWM layers is directly responsible for this substantial improvement. The thorough analysis highlights the significance of SSWM strengthening to greatly increase the load bearing capacity of reinforced concrete beams and clarifies its significant influence on structural engineering techniques. The work presented here emphasizes the clear benefits and significant consequences of SSWM strengthening in improving the structural integrity and load-bearing capacity of concrete beams, even though compromises in some areas are acknowledged. Sections 4.1, 4.2, and 4.3 present the current study comprehensive analysis. These sections' experimental and FEA outcomes demonstrate the significant advantages that SSWM strengthening provides. In contrast with the control beam, the strengthened beams (SB-1 to SB-5) demonstrated enhanced load capacity, decreased deflection, and controlled cracking propagation. These results highlight the influence of SSWM on load-bearing and durability, offering novel insights into the material's applications for structural strengthening. The thorough failure mode analysis emphasizes the importance of SSWM in structural engineering by highlighting its role in preventing the propagation of cracks and preserving structural integrity. The quality of the bond between SSWM, epoxy, and concrete, the total number and configuration of SSWM layers, the compressive strength of the concrete, the characteristics of the epoxy, and the curing conditions all influence the degree to which the SSWM-strengthened system performs. Furthermore, the system's overall behavior and durability are significantly affected by loading conditions and external factors including temperature, humidity, and chemical exposure.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 14: Failure patterns.

6 Conclusion

This experimental investigation and numerical modeling of the flexural strengthening of RC beams using SSWM provided the following outcomes:

- Flexural strength is remarkably affected by the SSWM layers. A major enhancement resulted from the incorporation of SSWM layers; load capacities increased by 99% to 149% when contrasted with the control beam. This significant enhancement highlights how well SSWM layers perform to improve flexural strength.

- The mid span deflection of the control beam was 35 mm, while the specimens (SB-1 to SB-5) showed deflections varying from 30 mm to 16.5 mm. This indicates a substantial reduction in deflection, with values decreasing by 53% to 53.7%.

- The control beam exhibited typical reinforced concrete behavior, with extensive cracks eventually leading to structural failure. In contrast, the strengthened beams displayed superior control over crack formation, reduced crack widths, and the ability to continue supporting loads even after cracking started.

- The finite element analysis (FEA) accurately predicted peak load with an accuracy of 2-9% and deflection at ultimate load with a precision of 3- 10%, verifying the efficiency of SSWM-strengthened RC beams in improving load-carrying capacity and structural performance.

- Although there may be trade-offs with other aspects, the overall strengthening effect of SSWM remained dominant, leading to a noticeably better level of structural performance. The number of SSWM layers had a major role in improving load-carrying capacity.

- Results demonstrate the significant influence of SSWM on structural integrity. When compared to control beams, strengthened beams exhibited enhanced load capacity, reduced deflection, and controlled cracking. The analysis highlights the significance of SSWM in contemporary structural engineering methods by emphasizing its critical role in reducing crack development.

- The progressive improvement in load-bearing capacity indicates the number of SSWM layers and enhancing structural strength are directly correlated.

- On the basis of this study, SSWM is a significant strengthening material that may improve the flexural performance of RC beams while providing advantages including increased load capacity, crack control, and structural integrity. Future studies should examine the performance of SSWM under varying loading conditions, evaluate its long-term durability, and look into how well it applies to other structural components like slabs and columns. Furthermore, more research on bond behavior and strengthening configuration optimization will yield a deeper understanding of how to maximize its efficacy in practical applications.

Author Contributions

Conceptualization, methodology, supervision, writing, N.H.; software, supervision, validation, revision, G.H.; investigation, data curation, revision original draft, G.B.; data collection and statistical application, R.A. All authors have read and agreed to the published version of the manuscript.

Funding

This research has not received any external funding.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Holschemacher, K., Iqbal, S., Ali, A., & Bier, T. A. Strengthening of RC beams using lightweight self-compacting cementitious composite. *Procedia Eng.* **172**, 369-376, doi: 10.1016/j.proeng.2017.02.042 (2017).

[2] Maraq, M.A.A., Tayeh, B. A., Ziara, M. M., & Alyousef, R. Flexural behavior of RC beams strengthened with steel wire mesh and self-compacting concrete jacketing- experimental investigation and test results. *J. Mater. Res. Technol.* **10**, 1002-1019, doi: 10.1016/j.jmrt.2020.12.069 (2021).

[3] Askandar, N. H., & Mahmood, A.D. Comparative investigation on torsional behaviour of RC beam strengthened with CFRP fabric wrapping and near-surface mounted (NSM) steel bar. *ADV CIV ENG.* **2019**, 1-15, doi: 10.1155/2019/9061703 (2019).

[4] Askandar, N.H., Mahmood, A.D., & Kurda, R. Behaviour of RC beams strengthened with FRP strips under combined action of torsion and bending. *EJECE* **26**(9), 4263-4279, doi: 10.1080/19648189.2020.1847690 (2022).

[5] Montaser, W.M., Shaaban, I. G., Zaher, A. H., Khan, S. U., & Sayed, M. N. Structural behaviour of polystyrene foam lightweight concrete beams strengthened with FRP laminates. *IJCSM* **16**(1), 1-20, doi: 10.1186/s40069-022-00549-1 (2022).

[6] Askandar, N.H., Jumaa, G.B., & Ahmed G.H. Modeling for torsional strength prediction of strengthened RC beams. *Multiscale Multidiscip. Model. Exp. Des.* **7**, 2535–2553, doi: 10.1007/s41939-023-00353-8 (2024).

[7] Askander, N.H. Machine learning models for predicting flexural behavior of FRP-strengthened RC beams. *Passer j. basic appl. sci.* **6**(1), 198-213, doi: 10.24271/psr.2024.435650.1472 (2024).

[8] Askandar, N.H., & Mahmood, A.D. Torsional strengthening of RC beams with continuous spiral near-surface mounted steel wire rope. *Int. j. concr. struct. mater.* **14**(1), 7, doi: 10.1186/s40069-019-0386-4 (2020).

[9] Alhadid, M.M.A., & Youssef, M.A. Analysis of reinforced concrete beams strengthened using concrete jackets. *Eng. Struct.* **132**, 172-187, doi: 10.1016/j.engstruct.2016.11.014 (2017).

[10] Hussein, M., Kunieda, M., & Nakamura, H. Strength and ductility of RC beams strengthened with steel-reinforced strain hardening cementitious composites. *Cem. Concr. Compos.* **34**(9), 1061-1066, doi: 10.1016/j.cemconcomp.2012.06.004 (2012).

[11] Askandar, N.H., & Mahmood, A. D. Torsional Strengthening of RC Beams with Near-Surface Mounted Steel Bars. *Adv. Mater. Sci. Eng.* **2020**, 1-11, doi: 10.1155/2020/1492980 (2020).

[12] Shaaban, I.G., Shaheen, Y. B., Elsayed, E. L., Kamal, O. A., & Adesina, P. A. Flexural behaviour and theoretical prediction of lightweight ferrocement composite beams. *CSCM* **9**, .e00204, doi: 10.1016/j.cscm.2018 (2018).

[13] Shaaban, I.G., Shaheen, Y. B., Elsayed, E. L., Kamal, O. A., & Adesina, P. A. Flexural characteristics of lightweight ferrocement beams with various types of core materials and mesh reinforcement. *Constr Build Mater.* **171**, 802-816, doi: 10.1016/j.conbuildmat.2018.03.167 (2018).

[14] Raiyani, S.D., & Patel, P.V. Torsional strengthening of reinforced concrete hollow beams with stainless steel wire mesh. *Proc. Inst. Civ. Eng. Struct. Build.*, 1-17, doi.org/10.1680/jstbu.20.00126 (2021).

[15] Raiyani, S.D., Patel, P.V., & Vora, S.D. Effectiveness of stainless steel wire mesh in shear strengthening of reinforced concrete flanged beam. *IJStructE* **10**(3), 195-216, doi: 10.1504/IJSTRUCTE.2020.108525 (2020).

[16] Makawana, R., Patel, P., & Joshi, D. Seismic performance of exterior RC beam-column junction strengthened with Stainless Steel Wire Mesh (SSWM). *Mater. Today Proc.*, 607-619, doi: 10.1016/j.matpr.2023.04.072 (2023).

[17] Makawana, R., Joshi, D., & Patel, P. Seismic strengthening of precast beam column connection using stainless steel wire mesh (SSWM). in *SEE*, (2022).

[18] Bhavsar, S.V., Raiyani, S.D., & Patel, P.V. Performance of RC beams using CFRP, GFRP, and SSWM subjected to torsion: Numerical study. Lecture Notes in Civil Engineering, Springer.

[19] Khan, M.A., & Venu, M. Enhancing the performance of reinforced concrete beams using wrapping technique. *AEEIE* **2**(5),1-7, doi: 10.5281/zenodo.7285627 (2022).

[20] Fang, S. Axial compressive performance of corroded concrete columns strengthened by alkali-activated slag ferrocement jackets. *Front. Mater. Sci.* **7**, 567777, doi: 10.3389/fmats.2020.567777 (2020).

[21] Emara, M., Rizk, M., Mohamed, H., & Zaghlal, M. Enhancement of circular RC columns using steel mesh as internal or external confinement under the influence of axial compression loading. *F&SI* **15**(58), 86-104, doi: 10.3221/IGF-ESIS.58.07 (2021).

[22] Xie, X., Guo, Z., Basha, S. H., & Huang, Q. A novel shear strengthening of existing RC shear walls using steel wire mesh and polymer mortar. *Buildings* **12**(2), 219, doi: 10.3390/buildings12020219 (2022).

[23] Tripathy, D., & Singhal, V. Behavior and design of masonry strengthened with steel-wire–reinforced cementitious matrix under flexure. *J. Compos. Constr.* **27**(2), 04023012, doi: 10.1061/JCCOF2.CCENG-4032 (2023).

[24] Kumar, V., & Patel, P. Strengthening of axially loaded circular concrete columns using stainless steel wire mesh (SSWM)–Experimental investigations. *Constr Build Mater.* **124**, 186-198, doi: 10.1016/j.conbuildmat.2016.06.109 (2016).

[25] Kumar, V., & Patel, P. Strengthening of axially loaded concrete columns using stainless steel wire mesh (SSWM)-numerical investigations. *Structural Engineering and Mechanics* **60**(6), 979-999, doi: 10.12989/sem.2016.60.6.979 (2016).

[26] Choi, J.H. Seismic retrofit of reinforced concrete circular columns using stainless steel wire mesh composite. *Can. J. Civ. Eng.* **35**(2), 140-147, doi: 10.1139/L07-079 (2008).

[27] Kim, S.H., & Kim, D.K. Seismic retrofit of rectangular RC bridge columns using wire mesh wrap casing. *KSCE J. Civ. Eng.* **15**, 1227-1236, doi: 10.1007/s12205-011-0881-x (2011).

[28] Kim, S.H., & Choi, J.H. Repair of earthquake damaged RC columns with stainless steel wire mesh composite. *Adv. Struct. Eng.* **13**(2), 393-401, doi: 10.1260/1369-4332.13.2.393 (2010).

[29] Zhang, M.J., He, M. H., Xin, K. G., Zhang, T. S., & Ma, Y. Experimental study on RC beams strengthened by a novel large diameter pre-stressed stainless steel wire mesh–mortar structure. *AMM* **256**, 911-917, doi: 10.4028/www.scientific.net/AMM.256-259.911 (2013).

[30] Molkens, T., Cashell, K. A., Malaska, M., Alanen, M., & Rossi, B. Performance of structural stainless steel following a fire. *Eng. Struct.* **235**, 112001, doi: 10.1016/j.engstruct.2021.112001 (2021).

[31] Rabi, M., Cashell, K., & Shamass, R. Flexural analysis and design of stainless steel reinforced concrete beams. *Eng. Struct.* **198**, 109432, doi: 10.1016/j.engstruct.2019.109432 (2019).
[32] Li, K., Wei, Y., Li, Y., Li, Z., & Zhu, J. Flexural behavior of reinforced concrete beams strengthened with high-strength stainless steel wire rope meshes reinforced ECC. *Constr. Build. Mater.* **362**, 129627, doi: 10.1016/j.conbuildmat.2022.129627 (2023).
[33] Fan, J.J., Zhu, H., Li, Y.P., Hou, S.T., Zhao, Y.K., & Li, K. Mechanical properties of RC columns strengthened with high-strength stainless steel wires-ECC under large eccentric loading. *CASE STUD CONSTR MAT*. **21**, e03758, doi: 10.1016/j.cscm.2024.e03758 (2024).
[34] Shah, S., Raithatha, P., & Raiyani, S. Improved flexural behaviour of reinforced concrete beam strengthened using stainless steel wire mesh. *FRAT INTEGRITA STRUT* **19**(72), 34-45, doi: 10.3221/IGF-ESIS.72.04 (2025).
[35] Patel, P.V., Joshi, D.D., & Makawana, R.V. Experimental studies on confined compressive strength of Stainless Steel Wire Mesh (SSWM) wrapped concrete columns. *Mater. Today Proc.* **93**, 453-459, doi: 10.1016/j.matpr.2023.08.087 (2023).
[36] ASTMC94/C94M, Standard Specification for Ready-Mixed Concrete, American Society for Testing and Materials (ASTM) (2023).
[37] ASTMC39/C39M, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, American Society for Testing and Materials (ASTM) (2023).
[38] ASTMA615/A615M, Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement, American Society for Testing and Materials (ASTM) (2023).
[39] ACI318M-19, Building Code Requirements for Structural Concrete, American Concrete Institute. American Concrete Institute: Farmington Hills, MI, USA (2019).
[40] ASTMD3039/D3039M-08, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. American Society for Testing and Materials (ASTM) (2008).
[41] Amirul, M.M., Saifulnaz, M. R., Farah, N., & Norazizi, S. Bond slip model of FRP–to–concrete surfaces. *IJSMSS* **1**(4), 332-350, doi: 10.1504/IJSMSS.2014.068809 (2014).
[42] Patel, P.V., Jariwala, V.H., & Purohit, S.P. Torsional strengthening of RC beams using GFRP composites. *J Inst Eng India A.* **97**, 313-322, doi: 10.1007/s40030-016-0163-1 (2016).
[43] Patel, P.V., Raiyani, S.D., & Shah, P.J. Torsional strengthening of RC beams using stainless steel wire mesh - experimental and numerical study. *Struct Eng Mech.* **67**(4), 391-401, doi: 10.12989/sem.2018.67.4.391 (2018).
[44] Jeng, C.H., & Hsu, T.T. A softened membrane model for torsion in reinforced concrete members. *Eng. Struct.* **31**(9), 1944-1954, doi: 10.1016/j.engstruct.2009.02.038 (2009).