



Shear Strengthening and Repairing of Reinforced Concrete T-Beam Exposed to high Temperature Using Near Surface Mounted Carbon Fiber Reinforced Polymers Ropes

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Abstract

Strengthening and repairing of shear deficient T-beams subjected to high temperature is limited. This research investigates experimentally the strengthening and repairing of reinforced concrete (RC) T-beams using Near Surface Mounted Carbon fiber reinforced polymers (NSM-CFRP) ropes. In this study eight RC T-beams with shear deficient were cast. Four beams were strengthened using NSM-CFRP ropes with different configurations. Another four beam were subjected to high temperature (650 °C) and then were repaired using NSM-CFRP rope. The experimental results showed that using different NSM-CFRP ropes in various configurations effectively improved the shear capacity of RC T-beams. Compared to the control beam, the three groups (Full circulation, 45° inclined and U-Wrapped (bottom and the two sides)) chosen to strengthen the shear of RC T-beams were successful in increasing the maximum load capacity. The U-Wrapped of the CFRP ropes schemes recorded the highest enhancement in the shear capacity with an enhancement ratio of 37% for the non-heated beam with 100 mm spacing and by a ratio of 26% for the heated beam with 100 mm spacing.

Keywords: T-Beams; Strengthening; Repairing; CFRP ropes; Shear strength; Experimental study.

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1. Introduction

Concrete is a fundamental material in building construction due to its numerous properties. It is known for its fire resistance and ability to withstand various environmental conditions. Additionally, concrete is highly durable and has been extensively used in construction throughout history. Reinforced concrete floor systems typically consist of monolithically connected slabs and beams. These two components work together to bear loads. In such systems, the beams often have wider sections at their top, called flanges, resulting in T-shaped beams known as T-beams. The behavior of a T-beam in relation to its neutral axis (NA) determines

whether it acts as a rectangular or T-section. If the NA is located within the flange, the beam behaves as a rectangular section. Conversely, if the NA is within the web, the beam behaves as a T-beam.^[1-3]

Concrete structures may break down with time due to natural and material variables, the concrete modes failure by fire exposure depends on the fire nature, length, and types of structure.^[4-6] The most impacts of fire on concrete are the loss of compressive strength and explosive spalling.^[7,8] Deteriorated structures ought to be repaired to guarantee appropriate functioning and to expand their life service. Structures without damage may moreover have to be strengthened due to the design or construction aspects or to suit changes within the structure utilization or expanding loads. In spite of the fact that strengthened concrete (RC) individuals show high fire resistance characteristics, their structural behavior can essentially deteriorate when exposed to a direct serious fire due to the loss in mechanical properties of concrete and steel reinforcements, as well as bonding between them, at elevated temperatures.

One of the most successful methods for restoration and reinforcing concrete structures is Fiber Reinforced Polymer

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(FRPs) composites. The growing interest in fiber reinforced polymer (FRP) composite in strengthening and retrofit is getting to be clear in recent years due to the interesting properties of these composite materials. The high strength and lightweight make them easy to carry, corrosion-resistant, durable, excellent fatigue resistance, multifunctional use, and easy to install.^[9-11]

Two primary strengthening techniques have been investigated: externally bonded (EB) systems; and near-surface mounted (NSM), both of which are utilized to overhaul the load-carrying and deformation capacities of deteriorated concrete structural components. In EBR technique the FRP is bonded externally to the structure surface. Several research has been conducted on repairing structure using EBR technique.^[12-18] Arslan *et al.*^[15] investigated the strengthening of shear deficient T-beam using externally bonded reinforcement (EBR) with and without anchorage in different CFRP configurations. Seven T-beams were strengthened with partial CFRP strip and one was strengthened with full CFRP wrapped in the shear span. The experimental results indicated that the contribution of EBR to the shear capacity is significant and depends on different variables such as anchorage angle, strengthening type. Moreover, the strengthening method that gives the most effective results in strengthening T-beams are full wrapping CFRP and partial CFRP with a 45-degree anchorage type.

Abdel-Jaber *et al.*^[11] investigate the use of externally bonded carbon fiber reinforced polymer (CFRP) and its effect on the strengthening and rehabilitation of reinforced concrete (RC) T-beams. He used inclined strips, straight strips and U-wrapped sheets. The results showed that all beams containing CFRP recorded higher strength than the control sample; the highest enhancement in the shear capacity was recorded by the horizontal straight strips of the CFRP schemes followed by the U-wrapped sheets and inclined strips. Spadea *et al.*^[17] investigated the strength and ductility aspects of reinforced concrete (RC) beams strengthened with an externally bonded carbon fiber reinforced polymer (CFRP) laminate. The results show that when strengthened beams with bonded CFRP plates without external anchorages both deflection and energy absorption are reduced and the effects arising from strengthening existing RC beams with CFRP laminates on ductility cannot be ignored. The regained of much of this lost ductility caused by suitably designed and positioned external anchorages. Beramly *et al.*^[18] studied shear strengthening of RC T-beams using externally bonded carbon fiber-reinforced polymers (CFRPs) sheet. The experimental results showed that using different CFRPs materials in various configurations effectively improved shear capacity for strengthening and rehabilitating RC T-beams. Yang *et al.*^[19] examines the shear behavior of reinforced concrete T-beams with prestressed steel straps exposed to fire. The main parameters in the study were: heating time, the number of layers reinforced by straps, and the spacing of straps. The comparison between the post-fire retrofitted and the unstrengthened specimens showed that the

shear ductility and capacity of post-fire retrofitted specimens were higher and that prestressed steel straps is effective in repairing T beams.

Various failure modes were detected in reinforced concrete beams and slabs upon external reinforcement with EBR-FRP laminates. The predominant failure modes, which impede the optimal utilization of FRP, are primarily associated with debonding in externally bonded FRP.^[16-19] Conversely, a more recent approach for strengthening and retrofitting reinforced concrete structures involves near-surface mounted (NSM) techniques. NSM entails creating grooves in the concrete cover, inserting FRP, and securely affixing it to the concrete through the use of epoxy. Numerous studies have investigated the use of near-surface carbon fiber reinforced polymer (NSM) as a reinforcement method for reinforced concrete (RC) beams^[20-39] used innovative material of carbon fiber ropes for the strengthening of reinforced concrete exterior beam-column connections. In this study eight beam column joint where cast, six of the specimens were strengthened by applying external X-shaped ropes at each side of the body of the joint and straight ropes at each side of the beam while two control specimens were tested without being strengthened. It is found that all strengthened joints exhibited improved hysteretic response compared to their unstrengthened counterparts in terms of maximum loads per loading step, stiffness and energy dissipations. The increase in maximum load and stiffness reached 57% and 39% respectively compared to unstrengthened control sample.

Obaidat *et al.*^[30] investigated the behavior of heat damaged reinforced concrete RC circular column repaired using NSM-CFRP rope. The results showed that the repaired columns damaged by heat restored their capacity. Also, using one layer of CFRP rope at spacing of 100 mm was more successful than two layers at spacing of 200 mm. In addition, as the temperature increases the regained capacity of the repaired column increase. Zhang *et al.*^[21] investigates the behavior of strengthened RC T-section beams with NSM FRP bars. Ten RC T-section beams were strengthened with NSM FRP bars. The ultimate capacity and failure mode, cracking resistance, yielding, flexural stiffness, and ductility of specimens were analyzed and compared. The results showed that; a general increase in flexural stiffness of the strengthened specimens was observed at the postyield stage of loading. The failure modes of the specimens were sensitive to the NSM FRP bar type and other conditions such as bar diameter, and bar end anchorage. The most ductile response achieved by GFRP bars with a smooth surface profile. The strength grade of concrete was the most effects factor on the yield load and ultimate loads. The strain of FRP bars and their utilization ratio became lower as the diameter of NSM FRP.^[38] investigated the shear strengthening of RC T-Beams using carbon fiber reinforced polymer (CFRP) laminates anchored with spike anchors. In this study six beams were strengthened with CFRP laminates at 45° and at 90° inclination angles and anchored with embedded CFRP spikes with different depths (50 mm and 75

mm) and different diameters (10 mm and 12 mm). Wrapping (U-Wrapped) was also used for anchoring the flexural CFRP laminates. The results showed that the capacity of the strengthened beams is increased up to 45% compared to that of the control beam. Also, anchoring the U-jackets improved the FRP contribution to shear capacity by 27-55% compared to the unanchored U-wraps.

AL-Shalif *et al.*^[39] investigated the shear strengthening of reinforced concrete T beam using glass fiber reinforced polymer composites (GFRP) in various configurations. GFRP composites were applied along the shear spans of the beams in different wrapping styles, with or without anchorage. Shear failure was prevented by increasing the bonding surface between the GFRP and the concrete surface. The shear capacity of strengthened T beam increased between 8% to 20%. Number of the configuration changed the failure mode from shear failure to typical flexural failure. The experimental results were compared with codes and there were different results from the experimental studies, especially due to the conservative acceptance of GFRP's deformation limits. Based on the literature review limited research has been conducted on RC-T beam subjected to high temperature. Also, most of the T beam behavior was as a rectangular section. So, in this study all the beams were designed to behave as T-beams, *i.e.*, NA is designed to be located at the web. In this study eight T beam with shear deficient were cast half of the beams were subjected to high temperature. Then the beams were strengthened or repaired using NSM-CFRP rope with different configurations.

2. Materials and methods

2.1 Material properties

2.1.1 Concrete and steel

In casting the beam specimens, a normal-weight ready-mixed concrete was used. The Concrete mix design is shown in Table 1. The density of the concrete was 2342 kg/m³. Twelve (150 × 150 × 150) mm cubes were cast, cured for 28 days, and tested to determine the compressive strength. The average compressive strength of unheated and heated cubes was 26 MPa and 18.2 MPa, respectively. The steel used for all reinforcement was with average yield strength of 420 MPa and ultimate strength of 680 MPa as provided by the manufacturer. The maximum aggregate size used in the ready mix concrete was 12.5 mm.

Table 1. Concrete mix design.

Ordinary Portland cement (OPC) (kg/m ³)	223
Coarse Agg. (kg/m ³)	338
Medium Agg. (kg/m ³)	636
Silica Sand (kg/m ³)	742
Crushed fine Agg. (kg/m ³)	371
MICSHIELD SPG 251 (kg/m ³) (Superplasticizer)	8.2
Water to cement ratio (w/c)	0.75
Slump (mm)	200 ± 40
Density (kg/m ³)	2342

2.1.2 CFRP ropes

In this study Sika Wrap FX-50 °C was used for strengthening and repairing of RC-T beams. FX-50 is a unidirectional carbon fiber string, encased in a plastic envelope, which is utilized as near-surface mounted strengthening and as a fiber connector for the anchorage of Sika Wrap fabrics. The CFRP technical data as provided by the manufacture are shown in Table 2.

Table 2. CFRP technical data.

Materials type	Sika Wrap FX-50C
Fiber Density (g/cm ³)	1.82
Tensile Strength (MPa)	4000
Cross Section (mm ²)	≥28
Modules of Elasticity (GPa)	≥1.240
Mass per Unit Length (g/m)	≥50
Elongation at Break (%)	≥1.6%

2.1.3 Epoxy resin (adhesive)

Epoxy is considered an essential part; because good epoxy prevents de-bonding between the concrete surface and NSM-CFRP ropes and as a result, de-bonding failure will be avoided. For installing FX-50, two types of epoxy were used: Sikadur®-330 and Sikadur®-52 LP. The Epoxy Adhesive Properties are shown in Table 3.

2.2 Test specimens

2.2.1 Specimen details

All tested RC T- beams have cross-sectional dimensions of 500 mm width, 50 mm depth of flange and 150 mm width, 450 mm depth for web and the span length is 2000mm as shown in Fig. 1. All the beams were designed to behave as T-beams, *i.e.*, NA is designed to be located at the web. The formwork for all

Table 3. Epoxy adhesive properties.

Resin type/property	Sikadur®-330	Sikadur®-52 LP
	Resin: part A (white)	Resin: part A (Transparent)
	Hardener: part B(grey)	Hardener: part B(Brownish)
Packaging	5kg A+B (light grey)	4kg A+B (Yellowish brownish)
Density	1.3 ± 0.1 kg/liter	1.06 kg/liter
Tensile Strength	30 N/mm ²	~27 N/mm ²
Mixing Ratio	Part A: Part B = 4: 1 (by weight)	A: B = 2: 1 part by weight and by volume
Elongation at break	0.9%	1.9%

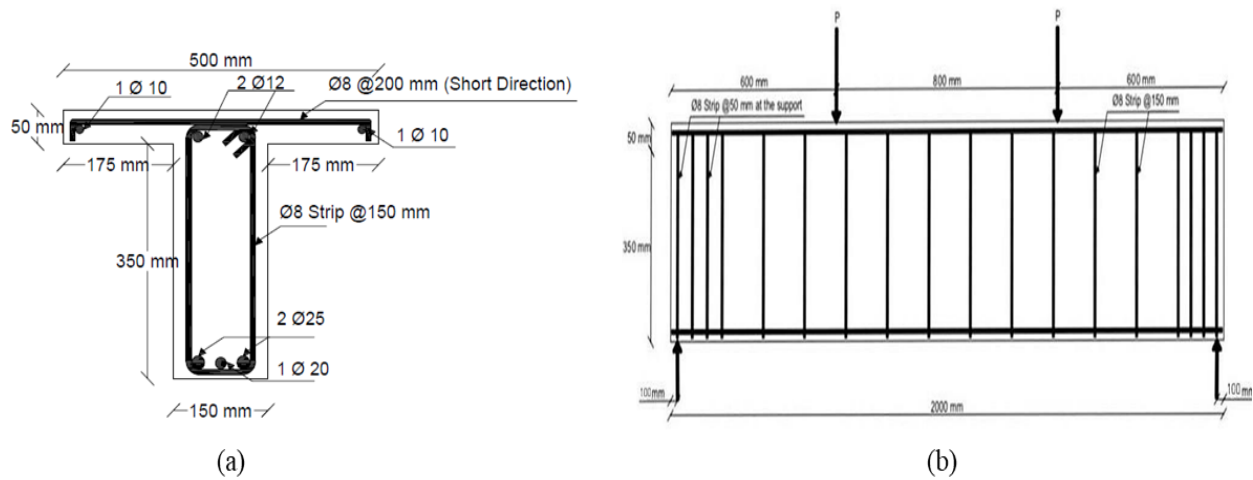


Fig. 1 Section details and reinforcement; (a) cross-section; (b) longitudinal section.

the beams was a steel box with thickness 6 mm as shown in Fig. 2. The design of specimens was according to ACI 318M-19 and ACI 440.2R-08^[36] specifications. All specimens were fully designed to fail in shear. Four types of deformed bar reinforcement were used in RC T-beams: one layer 2 Φ 25, one layer 1 Φ 20, one layer 2 Φ 12 and 1 Φ 10 as longitudinal reinforcement; Φ 8 @ 150mm as closed stirrups as shown in Fig. 1.



Fig. 2 Steel formwork used in casting the T beams.

2.2.2 Test Groups

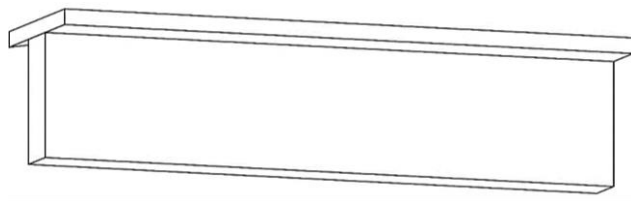
The 10 RC T-beams were categorized into four groups as

follows:

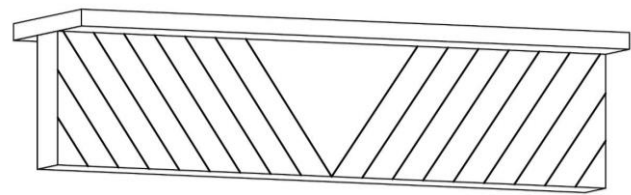
Group (1): This group consists of two beams named CB and H-CB. No NSM-CFRP materials were attached; H-CB was subjected to high temperature. Fig. 3a shows the control beam.

Group (2): This group consisted of two beams named IB1 and H-IB2 with 45° inclined NSM-CFRP ropes attached to the side faces of each beam. The spacing between any two consecutive NSM-CFRP ropes was 100 mm; H-IB2 exposed to high temperature effect before repairing it with the NSM-CFRP ropes while the IB1 strengthened with the NSM-CFRP ropes with no external heat effect. Fig. 3b shows the CFRP configuration of this group.

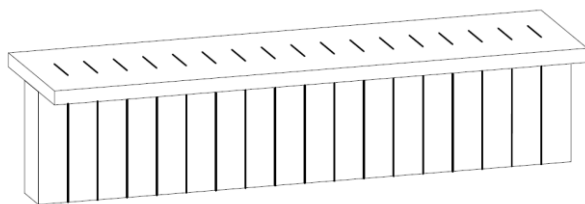
Group (3): This group consisted of two beams named FC-B and HFC-B with vertical straight NSM-CFRP ropes (90° inclination) full circulation. The spacing between the NSM-CFRP ropes was 100 mm. HFC-B exposed to high temperature effect before repairing it with the NSM-CFRP ropes while the FC-B strengthened with the NSM-CFRP ropes with no external heat effect. Fig. 3c shows the CFRP configuration of this group.



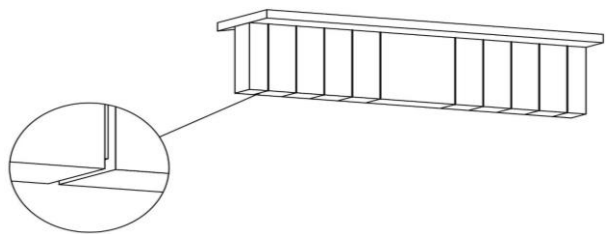
(a)



(b)



(c)



(d)

Fig. 3 Beams groups: (a) control group 1; (b) inclined 45° CFRP ropes-group 2; (c) Full circulation CFRP ropes-group 3; (d) U-wrap CFRP ropes-group 4.

Table 4. Test specimen notations.

CB	Control sample: T-beam with no CFRP ropes attached
H-CB	Heated Control sample: Heated T-beam with no CFRP ropes attached
IB1	T-beam strengthened with 45° inclined CFRP ropes attached to side faces of the web
H-IB2	Heated T-beam with 45° inclined CFRP ropes attached to the side faces of the web
FC-B	T-beam strengthened with full circulation of CFRP ropes
HFC-B	Heated T-beam with full circulation of CFRP ropes attached
UB	T-beam strengthened with U-wrap CFRP ropes (bottom and the two faces)
HUB	Heated T-beam with U-wrap CFRP ropes

Group (4): This group consisted of four beams named UB-100mm, HU-B-100mm, UB-200mm and HU-B-200mm with different orientation U-wrapped NSM-CFRP ropes attached to the web face of the beams, the spacing between the NSM-CFRP ropes was (100mm and 200mm). HU-B-100mm and HU-B-200mm exposed to high temperature effect before strengthening it with the NSM-CFRP ropes while the UB-100mm and UB-200mm strengthened with the NSM-CFRP ropes with no external heat effect. Fig. 3d shows the CFRP configuration of this group. Table 4 provides a full list of the beams and their notations

2.2 Heat application

In this study four RC-T beams were exposed to 650 °C for three hours and repaired using NSM-CFRP rope. To provide the heat, a fabricated high-temperature furnace was utilized, which has internal dimensions of 2 m × 2.5 m × 0.8 m and is covered by a steel slab cover measuring 2.2 m × 2.7 m (as shown in Fig. 4). The temperature was monitored until it reached 650 °C, and heating was maintained for three hours thereafter. The specimens were allowed to cool down for one day inside the oven.



Fig. 4 Furnace dimensions.

2.3 Installation of NSM-CFRP Ropes

After the beams gained the required strength within 28 days, number of the RC beams were subjected to high temperatures. Then heated and unheated T beams were strengthened and repaired using NSM-CFRB ropes based on the following procedures. Before gluing the NSM-CFRP ropes into the beams, the surfaces of the beams must be clean from any dust and loose materials to insure a good bond between RC T-beams and NSM-CFRP ropes. Hence, the beams were cleaned with a wet sponge, and then they were treated by roughening each surface using sandstone paper. As the last step in preparing the beams, they were rewashed using a sponge and waited for them to dry.

After completing the above procedures, lines were drawn and placed in both strengthened and repaired T beams specimens indicating the places of the required grooves. Then using an electric saw machine grooves were cut in the concrete cover with 20 mm depth and 15 mm width as shown in the Fig. 5. Then the grooves were cleaned from dust. The NSM-CFRP rope materials were cut to the required length. The CFRP rope was immersed in Sikadur -52 epoxy resin until fully saturated and then the excess air and resin were removed. The Sikadur 330 was mixed according to the instructions obtained from the manufacturer. To insure full bond of the rope to RC beams, the grooves were halfway filled with the epoxy, after which the CFRPs ropes were pushed into the groove then the groove was filled and the surface was leveled. After the installation of the CFRPs was finished, the beams were tested after 14 days of curing the epoxy in the air. The installation of NSM-CFRP and the groove preparation are shown in Fig. 5.

2.4 Test setup

A two-point loading test was conducted using a 750 kN capacity MFL Prüf-systeme Universal Testing Machine. All beams were treated as simply supported beams; all the beams were supported with 100 mm overhanging from both edges to the centerline of the supports so that the clear span was 1800 mm long. The load was applied in 10 kN increments until failure and was measured using a load cell. At the end of each load increment, cracks were marked, and to record the deflection a linear variable displacement transducers (LVDTs)

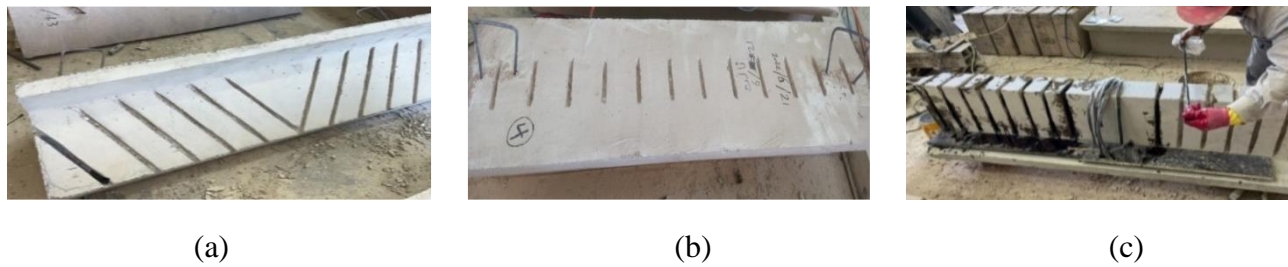


Fig. 5 NSM-CFRP installation: (a) preparation of groove and (b) NSM-CFRP ropes installation.

device was installed at the beam bottom at the mid-span under the soffit of the beam. Fig. 6 shows the test setup.

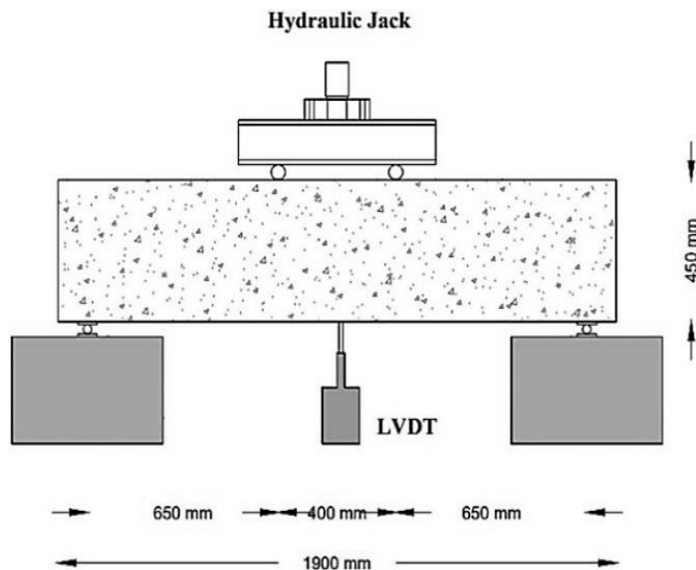


Fig. 6 Test setup.

3. Test results and discussions

3.1 Failure mode

Figures 7, 8, 9 and 10 show the RC-T beams failure mode. As shown in Fig. 7 for group 1 all beams failed in shear. For the control beam, diagonal shear cracks started to appear near the support at a load of 150 kN. Upon increasing the load, the diagonal cracks became wider and propagated upward with an inclination of about 45°, causing the failure of the beam. For the heated control beam an initial diagonal shear cracks were observed in the right shear span at a load of 200 kN. The top surface had diagonal cracks extending from the diagonal shear cracks in the right shear span, indicating a shear failure with an inclination of about 45°.

For group 2, as shown in Fig. 8, initial crack appeared at 80kN, a hair cracks showed up close to the right support at a load of 100 kN, one of the diagonal cracks began to appear behind the carbon fiber until it come to the upper face of the beam near the loading point, causing the failure. For the heated beam the initial diagonal shear crack started appearing at a load of 235 kN, and it was in the right-side of the beam, as the load increase the main diagonal crack started to make its way further above the support of the beam, at a load of 338 kN. The beam failure happened suddenly in shear by splitting the concrete on the bottom right of the edge along the crack. No

debonding or rupture in the FRP rope was noticed for the T beams specimens.

For group 3, as shown in Fig. 9, the load was applied incrementally in 10 kN steps up to 80 kN the initial hair cracks were observed at mid span of the beam and the diagonal crack started to appear when the load reached 150 kN on the two sides of the beam. At the final stage of loading, the only diagonal crack that had appeared started to get wide and reach the web of the beam until the failure happened. For the heated beam the initial cracks were vertical flexural cracks in the middle of the span at 65 kN, the sound of the epoxy started to appear at 75 kN, the diagonal shear cracks were observed in the left shear span at a load of 150 kN. The top surface had diagonal cracks expanding from the diagonal shear cracks in the left shear span, indicating a shear failure. No cover separation or FRP debonding or rupture was noticed for the T beams specimens.

For group 4, as shown in Fig. 10, for specimen UB-100mm, the initial diagonal shear crack started appearing at a load of 160 kN. Thereafter, the load was incrementally increased and the diagonal crack started to make its way further above the support of the beam until the beam failure occurred and the NSM-CFRP ropes moved as in the left side near the support at a load of 420 kN as shown in Fig. 10a. For the heated beam at 60 kN the cracks start to appear between the two-loading point area. The initial diagonal shear crack start appearing at a load of 225 kN. Thereafter, the load was incrementally increased and the diagonal crack started to make its way further above the support of the beam with an inclination angle of 45° on the right side from the support while the left side had no clear diagonal shear cracks until the failure happened as shown in Fig. 10b.

For the other orientation, the UB-200mm at 85 kN the vertical cracks start to appear between the two-loading point area. The initial diagonal shear crack started appearing at a load of 180 kN. Thereafter, the load was incrementally increased and the diagonal crack started to make its way further above the support of the beam, at 385 kN the cracks start to appear in an accurate way with an inclination angle of 45° on the right side from the support while the left side had no clear diagonal shear cracks until the failure happened as shown in Fig. 10c. For the heated beam the initial diagonal shear crack started appearing at a load of 110kN. Thereafter, the load was incrementally increased and the diagonal crack started to make its way further above the support of the beam



(a) Failure for the CB



(b) Failure for the H-CB

Fig. 7 Failure mode for control RC T beams.



(a) Failure for the IB1 T beam



(b) Failure for the H-IB1 T beam

Fig. 8 Failure mode for group(2) RC T beams.



(a) Failure for the FC-B T beam



(b) Failure for the H-FC T beam

Fig. 9 Failure mode for group (3) RC T beams.



(a) Failure for the UB-100 T beam



(b) Failure for the HUB-100 T beam



(c) Failure for the UB-200 T beam



(d) Failure for the HUB-200 T beam

Fig. 10 Failure mode for group (4) RC T beams.

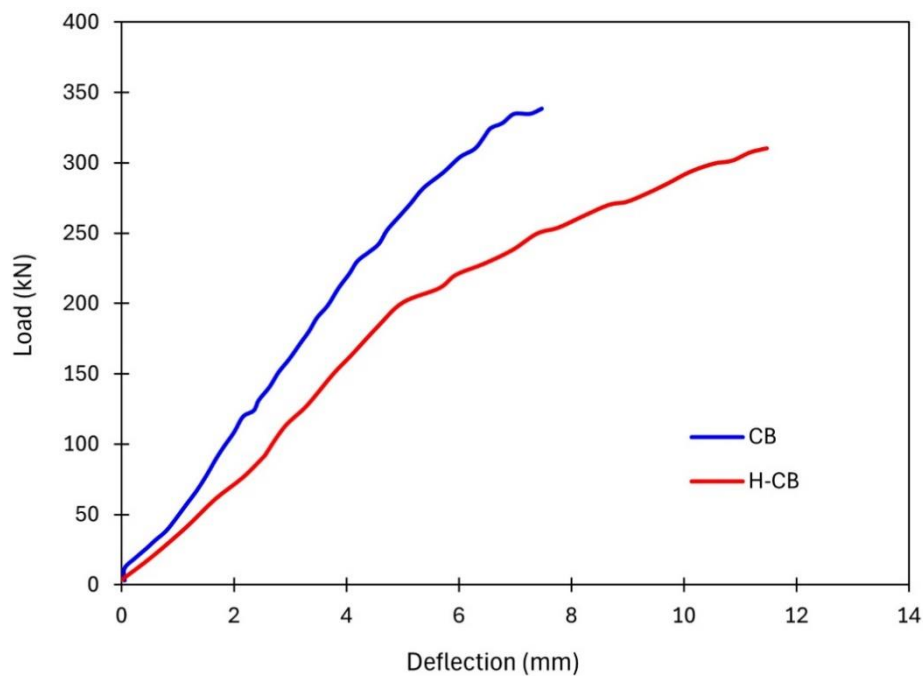


Fig. 11 Load deflection curve for control specimens.

at the two sides of the supports until the beam failure occurred as shown in Fig. 10d. All beams did not show cover separation or FRP debonding as shown in the figure.

3.2 Experimental shear capacity

Figure 11 shows the effect of heat on the ultimate capacity of RC-T beam. As shown in the figure RC-beam exposed to high temperature showed a reduction in the ultimate capacity by 8% compared to the control unheated. While the deflection increased for the heat control sample. The deflection at ultimate load was 11.5mm and 7mm for the control heat and unheated sample respectively. Yang *et al.*^[19] showed a reduction in ultimate capacity with increasing heat by [4% to 23%] depending on the exposure time.

Figure 12 shows the load deflection curve for RC-beam strengthened with different configurations. All the experimental results showed that strengthening RC-T beam using NSM-CFRP ropes was effective in increasing the ultimate load capacity. As shown in Table 5 and Fig. 12 using inclined configuration [IB] increased the ultimate capacity by 16%. Also, strengthening of RC T beam with 90 orientation [FC-B] full circulation of CFRP ropes gave approximately the same result in ultimate load capacity with increase in the ultimate deflection.^[42] found that strengthening of rectangular beam using NSM-CFRP ropes with inclined configuration increased the load carrying capacity by 42% 55–60% depending on the spacing between the ropes.^[16] found that strengthening T beam with externally bonded CFRP plates at 45° with 200mm spacing increase the ultimate capacity by 26%. Same results were reported by Ref. [18]. Al-Zu'bi *et al.*^[22] found that NSM-CFRP strengthening increased the load-carrying capacity of

rectangular beam by 8% and the specimens strengthened with inclined CFRP laminates showed more increment in terms of load carrying capacity compared to the straight. Using U wrapped configuration at spacing of 100mm and 200mm [UB] was effective in increase the capacity of the T beam as shown in Fig. 12. This technique increases the ultimate capacity by 17 to 25% compared to the control sample. The spacing between the rope was effective in increasing the ultimate capacity as shown in Fig. 12. Aryan *et al.*^[41] found that retrofitting of T beam using external full wrapping sheet increased the shear capacity of the beams by up to 37% and 20% for the normal and high strength beams. Arslan *et al.*^[15] found that the strengthening method that gives the most effective results in strengthening T-beams are full wrapping CFRP and partial CFRP with a 45-degree anchorage type. Also, Mhanna *et al.*^[38] found that using shear strengthening of T beam using U-wraps sheet enhanced the beam capacity by 30%.

As expected, the improvements of shear strength in group four (U-wrapped group) with 100mm spacing are higher than any arrangements when compared to control group as shown in Fig. 13. This result is in agreement with results in research.^[16,22,38]

Figure 14 shows RC-T beam subjected to high temperature and repaired using NSM-CFRP ropes. It is clear that using CFRP rope was efficient in regaining the structural capacity of RC-T beams damaged by heat. All beam showed a load capacity between (109% to 118%) of control heat beam.

As shown in Fig. 13 and Table 5 using inclined configuration has regained the structural capacity and showed an increase in the ultimate capacity by 9%. While the straight full configuration (HFC-B) showed an increase in the capacity

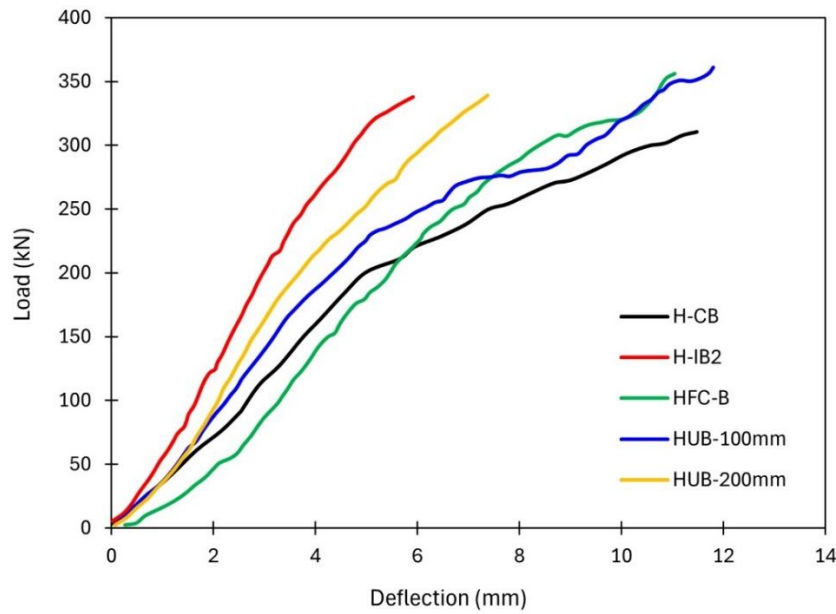


Fig. 12 Load deflection curve for RC-T beam strengthened using different configurations.

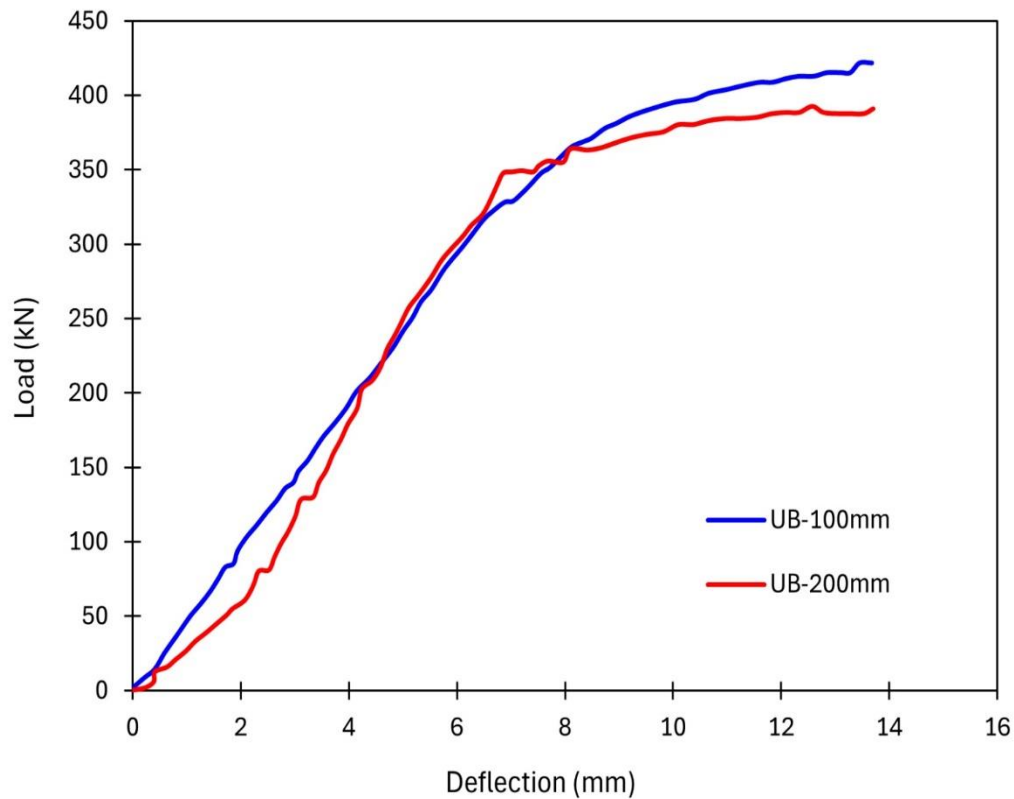


Fig. 13 Effect of spacing on the load deflection curve for reinforced concrete T beam.

by 14.5%. Yang *et al.*^[19] examined the shear capacity of T-beams subjected to high temperature and repaired using full wrapping using prestressed steel straps and the results showed an increase in the ultimate capacity by 20 to 26% depending on the spacing between straps.

It is clear from the Fig. 13 the using U-wrapping, had significantly improved the ultimate load capacity with percentage increase ranging from 18% to 11% depending on

the spacing between ropes. It is clear that the benefit percentage from retrofitting was affected by number of ropes, as well as position of ropes. All repaired specimens showed a reduction in the ultimate deflection compared to the control heat sample, specially the full wrapping configuration. Consequently, repairing and utilizing CFRP ropes improved the ductility behavior in all beams as there was an increase in vertical deflection when compared to the control beam H-CB.

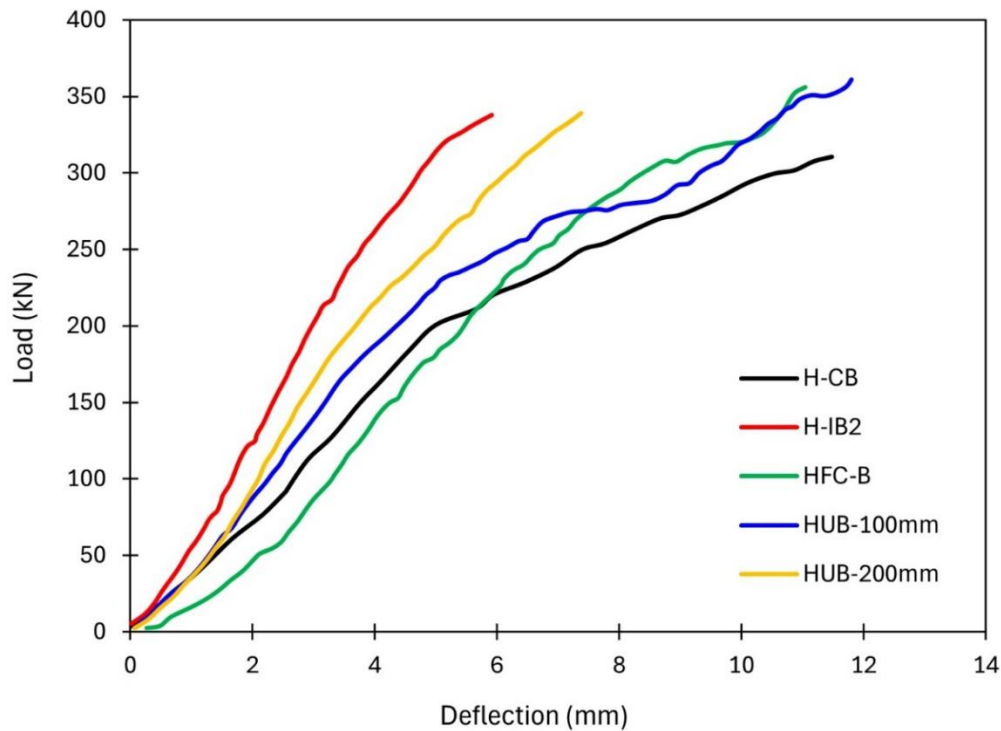


Fig. 14 Load versus deflection curve for repaired reinforced concrete T-beams.

Table 5. Experimental test results.

Sample	Experimental Shear Capacity (kN)	Ultimate load enhancement ratio (%)	
CB	337	0%	
H-CB	310	0%	
IB1	390	253	15.7%
H-IB2	338	199	9%
FC-B	393	281	16.6%
HFC-B	355	231	14.5%
UB-100 mm	420	372	24.6%
HUB-100 mm	365	261	17.7%
UB-200 mm	394	311	16.9%
HUB-200 mm	345	191	11.3%

4. Conclusions

In this study, an experimental program was performed to study the shear strengthening and repairing of reinforced concrete T-beam exposed to high temperature of 650 °C for three hours using near-surface mounted carbon fiber reinforced polymers (NSM-CFRP) ropes. For this purpose, 10 RC T-beams were designed to fail in shear. The test results clearly indicate that using Near-Surface Mounted CFRP ropes in T-beams is effective in improving the shear capacity, and the performance depends on the orientation and spacing of the CFRP ropes along the shear span length. Strengthening beam using U-Wrapped NSM-CFRP ropes with 100mm spacing in this experimental study showed the best strengthening results with an enhancement ratio of 25%. Increasing the spacing between ropes from 100 mm to 200 mm at the U-Wrapped NSM-CFRP ropes, decreased the shear capacity from 37% to 31% for the

non-heated T-beams and from 26% to 19% for the beams exposed to temperature. repairing of heat damaged beams utilizing CFRP ropes oriented at 90° at spacing of 100mm had the best outcomes, it should be noted that in this orientation the spacing made a difference as the spacing 100 mm had higher enhancement ratio compared to 200 mm spacing. The shear cracks were significantly reduced when RC T-beams were strengthened with NSM-CFRP ropes, on the other hand, the stiffness and the ultimate shear strength are improved.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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