



Novel approach for strengthening T-beams deficient in shear with near-surface mounted CFRP ropes in form of closed stirrups

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ABSTRACT

Existing reinforced concrete buildings frequently require shear-strengthening to ensure structural integrity, and externally bonded carbon fiber-reinforced polymers (EB-CFRP) have become a wide-applicable approach. However, slabs and geometric restrictions impede wrapping the element, necessitating incomplete U-shaped applications vulnerable to debonding failures. This experimental study introduces a novel approach for shear-strengthening nine full-scale T-beams using near-surface mounted CFRP ropes forming closed stirrups. Their effectiveness as shear reinforcement is investigated compared to an alternative method incorporating EB-CFRP sheets with CFRP rope anchorage. Test results indicate that both techniques enhance the beams' strength and performance. The load capacity increased 2 times for the reference specimen and 1.4–1.9 times for the strengthened beam with FRP sheets. The displacement at the maximum load increased 5.2–7.8 and 6.6–7.5 times, respectively. The rope stirrup arrangement outperforms the rope anchorage system in mechanical and construction efficiency. A thorough protocol for executing these processes to mitigate construction-related defects is introduced.

1. Introduction

The gradual deterioration of existing reinforced concrete (RC) buildings requires rehabilitation, repair, and strengthening to preserve structural integrity. The susceptibility to shear failure during seismic events, known for its brittle nature, often causing sudden collapse with catastrophic consequences, determines the particular strengthening issue. Moreover, many existing RC frame structures have a deficient arrangement of transverse reinforcement and inadequate shear capacity of structural components (Dong et al., 2023) while in other cases the existing shear reinforcement loses its efficiency over time due to environmental factors such as corrosion (Gao et al., 2021). Thus, addressing these shortcomings and promptly improving their shear resistance is imperative.

Several techniques have been developed and utilized to diminish vulnerabilities associated with shear failure. One of the widespread methods involves using externally bonded carbon fiber-reinforced polymer (EB-CFRP) sheets and laminates because of simple construction and strengthening efficiency (Arslan et al., 2022; Al-Shalif et al., 2022; Verbruggen et al., 2014a, 2014b; Joseph et al., 2023; Xu et al.,

2019; Gribniak et al., 2019; Samb et al., 2021). However, constructional limitations in existing RC buildings hinder EB-CFRP wrapping and cause anchorage problems (Arslan et al., 2022; Al-Shalif et al., 2022; Xu et al., 2019; Samb et al., 2021; Gribniak et al., 2016). The vulnerability of carbon fiber-reinforced polymer (CFRP) materials to forces acting in transverse to fiber direction complicates the strengthening of non-flat surfaces (Dong et al., 2023; Samb et al., 2021; Gribniak et al., 2023). Implementing EB-CFRP shear-strengthening systems for RC beams with L- or T-shaped cross-sections, typical for RC beam-slab assemblies (Wang et al., 2022), also presents a significant challenge. Thus, the specific retrofitting approach involves the EB-CFRP installation on the beam web's three sides, forming a U-shaped arrangement (Wang et al., 2022; Gebreyes and Mohammed, 2020; Nguyen et al., 2022; Samb et al., 2022). This approach often results in brittle failures because of the CFRP debonding (Mohammadi et al., 2017; Tatar et al., 2023; Aggelis et al., 2015; Hanif et al., 2023; Tsangouri et al., 2021).

Various anchoring methods have been developed to delay or address the premature debonding issue and improve the overall performance of the EB-CFRP strengthening systems (Gribniak et al., 2017, 2023; Godat et al., 2020; Aksoylu, 2021). Among these, spike anchors, typically CFRP

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ropes, gained traction as a practical solution, anchoring the EB-CFRP sheets to the concrete substrate (Godat et al., 2020). The spike anchor consists of the section embedded in the concrete (the dowel) and the part affixed to the anchored sheet (the fan). In the latter component, the fibers are gradually expanded (forming a fan) to improve adhesion to the EB-CFRP sheets. The anchor and CFRP sheet are made from the same material (material compatibility), which helps to avoid local damage to the material to be anchored; these anchors are easily installable and adaptable to space and geometry limitations (Del Rey Castillo et al., 2018; Ilia and Mostofinejad, 2019; Li et al., 2022; Abdulsalam et al., 2021).

There are several potential failure modes associated with the anchor, including the pullout of the anchor from the concrete, local fracture of the anchor at the point of bend (occurring when there is a sudden change in slope to facilitate the anchorage), local fiber fracture in the fan section, and debonding of the fan from the sheet to which it adheres (Godat et al., 2020). A preferred failure mechanism involves rupturing the anchored sheet, which completely utilizes the material strength. The spike anchors' efficacy has been studied by individually examining potential failure mechanisms through experimental testing (Carozzi et al., 2018; Del Rey Castillo et al., 2019a, 2019b; Llaurodo et al., 2017; Mahrenholtz et al., 2015; Saeed et al., 2020; Sun et al., 2020; Zhang and Smith, 2012; Zhang et al., 2012) or evaluating their performance in beam structural members (Abdalla et al., 2023; Alotaibi et al., 2019; Aryan et al., 2023; Kim et al., 2015; Mhanna et al., 2020, 2021a, 2021b; Smith et al., 2013; Zaki et al., 2020). However, even today, a universally accepted method for anchorage design has yet to be established. This is evident from the limited number of methodologies available at the research level (Shekarchi et al., 2020; Cortez Flores et al., 2020; Del Rey Castillo et al., 2019c; Villanueva Llaurodo et al., 2017), some of which rely on empirical data and the absence of specific design guidelines, challenging engineers and hindering the widespread adoption of this strengthening technique.

Furthermore, the experimental investigation (Del Rey Castillo and Kanitkar, 2021) demonstrated that the installing technology affects the anchoring efficacy even within a controlled laboratory environment conducted by proficient individuals. Insufficient fiber impregnation, inadequate embedding length in the concrete, and fan-forming errors can result in large deviations, a significant reduction in the anchorage's contribution, and premature failure of the strengthening system. Thus, increasing the dowel fiber content and fan length is necessary to realize the CFRP sheet's strength.

Strengthening method appropriate to be implemented by practice engineers must have simple and clear design requirements, be easy to apply, and maximize material consumption (resulting in lower financial costs). Considering the limitations and challenges associated with EB-CFRP sheet anchorage using CFRP spike anchors and also recognizing the adaptability and versatility of CFRP ropes, researchers have explored their potential as a primary strengthening material by using it to create closed form stirrups. Using CFRP rope to form a closed stirrup ensures that failure modes related to the anchor, such as fan debonding, fan fiber breakage, and anchor pullout, will be eliminated. Further, the technique is easier to apply because no fan formation is necessary, and it is a more cost-effective option due to its simplicity. The design of a closed stirrup configuration can also adhere to regulatory requirements in areas with anti-seismic building standards (Shekarchi et al., 2020; Cortez Flores et al., 2020).

Therefore, there has been a growing interest in using fibers in the form of rope for various strengthening applications. Experiments on external beam-column joints (Karayannis et al., 2022a; Goliás et al., 2021a, 2021b) and RC beams with rectangular cross-sections (Papadopoulos et al., 2023; Chaliotis et al., 2018) demonstrated the CFRP rope efficiency. The literature results proved the applicability of this technique for enhancing resistance against flexure (Kaya et al., 2017; Qaisi et al., 2022; Murad and Abu-Al Haj, 2021; Zheng et al., 2020), shear (Al-Khreisat et al., 2023; Obaidat et al., 2023; Saadah et al., 2021), and

torsion (Al-Bayati et al., 2018) in rectangular RC beams and against shear in beam-column joints (Karayannis and Goliás, 2022; Karayannis et al., 2022b; Obaidat, 2022; Murad and Alseid, 2021; Karabini et al., 2023; Ashteyat et al., 2023). However, current experimental research on application of CFRP ropes for shear strengthening in RC beams focus on rectangular cross-section specimens, disregarding the limitations and effects from the potential monolithic connection of beams to slabs in real structures. In addition, this system was efficient in confining RC columns (Obaidat et al., 2020; Hussain et al., 2020; Fanaradelli and Rousakis, 2020) and strengthening RC slabs (Makhlouf et al., 2023).

The above literature review indicates that slabs or other geometric restrictions impede wrapping the element, necessitating incomplete U-shaped applications vulnerable to debonding failure. So far, the application of CFRP spike anchors has been found to be an efficient solution for bonding performance. However, uneven stress distribution in composite sheets, causing premature failure, and complicated installation impede this method. Thus, the application of innovative composite building materials such as CFRP ropes as primary strengthening material in the form of closed transverse stirrups can overcome these limitations. Preliminary test results indicate that using composite ropes as shear reinforcement yields positive outcomes, significantly improving the response of RC members. Further, the ease of implementation, minimal disruption during installation, and cost-effectiveness contribute to the advantages of this approach.

This study investigates the use of CFRP ropes as near-surface mounted (NSM) reinforcement for shear-strengthening of RC T-beams. The CFRP ropes are employed in the form of closed-type transverse shear reinforcement, acting as external stirrups. The formation of CFRP ropes as closed stirrups is implemented in two different configurations, either by embedding the rope through the slab section or the beam's web section, and the efficiency of these two types is compared and examined. Further, this study also compares the proposed approach with a strengthening alternative that employs the combination of EB-CFRP sheets and CFRP rope anchorage to form a closed-type of strengthening. To the best of the authors' knowledge, these innovative materials and retrofitting techniques have not been extended for the shear strengthening of RC T-shaped beams. The experimental program includes nine full-scale beams featuring the different CFRP strengthening systems. In addition to the aforementioned, this current research presents a comprehensive, step-by-step methodology for applying the strengthening procedure to minimize construction-related defects.

2. Experimental program

2.1. Description of specimens

The experimental program encompassed nine RC beams. The beams' length was 2.0 m with a 0.8 m shear span. The specimens had a T-shaped cross-section with 300 × 150 mm web and 50 × 300 mm slab to imitate the slab-to-beam joint. The beams were designed considering the laboratory's capabilities and the intention the tested beams to fail in shear. The longitudinal steel reinforcement was the same for all the test specimens, consisting of four 16 mm bars in the tensile zone and two 14 mm bars at the web's top. In addition, two 10 mm longitudinal bars were placed in the slab area. The specimens had no transverse reinforcement in the shear span aside from three beams (S1, S1-U, and S1-RF) with an 8 mm stirrup in the middle of the shear span. Fig. 1 depicts the beam's geometric characteristics and arrangement of the steel reinforcement. The chosen shear span to effective depth ratio (2.92) has exceeded 2.5, satisfying the slenderness criterion by Eurocode 2 (Gribniak et al., 2021). The shear reinforcement was eliminated (or reduced to a single stirrup) to realize the strengthening effect.

The specimens were named to characterize the shear reinforcement peculiarities. Each specification begins with the letter S, followed by 0 or 1, denoting the steel stirrup's lack or presence. In the case of strengthening with U-shaped CFRP sheets, the third character is the letter U. The

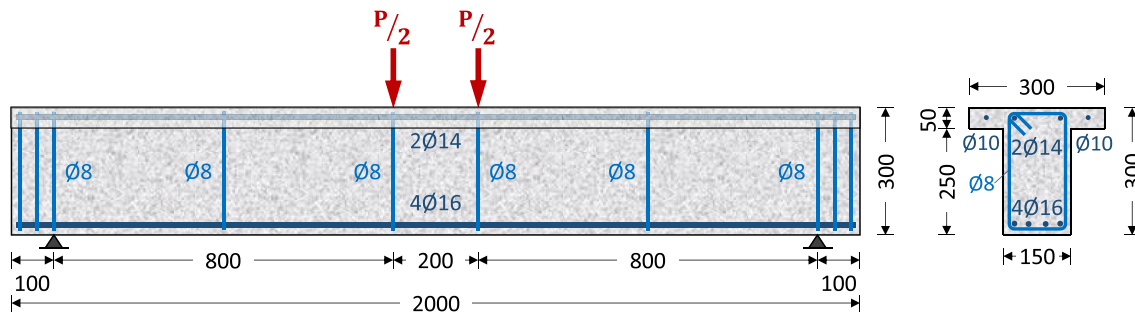


Fig. 1. Geometry and reinforcement arrangement of the reference specimen S1.

notation “U-AF” determines the anchorage with CFRP rope through the slab; “U-AW” designates the anchorage through the web. For instance, notation S0-U-AF describes a beam without a steel stirrup strengthened with U-shaped CFRP sheets anchored through the slab. In the rope-strengthening case, the letter “R” appears in the notation before “F” or “W.”

Two beams (S0 and S1) were the reference specimens, while the remaining beams were strengthened in the shear zone. Four beams (S0-U, S1-U, S0-U-AW, and S0-U-AF) had EB-CFRP sheets in a “U” shape (with or without CFRP rope anchorage), and three beams (S0-RF, S0-RW, and S1-RF) were strengthened using NSM CFRP rope. The strengthening percentage was approximately the same in all the beam specimens for comparison purposes. Table 1 summarizes the reinforcement characteristics of the beam specimens. In this table, the following expression determines the tension (ρ), stirrup (ρ_w), and strengthening (ρ_f) reinforcement percentages:

$$\rho = \frac{A_s}{b \cdot d} \quad (1)$$

$$\rho_w = \frac{A_w}{b \cdot l_w} \quad (2)$$

$$\rho_f = \frac{A_f}{b \cdot l_w} \quad (3)$$

In the above equations, A_s and A_w are the total cross-section areas of the tension reinforcement and a stirrup; b and d are the width and effective depth of the beam; l_w is the stirrup spacing (0.4 m in this case); A_f is the total cross-section area of dry fibers in CFRP sheet or rope.

The web of beams S0-U and S1-U was externally bonded with unidirectional CFRP sheets. The U-shaped sheets had a 0.331 mm equivalent thickness and 160 mm width. As Fig. 2 shows, the clear space between the sheets was equal to 160 mm. The identical configuration of

EB-CFRP sheets was used to strengthen beams S0-U-AW and S0-U-AF, except for the CFRP rope anchorage system (Table 1). The EB-CFRP sheets were anchored through holes in the web beneath the slab (Fig. 2a), imitating an inaccessible slab situation in specimen S0-U-AW, or holes in the slab (Fig. 2b), representing an accessible slab case in the test specimen S0-U-AF.

Smith et al. (2013) recommended implementing several anchors to avoid stress concentrations and reduce the fan size. Thus, every branch of the U-shaped sheet was anchored with two CFRP rope anchors (Fig. 3). The CFRP ropes in the anchors were long enough to create a closed-form loop with a cross-section area exceeding the sheet's fiber content following the literature recommendations (Mhanna et al., 2020). Gradually widening the fiber bundle formed the fan at the end of each anchor to fix the CFRP sheet. The fan's angle was 27°; its length and width were 80 mm. Fig. 3 provides a detailed representation of the CFRP rope configuration where the rope anchorage is installed through the slab. A similar configuration was employed when the rope anchorage is installed through the web section.

Unidirectional CFRP bundles (ropes) installed in vertical grooves in each shear span at a spacing of 160 mm were used to strengthen specimens S0-RF, S0-RW, and S1-RF. In specimens S0-RF and S1-RF, the ropes were mounted in grooves drilled around the web and in the upper side of the slab, with holes in the slab, allowing for a complete wrapping of the cross-section (representing accessible slab, Fig. 4a). In contrast, in beam S0-RW, the entire wrapping of the CFRP ropes was accomplished by drilling a hole slightly below the slab through the beam web (i.e., inaccessible slab, Fig. 4b). To form the closed-loop stirrup and prevent rope slippage, the rope at the top of the slab (specimens S0-RF and S1-RF) or inside the hole of the beam's web (specimen S0-RW) had a 100 mm overlap (10 times the nominal diameter of the rope, Fig. 5) corresponding to the available groove length after the intervention.

All the drilled grooves had a square 15 × 15 mm cross-section except for the tracks on the top of the slab of specimens S0-RF and S1-RFs,

Table 1
Reinforcement and strengthening characteristics of the beam specimens.

Beam	Steel bars (mm)		Stirrup	CFRP		Reinf. ratio (%)		
	Longitudinal			Type ^a	Anchor ^b	ρ	ρ_w	ρ_f
	Bottom	Top						
S0	4 × Ø16	2 × Ø14	–	–	–	1.96	–	–
S0-U				EB	–			0.221
S0-U-AW		+		EB	EtW			0.221
S0-U-AF				EB	EtF			0.221
S0-RW		2 × Ø10		Rope	EtW			0.233
S0-RF				Rope	EtF			0.233
S1	4 × Ø16	2 × Ø14	Ø8	–	–	1.96	0.168	–
S1-U		+		EB	–			0.221
S1-RF		2 × Ø10		Rope	EtF			0.233

^a Strengthening type: EB = U-shaped EB-CFRP sheets with a 0.331 mm equivalent thickness and 160 mm width; Rope = CFRP rope with dry fiber cross-section exceeding 28 mm² according to the manufacturer's specification.

^b Anchorage system: EtW = embedded through the web; EtF = embedded through the flange.

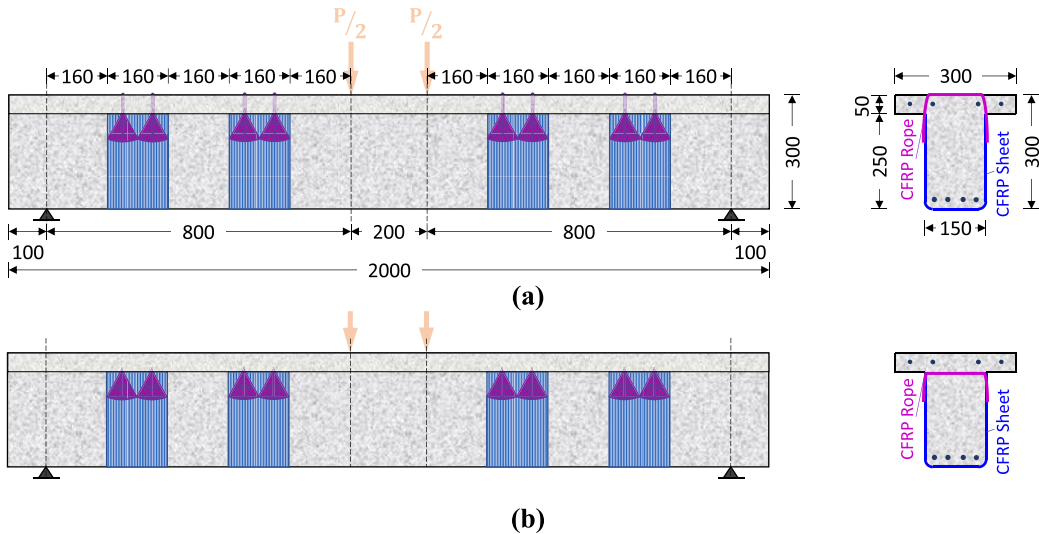


Fig. 2. Geometry and arrangement of CFRP sheets with CFRP rope anchors installed: (a) through the slab (beam S0-U-AF); (b) through the web (beam S0-U-AW).

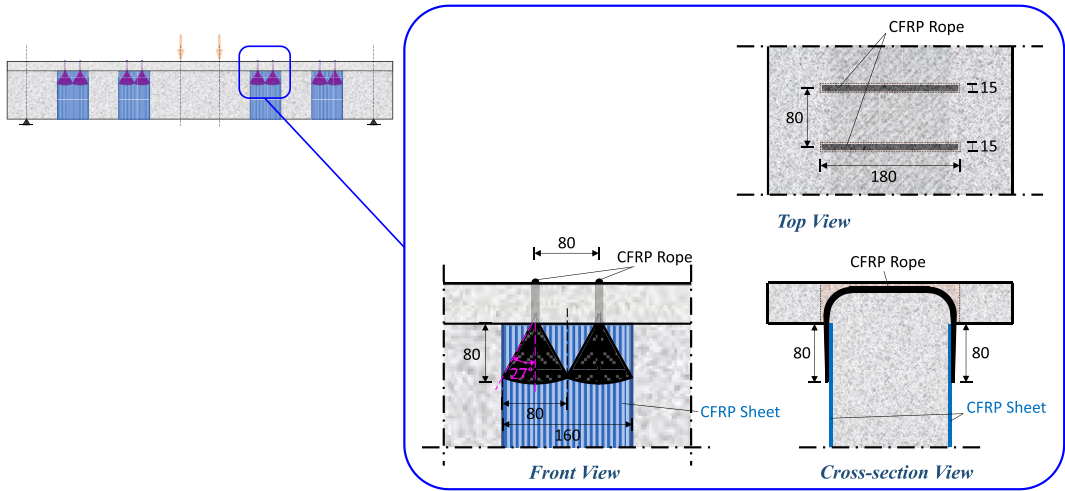


Fig. 3. Detail of the CFRP sheet with CFRP rope anchors installed through the slab (beam S0-U-AF).

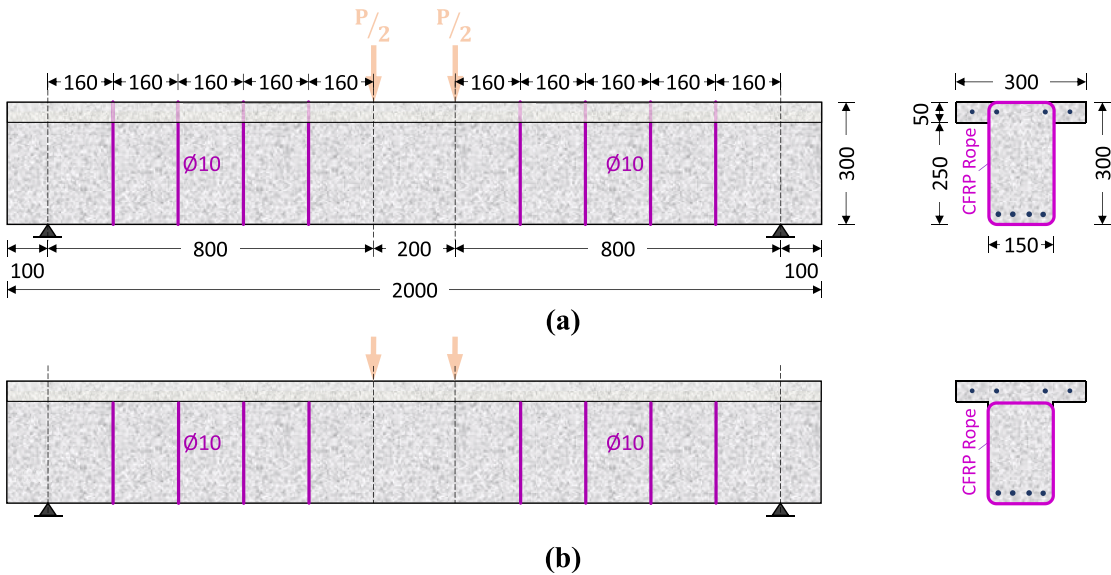


Fig. 4. Geometry and arrangement of the NSM CFRP ropes installed: (a) through the slab (beam S0-RF); (b) through the web (beam S0-RW).

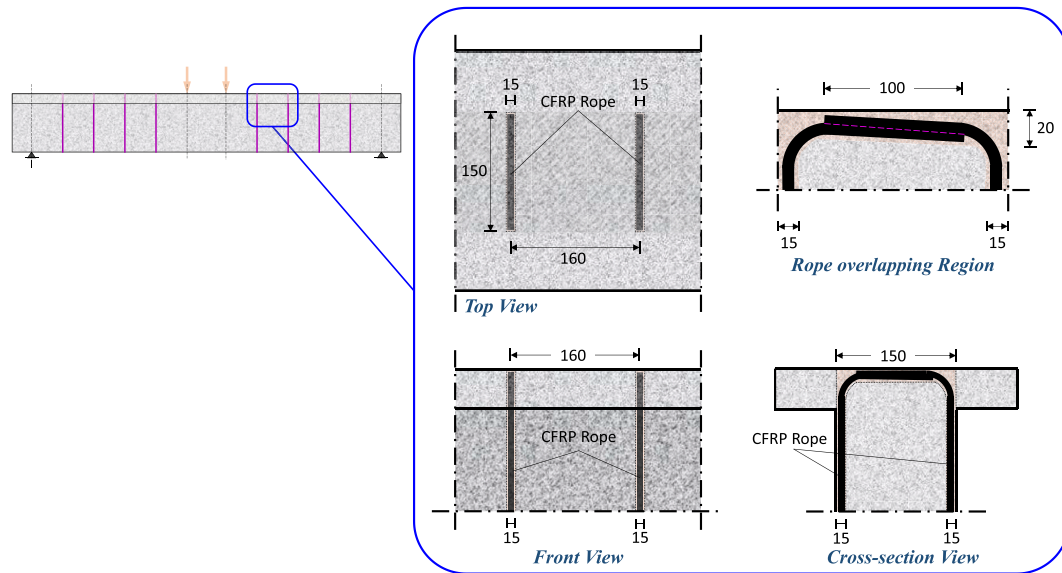


Fig. 5. Detailed view of the NSM CFRP rope installed through the slab.

which had a 20 mm depth to allow the rope overlapping. All the holes had a 16 mm diameter. All the groove edges (at the intersection and inclination points) were smoothed with a 30 mm bend radius to avoid stress concentration and local fiber breakage.

2.2. Materials

Twelve $\varnothing 150 \times 300$ mm cylindrical specimens were cast together with the beam specimens to determine the mechanical properties of concrete. They were tested together with the beam specimens eight months after concrete casting. The compressive strength of the concrete was ascertained using six cylinders; the remaining cylinders determined the splitting tensile strength. The mean compressive strength of the concrete was found to be 44.2 MPa, along with a standard deviation of 1.9 MPa. The mean tensile strength was 3.1 MPa with a 0.3 MPa standard deviation. The longitudinal and transversal reinforcements were either B500C class.

Unidirectional carbon fiber (CF) sheets SikaWrap®-600C were used in this study. The manufacturer specified the impregnated material's characteristics: the sheet's equivalent thickness was equal 0.331 mm, the average tensile strength was 3.00 GPa, the average modulus of elasticity was 225 GPa, and the elongation at rupture was equal to 1.33%. The epoxy Sikadur®-300 was used to impregnate and attach the sheet. The tensile strength, modulus of elasticity, and rupture elongation of the resin, as provided by the manufacturer, were 45 MPa, 3.50 GPa, and 1.5%, respectively.

Unidirectional CF ropes SikaWrap® FX-50C were employed to anchor the CFRP sheets and to strengthen the beams. The manufacturer specified the impregnated material's characteristics: the approximate rope area is 78 mm² (dry fiber cross-section >28 mm²), the tensile strength is 2.00 GPa, the elastic modulus is 230 GPa, and the ultimate strain is 0.87%. According to the manufacturer's instructions, the epoxy resin Sikadur®-52 Injection LP was used to impregnate the fibers and Sikadur®-330 to embed and anchor the CFRP reinforcement. According to the manufacturer, the impregnation resin had a 34 MPa compressive strength, a 24 MPa tensile strength, and a 1.10 GPa modulus of elasticity. Whereas, the Sikadur®-330 had tensile strength, elastic modulus, and rupture elongation values of 30 MPa, 4.5 GPa, and 0.9%, respectively.

2.3. Strengthening procedure

The beams were classified into two groups based on the strengthening technique used. One group contained the beams strengthened with EB-CFRP sheets in a U-shape (with or without CFRP rope anchorage); the second group included those reinforced with NSM CFRP rope.

In the beams belonging to the first group, the sheet application areas on the surface were pre-determined and marked before attaching CFRP. Subsequently, an angle grinder machine was utilized to remove a thin outer layer of concrete ($\approx 2\text{--}3$ mm) to reveal the coarse aggregate beneath (Fig. 6a). The web's edges were smoothed to mitigate the local stresses in the CFRP sheets (Fig. 6b). In specimen S0-U-AF, the holes were drilled in the slab to facilitate the anchoring of the sheets (Fig. 6c). The holes were prepared in the web of beam S0-U-AW just beneath the slab for the same reason.

The CFRP application zones were carefully cleaned using compressed air (Fig. 6d) to remove dust and other debris. Following precise measurements and careful cutting of the CFRP sheets and ropes to the desired dimensions (Fig. 6e and f), the designated areas of the surface of the beam were covered with epoxy resin (Fig. 6g). In the meantime, the CFRP sheets were thoroughly saturated with the impregnation resin (Fig. 6h), adhering to the instructions provided by the manufacturer. Finally, with a particular roll, the sheets were attached and pressed onto the beam's surface to ensure the release of any entrapped air between the sheet and the concrete (Fig. 6i). In the beams with anchored sheets (S0-RF and S0-RW), after the installation of the sheets, the CFRP rope was impregnated (Fig. 6j), and the grooves and holes were filled using Sikadur®-330 resin. The CFRP rope was placed in the predefined position, and the anchor fan was formed to ensure the proper length, opening angle, and consistent thickness (Fig. 6k).

Unidirectional carbon fiber bundles strengthened beams S0-RW, S0-RF, and S1-RF. The intervention areas were initially marked on the surface of the beams. Notches were created into the web region of the beam (and the slab area for specimens S0-RF and S1-RF) using a circular saw (Fig. 7a). Grooves were formed using a drilling apparatus (Fig. 7b and c), ensuring the constant 15 mm width and depth. For specimens S0-RF and S1-RF, the holes were drilled in the slab and connected using the drilling machine (Fig. 7d). In beam S0-RW, drilling holes were formed in the web close to the slab. The bottom edges of the web (Fig. 7e) and all intersection and inclination edges (e.g., near the drilled holes) were curved with a 30 mm radius to prevent stress concentration and local

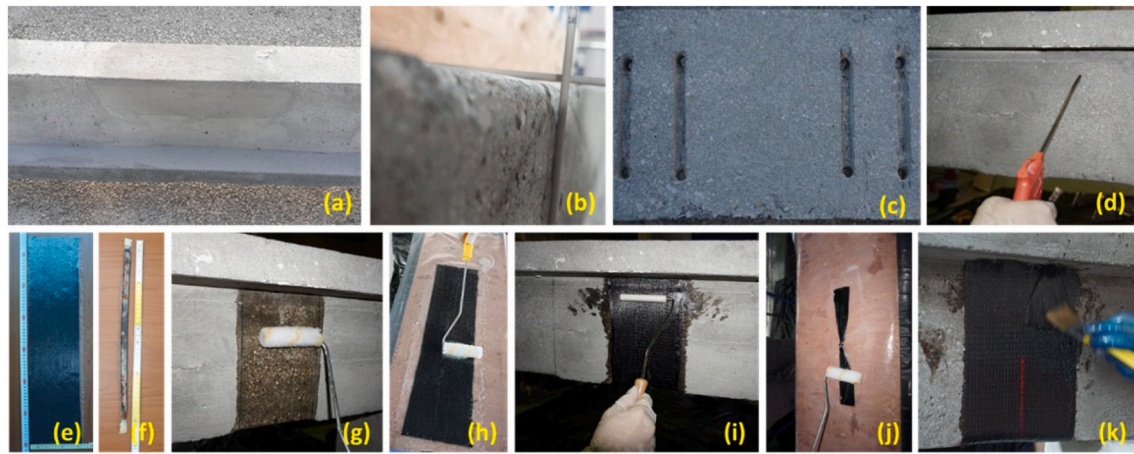


Fig. 6. Attaching U-shaped CFRP sheets with CFRP rope anchors: (a) removal of the outer layer of concrete; (b) smoothing the web's edge; (c) drilling the grooves and holes in the slab; (d) cleaning the dust and debris with compressed air; (e) and (f) cutting the CFRP sheet and rope in desired dimensions; (g) coating the concrete surface with epoxy resin; (h) impregnation of CFRP sheets; (i) attaching the sheets with a particular roll; (j) impregnation of the anchor ropes, (k) placing of the rope in the resin prefilled groove and forming the fan anchor.



Fig. 7. Attaching NSM CFRP ropes: (a) creating notches; (b) and (c) ensuring the groove geometry by using a drilling machine; (d) drilling holes; (e) smoothing the web edges; (f) impregnation of small part of the rope end and placing it in the grooves of the upper part of the beam (slab); (g) prefilling the holes and grooves with epoxy resin to attach and impregnate the remaining rope; (h) placing the rope; (i) filling the resin; (j) stretching the rope with small weights.

fiber breakage. Compressed air was used to clean dust and debris from the rope attachment areas.

The strengthening procedure was conducted in two phases to ensure the ropes' accurate installation and maximize the support effect. After being cut to the required length and impregnated with the epoxy resin, a small part of the rope free end was positioned in the groove at the top of the beam (or in the hole in the upper part of the web) and filled with the anchoring resin (Fig. 7f). The rope was left undisturbed for a day to allow the impregnation resin to harden. This small part, once hardened, serves as a fixed point crucial for stabilizing the rope when it is stretched during its application. The impregnation resin was then applied to the remaining part of the rope using a roller. Simultaneously, the interior surfaces of the holes and grooves were covered with the anchoring epoxy (Fig. 7g). The impregnated rope was distributed in the groove with particular care to minimize fiber damage (Fig. 7h). The anchoring resin was then used to fill all the remaining gaps (Fig. 7i). Lastly, a modest, steady load was applied to the free end of the ropes to ensure that the fibers were aligned correctly and thoroughly stretched (Fig. 7j). The weights were removed after 24 h as the resin had been hardened.

2.4. Experimental setup and instrumentation

The experimental setup of the beams involved the cylinder supports

positioned 100 mm from the element ends. The loading was imposed using a servo-hydraulic actuator with a 500 kN load capacity, using a displacement control mode at a rate of 0.01 mm/s. The displacement was applied through two steel cylinders 100 mm apart from the beam's midpoint. Two linear variable differential transducers (LVDT) were installed at the midspan. In addition, two LVDT devices were placed at supports. Fig. 8 shows the loading scheme and test setup.

3. Results and discussion

This research introduces a novel application of NSM CFRP ropes in closed-form stirrups for shear-strengthening T-beams. It also compares the proposed approach with an alternative strengthening method which employs both EB-CFRP sheets and CFRP rope anchorage to also form a strengthening of closed-type. In addition, this work also experimentally investigates the efficiency of the stirrup configurations embedded through the beam's web and slab.

3.1. Experimental response of the beams

This section describes the beam specimens' cracking behavior and discusses the failure mechanisms. All the specimens exhibited an equivalent behavior during the initial testing phase because of the

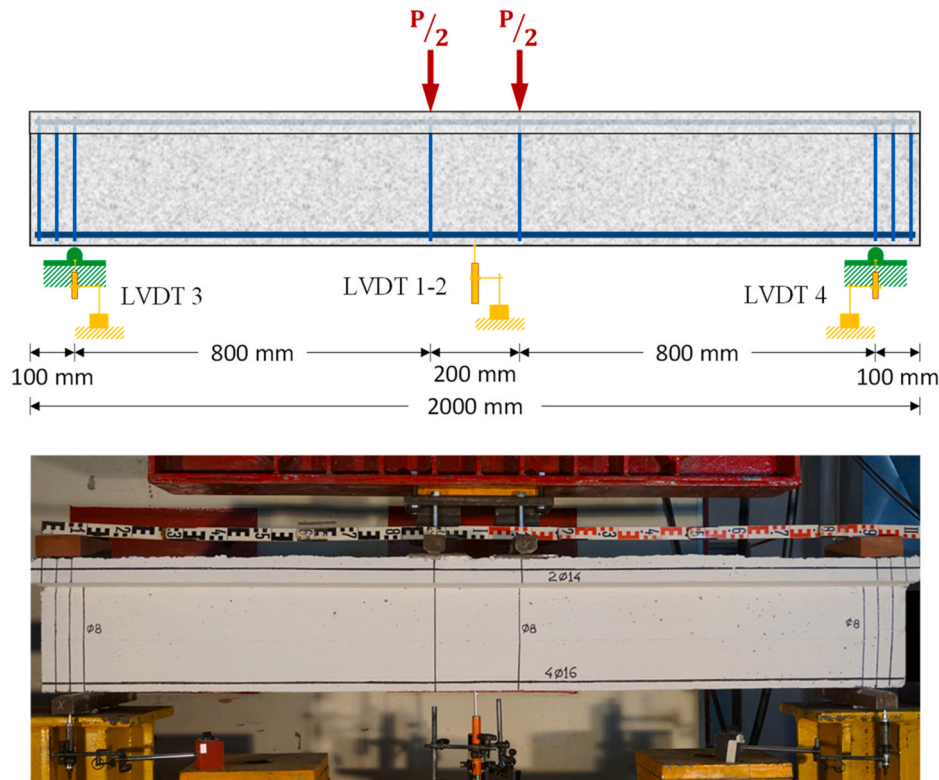


Fig. 8. Typical test setup and instrumentation (the reference specimen is illustrated).

similar cross-section and reinforcement details.

In beam S0, a reference beam lacking a shear stirrup, the first crack that appeared in a shear span (at a 131.9 kN load) steadily developed and spread onto the slab region. Expanding the slab's crack (at a 143.4 kN load) eventually destroyed the beam. On the contrary, in beam S1, a reference beam containing the shear stirrups, an additional load increase led to the formation of cracks within each shear span (156.8 kN and 158.9 kN). The crack opening observed in the shear spans and the concrete's severe damage in the slab area eventually led to the beam's failure (at a 167.0 kN load). Both specimens exhibited shear collapse, characterized by a brittle behavior and the development of one or two wide inclined cracks across the shear span.

In beams S0-U and S1-U strengthened with EB-CFRP sheets, the shear cracks were observed between the sheets in the middle of the shear spans (144.4 kN in S0-U and 123.7 kN in S1-U). Further shear cracks' growth intersected the CFRP sheets with a minimal load increase, causing debonding of the sheets in both specimens at the one shear span (175.9 kN in S0-U and 238.8 kN in S1-U). The sheet debonding onset resulted in a swift rise of the crack width, propagating into the slab area and finally resulting in the beams' failure. The presence of the strengthening led to the development of a few additional shear cracks. Nonetheless, the premature debonding of the EB-CFRP sheets still resulted in a brittle shear-failure.

The specimen S0-U-AF strengthened with EB-CFRP sheets with CFRP rope anchors embedded through the slab behaved similarly to specimen S0-U until the sheet debonded, activating the anchors. Contrary to the above-discussed specimens, the increasing load led to the formation of new cracks instead of the crack width increase characteristic of the previous specimens. Further load increase (to 303.6 kN) resulted in the gradual appearance of a pronounced cracking pattern in the middle of the beam, indicating the yielding of the tensile reinforcement. Individually, several flexural cracks were formed, but an increase in the length and width of already existing ones was predominant.

Specimen S0-U-AW, strengthened with CFRP sheets and CFRP rope anchors embedded through the web, and specimen S0-RW, with the rope

embedded through the web, exhibited similar behavior. Horizontal cracking emerged below the slab after the development of shear cracks intersecting the anchored sheets (282.5 kN in S0-U-AW and 282.4 kN in S0-RW). The crack started from the support, with an increased inclination up to the strengthening sheet, which was eventually driven under the slab (joint point of web and slab). Then, it gradually extended parallel to the beam's longitudinal axis, passing over the strengthened zone and towards the loading point. The yielding of the tensile reinforcement (284.9 kN in S0-U-AW and 297.4 kN in S0-RW) led by a modest increase in load and the formation of flexural cracks in the middle span. Growing and widening the horizontal crack accompanied the spreading of the flexural cracks. Specimen S0-U-AW has been destroyed at that moment. On the contrary, a second cracking branch emerged (312.1 kN) with an increased slope with direction from the support to the horizontal line after widening the flexural cracks in specimen S0-RW.

Specimens S0-RF and S1-RF strengthened with CFRP ropes through the slab demonstrated similar shear-resistance mechanisms. The initial shear cracks (141.0 kN in S0-RF and 147.6 kN in S1-RF) were succeeded by others that progressively intersected all the strengthening regions. Still, the strengthening entirely limited the crack width increase. At the same time, new flexural cracks appeared while existing ones prolonged (305.6 kN in S0-RF and 296.4 kN in S1-RF). As the load rose, the cracks primarily concentrated in the pure bending zone expanded substantially, and concrete crushing signs were observed at the top of the slab.

The shear failure of the reference specimens (S0 and S1) and those strengthened with CFRP sheets (S0-U and S1-U) was brittle. It resulted from creating one or two shear cracks. Implementing CFRP sheets with CFRP rope anchors (specimens S0-U-AW and S0-U-AF) and NSM CFRP ropes (specimens S0-RW, S0-RF, and S1-RF) altered the failure mechanism from brittle shear to ductile flexural. However, embedding CFRP support through the web, either the sheets with CFRP rope anchors or the closed-form stirrups, caused cracks to pass over most of the strengthening zone and spread horizontally afterward. Even if the failure of the beams changed to flexural, potentially higher stresses acting on the strengthening led to premature failure of the specimens regarding

the specimens where the rope was embedded through the slab. The beams' exhibited behavior aligns with the literature's observations (El-Saikaly et al., 2015; Bourget et al., 2017). The difference in response between the drilling methods resulted from increasing the confinement area when the rope passes through the slab. This effect is typical for the beams with a relatively small percentage of transversal reinforcement (El-Saikaly et al., 2015; Bourget et al., 2017); simultaneously, the mechanical behavior tended to be that of the strengthening applied through the slab with increasing the steel reinforcement percentage.

Table 2 specifies the failure mechanisms and the characteristic load and displacement values. It shows the load values at the onset of the shear crack (P_{Vcr}), shear resistance maximum (P_{Vu}), yielding of the steel reinforcement (P_{My}), and ultimate load-bearing capacity (P_{Mu}); the table also includes the corresponding vertical displacements at the midspan (d_{Vcr} , d_{Vu} , d_{My} , and d_{Mu}). Beams S0, S0-U, S1, and S1-U exhibited brittle shear failure with a critical diagonal crack formation. The retrofitted beams S0-U-AW, S0-U-AF, S0-RW, S0-RF, and S1-RF demonstrated adequate flexural ductility regarding vertical displacements. Specifically, the displacement ratio at ultimate load and steel yielding (d_{Mu}/d_{My}) are 3.4, 4.5, 2.0, 4.6, and 4.9, respectively. In contrast, the beams S0-U, S1, and S1-U collapsed due to shear in a brittle and abrupt manner, demonstrating the strengthening efficiency.

The load values at the shear cracking onset (Table 2) are expected because of the CFRP strengthening inefficiency before the first diagonal crack. However, the strengthening effect on the load-bearing capacity and especially the mechanical performance of the retrofitted beams S0-U-AW, S0-U-AF, S0-RW, S0-RF, and S1-RF is apparent by altering the brittle shear failure (characteristic of the reference specimens S0 and S1) to a flexural one with displacement ductility ratio d_{Mu}/d_{My} exceeding 2. The retrofitted beams with EB-CFRP sheets without CFRP rope anchors (i.e., specimens S0-U and S1-U) collapsed in shear ("S" failure type in Table 2), presenting an increased capacity (20% and 43%) regarding beams S0 and S1. Strengthening with the NSM CFRP ropes through the flange (specimens S0-RF and S1-RF) ensured a ductile flexural response and failure of the concrete compressive zone after yielding the tension steel reinforcement ("F" failure type in Table 2), enhancing load-bearing capacity (2.24 and 1.96 times) and displacement at ultimate load (7.5 and 5.2 times) regarding the reference beam specimens S0 and S1.

Beam S0-U-AF with EB-CFRP sheets and CFRP rope anchors through

the slab presented a similar flexural failure mechanism to the specimens strengthened with NSM CFRP ropes installed through the slab, exhibiting an enhanced load and displacement bearing capacity. The CFRP sheets with CFRP rope anchors through the web (specimen S0-U-AW) and the web-anchored ropes (beam S0-RW) also improved the flexural resistance after yielding the tension reinforcement. Still, a critical crack localized at the web-to-slab connection above the CFRP strengthening caused the collapse of those specimens ("FC" failure type in Table 2). Notwithstanding the formation of this critical cracking, both beams S0-U-AW and S0-RW demonstrated an improved load-bearing capacity (2.13 and 2.14 times) and increased displacement at ultimate load (7.0 and 3.7 times) regarding the reference beam S0.

3.2. Effectiveness of U-shaped CFRP sheets with CFRP rope anchors

Fig. 9 shows the load versus mid-span displacement diagrams and the representative cracking patterns of the beams S0 (reference), S0-U (strengthened with U-shaped CFRP sheets), S0-U-AW (with U-shaped CFRP sheets and CFRP rope anchors through the web), and S0-U-AF (with U-shaped CFRP sheets anchored through the flange). The diagrams of beams S0 and S0-U show that the U-jacketing technique slightly increases the shear resistance but does not affect the brittle failure mechanism. This result was expected because of the insufficient anchorage length of CFRP sheets.

On the contrary, the load-displacement diagrams of the U-jacketed beams with anchors (S0-U-AW and S0-U-AF) reveal that the rope installation as fan-type anchor can significantly improve the shear performance by avoiding the bond failure of the CFRP sheets. It is essential that both beams S0-U-AW and S0-U-AF exhibited a ductile response with tension steel reinforcement yielding and flexural failure because of the concrete crushing in the compression zone at high deformation capabilities. The load-bearing capacity improvement of these beams is also significant (regarding the reference beam S0 that collapsed in shear) since the well-predictable bending resistance of the RC beam cross-section governs it.

Table 2

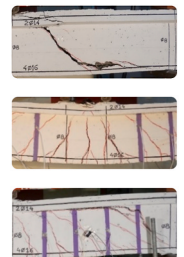
The load resistance characteristics of the test beams.

Beam	Failure type ^a	Load capacity (kN)				Displacement (mm)			
		Shear		Flexure		Shear		Flexure	
		P_{Vcr}	P_{Vu}	P_{My}	P_{Mu}	d_{Vcr}	d_{Vu}	d_{My}	d_{Mu}
S0	S	131.9	146.3	–	–	2.8	5.0	–	–
S0-U	S	144.4	175.9	–	–	3.1	5.2	–	–
S0-U-AW	FC	148.8	–	284.9	311.9	3.0	–	10.4	34.9
S0-U-AF	F	154.8	–	303.6	324.2	3.0	–	8.7	39.0
S0-RW	FC	148.9	–	297.4	313.5	3.0	–	9.5	18.6
S0-RF	F	141.0	–	305.6	327.3	2.7	–	8.1	37.4
S1	S	123.7	167.0	–	–	2.2	7.2	–	–
S1-U	S	143.6	238.8	–	–	2.5	5.6	–	–
S1-RF	F	147.6	–	296.4	327.5	2.5	–	7.6	37.2

S = the brittle shear response and diagonal cracking failure.

F = the ductile flexural response by crushing the concrete compressive zone after yielding the tension steel reinforcement.

FC = the ductile flexural response is because of the horizontal crack separating the concrete compressive zone over the CFRP anchors after yielding the steel reinforcement.



^a Failure mode and representative cracking patterns.

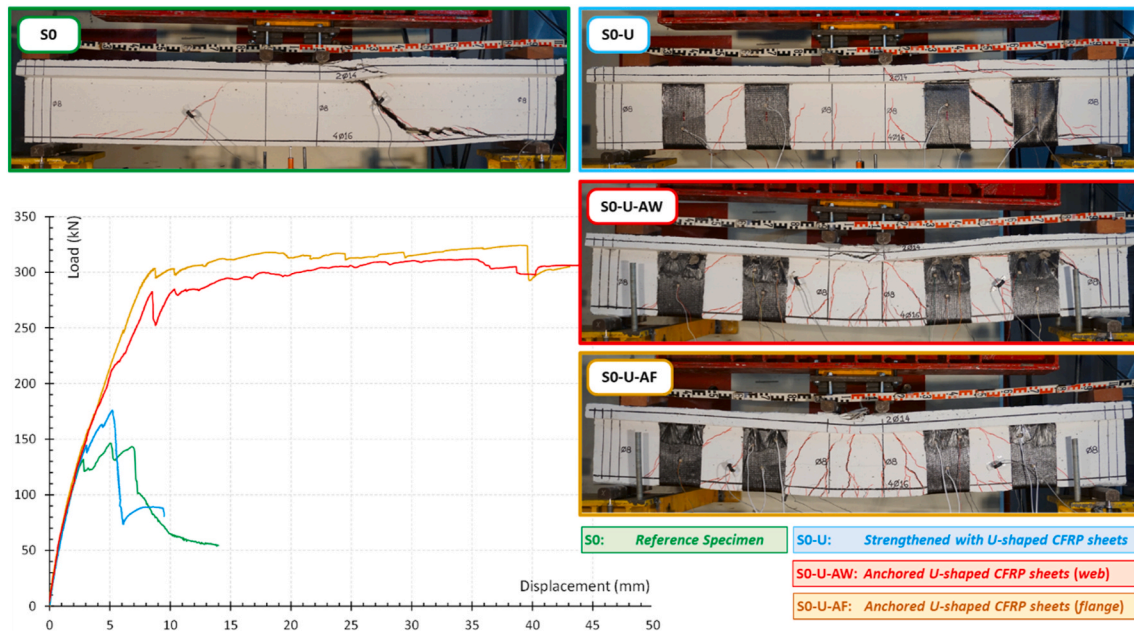


Fig. 9. Load-vertical displacement diagrams and final cracking patterns of specimens S0, S0-U, S0-U-AW, and S0-U-AF.

3.3. Effectiveness of CFRP ropes and U-shaped sheets with CFRP rope anchors

Applying CFRP ropes in existing RC beams as transverse NSM reinforcement is a relatively new shear-strengthening technique. The scheme of the retrofitted beams of this study with CFRP ropes involved complete wrapping of the rope around (a) the web of the beam, passing it through the web, beneath the slab area (specimen S0-RW), and (b) the total cross-section of the beam passing it through the flange (specimen S0-RF), representing the inaccessible and accessible slab situations.

Fig. 10 shows the load-displacement diagrams and final cracking patterns of beams S0-RW and S0-RF with NSM CFRP ropes, reference specimen S0, and specimens S0-U-AW and S0-U-AF strengthened beams with U-shaped CFRP sheets with anchorage through the web and the

flange. This figure shows that all the retrofitted beams demonstrated an almost identical flexural failure mechanism with high ductility capacities since the anchored sheets and ropes prevented shear failure. These specimens sustained the developed shear stresses without the formation of critical diagonal cracking due to the increased shear resistance of the CFRP-wrapped region.

Nevertheless, in the case of the beams S0-U-AW and S0-RW with anchorage and rope wrapping through the web, the critical crack beneath the slab (above the CFRP connection) has been formed at high loading levels. Although these cracks did not influence the overall load-displacement response, it could be a reason to prefer the retrofitting scheme through the slab.

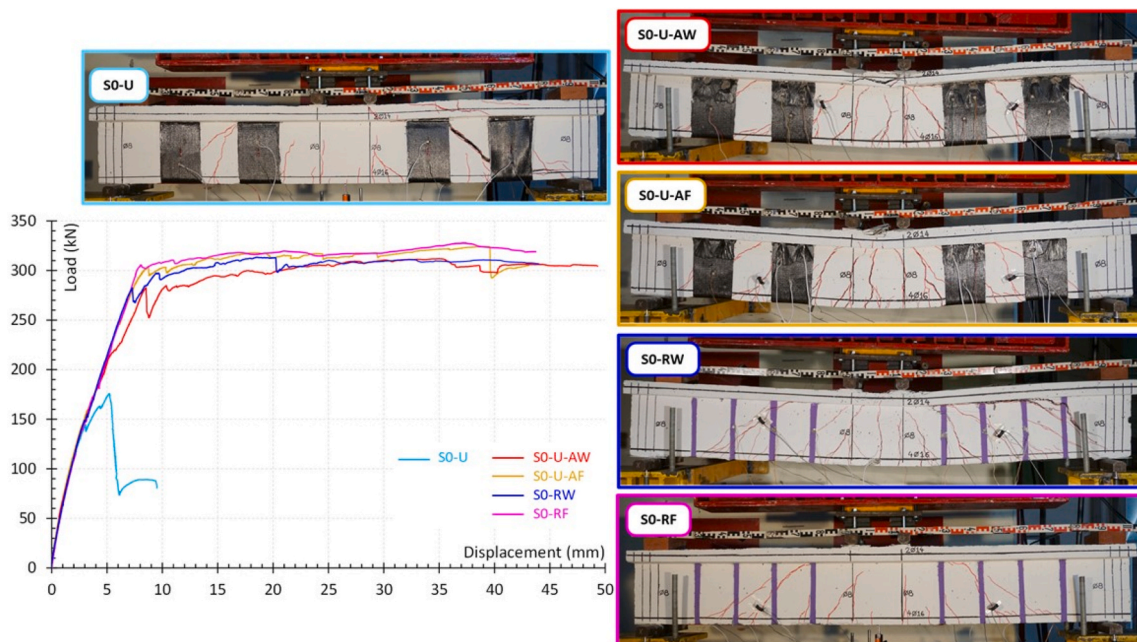


Fig. 10. Load-vertical displacement diagrams and final cracking patterns of specimens S0-U, S0-U-AW, S0-U-AF, S0-RW, and S0-RF.

3.4. The synergetic effect of steel stirrups and CFRP strengthening

Fig. 11 examines the steel stirrups' effect on the shear performance of the U-shaped CFRP sheets without anchors and NSM CFRP ropes wrapped through the flange in the closed-form loop form. This figure shows the load-displacement diagrams and the crack patterns of the beams with steel stirrups: the reference beam S1, specimen S1-U strengthened with U-shaped CFRP sheets, and specimen S1-RF strengthened with CFRP ropes wrapped through the flange. Comparing the S1 and S1-U results deduces that U-shaped sheets without anchors provided a notable increase in the shear capacity but did not alter the brittle shear failure since both specimens exhibited critical diagonal cracks. The beam counterparts S0 and S0-U without stirrups faced a similar shear collapse (Fig. 9), though the CFRP-jacketing effect on the shear resistance is more significant in the beams with steel stirrups.

The load-displacement diagrams in Fig. 11 demonstrate that the NSM CFRP rope retrofitting technique can improve the shear performance and alter the brittle shear failure to a more desirable flexural-dominated one. The results of specimen S1-RF support this conclusion.

Figs. 12 and 13 show the load-displacement diagrams and cracking patterns of specimen counterparts without and with stirrups: the beams S0-U and S1-U strengthened with U-shaped CFRP sheets, and specimens S0-RF and S1-RF retrofitted by the ropes installed through the flange. As expected, the influence of the steel stirrups in the shear strength is evident in the case of the U-jacketed beams since both specimens collapsed in shear, and beam S1-U exhibited 1.36 times higher load capacity than beam S0-U. On the contrary, the flexural failure is characteristic of beams S0-RF and S1-RF retrofitted with the CFRP ropes, and concrete crushing in the compression zone controls the load-bearing capacity. Thus, steel stirrups cannot contribute to mechanical resistance. On the other hand, the NSM CFRP rope strengthening approach demonstrated its efficiency even in the absence of steel stirrups, ensuring sufficient resistance of the shear zone.

3.5. Further research

Strengthening RC structures using NSM CFRP ropes is an innovative

and evolving field of engineering and research. This method can be easily applied with little intervention to the element. Due to the flexibility of the rope material, it can be adapted by satisfying severe structural limitations and adjusting to a complex shape. Examples of such cases include the shear strengthening of the monolithic beam-to-slab joints by forming closed-form loops (NSM stirrups) or cross-link supporting systems in the area of a beam-column connection. The preliminary experimental studies (Goliás et al., 2021a, 2021b; Karayannis and Goliás, 2022) revealed a promising performance of the X-type CFRP rope strengthening method in enhancing the mechanical performance of beam-column joints. Still, further investigations are necessary to examine this application's effectiveness and explore the effects of different variables, such as the reinforcement percentage and installation technology. Studies (Chalioris et al., 2018; Saadah et al., 2021; Al-Bayati et al., 2018) also investigated the CFRP rope strengthening performance in RC beams with rectangular cross-sections. Although these results demonstrated substantial performance of the strengthening technique, extensive research is still required to optimize the reinforcement arrangement and develop the design principles.

Experimental testing in which the strengthening reinforcement reaches its strength limit and fails, especially in specimens, is also necessary to optimize the strengthening technology, reaching the material performance of CFRP ropes and ensuring the strengthening reliability. The strength reduction of the CFRP material because of the local bending, curve-linear arrangement, and lack of stretching of NSM ropes determines the essential investigation object. The anchorage length, shape, and technology also need clarification. Different loading conditions (e. g., cyclic, dynamic, and long-term mechanical and temperature loads) must also be considered to evaluate the strengthening efficiency. The influence of the above mentioned should be expressed through analytical formulations. The development of such formulations will quantify the contribution of the strengthening reinforcement and further contribute to the applicability and practical implementation of the proposed reinforcement technique in structural engineering applications.

It is also essential to evaluate the cost-effectiveness of NSM CFRP ropes regarding the existing strengthening alternatives. The research parameters are determined by the material cost, installation expenses,

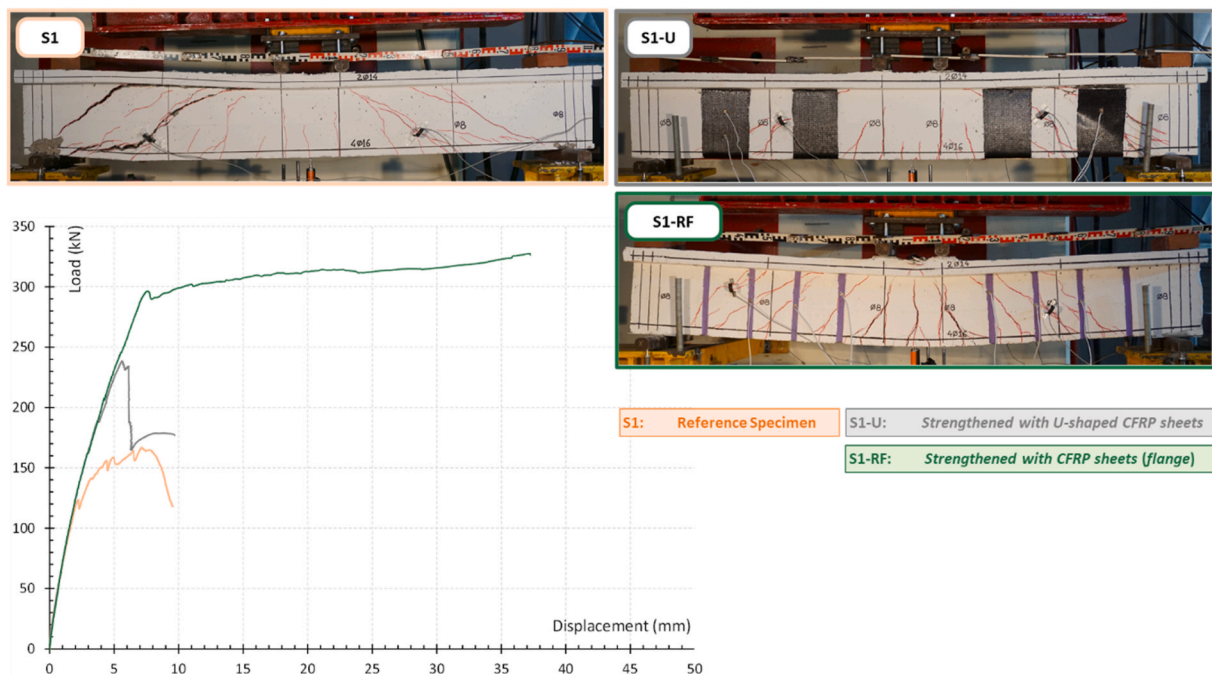


Fig. 11. Load-vertical displacement diagrams and final cracking patterns of specimens S1, S1-U, and S1-RF.

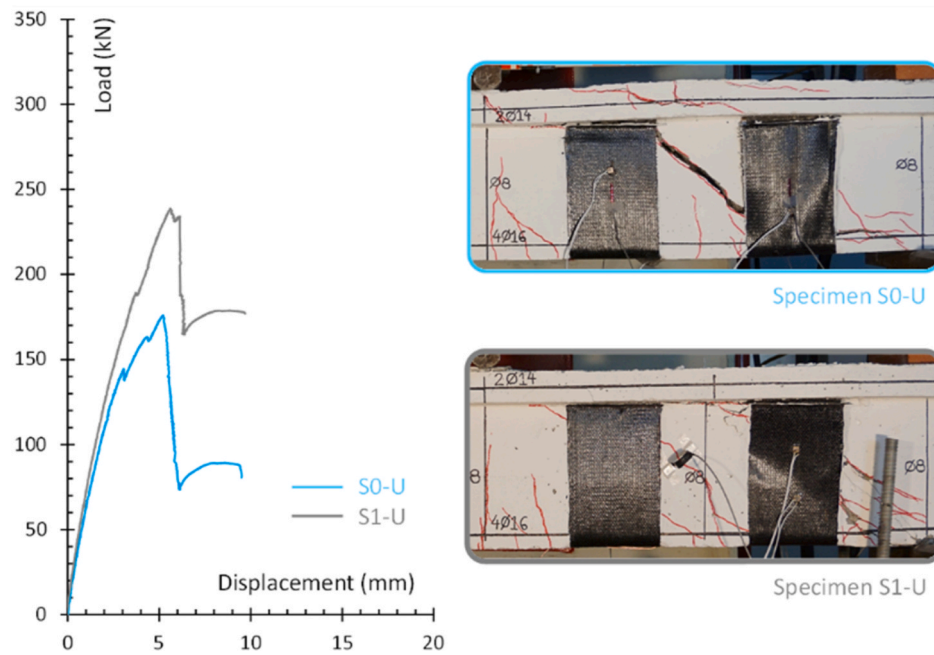


Fig. 12. Load-vertical displacement diagrams and final cracking patterns of specimens S0-U and S1-U.

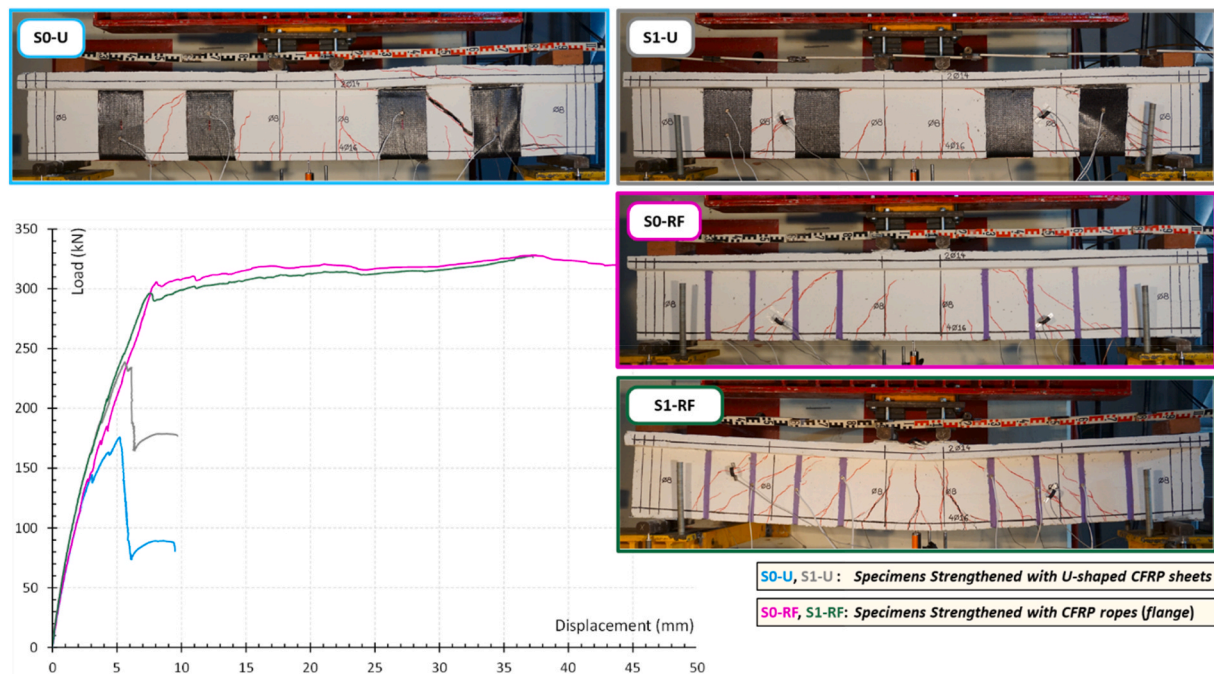


Fig. 13. Load-vertical displacement diagrams and final cracking patterns of specimens S0-U, S1-U, S0-RF, and S1-RF.

strengthening duration, service life extension, maintenance costs, and long-term structural performance.

3.6. Conclusions

This study developed a new application of CFRP ropes as near-surface mounted (NSM) reinforcement for shear-strengthening RC T-beams in the form of closed stirrups. Moreover, the study compared the efficacy of this strengthening method to an alternative one which incorporates the use of EB-CFRP sheets along with CFRP ropes and also leads to the formation of a closed type strengthening. An experimental

investigation was conducted on nine large-scale T-beams subjected to monotonic loading up to failure. Two reference specimens had no CFRP strengthening, four specimens were retrofitted using EB-CFRP sheets (with and without anchors), and three beams were strengthened with NSM CFRP rope. The application of the ropes (either as NSM or anchors) was performed in two different arrangements to replicate scenarios where the slab is either accessible (the rope embedded through the slab) or inaccessible (the rope embedded through the web). Based on the findings of this study, the following conclusions are delivered:

- The proposed NSM CFRP rope closed-form stirrups are particularly effective for T-beams' shear-strengthening. Both investigated arrangements, i.e., embedding the rope either through the slab or through the web, resulted in a substantial increase in the shear resistance of the beam. The strengthening altered the brittle shear failure observed in the reference beam to a ductile flexural collapse. The overall load-bearing capacity increased by 1.8 to 2.2 times regarding the reference specimens.
- The proposed strengthening technique is straightforward, fast, and flexible with minimal intervention in the structural member. It is barely affected by geometric restrictions, such as a monolithic beam connection with the slab. Moreover, the closed-loop application of CFRP ropes is more reliable and faster regarding the CFRP rope anchors of CFRP sheets, diminishing the installation and avoiding fan formation.
- As expected from the literature, forming the closed-form CFRP rope stirrups through the slab outperformed the strengthening alternative through the web. The specimens retrofitted through the web demonstrated a critical crack, separating the slab from the retrofitted web above the CFRP connections. The distinct resistance mechanisms resulted from the more effective confinement of the space inside the CFRP loop on the first alternative. At the same time, both strengthening setups succeeded in altering the brittle shear beam's failure to the acceptably ductile flexural mechanism.
- The beams strengthened with CFRP sheets having CFRP rope anchors and NSM CFRP ropes demonstrated similar shear resistance mechanisms. The strengthening resulted in a similar increase in shear strength, converting the brittle shear collapse to favorable ductile flexural failure. When the anchoring of the sheets was carried out through the web, similar horizontal cracking was observed, as in the corresponding beam strengthened with CFRP ropes. Until the alteration of the failure mechanism to a flexural, no indications of rupture were noticed in the sheet anchors.
- The NSM CFRP rope is more effective regarding the well-spread EB-CFRP sheet strengthening alternative until yielding the steel reinforcement. Dense cracks with a reduced width were observed, indicating a more efficient incorporation of the strengthening into the structural member. The CFRP rupture can change the structural behavior, determining the object for further research. In addition, research is required to determine the benefits and limitations of these strengthening methods and, ultimately, establish design formulations for engineering practice.

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CRediT authorship contribution statement

Adamantis G. Zapris: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Violetta K. Kytinou:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Viktor Gribniak:** Formal analysis, Funding acquisition, Validation, Visualization, Writing – review & editing. **Constantin E. Chaliotis:** Conceptualization, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal

relationships which may be considered as potential competing interests: Constantin Chaliotis reports financial support was provided by European Regional Development Fund (Project No 01.2.2-LMT-K-718-03-0010) under a grant agreement with the Research Council of Lithuania (LMTLT). Violetta K. Kytinou and Viktor Gribniak reports financial support was provided by European Regional Development Fund (Project No 01.2.2-LMT-K-718-03-0010) under a grant agreement with the Research Council of Lithuania (LMTLT). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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