Performance of RC Beams Using CFRP, GFRP, and SSWM Subjected to Torsion: Numerical Study

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Abstract The research on flexure, shear, and axial strengthening of reinforced concrete (RC) members has been conducted many times, but very few studies have been carried out on torsional strengthening of RC members. The main objective of the present study is to ascertain the better strengthening material in terms of torsional strength and damage patterns. A finite element (FE) study is carried out using ABAQUS software to understand the behavior of RC beam strengthened using different fiber reinforced polymers (FRPs), i.e., carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), and stainless-steel wire mesh (SSWM). Total sixteen beams are adopted from literature. One beam is kept as a control beam, while the other fifteen beams are strengthened using CFRP, GFRP, and SSWM with five different wrapping configurations. Torque-twist response, ultimate torque and corresponding twist, damage pattern, and maximum principal strain are measured and compared with experimental results from the literature. The study reveals that the effectiveness of SSWM as a strengthening material is as good as CFRP and GFRP in terms of torsional strength, failure pattern, and maximum principal strain.

Keywords Reinforced concrete beam · Glass fiber reinforced polymer · Stainless steel wired mess · Carbon fibre reinforced polymer

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1 Introduction

Torsion can appear in the structural elements when the load is applied away from the neutral axis. For the design of RC beams subjected to torsion, the number of stirrups can be increased up to a specific limit, but after that, it is tough to do the concreting. In that case, external strengthening of RC beams becomes essential. Strengthening of structural elements is necessary in case of an increase in loading, damage to the individual structural element, deterioration to the structural member, modification in the structural element and the cost of replacement of RC structural elements is very high. Structural elements subjected to torsion experience diagonal tension and compression and fail in a brittle manner. To avoid brittle failure, it is desirable to strengthen the element subjected to torsion. Ganganagoudar et al. [1] carried out an analytical and FE study to inspect the torsional behavior of FRP-strengthened RC elements to see the efficacy of FRP. The comparison was made between analytical results; FE results and experimental data from literature extracted that torsional strength of FRP strengthened beam is more than control specimen. Santhakumar et al. [2] presented FE study on retrofitted and non-retrofitted RC beams subjected to combined bending and torsion using CFRP. FE result was compared with experimental data published in the literature. Panchacharam and Belarbi [3] presented the behavior of RC members strengthened with GFRP subjected to pure torsion. Elwan [4] performed a parametric study using software ANSYS on the torsional strengthening of RC beams using CFRP and compared it with the previous experimental work by the author. Obaidat et al. [5] performed an experimental and FE studies on RC beams strengthened by near-surface-mounted CFRP strips subjected to pure torsion. From the results of the researchers [2–5], CFRP and GFRP can be used for torsional strengthening. Further, Jariwala et al. [6] performed an experimental study of RC beams using GFRP to enhance the torsional resistance. A beam having wrapping pattern corner and diagonal strip wrapping (CO&DS) exhibited a maximum (110%) increment in cracking torque and maximum (117%) increment in ultimate torque, compared to the control beam. Ameli et al. [7] presented an experimental and numerical study of RC beams using CFRP and GFRP for torsional strengthening. RC beams strengthened with CFRP showed better performance than GFRP-strengthened beams. Patel et al. [8] conducted an experimental study to interpret the behavior of RC beams strengthened with various wrapping configurations of SSWM subjected to pure torsion. Torque-twist behavior and failure modes for beams under pure torsion are obtained. The results obtained by the experimental study are further verified through numerical simulation using FE software ABAQUS [9]. Corner and diagonal strip (CO&DS) wrapping of SSWM on RC beam showed a maximum increase in cracking and ultimate torque compared to other wrapping patterns. FRPs or SSWM can upgrade the performance of existing RC structural elements as externally bonded materials. Researchers have selected CFRP, GFRP, and SSWM to strengthen the RC elements under torsional loading. Even though the experimental study presents very realistic results of RC elements under different types of loading and natural conditions, it is costly, time, and power-consuming, and experimental study on a full

scale is very difficult. At the same time, FE analysis provides results under various loading and boundary conditions.

The main objective of the present study is to understand the performance of RC beams with various wrapping configurations using CFRP, GFRP, and SSWM under pure torsion. The study is carried out using nonlinear FE-based software ABAQUS [9]. The results are obtained as torque–twist response, ultimate torque and corresponding twist, damage pattern and maximum principal strain. Results of CFRP and GFRP strengthened RC beams are compared with the experimental results of Ameli et al. [7]. It is further extended for SSWM-strengthened RC beams with the same wrapping configurations published by Ameli et al. [7].

2   Numerical Investigation

A nonlinear FE model is developed to predict the torsional behavior of RC beams strengthened using CFRP, GFRP, and SSWM using FE-based software ABAQUS. FE modeling of RC beam strengthened using FRP or SSWM is challenging as it should respond to the nonlinearity of the materials such as concrete, steel, and FRPs or SSWM in the form of cracking, crushing, concrete plasticity, yielding of reinforcement or SSWM, and FRP rupture. Concrete is modeled using 3D-eight-node solid brick elements (C3D8R).

The concrete damage plasticity model is used for nonlinear analysis. The compressive and tensile stress–strain relationship of concrete is derived from the literature by Jeng and Hsu [10]. Longitudinal and transverse reinforcements are modeled with 3D, three-node truss elements (T3D3). The stress–strain curve for reinforcement bars is derived from the literature by Jeng and Hsu [10]. CFRP, GFRP, and SSWM are modeled as 3D shell extrusion type of elements (S4R). The elastic properties of CFRP and GFRP are taken from the literature by Ameli et al. [7], and elastoplastic properties of SSWM are taken from the study of Patel et al. [8]. The damage parameters for compression and tension failure of concrete are adopted as described in ABAQUS manual [9].

For defining interaction between reinforcement and concrete, embedded constraint is used. Tie constraint is used to define the interaction between concrete and FRPs or SSWM. In tie constraint, perfect bonding is assumed between concrete and FRPs or SSWM. For that concrete surface is selected as master surface, and FRP or SSWM is selected as slave surface. Coupling constraint is used to provide twist about longitudinal axis. One end of the beam is kept as fixed. At another end, load is applied in the form of twist about member axis at reference point in terms of radian. Dynamic explicit analysis is used for the present study.

In this study, 11 specimens are adopted from the research presented by Ameli et al. [7]; out of which, one beam is kept as control beam, while other ten beams are strengthened with CFRP and GFRP. In addition to that, by keeping the same

five wrapping configurations, SSWM is used to strengthen the beam. All the cross-sectional, mechanical properties, reinforcement detailing, and five different wrapping patterns are taken from the literature by published Ameli et al. [7].

3 Results and Discussion

In this paper, only JS (U-Jacket, 7 strips of 100 mm spaced at 100 mm, one-layer of CFRP/GFRP/SSWM wrapping pattern) [7] is described for better understanding in terms of torque-twist behavior, ultimate torque and corresponding twist, damage pattern, and maximum principal strain. In addition, the torque-twist behavior of RC beams having remaining wrapping configurations is also presented in subsequent Sect. 3.1.

3.1 Torque-Twist Response

The torque-twist behavior of RC beams strengthened using CFRP and GFRP for JS wrapping pattern is compared with experimental results [7] as shown in Fig. 1a, b. The FE results for CFRP and GFRP strengthened beams are found in close agreement with experimental results [7]. The stiffness of the test specimen [7] at all ranges of response is well simulated using numerical analysis. The descending portion of the torque-twist response is also well predicted by the FE models, which reveal the precision of the material model adopted for the present study. Beside that, the torque-twist response of finite element analysis for RC beams strengthened with all three materials (i.e., CFRP, GFRP, and SSWM) are also presented in Fig. 1c to evaluate the capability of individual material for JS wrapping pattern. From Fig. 1, the ultimate torque for the beam strengthened using CFRP, GFRP and SSWM, i.e., CJS, GJS, and SJS, are 17.43 kN m, 17.22 kN m, and 17.24 kN m, respectively. The identical torque-twist behavior is observed for all three CJS, GJS and SJS cases.
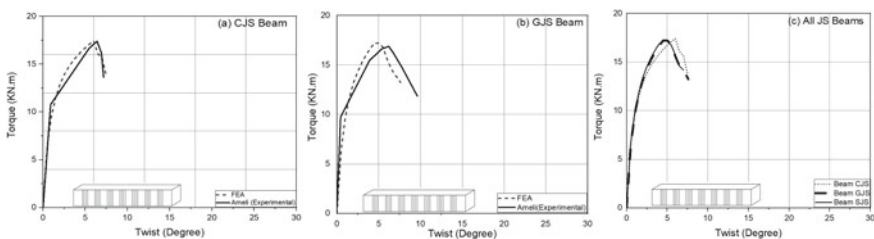

Fig. 1 a Comparison of torque-twist response for CJS (CFRP-JS) beam from experimental and FE study. **b** Comparison of torque-twist response for GJS (GFRP-JS) beam from experimental and FE study. **c** Comparison of torque-twist response for all JS beams from FE study
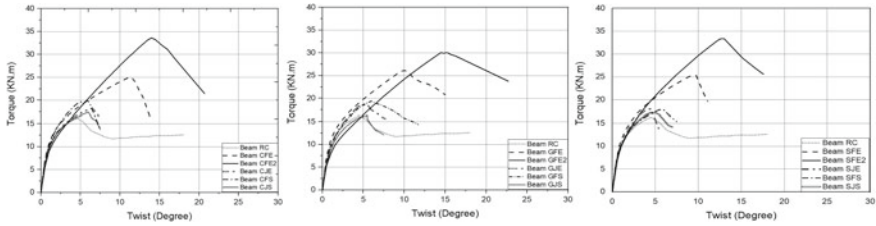
Fig. 2 FE results of torque versus twist behavior for CFRP, GFRP, and SSWM strengthened beams, respectively

As shown in Fig. 2, a comparison is made for all the beams strengthened using CFRP, GFRP, and SSWM with different wrapping patterns. It is noticed that torque-twist behavior is almost linear up to the first cracking of concrete for all the beams. After cracking, a sudden increase in the twist and the torque-twist response becomes nonlinear up to failure.

3.2 Ultimate Torque and Corresponding Twist

The ultimate torque and corresponding twist for all JS beams are shown in Fig. 3. The figure shows that the increase in ultimate torque for beam CJS is 6.93%, for the beam GJS 5.64% and for the beam SJS 5.77% regarding control specimen. Twist corresponding to ultimate torque for CFRP, GFRP, and SSWM strengthened beams also increases concerning the twist of control beam.

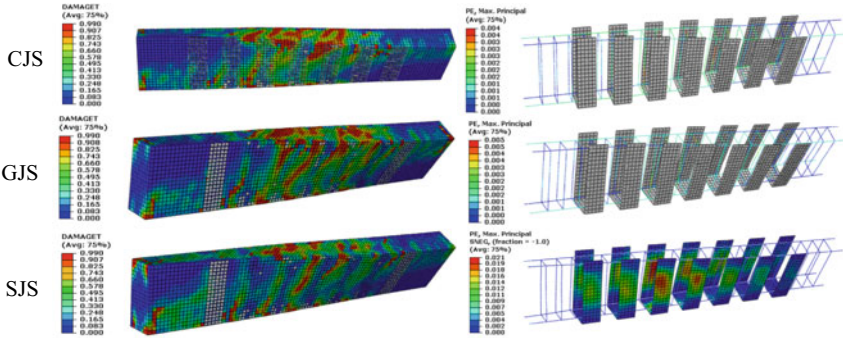**Fig. 3** Ultimate torque and corresponding twist for beams having JS wrapping pattern
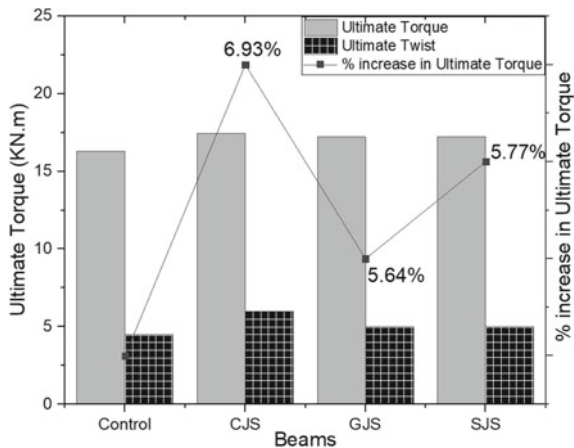
Fig. 4 Damage pattern and maximum principal strain for beams having JS wrapping pattern strengthened using CFRP, GFRP, and SSWM, respectively

3.3 Damage Pattern and Maximum Principal Strain

From Fig. 4, it is observed that the damage patterns for all the beams strengthened using CFRP, GFRP, and SSWM are almost identical for JS wrapping pattern. The maximum principal strain for beams CJS, GJS, and SJS is also shown in Fig. 4. It is observed that SSWM has contributed more effectively to strain distribution than CFRP and GFRP due to its elastoplastic nature.

4 Conclusions

A nonlinear FE model is developed in ABAQUS to register the torque-twist response and understand the failure progression, ultimate torque, corresponding twist and maximum principal strain. Major conclusions derived from the study can be summarized as below.

- The FE results are in good agreement with experimental results.
- The torque-twist response for all the beams having a similar strengthening pattern of FRPs, i.e., CJS, GJS, and SJS beams showed almost similar behavior up to the elastic region. A minor difference is observed in the post-cracking stage for all beams having the same wrapping pattern.
- It is observed that the ultimate torque for beam SJS is 1.15% lower than CJS beam and 0.13% more than GJS beam. Hence, the torsional strength of SSWM strengthened beam is almost similar to the beams strengthened using CFRP and GFRP.
- In all JS beams, diagonal torsional cracks occurred and widened in the unwrapped concrete part of the beams between FRP strips. Damage patterns derived from the numerical study replicate the experimental failure pattern.

- CFRP and GFRP have not contributed to strain distribution as effectively as SSWM due to their plastic properties, whereas SSWM has elastoplastic properties.

From the study, the behavior of RC beams under torsion using CFRP, GFRP, and SSWM can be identified. From the behavior, it can be understood that GFRP and SSWM are behaving more or equal to the same, whereas CFRP is giving better torsional resistance. So, either CFRP can be used to increase the torsional resistance, or GFRP can be replaced by SSWM because of its lower cost to strengthen the RC beam under torsion. Also, it is noticed that the performance of SSWM is as good as CFRP and GFRP in terms of torque-twist behavior, damage pattern, ultimate torque, and maximum principal strain to enhance the torsional behavior of RC beams. Hence, one can use SSWM for strengthening of RC beams subjected to torsion.

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