INNOVATIVE TORSIONAL STRENGTHENING OF RC T-BEAMS USING NSM FRP ROPES

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This study addresses the critical need for effective torsional strengthening techniques in reinforced concrete (RC) structures, with a focus on T-beams. Existing methods, particularly those utilizing externally bonded fiber-reinforced polymer (FRP) composites, have been extensively studied for axial, bending, and shear loads, but torsional behavior remains a complex and underexplored area. The paper introduces a novel approach employing FRP ropes configured as closed stirrups, aiming to enhance torsional capacity while addressing practical challenges associated with conventional methods. Experimental investigations on T-shaped RC beams reveal promising results, demonstrating the effectiveness of FRP ropes in closed stirrup form. The findings not only contribute to a deeper understanding of this specific strengthening technique but also offer practical insights for designing and retrofitting RC structures susceptible to torsional loading. The study's outcomes have the potential to influence design practices, contribute to sustainable infrastructure development, and inform future guidelines for optimizing FRP strengthening strategies in T-beams.

Keywords: Reinforced concrete, Torsion, CFRP Rope, Strengthening.

1 INTRODUCTION

In the last two decades, the attention of researchers and engineers has been drawn to the enhancement and seismic retrofitting of existing reinforced concrete (RC) structures that fall short of prescribed performance requirements. Amid the array of techniques available for strengthening and retrofitting, the use of fiber-reinforced polymer (FRP) composites has emerged as a prominent solution (Gribniak et al. 2016, Chalioris et al. 2020). Two primary methods of applying FRP materials to RC structures have gained recognition: externally bonded (EB) FRP, and near-surface mounted (NSM) techniques (Naser et al. 2019).

While extensive research has focused on axial load, bending, and shear in FRP-strengthened RC members, the torsional behavior remains a relatively unexplored and complex area (Alabdulhady and Sneed 2019, Deifalla et al. 2021). Certain RC members, such as spandrels, flanged and curved beams, cantilevers, and eccentrically loaded bridge girders, are particularly prone to torsional effects (Abdoli and Mostofinejad 2023). The existing studies regarding the torsional effects in RC members have mostly employed EB-FRP for strengthening of conventional RC beams, in several strengthening configurations (Ameli et al. 2007, Chalioris 2008, Deifalla et al. 2013). However, the research on torsional behavior of NSM-strengthened beams, especially with regard to non-rectangular cross sections, is limited (Al-Bayati et al. 2018).
A fully wrapped configuration maximizes the FRP contribution to torsional capacity due to the circularity of shear flow stresses. However, practical challenges arise in real structure members where elements such as slabs restrict the application of full wrapping (Abdoli et al. 2023).

The current study introduces a novel strengthening technique utilizing FRP ropes configured as externally closed stirrups via the NSM technique. This technique aims to provide effective torsional strengthening while accommodating structural limitations and causing minimal disturbance to surrounding elements. The experimental investigation involves four T-shaped cross-section RC beams subjected to torsion. Two configurations are examined: one with the rope embedded through the slab section to form a closed stirrup, and the other embedded through the web section, simulating scenarios where the upper part of the slab is inaccessible.

2 EXPERIMENTAL PROGRAM

2.1 Specimen Characteristics

The experimental program comprises a total of four beams. The beams had common dimensions and reinforcement (Fig. 1). To imitate the presence of a slab in real structures, the middle section of the beam (section under study) was constructed as a T-section. The beam ends had a rectangular cross-section and were over-reinforced with a high percentage of transverse reinforcement and fully wrapped in two layers of CFRP sheets. One beam (T-0), served as the reference specimen and was not subjected to any strengthening measures. The remaining three beams were strengthened transversely to their axis within the designated area of investigation, as depicted in Fig. 2.

Fig. 1. Geometry and reinforcement arrangement of the reference specimen T-0 (dimensions in mm).

Fig. 2. Configuration of strengthened specimens (dimensions in mm).
The T-SU beam was strengthened with EB-CFRP strips placed around the periphery of the beam core (U-shaped). The strips were 0.331 mm thick and 75 mm wide. The clear distance between the strips was 75 mm. The T-RF and T-RW beams were strengthened by incorporating NSM CFRP rope, which was arranged in a closed stirrup configuration. In the T-RF beam the closed-type reinforcement was installed through the slab section (accessible slab case) while in the T-RW beam through the beam section below the slab (inaccessible slab case) (Fig. 2). The rope had a dry fiber area of 28 mm$^2$ and was spaced every 150 mm. The rope had 100 mm overlap to form the closed-loop stirrup and prevent rope slippage at the top of the slab (T-RF) or inside the hole of the beam’s web (T-RW). The geometric ratio of the strengthening reinforcement of the beams was approximately the same for comparison purposes.

### 2.2 Materials Properties

The mechanical properties of the concrete were assessed through the fracture of cylindrical specimens on the day of experimentation. The average compressive strength of the concrete was found to be 44.2 MPa with a standard deviation of 1.9 MPa, while the average split tensile strength was 3.1 MPa with a standard deviation of 0.3 MPa. The reinforcement was of class B500C, possessing a yield strength of 547 MPa and a fracture strength of 642 MPa.

The T-SU beam was strengthened with unidirectional carbon fiber sheets (SikaWrap®-600C), and the T-RF and T-RW beams were strengthened with unidirectional carbon fiber ropes (SikaWrap® FX-50C). The epoxy Sikadur®-300 and Sikadur®-330 were used to impregnate and adhere the sheet and rope, respectively. The properties of the materials are given in Table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>SikaWrap®-600C</th>
<th>SikaWrap® FX-50C</th>
<th>Sikadur®-300</th>
<th>Sikadur®-330</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>225</td>
<td>230</td>
<td>3.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Ultimate strain capacity (%)</td>
<td>1.33</td>
<td>0.87</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>3000</td>
<td>2000</td>
<td>45</td>
<td>30</td>
</tr>
</tbody>
</table>

### 2.3 Strengthening Application Procedure

A closed-form stirrup was created using NSM CFRP rope in the beams T-RF and T-RW. The locations where the strengthening would be applied were first determined. Notches were created with a cutting wheel, which were then drilled using an impact drill to form the grooves. Holes were drilled in the slab section (and also in the web section beneath the slab for specimen T-RW) to connect (join together) the notches. Each edge within the grooves and holes was bent. The grooves underwent a cleaning process with compressed air.

The implementation of the strengthening took place in two stages. First, a small portion of one end of each FRP rope was impregnated with resin and affixed to the upper part of the beam. After placement, it was left undisturbed for a day to allow the resin to develop some initial strength. Subsequently, the notches were coated with the anchoring resin, followed by impregnation of the remaining part of the rope, and then inserted into the notches. In order to achieve a sufficient stretching of the fibers, a modest load was applied at the endpoint of the rope. Finally, the grooves were filled with anchoring resin.

### 2.4 Test Setup and Instrumentation

The experimental setup is depicted in Fig. 3. The free end of the beams was fixed, and the other end was allowed to rotate freely and elongate longitudinally. The application of the torsional
moment was facilitated by a hydraulic jack, which applied force through a steel lever arm of 400 mm in length. The beams were tested at a rate of 0.02 mm/s in displacement control mode. Piston load was measured via a load cell. While the LVDT readings, which were set up at the beginning, end, and every 350 mm in the section under investigation (four LVDTs), were used to calculate the average torsion angle per unit length of the beam.

![Fig. 3. Test setup and instrumentation.](image)

### 3 RESULTS AND DISCUSSIONS

In Fig. 4 depicts the final cracking pattern of the beams. All beams failed in torsion by developing helical shear cracks. In the T-0 and T-SU beams, a wide crack emerged which led to the failure of the beam. In the specific case of the T-SU beam, the crack intersected the EB-CFRP strip, resulting in the strip debonding as the crack marginally widened. In the beams with closed reinforcement type (T-RW and T-RF) multiple cracks formed. Eventually the significant increase of crack width led to the ultimate failure of the beams.

![Fig. 4. Specimens’ failure mode.](image)

Table 2 presents the values of the beam cracking moment ($T_{cr}$), the torsion angle per unit length during cracking ($\theta_{cr}$), the maximum moment after cracking ($T_u$), and the corresponding rotation angle per unit length ($\theta_u$). The provided information displays the angle of rotation per unit length at the point of failure of the beam ($\theta_{0.8T}$), on the assumption that this failure occurs at 80% of the maximum torsional moment. The table illustrates that each of the three strengthened beams had a marginal enhancement in torsional strength, approximately amounting to 10%. However, the T-RW and T-RF beams, which have been strengthened using closed-type rope strengthening, exhibit a much higher rotational capacity per unit length when compared to the T-0 and T-SU specimens. Specifically, the T-RW beams demonstrate an increase of 1.9 times, while the T-RF beams show an increase of 5.5 times.
Table 2. Experimental results of the tested beams.

<table>
<thead>
<tr>
<th>Beam</th>
<th>$T_{cr}$ (kNm)</th>
<th>$\theta_{cr}$ (rad/m)</th>
<th>$T_u$ (kNm)</th>
<th>$\theta_{Tu}$ (rad/m)</th>
<th>$\theta_{0.8T}$ (rad/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-0</td>
<td>11.96</td>
<td>$2.6 \times 10^{-3}$</td>
<td>-</td>
<td>-</td>
<td>$24.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>T-SU</td>
<td>11.94</td>
<td>$2.6 \times 10^{-3}$</td>
<td>13.00</td>
<td>$4.8 \times 10^{-3}$</td>
<td>$27.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>T-RW</td>
<td>12.28</td>
<td>$4.8 \times 10^{-3}$</td>
<td>12.96</td>
<td>$17.0 \times 10^{-3}$</td>
<td>$47.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>T-RF</td>
<td>12.08</td>
<td>$2.4 \times 10^{-3}$</td>
<td>12.95</td>
<td>$48.1 \times 10^{-3}$</td>
<td>$134.2 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Fig. 5 presents the experimental response curves of the beams. Initially, all beams demonstrate an elastic response characterized by substantial torsional stiffness. The torsional strength of the reference beam (T-0) drops after fracture, as both reinforcement and strengthening in the span under investigation are absent. The T-SU beam exhibits a marginal enhancement in torsional strength post-cracking; however, the sudden failure resulting from the debonding of the EB-CFRP strips at low rotation values counteracts this improvement. The beam's response indicates that the reinforcement's contribution is negligible, highlighting the necessity to either anchor the sheets or construct a closed strengthening configuration. The beams strengthened with NSM CFRP rope exhibit a more noticeable post elastic response, particularly in the T-SF specimen, where the construction of a closed type strengthening is performed through the slab. The specimen exhibits the capacity to withstand high torque loads during considerable rotational displacements. Nevertheless, if this setup is not feasible, the implementation of a closed stirrup through the slab structure also offers a modest enhancement to the overall response.

4 CONCLUDING REMARKS

The current study introduces a novel strengthening technique utilizing FRP ropes configured as externally closed stirrups for strengthening T-shaped cross-section RC beams subjected to torsion. Two configurations are investigated, embedding the FRP ropes through the slab section.
and the web section, simulating scenarios with varying slab accessibility. The results lead to the following conclusions:

- Compared to the EB-CFRP strips in U-shape configuration, the proposed method provides enhanced torsional response and demonstrates promise in mitigating the early debonding issues associated with traditional external bonding configurations.
- The through-slab formation is more efficient when comparing the two configurations of closed type strengthening formation. If this application setup is not feasible, the closed strengthening configuration through the web offers a modest enhancement to the overall responsiveness.

The torsional strengthening using FRP rope closed stirrup configuration seems to be an effective method with promising results while also addressing practical challenges associated with the presence of surrounding elements.

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