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ORIGINAL ARTICLE

Strengthening Deficient Steel Member Joints Using CFRP under Compressive Loading

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ABSTRACT - Carbon fiber reinforced polymer (CFRP) is a matrix-embedded material frequently utilized for strengthening and repairing various metal structural components. Its corrosion resistance, durability, and high strength make CFRP an important material for retrofitting and strengthening purposes. CFRP is structurally robust and capable of carrying significant loads, while being lightweight, leading to its widespread use. Steel structures can become deficient due to factors such as corrosion, temperature effects, increased live loads, static and dynamic loads, compressive and axial loading, fatigue, design and calculation errors, and construction mistakes. This research aims to observe the strength and behavior of CFRP-strengthened T, C, and L joints under compressive loading. A series of experiments were conducted on T, C, and L-shaped steel joints strengthened by CFRP. Five T-shaped, five C-shaped, and five L-shaped square steel joints, including two reference specimens and two CFRP-strengthened specimens from each type, were tested. The specimens were subjected to vertical and horizontal cuts at the joints, and CFRP strips were applied to the joints. Compressive loading was performed using a Compression Testing Machine. The ultimate load at which the joints collapsed and the load deformation behavior of the reference and CFRP-strengthened specimens were documented. The results demonstrated that the pre-cracked steel joints strengthened with CFRP exhibited better performance compared to the reference steel joints. The experimental results indicate that using CFRP in steel joints enhances their performance under compressive loading.

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INTRODUCTION

Steel constructions made of thin-walled structures offer significant advantages in terms of material consumption and construction costs. These benefits make them a preferred choice in various industries, including bridges and other infrastructure projects. Traditional strengthening techniques, such as welding and the use of mechanical fasteners, are not always feasible due to the thinness of the element cross-sections. In such cases, Carbon Fiber Reinforced Polymers (CFRPs) present a viable alternative [1]. CFRP is a composite material comprising a polymer matrix reinforced with carbon fibers, which significantly enhances the strength and stiffness of metallic beams when bonded to them. Numerous studies have confirmed the efficacy of CFRP in improving the strength and stiffness of metallic beams [2]. This improvement is particularly advantageous when load conditions change in the construction [3]. For instance, distortion-induced fatigue damage at cross frame-to-girder connections is a common issue in steel bridges built before the mid-1980s, due to the detailing practices of that era. These practices avoided welding connection plates to girder flanges, resulting in flexible gap regions in the girder web where

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fatigue cracks frequently develop. Traditional retrofitting methods, such as replacing plating or bolting and welding steel plates, often introduce new drawbacks, including poor fatigue performance, residual stress, loss of cross-section from bolt holes, corrosion threats, increased self-weight, and the need for skilled labor and extensive installation time [4]. The limitations of traditional techniques have spurred a growing interest in the application of fiber-reinforced polymer (FRP) materials [5]. Advanced composites like FRP have been utilized since World War II in aerospace and military industries due to their high strength-to-weight ratios and weather resistance. Since the late 1970s, these materials have gained attention for bridge repair and rehabilitation [4; 5].

In this study, mild steel joints, which unite cross-sectional, vertical, and horizontal members, are retrofitted using CFRP to enhance their structural performance. The combination of mild steel and CFRP retrofitting material forms a composite structural member, where the fiber surrounds L, C, and T joints. This integration allows the steel and FRP elements to interact through bonding and friction, effectively withstanding external loads. Retrofitted steel connections with CFRP under tensile and compressive loads are increasingly used as load-bearing components in truss-like framed structures. CFRP retrofitting significantly increases the compressive load capacity of pre-cracked joints, facilitating quicker, easier, and more reliable construction [5; 6]. This method is particularly effective for the rapid recovery of fractured joints under load, reducing overall construction costs and time, which is crucial for both contractors and property owners. The technique's efficiency makes it ideal for scenarios with limited resources and time constraints, ensuring robust and dependable repairs of pre-cracked steel connections under load [7]. This research aims to investigate the structural behavior of CFRP retrofitted deficient steel square T-joints, C-joints, and L-joints under axial loading. By conducting a series of tests and presenting load-deflection behavior, failure loads, and failure modes, this study demonstrates the significant improvement in load-carrying capacity and structural performance achieved through CFRP strengthening.

MATERIALS AND METHODOLOGY

Tubular metallic structures are widely employed due to their lightweight and high load-carrying capacity. This study involved the preparation of test specimens using three different materials: mild steel (MS), CFRP wrap, and adhesive, as depicted in Figure 1. The effectiveness of externally bonded strengthening primarily relies on the characteristics of the metal surface, adhesive, and CFRP materials [8]. Key mechanical properties for strengthening structures include the effective bond strength, elastic modulus, and elongation of the adhesive [9; 10]. CFRP material is a composite consisting of fibers embedded in a resin matrix, with epoxy resin being the most commonly used for CFRP. In this research, CFRP fabrics of the Kor-CFW450 type were utilized, featuring a fiber strength of 4900 MPa, fiber stiffness of 230 GPa, a weight of 450 g/m^2, and a fabric thickness of 0.255 mm. Primer and saturant were used with densities of 1.14 gm/cm^3 and 1.8 gm/cm^3, pot life durations of 30 minutes and 1 hour 30 minutes, and tensile strengths of 1350 MPa and 4875 MPa, along with moduli of elasticity of 99.37 GPa and 238.00 GPa, respectively. The adhesive used in this research is Kor-CPA 10 Base Resin, and its associated hardener has a tensile strength of 49.8 MPa and a shear strength of 29 MPa, with a pot life of 70 minutes. The mild steel coupon specimens had a thickness of 1.3 mm and 2.3 mm were prepared from tubular sections in accordance with American and Australian standards [11]. The mild steel tubular sections had a tensile yield stress of 390 MPa, an ultimate stress of 450 MPa, and an initial Young's modulus of 198.6 GPa. These mechanical properties of mild steel were obtained from the previous research conducted by Islam et al., 2023.

A total of 15 specimens were prepared for this study. Among them 5 specimens (four of them is cracked) of square shaped T-joints, 5 specimens (four of them cracked) of C-joint and 5 specimens (four of them cracked) of L-joint.

Figure 1. Cutting steel

Figure 2. Welding Steel

The steel joints were intentionally cut horizontal and vertical to create a weakened member, as depicted in Figure 3. This cutting process was performed using a grinding machine with a diamond-tipped blade. Each joint underwent a detailed surface preparation process, beginning with thorough cleaning to remove any contaminants [12]. After cleaning, the surface was roughened to enhance adhesion. A primer was then applied to the prepared surface, followed by a waiting period of 30 minutes to ensure proper bonding. Once the primer had set, epoxy adhesive was carefully applied to the joints. The CFRP was then wrapped around the joints, with particular attention to shaping it precisely to fit the joint contours. Finally, the specimens were left to cure for 7 days to ensure that the CFRP and epoxy bonded effectively to the steel joints. This step-by-step process ensured the integrity and durability of the composite repair [13].

Figure 3. Cracking to make deficient

Figure 4. Square section C, L & T-joint specimen

The testing of all joints for deformation was carried out using a compression test machine. The experimental research incorporated two control methods: load control and displacement control [14]. Initially, load control was applied, with the load being restricted to the yield strength of the joint. Subsequently, displacement control was implemented, with a focus on monitoring and controlling displacement until the failure of joint [6].

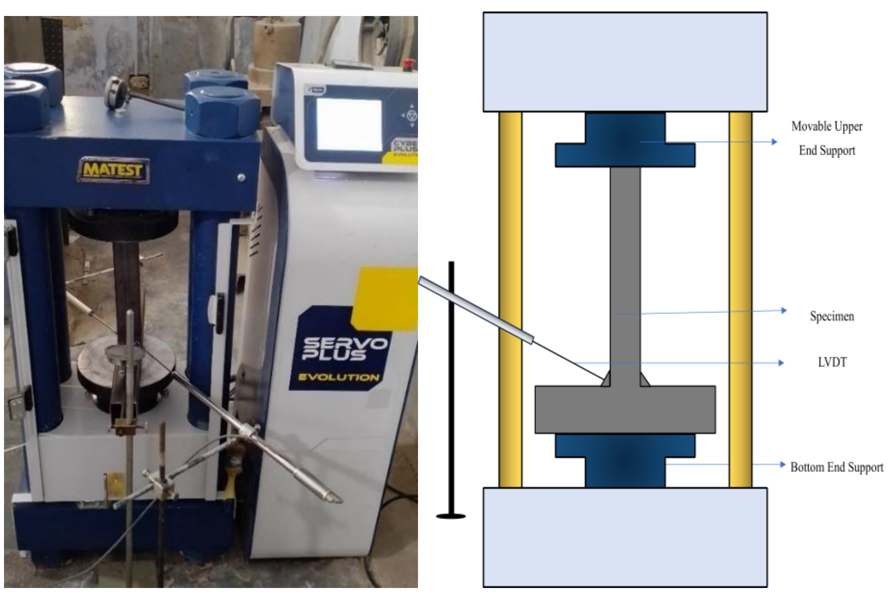

Figure 5. Test arrangement of the square steel section T-joints with schematic view.

RESULTS AND DISCUSSION

An extensive test program has been conducted on CFRP retrofitting of deficient steel square T, C & L-joint under axial loading. Fifteen square mild steel member T, C & L-joint specimens including reference and initially pre-cracked T, C & L-joint was tested in this research to verify the influence of two parameters such as horizontal cutting and vertical deficient [15; 16]. The specimens were labelled as TF0C0, TF0CV, TF0CH, TF1CV, TF1CH, CF0C0, CF0CV, CF0CH, CF1CV, CF1CH, LF0C0, LF0CV, LF0CH, LF1CV, LF1CH Where, T, C & L indicates T, C & L joints, F0 indicates without CFRP, F1 indicates with CFRP, CV indicates vertical cut, CH indicates horizontal cut. The mild steel T, C & L-joint tests were conducted by compressive testing machine. The loadings were obtained from the test machine as it is built with the help of manual function. The failure loads, failure modes and the load-deformation behavior of reference joint and CFRP retrofitted joint were observed in this research [17]. The ultimate load for the horizontal cuts were greater then vertical cut for C & L joints but for T joints the ultimate load were greater in vertical cut and less in horizontal cut for both with and without CFRP retrofitted. Using CFRP increases load up to 40.72% which is a good amount of increase in a deficient steel [18].

The values from the T-joint experiment demonstrate the effectiveness of CFRP for strengthening purposes. At a vertical crack condition, burden carrying capacity increases by approximately 27.6 %. For horizontal cut conditions, the burden carrying capacity increases by nearly 40.72 % [5]. The values from the C-joint experiment demonstrate the effectiveness of CFRP for strengthening purposes. At a vertical crack condition, burden carrying capacity increases by approximately 12.27 % [19; 20]. For horizontal cut conditions, the burden carrying capacity increases by nearly 19.76 % [7; 21]. The values from the L-joint experiment demonstrate the effectiveness of CFRP for strengthening purposes. At a vertical crack condition, burden carrying capacity increases by approximately 24.65 %. For horizontal cut conditions, the burden carrying capacity increases by nearly 19.61% [7; 22].

Table 1. Experimental data for T-section specimen

Specimen Name	Specimen Type	Ultimate Load (kN)	Displacement(mm)	Enhanced load carrying capacity (%)
TF_0C_0 (Uncracked; No CFRP)	Reference specimen	36.43	7	-
TF_0C_V (Vertical cracked; No CFRP)	Reference specimen	24.63	7	-
TF_0C_H (Horizontal cracked; No CFRP)	Reference specimen	21.39	6	-
TF_1C_V (Vertical crack; CFRP used)	Retrofitted Specimen	31.45	7	27.6
TF_1C_H (Horizontal Cracked; CFRP used)	Retrofitted Specimen	30.1	7	40.72

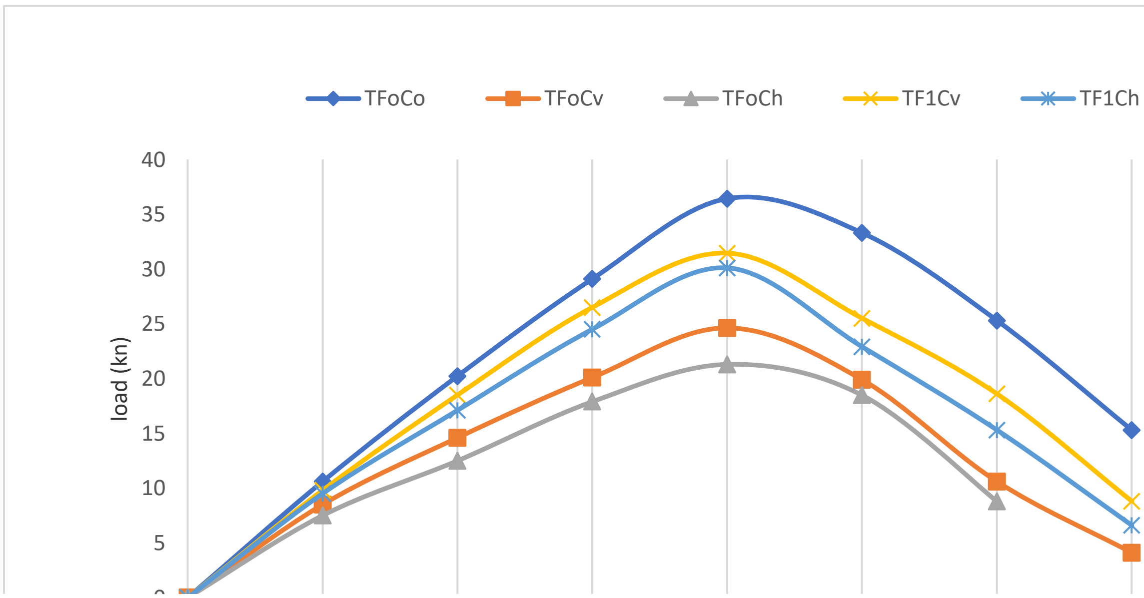

Figure 6. Load vs Displacement (T-joint)

Table 2. Experimental data for C-section specimen

Specimen Name	Specimen Type	Ultimate Load (kN)	Displacement(mm)	Enhanced load carrying capacity (%)
CF_oC_o (Uncracked; No CFRP)	Reference specimen	9.58	6	-
CF_oC_V (Vertical cracked; No CFRP)	Reference specimen	8.47	6	-
CF_oC_H (Horizontal cracked; No CFRP)	Reference specimen	8.60	6.6	-
CF_1C_V (Vertical crack; CFRP used)	Retrofitted Specimen	9.51	6.6	12.27
CF_1C_H (Horizontal Cracked; CFRP used)	Retrofitted Specimen	10.30	6	19.76

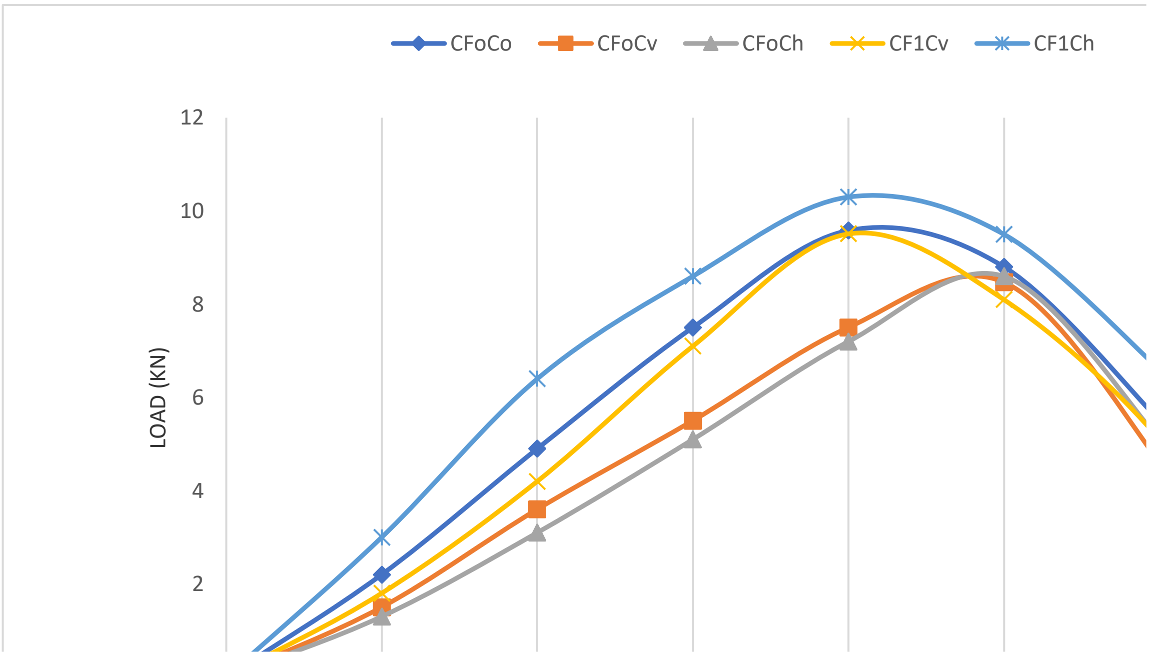

Figure 7. Load vs Displacement (C-joint)

Table 3. Experimental data for L-section specimen

Specimen Name	Specimen Type	Ultimate Load (kN)	Displacement (mm)	Enhanced load carrying capacity (%)
LF_0C_0 (Uncracked; No CFRP)	Reference specimen	20.38	5	-
LF_0C_V (Vertical cracked; No CFRP)	Reference specimen	14.52	6	-
LF_0C_H (Horizontal cracked; No CFRP)	Reference specimen	15.61	5	-
LF_1C_V (Vertical crack; CFRP used)	Retrofitted Specimen	18.10	6	24.65
LF_1C_H (Horizontal Cracked; CFRP used)	Retrofitted Specimen	18.67	5	19.61

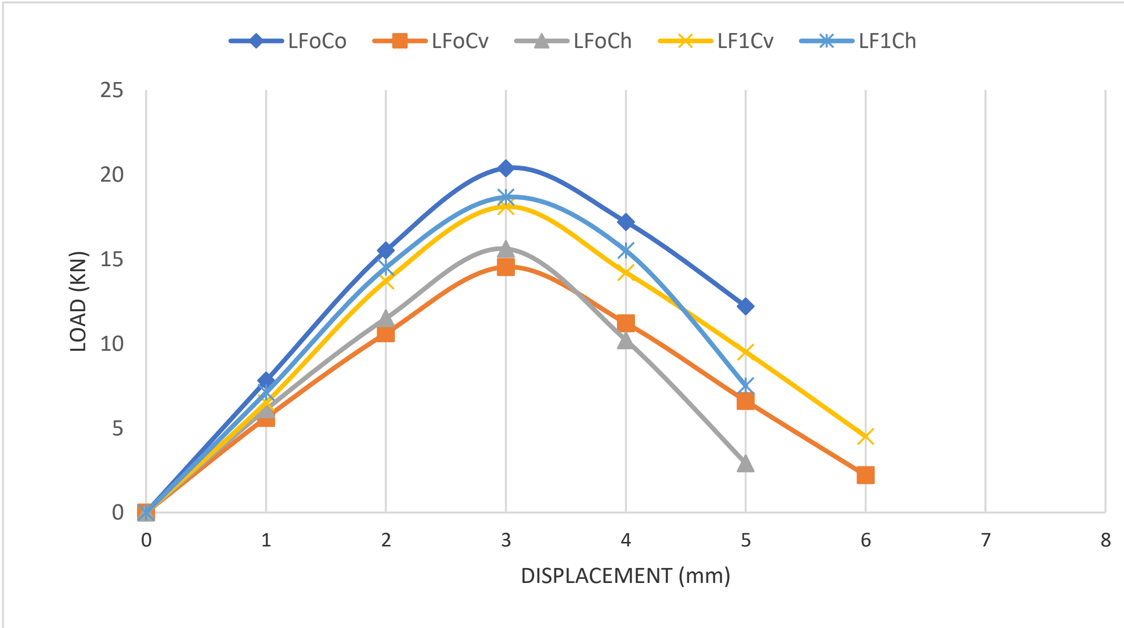

Figure 8. Load vs Displacement (L-joint)

CONCLUSION

An experimental study was designed to evaluate the performance of strength tests for CFRP-to-steel T, C, and L-joints with varying degrees of deficiencies, focusing particularly on different types of cuts. The purpose of this research was to understand how these deficiencies impact the structural integrity and strength of the joints. The study involved creating joints with specific types of cuts to simulate real-world scenarios where the joints might be compromised. Through rigorous testing and analysis, the study aimed to identify patterns in performance and strength degradation. The findings from this research provided valuable insights into the behavior of CFRP-to-steel joints under different conditions of deficiency, highlighting critical factors that influence their performance. These results are instrumental for developing better retrofitting strategies and improving the design and maintenance of steel structures reinforced with CFRP. The results of this study yielded the following findings:

- For T-joints, the application of CFRP strengthening leads to a significant increase in load-carrying capacity, specifically by 27.6% for vertical cracks and 40.72% for horizontal cuts. This indicates a substantial improvement in the structural integrity of T-joints with both types of deficiencies.

- C-joints also benefit from CFRP strengthening, with an observed enhancement in capacity by 12.27% for vertical cracks and 19.76% for horizontal cuts. This suggests that CFRP retrofitting is effective in mitigating the effects of deficiencies in C-joints.

- L-joints show an increase in load-carrying capacity by 24.65% for vertical cracks and 19.61% for horizontal cuts when strengthened with CFRP. This highlights the versatility and effectiveness of CFRP in reinforcing different types of joint configurations.

Based on these findings, it can be concluded that CFRP composites retrofitting is an effective technique for improving the structural performance of steel T, C, and L-joints under axial loading. This method enhances the joints' ability to bear loads and mitigates the impact of deficiencies, ensuring greater structural reliability and longevity.

REFERENCES

1. Liu, Z. Q., Luo, B., Wang, Q., Qin, Y. F., & Zhang, W. T. (2022). Test and theoretical investigation of an improved CFRP-steel tube composite member under axial compressive loading. Engineering Structures, 250, 113426.
2. Keykha, A. H. (2019). Structural performance evaluation of deficient steel members strengthened using CFRP under combined tensile, torsional and lateral loading. Journal of Building Engineering, 24, 100746.
3. Mahmoud, M. H., Afefy, H. M., Kassem, N. M., & Fawzy, T. M. (2014). Strengthening of defected beam–column joints using CFRP. Journal of advanced research, 5(1), 67-77.
4. Keykha, A. H. (2020). Investigation of the behavior of deficient steel members strengthened using carbon fiber reinforced polymer under combined compressive load and torsional moment. Mechanics of advanced materials and structures, 27(11), 894-902.
5. Alam, M. I., and Fawzia, S. (2015). "Numerical studies on CFRP strengthened steel columns under transverse impact." Composite Structures, 120(0), 428-441.
6. Al-Mosawe, A., Al-Mahaidi, R., and Zhao, X.-L. (2016). "Bond behavior between CFRP laminates and steel members under different loading rates." Composite Structures, 148, 236-251.
7. Ali, H. T., Akrami, R., Fotouhi, S., Bodaghi, M., Saeedifar, M., Yusuf, M., & Fotouhi, M. (2021). "Fiber-reinforced polymer composites in the bridge industry". Structures, 30, 774–785.
8. Al-Thairy, H., and Wang, Y. (2013). "A simplified analytical method for predicting the critical velocity of transverse rigid body impact on steel columns."International Journal of Impact Engineering, 58, 39-54.
9. Al-Zubaidy, H. A., Zhao, X.-L., and Al-Mahaidi, R. (2012). "Dynamic bond strength between CFRP sheet and steel." Composite Structures, 94(11), 3258- 3270.
10. Colombi, P., & Poggi, C. (2006). Strengthening of tensile steel members and bolted joints using adhesively bonded CFRP plates. Construction and Building Materials, 20(1-2), 22-33.
11. Xu, C., Peng, S., Liu, X., Wang, C., & Xu, Q. (2020). Analysis of the seismic behavior of CFRP-strengthened seismic-damaged composite steel-concrete frame joints. Journal of Building Engineering, 28, 101057.
12. Keykha, A. H. (2018). Behavior of Deficient Steel Members Strengthened Using CFRP Under Combined Compressive Load and Torsional Moment. AUT Journal of Civil Engineering, 2(1), 59-68.
13. Karimian, M., Narmashiri, K., Shahraki, M., & Yousefi, O. (2017). Structural behaviors of deficient steel CHS short columns strengthened using CFRP. Journal of Constructional Steel Research, 138, 555-564.
14. Areiza Hurtado, M., Bansal, A., Paulotto, C., Primi, S. (2012) " FRP girder bridges: lessons learned in Spain in the last decade. " Proceedings of CICE 2012 6th International Conference on FRP Composites in Civil Engineering, Rome, Italy, 13-15 June 2012.
15. Bambach, M., Jama, H., and Elchalakani, M. (2009). "Static and dynamic axial crushing of spot-welded thin-walled composite steel–CFRP square tubes." International Journal of Impact Engineering, 36(9), 1083-1094.
16. Bambach, M. (2011). "Design of hollow and concrete filled steel and stainless steel tubular columns for transverse impact loads." Thin-Walled Structures, 49(10), 1251-1260.
17. Chen, C., Zhao, Y., and Li, J. (2014). "Experimental investigation on the impact performance of concrete-filled FRP steel tubes." Journal of Engineering Mechanics, 141(2), 04014112.
18. Chen, L., Xiao, Y., Xiao, G., Liu, C., and Agrawal, A. K. (2015). "Test and numerical simulation of truck collision with anti-ram bollards." International Journal of Impact Engineering, 75(0), 30-39.
19. Da Silva, J. G. S., Sieira, A. C. C. F., Debona, G. L., Da Silva Velasco, P. C. G., and De Lima, L. R. O. (2012). "Finite element modeling of the dynamic behavior of tubular footbridges." International Journal of Modeling and Simulation for Petroleum Industry, 6(1), 9-18.
20. Dawood, M., and Rizkalla, S. (2010). "Environmental durability of a CFRP system for strengthening steel structures." Construction and Building Materials, 24(9), 1682-1689.
21. Fernando, D., Yu, T., Teng, J., and Zhao, X. (2009). "CFRP strengthening of rectangular steel tubes subjected to end bearing loads: effect of adhesive properties and finite element modeling." Thin-Walled Structures, 47(10), 1020-1028.
22. Franklin, K., Ozkan, E., and Powell, D. (2010). "Design of the Kurilpa pedestrian bridge for dynamic effects due to pedestrian and wind loads." 5th Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference, Engineers Australia, 885.