State-of-the-art Review on Strengthening Elements of Steel Bridges using CFRP

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Abstract: In the last few decades, the use of carbon fibre reinforced polymer (CFRP) for strengthening structures has attracted structural engineers due to its superior properties, such as its high strength-to-weight ratio, corrosion resistance and ease of installation. Retrofitting of deteriorated structures is required to sustain new applied loads or to enhance degraded elements. Previous studies focused on the investigation of bond behaviour between CFRP and steel members under static and fatigue loadings. However, there is a lack of understanding of strengthening of steel members subjected to static and dynamic loads using CFRP. This paper presents a review of previous research on the behaviour of steel members strengthened with CFRP and subjected to static and dynamic loadings. Topics covered by the state-of-the-art review include torsional, axial, flexural and impact loadings. In addition, a range of parameters is included for each loading case, such as different cross-sections, load speeds and types of composite material.

Keywords: Steel structures, Strengthening, CFRP, Composite materials, Impact load.

1. Introduction

The application of carbon fibre reinforced polymers (CFRP) has emerged as a modern technique in retrofitting steel structures in place of conventional materials and methods. Deterioration of ageing steel bridges is a worldwide problem due to increased loading requirements, increased traffic loads or reduced functionality resulting from ageing and corrosion [1-3]. According to recent surveys, more than 25% of steel bridges in US are deficient and obsolete in terms of monitoring., and steel bridges make up around 50% of these degraded bridges [4],[5]. Therefore, many studies on strengthening steel elements have been carried out to prevent the collapse of steel structures. Structural repair has emerged as a promising solution instead of replacing damaged members, and low construction costs and minimal obstruction of traffic are the main advantages [6]. Globally, repairing existing steel girders by welding or bolting steel plate is a common method, although this method has drawbacks that cannot be avoided, such as increased permanent loads, the use of heavy equipment, and changes in the mechanical properties of the repaired zone [7]. Rehabilitation of deteriorated structures using CFRP has a wide range of advantages, including reduced long-term maintenance costs, high strength-to-weight ratios, good durable performance, and fatigue resistance [8]. Continuous fibres and a polymeric resin are the main components of fibre reinforced polymer (FRP). The most common fibres are carbon, glass, and aramid and the industrial resins are epoxy, polyester and vinyl ester. Recently, studies have demonstrated that CFRP is the best type of FRP for use in the rehabilitation of structural elements by increasing the strength and stiffness of the whole structure[9]. However, there is a lack of research on the behaviour of whole structures strengthened by CFRP subjected to various load types, and, limited reviews have been conducted on this. This paper reviews successful methods of strengthening steel structures that are the main parts of steel bridges under a wide variety of load conditions, both static and dynamic.

2. Bridge collision

Bridge collisions including vehicles hitting the side of the bridges or car collisions on the bridges is one of the sever impact loadings on the structural bridge elements. Designing all bridge elements to overcome worst- collision load case is not feasible for the long term, due to the daily increase of lading requirements (Figure 1) [10-12]. However, overloading of existing bridge can be estimated based on new working conditions that require increasing durability of these bridges. CFRP has been used widely in different aspects for the superior properties compared to steel and GFRP[9],[13]. Figure 2 shows stress-strain response of different type of CFRP compared to mild steel[13]. CFRP can be the effective approach to enhance the critical areas of bridges or to strengthen the deteriorated element of bridges to withstand overloading.

(a) (b) (c)

Figure 1. (a) A car collision with barrier; (b) Dump truck collision with the Burlington Skyway; (c) A cargo ship struck and destroyed a Kentucky bridge span [10-12].

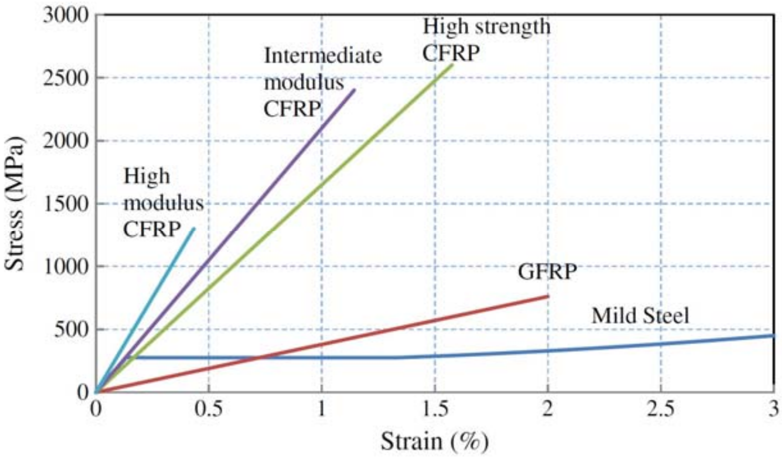


Figure 2. Stress-strain curves of CFRPs, GFRP and mild steel [9].

3. Bond characteristic between FRP and steel members

Generally, CFRP is bonded to steel elements by adhesive and the adhesive layer transfers the load uniformly to from the structural element to CFRP. Therefore, the use of suitable adhesives with a proper surface preparation play significant roles in providing a successful composite action. Many studies have investigated the bond characteristics of different types of adhesives under various circumstances and loads. Tensile tests of joints at different pulling speeds are the main approach in determining the bond properties between CFRP and steel elements. Jiao et al. [14] found that the bond strength of CFRP/steel joints under axial tensile load is higher when utilising Araldite 420 compared to other types of adhesives such as Sikadur-330 and Araldite1 Kit K138. Al-Mosawe et al. [15] showed that the selection of appropriate CFRP sections is very important to evaluate the characteristics of the bond between CFRP and steel. In addition, the bond properties between CFRP and steel are significantly influenced by ultra-high CFRP modulus with low tensile strength. Furthermore, the same authors found that joints bonded by Araldite 420 epoxy and tested under high loading rates demonstrate a significant increase in the load-carrying capacity compared to those tested under quasi-static loading[16]. Al-Mosawe et al. [17] also conducted experimental and numerical studies on ultra-high modulus CFRP steel composite under dynamic load. The results showed a significant decrease in the effective bond length, an insignificant increase in the ultimate strain values, and an increase in ultimate joint capacity.

4. Static load

4.1 Axial loading

Axial compressive or tensile loadings are effective approaches in determining the performance of CFRP steel beams. A number of researchers have investigated buckling behaviour along the longitudinal axes of specimens under compression tests, and found that buckling occurs if the length-to-width ratio is larger than a critical value. Bambach et al. [18] conducted experimental tests to investigate the influence of CFRP sheet on strengthening a steel square hollow section (SHS) under axial compression load. Spot-welding with wall thicknesses ranging from 1.6mm to 2mm was used to fabricate the specimens of SHS.

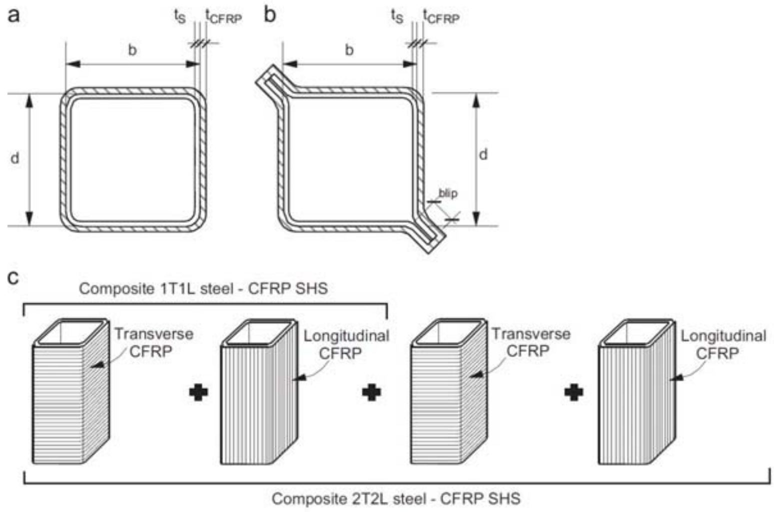


Figure 3. Specimens with CFRP strengthening; (a) SHS (commercially produced); (b) SHS (spot-welded); (c) Preparation method for bonded specimens [18].

Araldite 420 resin was applied to bond high-strength CFRP (MBraceCF-130) with the exterior surface of the SHS member. The specimens were designed with two different layouts (see **Error! Reference source not found.**).The first fibre layout was designed using two layers each 0.176mm thick, one laid perpendicular to the direction of axial load and around the SHS whereas the second layer was attached in the direction of applied load. In the second case, two layers laid longitudinally with two layers laid transversely were tested. The composite models were examined under pure axial compression load quasi-statically (0.2mm/min). The CFRP restrained the elastic buckling defections, which led to delayed local buckling up to 4 times compared to the reference specimen.

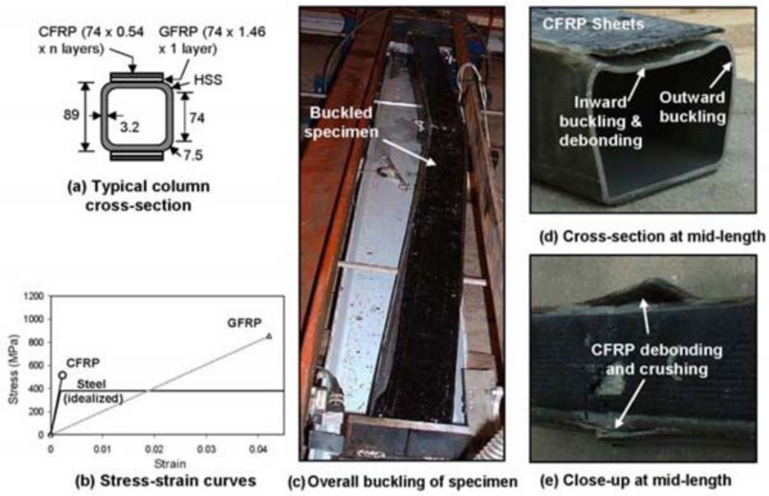


Figure 4. (a) Cross-section of specimen; (b) Stress strain curves of materials; (c) Test setup; (d) and (e)Failure modes [19].

Similarly, a study of the structural behaviour of short and long hollow steel columns strengthened with CFRP sheets under axial loading was carried out by Shaat et al. [19] . The major parameter was the orientation of CFRP sheet for short columns, two orientations were used the transverse and longitudinal directions. For long columns, the longitudinal direction of CFRP layers was used only (Figure 4). This study showed that the ultimate strength was increase by 18% for short columns when two CFRP layers wrapped transversely, while it was 23% for long columns wrapped with three CFRP layers laid in the longitudinal direction. As a result, the lateral deflections were reduced in all CFRP-strengthened long specimens.

In the same way, Shaat et al. [20] developed an analytical model for slender members with hollow steel sections (HSSs), retrofitted with high modulus CFRP sheet. Their study provided a prediction of the behaviour of HSS subjected to axial compression loads. Their model takes into account the residual stresses, initial imperfections, and material and geometric nonlinearities. Load versus lateral and axial displacements can be predicted by this model. Experimental results from a previous study[19] verified their model, and showed reasonable agreement. The stiffness and axial strength of HSS compression members were effectively increased by bonding external CFRP sheets.

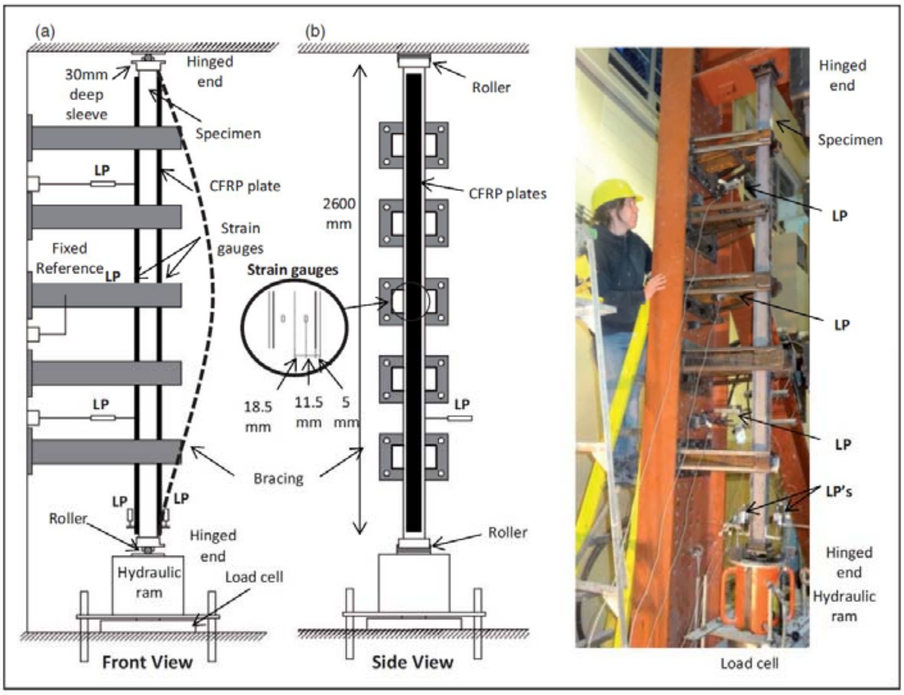


Figure 5. Experimental set-up; (a) front view; (b) side view [21].

A strengthening technique of slender S-section steel columns for increasing buckling capacity was demonstrated experimentally by Ritchie et al. [21], [22] . Different layers and different Young's modulus of carbon fibre-reinforced polymer plates were bonded to the steel flanges by Sikadur 30 resin to fabricate reinforcement ratios of 11–34%[21]. Eight steel column specimens with 2.6m long standard steel S75×8 sections were tested to failure under compression load along the strongest axis, as shown in Figure 5. This set of 8 columns includes three specimens were without strengthening and five were strengthened with CFRP laminates. The major parameters examined in this study were the number of CFRP laminates, the CFRP Young's modulus and the out-of-straightness geometric imperfection. It was found that axial strength and resistance to buckling in the strengthened columns are increased by range of ration of 15% to 25%. However, the effect of one layer CFRP reinforcement was varied depending on the type of CFRP, the increase in strength was up to 5.35% for specimens strengthened with normal modulus CFRP (168 GPa) while the ultra-high modulus (430 GPa) had no effect on the results. This behaviour was due to the CFRP with ultra-high modulus reaching crushing failure early before global buckling took place. The authors conducted another study considering all parameters mentioned above [22]. CFRP plates bonded to the flanges were used to inspect buckling about the weak axis of columns subjected to axial loads. The enhancement of axial strength of the 2,600 mm long columns increased significantly, gaining 11% to 29%.

4.2 Flexural strength

Increasing maximum stress value is important for steel beams to sustain high loading. Steel structures subjected to static load may require retrofitting or repair during its life. Bonding CFRP to steel structural members can enhance the ultimate load and the stiffness of the elements. There are many possible failure modes for FRP-plated steel beams [9, 23], including (a) plate-end debonding; (b) intermediate debonding due to local cracking or yielding away from the plate ends ; (c)in-plane bending failure ; (d) lateral buckling; (e) local buckling of the web; and (f)local buckling of the compression flange (see Figure 6).

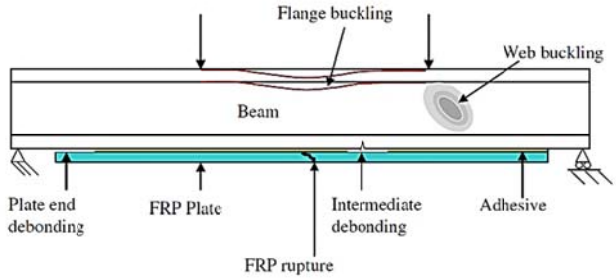
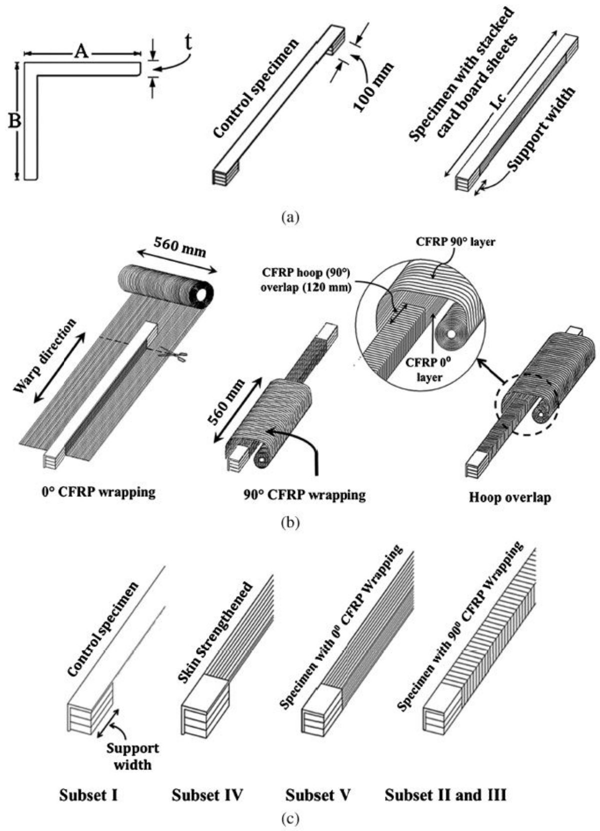


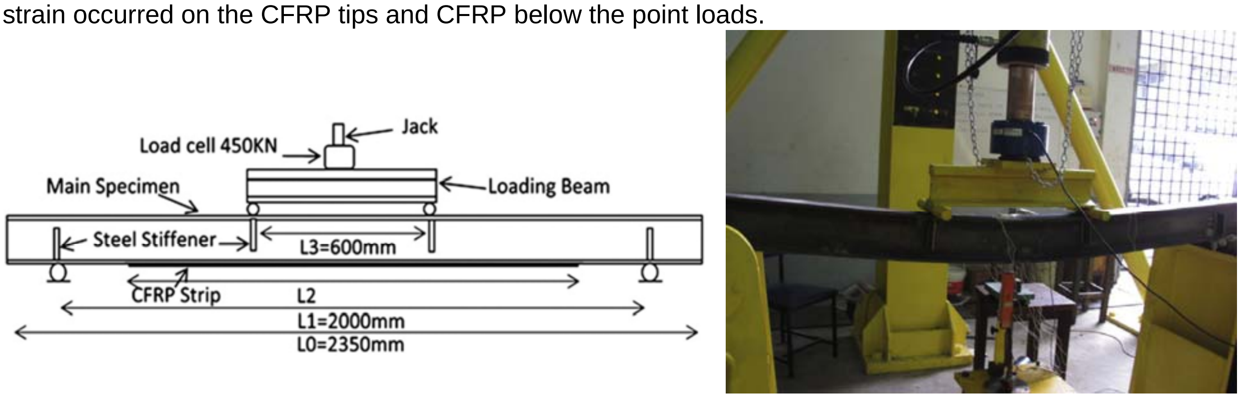
Figure 6. Main failure modes of strengthened steel beams by CFRP laminate [9].

Madhavan et al. [24] studied the effect of open-angle sections bonded with CFRP. The ultimate load behaviour of open steel angle sections covered by wrapping CFRP sheet was investigated experimentally by altering the open-angle section to a closed section in order to enhance the strength and flexural stiffness, as shown in Figure 7. This approach included the use of an internal formwork formed from stacked cardboard sheets around which CFRP was wrapped. Identical specimens of 30 steel angle sections were cut to 1.4m length with equal angle sections of 45 × 45 × 5 and 50 × 50 × 5 mm.



In this study, two equal angle sections were tested in 4-point bending with different wrapping configurations to replicate more than one angle section. For the 4-point bending test, a servo-hydraulic testing machine series 244 with an actuator capacity of 250 kN was utilised. A number of parameters were selected to identify the failure behaviour for various wrapping configurations, including different CFRP layers, slenderness ratios (b=t), and orientations of CFRP. A schematic view of the steel angle sections with CFRP is shown in Figure 7. Generally, the results showed that by using an adequate number of CFRP layers and appropriate reinforcement patterns, the strength and stiffness can be significantly increased.

Another four-point test on full-scale FRP-strengthened steel I-beams as shown in Figure 8 was carried by Narmashiri et al. [25]. I-section steel beams with similar dimensions were strengthened with different CFRP types and dimensions in order to investigate the structural behaviour and analyse the failure mode. The selected thicknesses of CFRP strips were 1.2 mm, 1.4 mm, 2 mm, and 4 mm. The engineering epoxy (structural adhesive) consist of a two-part epoxy resin was chosen (resin and hardener, in 3:1proportions) for installing the CFRP strips on the steel structure. A hydraulic jack with a load cell capacity of 450 kN was used for the 4-point bending test with static gradual loading (Figure 8). Many linear variable deformation transducers (LVDTs) and strain gauges were placed at different locations on the specimen to measure deflection and strain. For the numerical simulation, the authors performed a full 3-D non-liner simulation using ANSYS software. The results of the four-point tests of strengthened steel I-beams showed that the CFRP failure modes included: (a) below point load-debonding (BD), (b) below point load-splitting (BS), (c) end-delamination (EDL), and (d) end-debonding (ED). The sequences and occurrences of these failure forms relied on the strengthening schedule. The implementation of longer CFRP laminates increased the resistance against end-debonding (ED), and premature end-debonding occurred with shorter CFRP strips. The below point load-splitting (BS) was overcome by increasing the thickness of the CFRP plate in comparison with laying thicker CFRP laminate which led to premature debonding. The authors clearly showed that the vertical deflection of the strengthened steel beam decreased, and high strain occurred on the CFRP tips and CFRP below the point loads.



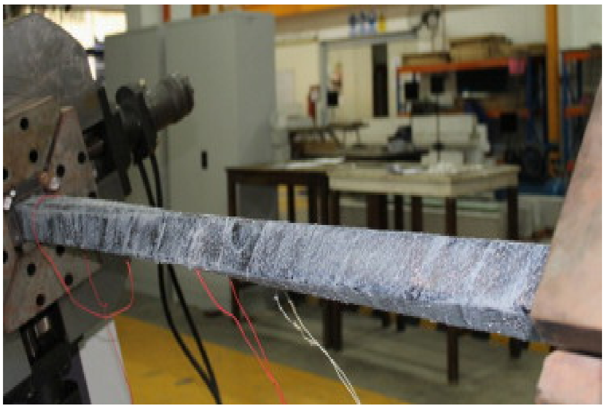
(a) **(b)**

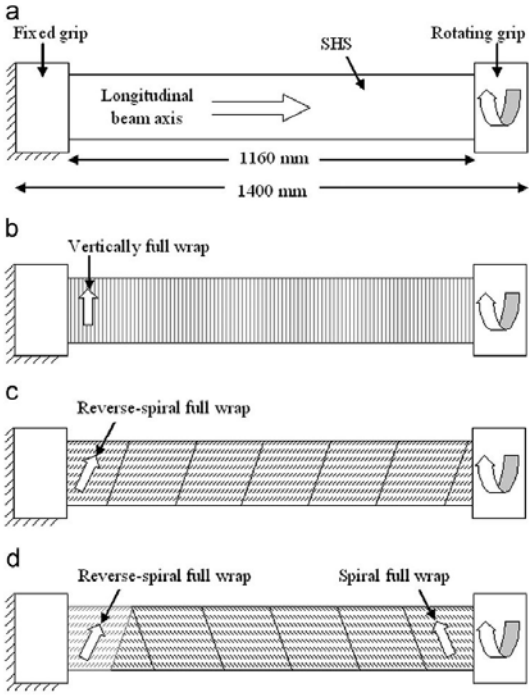
Figure 8. (a) Schematic of the test set-up; (b) four-point bending experimental set-up [25].

4.3 Torsional load

One of the significant aspects of strengthening steel members by CFRP is the capacity to resist torsion or absorb torsional energy. Torsional forces in steel structures are expected when steel members are used in bridges and buildings. Therefore, some studies have explored the behaviour of CFRP-strengthened steel structures in torsion. Tests of SHSs, experimentally and theoretically, strengthened by CFRP and subjected to torsion load were carried out by Abdollahi Chahkand et al. [26]. Different parameters were tested, such as the number of CFRP layers and the strengthening configurations, which included spiral, vertical, and reverse-spiral wrapping (Figure 9).

Figure 7. Specimen preparation: (a) transforming the open angle beam to closed section; (b) CFRP wrapping methodology; (c) configuration of test specimens [24].





(a) (b)

Figure 9. (a) experimental test setup of strengthened beam; (b) configurations of CFRP strengthening [26].

The CFRP and epoxy used in their study were a Sika Wraps®-200C and Sikadurs®-330. The torsion testing rig included a pivoting rotating grip and a fixed grip, and the specimen could twist about its longitudinal axis. The results were gathered using computer software, and the torsion load versus torsion angle was plotted. The authors reported that all strengthened steel specimens gained more ultimate torque compared to SHSs without strengthening, and the orientation angle of CFRP was a key factor in improving ultimate torque. For better resistance to cyclic torque, the combination of spiral and reverse-spiral CFRP wraps was recommended, while the best strengthening configuration that provided higher torsional resistance could be obtained by replacing spiral-reverse wrapping by spiral wrapping only. It was observed that the torsional resistance was increased by changing to an open section steel.

5. Impact load

Most structures perform differently under quasi-static and dynamic loadings. This section reviews the most recent research on CFRP-steel systems under impact load. A numerical study was conducted by Alam et al. [27] on SHS steel columns strengthened by CFRP subjected to transverse impact loading to investigate the deformation and failure modes. The tests carried out under transverse impact loading considered the main parameters (Figure 10), including impact mass, impact velocity, axial loading, CFRP thickness and support condition. A finite element model was presented in ABAQUS with four parts: the steel tube was modelled with 4-node shell elements, 8-node linear brick elements for the drop hammer, a longitudinal spring was also modelled at the left end of the specimen, and a transverse spring with minor stiffness in consideration of friction force was used. The number of CFRP laminates was modeled as three layers on four sides and three layers on two sides, and the thickness of the CFRP lamina was assigned as 0.54 mm. The authors confirmed that the externally-attached CFRP composites of SHS steel columns enhance impact resistance capacity. The two-side strengthening system was not effective compared with confinement on all four sides, which provides more resistance and effectiveness in buckling control of SHS steel columns by sustaining imposed lateral impact and static compressive loads.

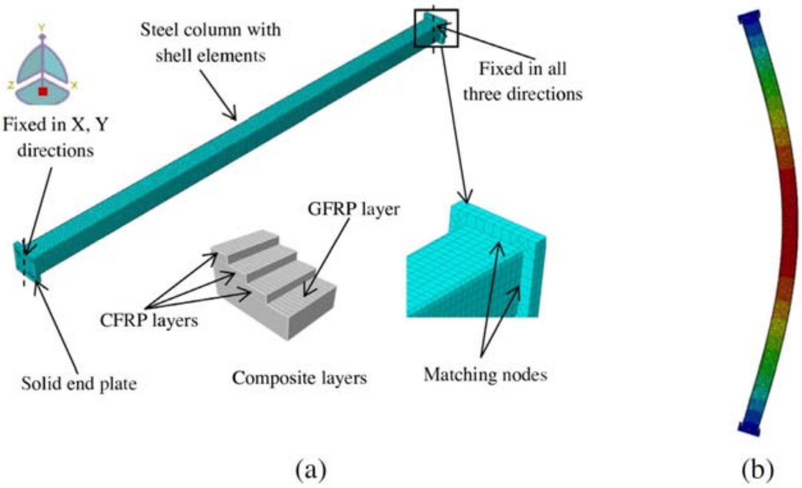


Figure 10. (a) FE model; (b) first buckling mode [27].

Concrete-filled steel tubes retrofitted with CFRP were examined under transverse impact in the study by Alam et al. [28]. Alam and Fawzia in (2015) continued their research by conducting a numerical simulation using ABAQUS/explicit to investigate the effective bond length of CFRP wrapping. Similarly, all parameters mentioned in Alam et al. [27] study were considered in this research. The cross-sections of models were designed identically with a thickness of 3.5 mm and steel tube inner diameter of 107 mm. Different lengths of models were adopted, varying from 1400 mm (short column) to 1700 mm (long column).

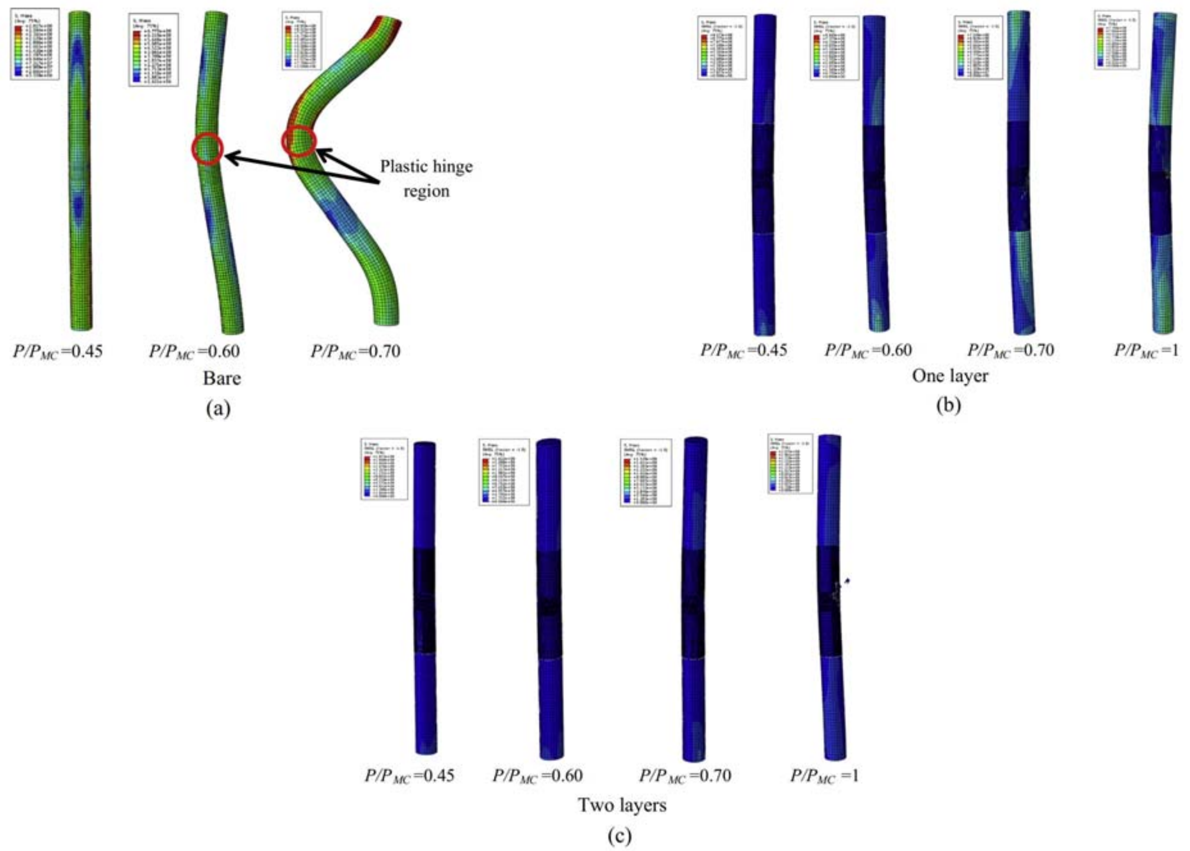


Figure 2. Failure modes of (a) non-strengthened bare; (b) one layer; (c) two layers strengthened columns[28].

The researchers found that strengthening a nominated length of the column with CFRP sheets had a great effect on enhancing transverse impact resistance, and the outcomes indicated that the impact resistance capacity of CFRP bonding of 70% length of column was similar to that of the full-length CFRP bonded column (Figure 11). Furthermore, it was shown that the displacement responses of both normal modulus and high modulus CFRP composites were roughly similar to the change of bond length, whereas displacement responses were more sensitive to adhesive properties, and high strain capacity was more desirable than low strain capacity under transverse impact loading.

An experimental investigation was reported by Bambach et al. [29] , in which SHS steel tubes strengthened with CFRP were subjected to axial impact. The investigation included two different matrix layouts of the CFRP and various SHS geometries. Araldite 420 epoxy was adopted to attach high-strength CFRP (MBrace CF-130) sheets to the outside of SHS specimens 300 mm in length, and 50 × 50 × 2 mm, 65 ×65 × 2 mm, 75 × 75 × 2 mm and 100 × 100 × 2 mm in section sizes. A drop-mass rig was used to produce axial impact for testing the SHS members. An impact velocity of 6 m/s and impact energy of 10.3 kJ were produced by dropping a mass of 574 kg from a height of 1.835 m. Bambach et al. [29] identified two main failure modes for the steel SHS: stable plastic and axi-symmetric ductile, where the flat faces folded axially, whereas, the second failure mode showed some delamination between CFRP sheets in one or two faces from the four sides of the specimens after formulating a first fold, while the remaining faces folded in a crushing manner, as shown in Figure 12. Under dynamic axial load, the failure mode due to delamination was more likely to occur than under quasi-static load. The CFRP SHS displayed an increase of 82% in the dynamic mean crushing load, and 52 % in the energy absorption value.

Figure 12. Failure of square hollow section steel tube [29].

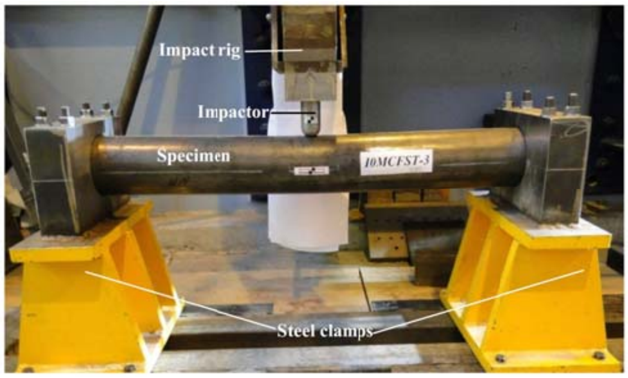


Figure 3. Set-up of experimental impact test [30].

Another series of tests of lateral impact response was carried out by Shakir et al. [30]. Steel tube columns were filled with normal (NACFST) or recycled (RACFST) aggregate concrete, and investigated by subjecting them to lateral projectile impact (Figure 13). The influence of the CFRP sheet on the structural behaviour was examined. The main factors studied were: configuration of the impactor, the influence of the tube length, concrete type, and local reinforcement by CFRP sheet on the dynamic response of specimens. In regard to the influence of CFRP, the results indicated that the global displacements for both the RACFST and NACFST specimens were reduced by adding further confinement of CFRP. For the long and medium tubes, the global displacement was decreased by around 8.3% and 6.2% respectively, by using a single layer of CFRP reinforcement.

6. Conclusions

Reinforcement of steel structures by bonding CFRP has clearly gained the attention of researchers as a successful technique. A brief description of recent research on the application of CFRP in strengthening structures of steel bridges has been provided in this paper. The main outcome is that there is a significant increase in the load-carrying capacity for specimens strengthened by CFRP under high loading rates. The application of CFRP to existing steel structures can provide an average increment in strengthening of steel elements by 25%. The type of adhesive, CFRP and the procedure of bonding both CFRP and steel elements are the main limitations of a successful strengthening method. In some cases, there is an effective bond length that provides nearly similar outcomes to full-length CFRP bonded to elements. By using sheet and laminate CFRP, different cross-sections can be reinforced effectively, such as I-beam, open angle, square and circular SHS These strengthened elements can withstand one or a combination of various loads. Further research is recommended to cover strengthened steel structures subjected to a combination of various loadings, fire resistance and corrosion protection.

7 Acknowledgement

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