Journal of the Chinese Institute of Engineers

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tcie20

Enhancement of flexural performance of RC beams with steel wire rope by external strengthening technique

Yanuar Haryanto , Ay Lie Han , Hsuan-Teh Hu , Fu-Pei Hsiao , Banu Ardi Hidayat & Arnie Widyaningrum

JOURNAL OF THE CHINESE INSTITUTE OF ENGINEERS
https://doi.org/10.1080/02533839.2021.1871651

Enhancement of flexural performance of RC beams with steel wire rope by external strengthening technique

Yanuar Haryanto[a,b], Ay Lie Han[c], Hsuan-Teh Hu[a,d], Fu-Pei Hsiao[e], Banu Ardi Hidayat[a,c] and Arnie Widyaningrum[b]

[a]Department of Civil Engineering, National Cheng Kung University, Tainan, Taiwan; [b]Department of Civil Engineering, Jenderal Soedirman University, Purwokerto, Indonesia; [c]Department of Civil Engineering, Diponegoro University, Semarang, Indonesia; [d]Department of Civil and Disaster Prevention Engineering, National United University, Miaoli, Taiwan; [e]National Center for Research on Earthquake Engineering, Taipei, Taiwan

ABSTRACT

Reinforced concrete structures around the world need repairing or strengthening at some stage in their lifetimes for different reasons. Steel wire rope is one of the potential materials to strengthen reinforced concrete structures do to its high strength, lightweight, and high flexibility properties. This research was, therefore, conducted to investigate a relatively new technique to strengthen reinforced concrete beams using external steel wire ropes. This involved testing five beam specimens under a four-point bending configuration for failure, and the strengthening effects of external wire ropes on their performance were also studied. The results showed the ultimate load capacity was also significantly enhanced up to 250% compared to the control specimen. Moreover, the stiffness and energy absorption capacity of the strengthened specimens were improved due to the external strengthening technique. This means reinforced concrete beams strengthened with external steel wire rope are capable of fulfilling the flexural performance required for reinforced concrete structures.

ARTICLE HISTORY
Received 6 March 2020
Accepted 28 December 2020

KEYWORDS
Beam; flexural performance; external strengthening; steel wire rope

1. Introduction

Reinforcerd concrete (RC) has been considered as a key structural material and used in public structures all over the world for more than a century (Al-Mahaidi and Kalfat 2018). This is associated with the ability to retain form for many decades. However, RC structures need to be rehabilitated or strengthened due to the occurrence of design and construction faults, elevated service loads, natural disasters like earthquakes, environment-related impacts, and mechanical damage (Hosen et al. 2014; Peansupap and Ly 2015). These scenarios require the application of strengthening techniques to improve or recover the load-carrying capacity and original serviceability of the structures.

Nonmetallic materials have often been adopted by people to strengthen RC structures due to their effectiveness and this has attracted several studies on their effects on the structures' behavior. When it comes to the structural upgrading discipline, nonmetallic material was first considered for enabling fiber-reinforced polymer (FRP) usage to conduct flexural strengthening on RC structures (Szabó and Balázs 2007; Lesmana et al. 2013; Hu, Lin, and Tu 2015) and a great potential was reported by Lesmana and Hu (2014) and Tudjono, Lie, and Hidayat (2015). FRP resembles a thin polymer layer with different fibers and some of the specific standard materials available include glass FRP (GFRP), carbon FRP (CFRP), aramid FRP (AFRP), and basalt FRP (BFRP) (Gudonis et al. 2013; Siddika et al. 2019; Choobbor et al. 2019). Meanwhile, it is also possible to use FRP composites as laminates, dry fibers, rods, and plates attached to concrete with adhesives and fasteners.

The increased focus on improving RC structures has led to the deployment of another nonmetallic material, bamboo, due to its excellent tensile strength. It is possible to improve the load-carrying capacity of the reinforced concrete beam, compared to the controlled specimens, using different percentages of bamboo fibers with full wrapping technique in all four sides (Sen and Reddy 2011) and by applying bamboo sticks or strips as a strengthening material (Nahar and Rahman 2015; Haryanto et al. 2017). A non-linear finite element analysis was conducted by Hidayat et al. (2019) on the use of bamboo to strengthen concrete beams and found an increment in the load-carrying capacity of the beams after using the material. Experimental tests conducted by Xu et al. (2019) showed that strengthened masonry structures with bamboo components are promising methods and can be used especially in remote areas.

FRP application is limited despite its several advantages due to its lower resistance to high-temperature exposure (Firmo, Correia, and Bisby 2015; Fayed, Basha, and Hamoda 2019), incompatibility with the concrete substrate, inability to be applied in moist or low-temperature environment, and the possibility of abrupt failure without any notice (Peled 2007; Zhang et al. 2019). These drawbacks also arise in the utilization of bamboo as the strengthening material. Some metals such as steel wire rope (SWR) which are commonly used in mechanical applications (Fontanari et al. 2015) have properties with the ability to overcome the deficiencies of the FRP and bamboo material properties. They are also economical, effective, and simple enough to be acceptable as strengthening ductile materials and the major advantage of the steel wire rope is its lightweight, high strength, and high flexibility properties.

CONTACT Yanuar Haryanto yanuar_haryanto@yahoo.com; Hu Hsuan-Teh Taiwan hthu@ncku.edu.tw Department of Civil Engineering, National Cheng Kung University, No. 1 University Road, Tainan 701

Several investigations have been conducted in recent years on the behavior of RC structures strengthened with steel wire rope. For example, Yang, Byun, and Ashour (2009) tested 10 T-beams with unbonded-type shear strengthening employing wire rope units and found those with closed type wire rope units to have exhibited more ductile failure than those not strengthened, control beams, and those with U-type wire rope units. A practical strengthening technique was also proposed by Yang et al. (2012) to use unbonded prestressed wire rope units in enhancing the in-plane shear strength and ductility of unreinforced masonry (URM) walls and the method was found to be very efficient. It was also observed to have the ability to control the propagation of cracks in the head and bed mortar joints and led to the improvement of the stiffness and capacity of the wall to resist cracks because of the axial compression force added to the wire ropes by the prestressing force.

Another innovative technique was introduced by Wu et al. (2014) to increase the flexural capacity of concrete structures through the use of prestressed high-strength steel wire rope (P-SWR) which is also known as the P-SWR strengthening technique. The findings of the experiment indicated 111 and 178% increment in the cracking load and the same enhancement of 49 and 121% was recorded for both yield and ultimate bearing strength of the beams strengthened using one-layer and two-layer SWRs, respectively. Moreover, the P-SWR-strengthened beam finally had a ductile failure as observed in the crushed concrete, steel yielding, and fractured SWRs. Experimental investigations have also been conducted by Wei and Wu (2014) on concrete columns confined with high-strength wire (HSW) using 15 specimens and the confinement pressure was varied with the HSW winding spacing. The findings showed the strength and ductility of the columns was significantly improved and this means the winding HSW was efficient and effective for column jacketing. Furthermore, the JGJ/T325-2014 guide developed by the Ministry of Housing and Urban-Rural Development of China (2014) has also presented several key conclusions and findings.

The study conducted by Li et al. (2018) proposed two new methods to strengthen hollow core slabs with mounted steel bars and prestressed steel wire ropes (P-SWRs) and the results showed the prestressing technique and anchorages developed were able to be feasibly and easily used in prestressing the steel wire ropes. The efficiency of the P-SWRs to improve the cracking load was observed to be more than those recorded for the mounted steel bars due to the prestress in P-SWRs. Another experimental test was conducted by Haryanto, Satyarno, and Sulistyo (2012) on T-section RC beams strengthened in the negative moment region with bonded wire ropes and found an increment in the strengthened specimens' load capacity with a positive ratio up to 2.03. Furthermore, a finite element (FE) simulation conducted with an initial 20% prestress force on this strengthening technique produced a 52.15% flexural strength improvement. The relationship between the load and displacement observed in the FE simulation had the similar trend with those recorded in the experiment (Haryanto, Gan, and Maryoto 2017). Another approach involves adding steel rebars on the compression block with the use of steel wire ropes in the negative moment region to strengthen the T-section RC beams and this was observed to have increased the flexural strength with 2.09 ratio (Haryanto et al. 2019).

Haryanto et al. (2018) also studied the performance of two 6 mm diameter steel wire ropes used to externally strengthen RC beams with different end-anchor. The results showed the ratios of end-anchor type 1 to 2 tended toward 1 for all the parameters and this means they both equally contributed effectively to the steel wire rope performance. A closer examination of the open literature showed there is limited work on the SWR-strengthening of RC beams through external strengthening techniques. In order to bridge the knowledge gap and to continually expand the scope of the research conducted by Haryanto et al. (2018), this present study aimed to investigate the application of steel wire rope to strengthen RC beams using different numbers and diameters after which there was a comparison between the flexural capacity, ductility, stiffness, failure modes, and the energy absorbed by the control and strengthened beams. Moreover, a comparison between the values obtained for the ultimate load-carrying capacities from the experiment and the theoretical model was also examined.

2. Experimental program

2.1. *Specimen configurations*

Five simply-supported beams were constructed and tested at a length of 1000 mm and a rectangular cross-section with 100 mm width and 150 mm depth. All the specimens were cast using normal weight concrete and the average compressive strength was measured to be 25.27 MPa at 28 days. Moreover, two 6 mm diameter steel bars were placed at 29 mm and 121 mm from top of the beam in terms of both compression and tension, respectively, for reinforcement. In the shear span, the stirrups of 6 mm diameter steel bars spaced at 50 mm were fastened firmly together using the binding wire. The tested elastic modulus and yield strain of the reinforcement bars were 1.959×10^5 MPa and 0.0012, respectively. Furthermore, the tested yield and ultimate strengths were 236.74 and 369.40 MPa, respectively, while the concrete cover was determined to be 20 mm thick. A beam was left without strengthening and applied in this study as the control specimen while the remaining four were strengthened using external steel wire ropes.

Figure 1 and Table 1 demonstrate the diameter and number of steel wire ropes used as the test parameters. The specimen ID is designed to have the number of steel wire ropes as the first value while the diameter is the second. Specimen B0 was not strengthened in this study and used as the control beam for comparison. Meanwhile, two 6 mm diameter and four 8 mm diameter steel wire ropes were used to strengthen specimens B26 and B48, respectively. The tension reinforcement ratio (ρ) for all the specimens which was defined as the ratio between the area of tension reinforcement to the effective area of the section was found to be 0.467, 0.826, 1.192, 1.105, and 1.765%, respectively.

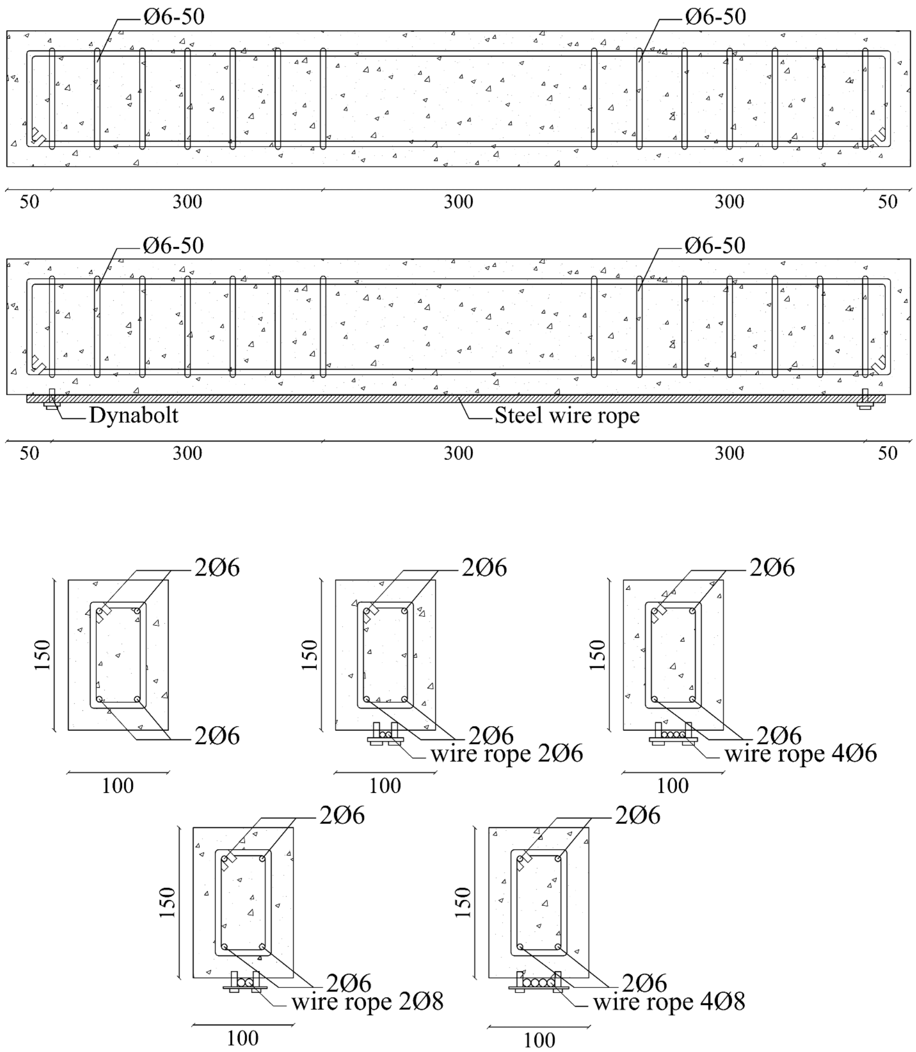

Figure 1. Details of specimens (Haryanto et al. 2018).

Table 1. Description of the tested beams.

Specimen	L (mm)	B (mm)	H (mm)	Longitudinal reinforcement Tension	Longitudinal reinforcement Compression	Stirrups	Steel wire rope	Location
B00	1000	100	150	2Ø6	2Ø6	Ø6-50	-	-
B26	1000	100	150	2Ø6	2Ø6	Ø6-50	2Ø6	external
B46	1000	100	150	2Ø6	2Ø6	Ø6-50	4Ø6	external
B28	1000	100	150	2Ø6	2Ø6	Ø6-50	2Ø8	external
B48	1000	100	150	2Ø6	2Ø6	Ø6-50	4Ø8	external

2.2. *Strengthening materials*

Steel wire ropes and end-anchor in the form of 6 mm diameter dynabolt with a shear resistance of 10.3 kN were used as the strengthening materials. They were used in combination with a 2 mm-thick steel plate sized 50 mm x 100 mm for single plate and 25 mm x 100 mm for double plate end-anchors as indicated in Figure 2. The tensile strength for the steel wire rope with 6 mm nominal diameter was recorded to be 599.48 MPa while 8 mm had 755.92 MPa. Each steel wire rope contained six typical helical strands which were placed over the central core containing smaller independent wire ropes (IWRC).

2.3. *Strengthening procedures*

The strengthening process as presented in Figure 3 started with the identification of the reinforcement location in the RC beam which needed to be strengthened using a rebar scanner. This was followed by the identification of the drilling points and no physical contact was made with the current reinforcement while the dynabolt mounting drilling was conducted after which the RC beam was drilled up to 6 cm deep. An air compressor was used to clean the drilling dust while a chemical bonding agent was applied to fill the cleaned holes. The end-anchor in the form of the steel plate and dynabolt was installed and the clamp and steel wire rope was completely mounted. In

Figure 2. The strengthening materials (Haryanto et al. 2018).

the end, the dynabolt was tightened at the top of the end-anchor.

2.4. *Loading program and instrumentations*

Figure 4 shows a four-point bending scheme that was used to test the specimens. Each beam specimen underwent similar testing and loading procedures. This involved the application of two monotonic-concentrated loads at the center of the midspan specimen using Universal Testing Machine (UTM). Moreover, the steel spreader was made of unused steel members to ensure strong rigidity while a dial gauge was placed under the beams at the midspan to monitor displacement and the crack patterns obtained by visual observation.

3. Results and discussion

This section thoroughly presents the observed and measured results for the load-carrying capacity, load versus mid-span deflection response curve, ductility, failure modes, stiffness, and energy absorption capacity. An analysis was also conducted to determine the theoretical ultimate load.

3.1. *Load-deflection curves and failure modes*

The failure deflection was considered in this research to be the first to occur between a 20% decrease in the peak load, and longitudinal reinforcement buckling or the longitudinal or transverse reinforcement fracture (Paulay 1989; Paulay and Priestley 1992). The yield deflection was explained to

Figure 3. Strengthening process involved the location of the current reinforcement to be determined through rebar scanner, drilling, dynabolt and steel plate installed as the end-anchor, steel wire rope installed and dynabolt tightened (Haryanto et al. 2018).

be deflection of the theoretical yield point of an equivalent elasto-plastic system with the secant stiffness being equal to its equivalent elastic stiffness such that the load is 75% before reaching the ultimate load. Figure 5 shows the curves produced by the tests for the load versus mid-span deflection response while Table 2 presents the testing outcomes for the ultimate load (P_u), mid-span displacement at the theoretical yielding of the flexural steel (δ_y), at ultimate load (δ_u), and the failure load (δ_f) for each specimen including the unstrengthenend beam (B0). Meanwhile, the failure mode for all specimens is shown in Figure 6.

In the unstrengthened beam (B0), the first crack occurred when the load reached 9.70 kN with a coressponding displacement of 1.82 mm. As the applied load increased, cracks in the specimen became wider and expanded toward the compressive zone, followed by the appearance of new spreading cracks. The displacement continues to increase with a relatively small increment up to when the load exceeded 0.75P_u or 13.26 kN, thereby, causing a crushing between the loading points as indicated in Figure 6(a). The control specimen was recorded to have experienced a pure flexural failure with 17.70 kN ultimate load and 13.26 mm corresponding deflection.

The specimen strengthened with two 6 mm diameter of steel wire ropes (B26) showed similar pattern for flexural cracking with the control specimen (B0) as indicated in Figure 6(b). The first crack was experienced at 19.80 kN with a corresponding displacement of 3.19 mm and after flexural reinforcement was theoretically yielded at 0.75P_u or 22.42 kN, a noise caused by the slipping of steel wire rope at the end-anchor was heard when the load value was approximately 27.00 kN (Figure 5). The external steel wire rope provided as the strengthening material was, however, still working. Moreover, an ultimate load-carrying capacity of 29.90 kN was also achieved with a corresponding mid-span deflection of 19.49 mm as shown in Figure 5 and the specimen B26 was able to yield 69% extra strength compared to the control specimen.

The crack load obtained for the beam strengthened with four 6 mm diameter steel wire ropes (B46) was 29.70 kN at a corresponding deflection of 5.24 mm. In addition, the ultimate load acquired was 55.90 kN which is equivalent to 216% improvement in the load-carrying capacity in comparison with the control beam (B0). Moreover, a deflection of 28.95 mm was recorded to have corresponded with the ultimate load as presented in Figure 5. The beam was also found to have a good performance as recorded with B26 despite the slip observed visually and auditorily to have occurred at the end-anchor at approximately 51.00 kN load value after the flexural reinforcement was theoretically yielded at 0.75P_u or 41.92 kN as shown in Figure 5. A similar pattern of flexural cracking was also observed with the control specimen (B0) as indicated in Figure 6(c).

There was a crack-applied load of 20.50 kN with a corresponding 2.68 mm mid-span deflection recorded at B28, for the beam strengthened with two 8 mm diameter steel wire ropes. This beam also displayed a similar pattern of flexural cracking with the control specimen (B0) as indicated in Figure 6(d). The external steel wire rope used was observed to have performed well like the B26 and B46 beams. Moreover, the specimen B28 experienced steel wire rope slip at the end-anchor as the noise of slipping could be heard again when the load value reached 33.00 kN after the flexural reinforcing theoretically yielded at 0.75P_u or 27.60 kN. Finally, this specimen achieved a strength gain of 108% over the control specimen shown by an ultimate applied load of 36.80 kN with a 16.91 mm corresponding mid-span deflection.

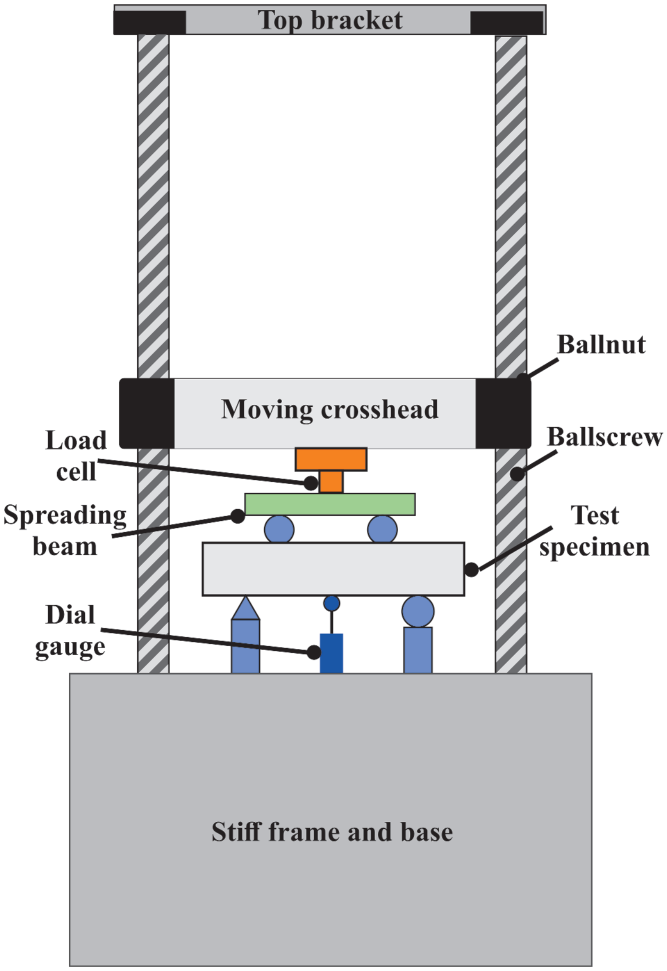

Figure 4. Test setup.

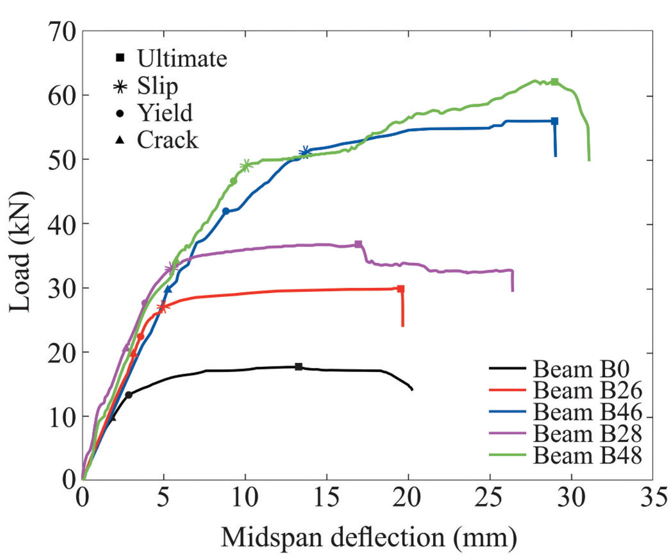

Figure 5. Load-midspan deflection curves of the tested beams.

The crack load obtained for the beam strengthened with four 8 mm diameter steel wire ropes (B48) was found to be 34.20 kN with the corresponding deflection recorded to be 5.75 mm. The ultimate load was 62.01 kN and this is equivalent

Table 2. Summary of ultimate loads and failure modes.

Specimen	P_u (kN)	P_u /$P_{u\text{-}B0}$	δ_y (mm)	δ_u (mm)	δ_f (mm)	Failure Modes
B0	17.70	-	3.73	13.26	20.25	Flexural failure
B26	29.90	1.69	4.76	19.49	19.64	Flexural failure and slip
B46	55.90	3.16	11.73	28.95	29.02	Flexural failure and slip
B28	36.80	2.08	5.14	16.91	26.40	Flexural failure and slip
B48	62.01	3.50	12.37	28.82	31.07	Flexural failure and slip

to a 250% increase in the load-carrying capacity relative to the control beam (B0) while the corresponding deflection was 28.82 mm as presented in Figure 5. The strengthening system for the specimen also showed a good performance despite the slip observed visually and auditorily with the steel wire rope at the end-anchor when the load was approximately equal to 49.00 kN and after the flexural reinforcement was theoretically yielded at $0.75P_u$ or 46.58 kN as shown in Figure 5. The specimen B48 also had a similar pattern for the flexural cracking with the control specimen (B0) as presented in Figure 6(e).

3.2. *Ductility index and stiffness*

The ability of a structure, section, or material to withstands inelastic deformation before collapse without losing its strength or resistance to a great extent is known as ductility. This structural characteristic is quite favorable because it provides failure warnings in the form of an increase in deflection and redistribution of stress. A variety of RC design methods require reinforcement members have the ability to deform gradually on the plastic level. It is possible for the energy to be dissipated when subjected to cyclic or seismic loading and for sudden local impact accidental loading to be withstood rather than causing collapse through the concept of robustness with the help of ductility (Morais and Burgoyne 2001). The relationship between steel wire ropes and the ductility of the specimen was determined by computing the ductility index at the failure load using $I_f = \delta_f/\delta_y$ with the reference standard for each computed ductility index being the mid-span yield deflection (δ_y).

The possibility of resisting displacement/load using stiffness was observed in RC structures (Obaydullah et al. 2016). The displacement, cracking, and other properties such as serviceability of RC structures is attributed to their stiffness. The strengthening reinforcements, cracks, and applied load determine the specimens' stiffness (Hosen et al. 2018). The ratio of applied ultimate load to yield deflection ($K = P_u/\delta_y$) represents stiffness for this research and its results with the ductility index are presented in Table 3. Furthermore, the ratio of the strengthened specimens to the control (B0) for the ductility index ($I_f/I_{f\text{-B0}}$) and stiffness ($K/K_{\text{-B0}}$) are also presented.

The result showed the ductility index at the failure load of the strengthened RC beams were less than that of the control beam by 5–54%. As previously reported by Rasheed et al. (2010), increasing the amount of tension reinforcement ratio of a beam decreases its ductile behavior and

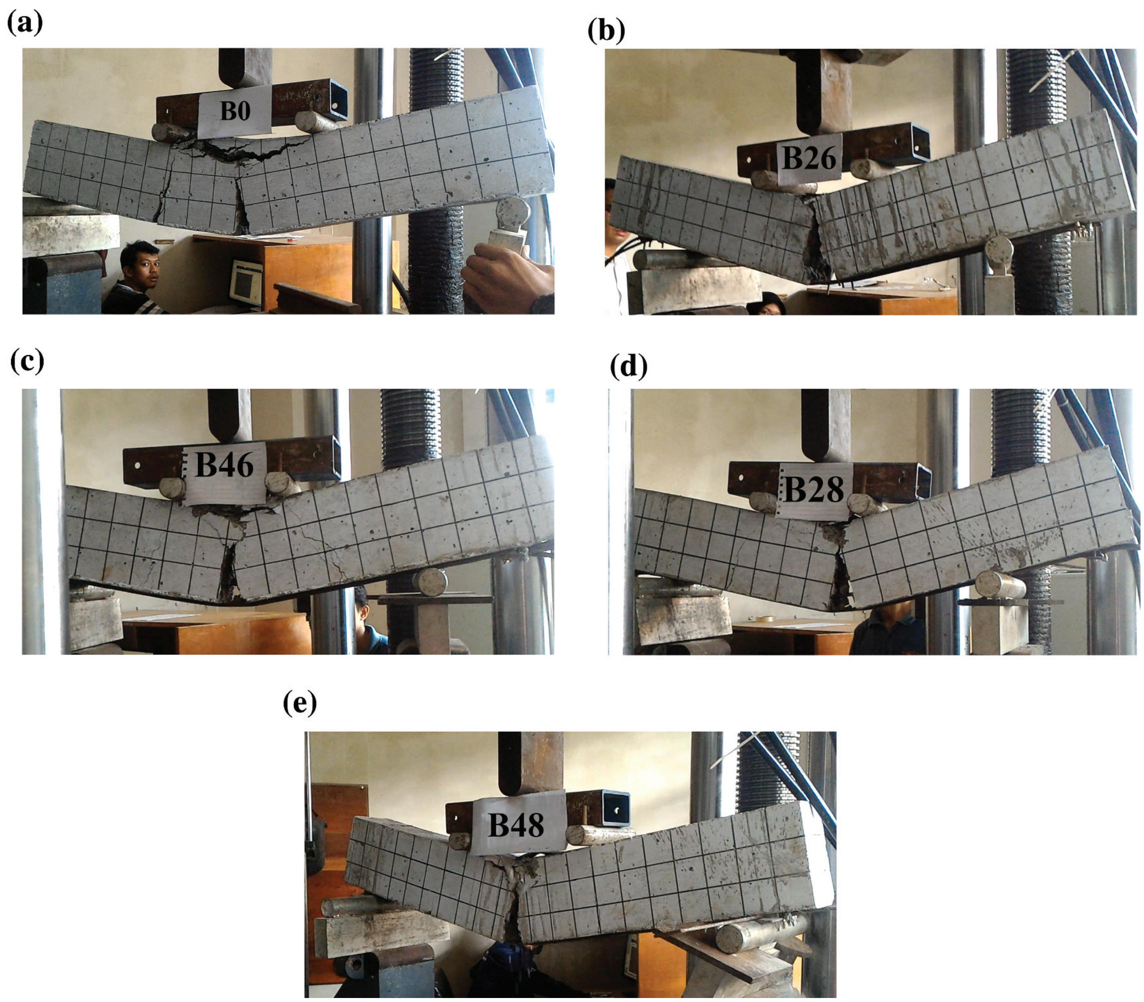

Figure 6. The failure mode of all tested specimens (a) Failure of B0; (b) Failure of B26; (c) Failure of B24; (d) Failure of B28; (e) Failure of B48.

Table 3. Ductility index and stiffness.

Specimen	$I_f = \delta_f/\delta_y$	$I_f/I_{f\text{-}B0}$	$K = P_u/\delta_y$ (N/mm)	K/K_{-B0}
B0	5.43	1	4745.31	1
B26	4.13	0.76	6281.51	1.32
B46	2.47	0.46	4765.56	1.01
B28	5.15	0.95	7159.53	1.51
B48	2.51	0.46	5012.93	1.06

this was supported by several other researchers with different types of strengthening materials and techniques (Qeshta, Shafigh, and Jumaat 2016; Ebead and El-Sherif 2019). It is, however, important to note that the ductility index at failure load for B26 and B28, was higher than for B46 and B48. Moreover, upon ultimate point, steel wire rope exhibits almost no ductility resulting in brittle failure modes where the structural member falls back on the residual strength steel reinforcement.

In comparison to the control specimen, a higher stiffness was observed for the beams strengthened with two steel wire ropes (B26 and B28) with an increase of 32% and 51%, respectively. The stiffness of normal unstrengthened beams is affected by internal steel reinforcement as it controls how much the cracks grow (Obaydullah et al. 2016). This means the strengthened beams are stiffer as they show extra resistance to crack initiation and propagation due to the presence of the strengthening material (Qeshta, Shafigh, and Jumaat 2016). Nevertheless, the end-anchor experiencing more steel wire rope slip resulted in the strengthened beams of four steel wire ropes (B46 and B48) having the stiffness approximately similar with unstrengthened beam, showed by an increase of only 1% and 6%, respectively.

3.3. *Energy absorption*

It is impossible to evaluate the general structural component in terms of fracture work without considering energy absorption (Qeshta et al. 2014). The energy absorption capacity, also known as toughness, was calculated as the area under the load-deflection curve (Ghosni, Samali, and Vessalas 2013; Topcu and Unverdi 2018) and the results are shown in Figure 7. All the strengthened specimens showed a higher energy absorption level than the control specimen. In this study, the performance of steel wire rope as external strengthening resulted in an increase of the energy absorption over the control beam by 62.26, 307.10, 169.35, and

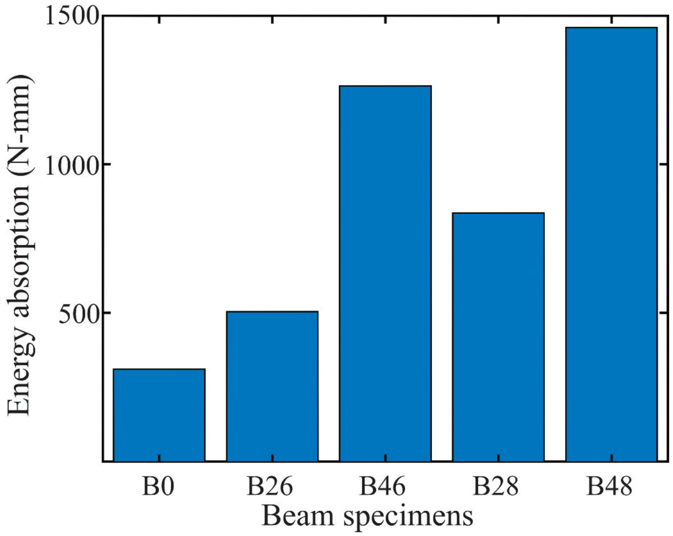

Figure 7. Energy absorption of externally steel wire rope-strengthened specimens.

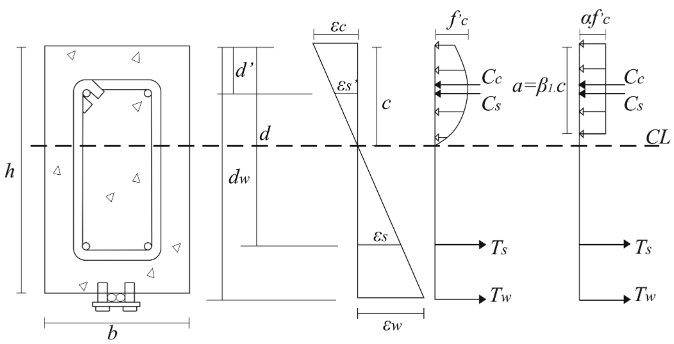

Figure 8. Theoretical model at the ultimate stage.

370.32%, respectively for B26, B46, B28, and B48. Each of the strengthened beams had an increased energy absorption due to the delayed crack formation as well as an increase in stiffness, yield, and ultimate load.

3.4. Theoretical calculation

There was a comparison between the values obtained for the ultimate load-carrying capacities, P_u, from the experiment and the theoretical model presented in ACI Committee 318 (2014) as shown in Figure 8. Several assumptions were made for the analysis and they include:

•The plane sections are still plane after they are loaded.

•The steel reinforcement and concrete substrate have a perfect bond between them.

•The concrete's ultimate compressive strain is 0.003.

•It is assumed that the steel reinforcement has an elastic-perfectly plastic behavior.

•The steel wire rope follows a linear behavior.

Effective concrete strain (ε_c), steel reinforcement strains (ε_s and ε_s'), and steel wire rope strain (ε_w) were calculated using Equation (1) in accordance with strain compatibility:

$$\frac{\varepsilon_w}{d_w - c} = \frac{\varepsilon_s}{d - c} = \frac{\varepsilon_s'}{c - d'} = \frac{\varepsilon_c}{c}, \tag{1}$$

where d is distance between the beam's top and the main steel reinforcement, d' is distance between the beam's top and the top steel reinforcement, d_w is distance between the beam's top and the steel wire rope reinforcement center while c is the depth of the neutral axis from the top.

The equilibrium of the internal forces was satisfied as provided by Equations (2) through (5):

$$T_s + T_w = C, \tag{2}$$

$$T_s = A_s f_y - A_s' E_s \varepsilon_s', \tag{3}$$

$$T_w = A_w E_w \varepsilon_w, \tag{4}$$

$$C = \alpha_1 f_c' \beta_1 cb, \tag{5}$$

where T_s is steel reinforcement tension force, T_w is steel wire rope reinforcement tension force, C is compression force in the concrete, A_s is cross-sectional area of main steel reinforcement, A_s' is cross-sectional area of top steel reinforcement, A_w is cross-sectional area of steel wire rope reinforcement, ε_s' is strain in top steel reinforcement, ε_w is strain in steel wire rope reinforcement, and E_w is elastic modulus of steel wire rope reinforcement. The stress block parameters α_1 and β_1 equal to 0.85 in accordance with ACI (2014).

The nominal flexural moment M_n of the beam was calculated according to Equations (6) through (8):

$$M_n = M_s + M_w, \tag{6}$$

$$M_s = A_s f_y \left(d - \frac{\beta_1 c}{2} \right) + A_s' E_s \varepsilon_s' (d - d'), \tag{7}$$

$$M_w = T_w \left(d_w - \frac{\beta_1 c}{2} \right), \tag{8}$$

where M_s is moment contribution of steel reinforcement, and M_w is moment contribution of steel wire rope reinforcement. The theoretical ultimate load-carrying capacity P_{u-th} was calculated using Equation (9):

$$P_{u-th} = \frac{2M_n}{l}, \tag{9}$$

where l is shear span of the loaded beam (300 mm).

A reasonable agreement between theoretical and experimental load-carrying capacity results has been obtained in most of the specimens with the theoretical values being relatively over-predicted as indicated in Table 4. On the average, the ultimate load-carrying

Table 4. Predicted load-carrying capacity.

Specimen	M_n (kN.mm)	$P_{u\text{-}th}$ (kN)	P_u (kN)	$P_{u\text{-}th}/P_u$
B0	1840.50	12.27	17.70	0.69
B26	4855.50	32.37	29.90	1.08
B46	7539.00	50.26	55.90	0.90
B28	6955.50	46.37	36.80	1.26
B48	10,821.00	72.14	62.01	1.16

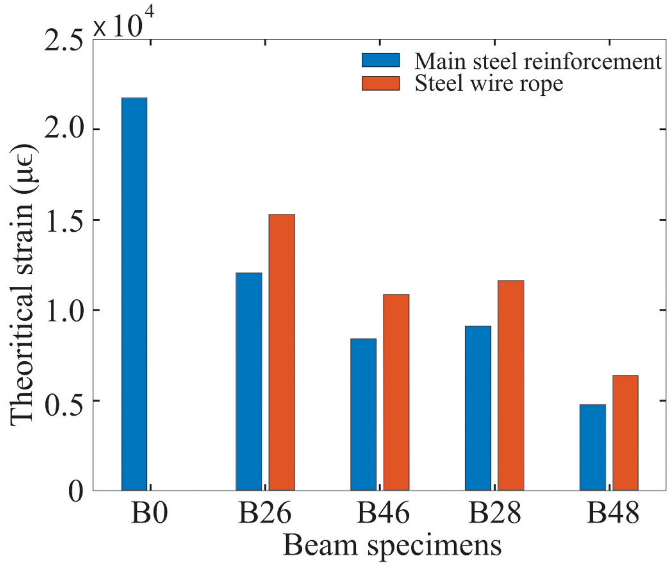

Figure 9. Theoretical strain values.

capacity predicted for the strengthened beams was approximately 10% higher and those strengthened with 6 mm steel wire rope including B26 and B46 had the closest *P* value to the theoretical capacity while those strengthened with 8 mm such as B28 and B48 varied the most compared owing to the fact that there is steel wire rope slip occurrence.

Figure 9 presents the theoretical tensile strain in the bottom main steel reinforcements and steel wire ropes of the beam specimens at the ultimate stage. The strengthened beams' tensile strains are shown in the figure to have significantly decreased in comparison with the control beam at the ultimate stage mainly because of the increase in the stiffness. Moreover, the higher amounts of strengthening material in the section produced a greater tension reinforcement ratio (ρ) which caused improved stiffness and, consequently, more reduction in tensile strain. All the specimens generally have a tension-controlled section as the tensile strains in the bottom main steel reinforcements are greater than or equal to 5000 $\mu\varepsilon$ (ACI 2002; Orozco 2015). However, the strengthened beam with the highest (ρ) value, beam B48, showed a transition region between compression-controlled and tension-controlled section due to the fact that the strain in the bottom main steel reinforcements was 4780 $\mu\varepsilon$.

4. Conclusion

The flexural performance of the RC beams strengthened with external steel wire rope was investigated through experimental tests and the results of the four specimens used were compared with a control specimen. The findings, therefore, showed:

1)The ultimate load-carrying capacity of the strengthened beam through external steel wire rope was enhanced up to 250% and this means the material is efficient for the flexural strengthening of RC beams.

2)The control beam failed in flexure by concrete crushing at the top fiber which was the expected failure mode. Even though exhibiting the same flexural cracking pattern as the control beam, the occurrence of steel wire rope slip at the end anchor was observed in the strengthened beams.

3)The ductility index of the strengthened beams were less than that of the control beam by up to 54%. It should be noted that the ductility index of the beams strengthened with two steel wire ropes (B26 and B28) is higher than that with four steel wire ropes (B46 and B48).

4)A higher stiffness was also observed with B26 and B28 with an increase of 32 and 51%, respectively, compared to the control specimen. Nevertheless, the more slip experienced by the steel wire ropes in B46 and B48 led to its approximately similar stiffness with unstrengthened beam, showed by an increase of only 1 and 6%, respectively.

5)The strengthened beams had a better ability to absorb energy up to 370.32% than the control beam. The energy absorption capacity was observed to have improved as the crack formation was delayed, stiffness increased, and yield and ultimate load greatly enhanced.

6)The ACI Committee 318 (2014) procedure used to evaluate the ultimate load show an average of 10% higher prediction for strengthened beams.

7)Based on the theoretical strain values, the strengthened beam with the highest (ρ) value, beam B48, shows a transition region between compression-controlled and tension-controlled section while other beams have tension-controlled section. The true strain values need to be further studied in future work.

8)The results of this study imply that the RC beams strengthened with external steel wire rope are capable of fulfilling the flexural performance required for reinforced concrete structures.

Acknowledgments

The authors would like to recognize the main sponsor of this research, the Jenderal Soedirman University, Indonesia. Their support (contract number 3747/UN23.14/PN/2018) is gratefully acknowledged.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Jenderal Soedirman University [3747/UN23.14/PN/2018].

Nomenclature

AFRP	cross-sectional area of steel wire rope reinforcement
A_s	cross-sectional area of main steel reinforcement
A'_s	cross-sectional area of top steel reinforcement
BFRP	balast fiber-reinforced polymer
b	the width of the beam
c	the depth of the neutral axis from the top
C	compression force in the concrete
CFRP	carbon fiber-reinforced polymer
d	distance between the beam's top and the main steel reinforcement
d'	distance between the beam's top and the top steel reinforcement
d_w	distance between the beam's top and the steel wire rope reinforcement center
E_w	elastic modulus of steel wire rope
T_s	steel reinforcement tension force
FE	finite element
FRP	fiber-reinforced polymer
GFRP	glass fiber-reinforced polymer
h	the depth of the beam
I_f	the ductility index at the failure load
IWRC	independent wire rope core
l	shear span of the loaded beam
K	stiffness
L	the length of the beam
M_n	the nominal flexural moment
P-SWR	prestressed high-strength steel wire rope
P_u	ultimate load
RC	reinforced concrete
SWR	steel wire rope
T_w	steel wire rope reinforcement tension force
URM	unreinforced masonry
UTM	universal testing machine
α_1 and β_1	the stress block parameters
ε_c	effective concrete strain
ε_s and ε'_s	steel reinforcement strains
ε_w	steel wire rope strain
δ_f	mid-span displacement at the failure load
δ_u	mid-span displacement at the ultimate load
δ_y	mid-span displacement at the theoretical yielding of the flexural steel
ρ	the tension reinforcement ratio

References

ACI Committee 318. 2002. *Building Code Requirements for Structural Concrete and Commentary (ACI 318-02)*. Farmington Hills: American Concrete Institute.

ACI Committee 318. 2014. *Building Code Requirements for Structural Concrete and Commentary (ACI 318-14)*. Farmington Hills: American Concrete Institute.

Al-Mahaidi, R., and R. Kalfat. 2018. *Rehabilitation of Concrete Structures with Fiber-Reinforced Polymer*. Oxford, UK: Butterworth-Heinemann.

Choobbor, S. S., R. A. Hawileh, A. Abu-Obeidah, and J. A. Abdalla. 2019. "Performance of Hybrid Carbon and Basalt FRP Sheets in Strengthening Concrete Beams in Felxure." *Composite Structures* 227: 111337. doi:10.1016/j.compstruct.2019.111337.

Ebead, U., and H. El-Sherif. 2019. "Near Surface Embedded-FRCM for Fexural Strengthening of Reinforced Concrete Beams." *Construction and Building Materials* 204: 166–176. doi:10.1016/j.conbuildmat.2019.01.145.

Fayed, S., A. Basha, and A. Hamoda. 2019. "Shear Strengthening of RC Beams Using Aluminum Plates: An Experimental Work." *Construction and Building Materials* 221: 122–138. doi:10.1016/j.conbuildmat.2019.06.068.

Firmo, J. P., J. R. Correia, and L. A. Bisby. 2015. "Fire Behaviour of FRP-Strengthened Reinforced Concrete Structural Elements: A State-of-the-Art Review." *Composites Part B: Engineering* 80: 198–216. doi:10.1016/j.compositesb.2015.05.045.

Fontanari, V., M. Benedetti, D. B. Monelli, and F. Degasperi. 2015. "Fire Behavior of Steel Wire Ropes: Experimental Investigation and Numerical Analysis." *Engineering Structures* 84: 340–349. doi:10.1016/j.engstruct.2014.12.004.

Ghosni, N., B. Samali, and K. Vessalas. 2013. "Energy Absorption and Flexural Toughness Evaluation of Fibre Reinforced Polymer Modified Concrete." *Proceeding of VIII International Conference on Fracture Mechanics of Concrete and Concrete Structures (FraMCoS-8)*, Toledo, Spain, 11–14 March 2013:1–9. Spain: International Center for Numerical Methods in Engineering.

Gudonis, E., E. Timinskas, V. Gribniak, G. Kaklauskas, A. K. Arnautov, and V. Tamulenas. 2013. "FRP Reinforcement for Concrete Structures: State-of-the-Art Review of Application and Design." *Engineering Structures and Technologies* 5 (4): 147–158. doi:10.3846/2029882X.2014.889274.

Haryanto, Y., B. S. Gan, and A. Maryoto. 2017. "Wire Rope Flexural Bonded Strengthening System on RC-Beams: A Finite Element Simulation." *International Journal of Technology* 8 (1): 134–144. doi:10.14716/ijtech.v8i1.2734.

Haryanto, Y., B. S. Gan, A. Widyaningrum, and A. Maryoto. 2017. "Near Surface Mounted Bamboo Reinforcement for Flexural Strengthening of Reinforced Concrete Beams." *Jurnal Teknologi (Sciences & Engineering)* 79 (6): 233–240. doi:10.11113/jt.v79.10767.

Haryanto, Y., B. S. Gan, A. Widyaningrum, N. G. Wariyatno, and A. Fadli. 2018. "On the Performance of Steel Wire Rope as the External Strengthening of RC Beams with Different End-Anchor Type." *Jurnal Teknologi (Sciences & Engineering)* 80 (5): 145–154. doi:10.11113/jt.v80.11588.

Haryanto, Y., H.-T. Hu, A. L. Han, A. T. Atmajayanti, D. L. C. Galuh, and B. A. Hidayat. 2019. "Finite Element Analysis of T-Section RC Beams Strengthened by Wire Rope in the Negative Moment Region with an Addition of Steel Rebar at the Compression Block." *Jurnal Teknologi (Sciences & Engineering)* 81 (4): 143–154. doi:10.14716/ijtech.v8i1.2734.

Haryanto, Y., I. Satyarno, and D. Sulistyo. 2012. "Strength and Ductility of Reinforced Concrete T-Beams Strengthened in the Negative Moment Region with Wire Rope and Mortar Composite." *Journal of the Civil Engineering Forum* 21 (1): 1163–1169. doi:10.22146/jcef.18938.

Hidayat, B. A., H.-T. Hu, A. L. Han, Y. Haryanto, A. Widianingrum, and G. Pamudji. 2019. "Nonlinear Finite Element Analysis of Traditional Flexural Strengthening Using Betung Bamboo (Dendrocalamus Asper) on Concrete Beams." *IOP Conference Series: Materials Science and Engineering* 615: 012073. doi:10.1088/1757-899X/615/1/012073.

Hosen, M. A., M. Z. Jumaat, U. J. Alengaram, and N. H. R. Sulong. 2018. "CFRP Strips for Enhancing Flexural Performance of RC Beams by SNSM Strengthening Technique." *Construction and Building Materials* 165: 28–44. doi:10.1016/j.conbuildmat.2017.12.052.

Hosen, M. A., M. Z. Jumaat, K. M. U. Darain, M. Obaydullah, and A. B. M. S. Islam. 2014. "Flexural Strengthening of RC Beams with NSM Steel Bars." *Proceeding of International Conference on Food, Agriculture and Biology (FAB-2014),* Kuala Lumpur, Malaysia, 11–12 June 2014:8–13. Malayisa: International Institute of Chemical, Biological & Environmental Engineering.

Hu, H.-T., W.-P. Lin, and F.-T. Tu. 2015. "Failure Analysis of Fiber-Reinforced Composite Laminates Subjected to Biaxial Loads." *Composites Part B: Engineering* 83: 153–165. doi:10.1016/j.compositesb.2015.08.045.

Lesmana, C., and H.-T. Hu. 2014. "Parametric Analyses of Square Reinforced Concrete Slabs Strengthened by Fiber-Reinforced Plastics." *Construction and Building Materials* 53: 294–304. doi:10.1016/j.conbuildmat.2013.11.083.

Lesmana, C., H.-T. Hu, F.-M. Lin, and N.-M. Huang. 2013. "Numerical Analysis of Square Reinforced Concrete Plates Strengthened by Fiber-Reinforced Plastics with Various Patterns." *Composites Part B: Engineering* 55: 247–262. doi:10.1016/j.compositesb.2013.06.021.

Li, X., G. Wu, M. S. Popal, and J. Jiang. 2018. "Experimental and Numerical Study of Hollow Core Slabs Strengthened with Mounted Steel Bars and Prestressed Steel Wire Ropes." *Construction and Building Materials* 188: 456–469. doi:10.1016/j.conbuildmat.2018.08.073.

Ministry of Housing and Urban-Rural Development of China. 2014. *Technical Specification for Strengthening Concrete Structures with Prestressed High Strength Steel Wire Ropes.* [In Chinese.] JGJ/T 325-2014.

Beijing: General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

Morais, M., and C. Burgoyne. 2001. "Energy Dissipation in Sections Prestressed with FRP Tendons." *The International Conference on Composites in Construction (CCC 2001),* Porto, Portugal, 10–12 2001: 421–426. Exton, PA: Lisse.

Nahar, T. T., and M. M. Rahman. 2015. "Strengthening of RCC Beams Using Bamboo Sticks." *International Journal of Advanced Science and Technology* 79: 15–24. doi:10.14257/ijast.2015.79.02.

Obaydullah, M., M. Z. Jumaat, U. J. Alengaram, K. M. U. Darain, M. N. Huda, and M. A. Hosen. 2016. "Prestressing of NSM Steel Strands to Enhance the Structural Performance of Prestressed Concrete Beams." *Construction and Building Materials* 129: 289–301. doi:10.1016/j.conbuildmat.2016.10.077.

Orozco, C. E. 2015. "Strain Limits Vs. Reinforcement Ratio Limits – A Collection of New and Old Formulas for the Design of Reinforced Concrete Sections." *Case Studies in Structural Engineering* 4: 1–13. doi:10.1016/j.csse.2015.05.001.

Paulay, T. 1989. "Equilibrium Criteria for Reinforced Concrete Beam-Column Joints." *ACI Structural Journal* 86 (6): 635–643. doi:10.14359/2649.

Paulay, T., and M. J. N. Priestley. 1992. *Seismic Design of Reinforced Concrete and Masonry Buildings*. New Jersey: Wiley Interscience.

Peansupap, V., and R. Ly. 2015. "Evaluating the Impact Level of Design Errors in Structural and Other Building Components in Building Construction Projects in Cambodia." *Procedia Engineering* 123: 278–370. doi:10.1016/j.proeng.2015.10.049.

Peled, A. 2007. "Confinement of Damaged and Non-Damaged Structural Concrete with FRP and TRC Sleeves." *Journal of Composites for Construction* 11 (5): 514–522. doi:10.1061/(ASCE)1090-0268(2007)11:5(514).

Qeshta, I. M. I., P. Shafigh, and M. Z. Jumaat. 2016. "Research Progress on the Flexural Behaviour of Externally Bonded RC Beams." *Archives of Civil and Mechanical Engineering* 16 (4): 982–1003. doi:10.1016/j.acme.2016.07.002.

Qeshta, I. M. I., P. Shafigh, M. Z. Jumaat, A. I. Abdulla, Z. Ibrahim, and U. J. Alengaram. 2014. "The Use of Wire Mesh-Epoxy Composite for Enhancing the Flexural Performance of Concrete Beams." *Materials & Design* 60: 250–259. doi:10.1016/j.matdes.2014.03.075.

Rasheed, H. A., R. R. Harrison, R. J. Peterman, and T. Alkhrdaji. 2010. "Ductile Strengthening Using Externally Bonded and near Surface Mounted Composite Systems." *Composite Structures* 92 (10): 2379–2390. doi:10.1016/j.compstruct.2010.03.009.

Sen, T., and H. N. J. Reddy. 2011. "A Numerical Study of Strengthening of RCC Beam Using Natural Bamboo Fibre." *International Journal of Computer Theory and Engineering* 3 (5): 707–713. doi:10.7763/IJCTE.2011.V3.396.

Siddika, A., M. A. Al Mamun, R. Alyousef, and Y. H. M. Amran. 2019. "Strengthening of Reinforced Concrete Beams by Using Fiber-Reinforced Polymer Composites: A Review." *Journal of Building Engineering* 25: 100798-1-100798-12. doi:10.1016/j.jobe.2019.100798.

Szabó, Z. K., and G. L. Balázs. 2007. "Near Surface Mounted FRP Reinforcement for Strengthening of Concrete Structures." *Periodica Polytechnica Civil Engineering* 51 (1): 33–38. doi:10.3311/pp.ci.2007-1.05.

Topçu, İ. B., and A. Unverdi. 2018. "Scrap Tires/Crumb Rubber." In *Waste and Supplementary Cementitious Materials in Concrete*, edited by R. Siddique and P. Cachim, 51–77. Amsterdam: Elsevier.

Tudjono, S., H. A. Lie, and B. A. Hidayat. 2015. "An Experimental Study to the Influence of Fiber Reinforced Polymer (FRP) Confinement on Beams Subjected to Bending and Shear." *Procedia Engineering* 125: 1070–1075. doi:10.1016/j.proeng.2015.11.164.

Wei, Y., and Y.-F. Wu. 2014. "Compression Behavior of Concrete Columns Confined by High Strength Steel Wire." *Construction and Building Materials* 54: 443–453. doi:10.1016/j.conbuildmat.2013.12.083.

Wu, G., Z. S. Wu, J. B. Jiang, Y. Tian, and M. Zhang. 2014. "Experimental Study of RC Beams Strengthened with Distributed Prestressed High-Strength Steel Wire Rope." *Magazine of Concrete Research* 62 (4): 253–265. doi:10.1680/macr.2010.62.4.253.

Xu, Q., X. Chen, J.-F. Chen, K. A. Harries, L. Chen, and Z. Wang. 2019. "Seismic Strengthening of Masonry Walls Using Bamboo Components." *Advances in Structural Engineering* 22 (14): 2982–2997. doi:10.1177/1369433219855902.

Yang, K.-H., H.-Y. Byun, and A. F. Ashour. 2009. "Shear Strengthening of Continuous Reinforced Concrete T-Beams Using Wire Rope Units." *Engineering Structures* 31 (5): 1154–1165. doi:10.1016/j.engstruct.2009.01.003.

Yang, K.-H., D.-B. Joo, J.-I. Sim, and J.-H. Kang. 2012. "In-Plane Seismic Performance of Unreinforced Masonry Walls Strengthened with Unbonded Prestressed Wire Rope Units." *Engineering Structures* 45: 449–459. doi:10.1016/j.engstruct.2012.06.017.

Zhang, H. Y., J. Yan, V. Kodur, and L. Cao. 2019. "Mechanical Behavior of Concrete Beams Shear Strengthened with Textile Reinforced Geopolymer Mortar." *Engineering Structures* 196: 109348–1–109348–11. 109348-1-109348-11. doi:10.1016/j.engstruct.2019.109348.