Numerical Investigation on the CFRP Strengthened Steel Frame under Earthquake

T. Tafsirojjaman[1,a], Sabrina Fawzia [1,b], David Thambiratnam [1,c]

[1] School of Civil Engineering and Built Environment, Faculty of Science and Engineering,
Queensland University of Technology, 2 George Street, Brisbane, QLD 4000, Australia.

[a]tafsirojjaman@hdr.qut.edu.au, [b]sabrina.fawzia@qut.edu.au, [c]d.thambiratnam@qut.edu.au

Keywords: CFRP, Steel Frame, Earthquake, FE modelling, CFRP Thickness

Abstract. Steel structures are commonly used in seismic regions of the world because of its strength and ductility. However, these structures are still prone to damage during an earthquake. With this risk of seismic damage, the strengthening of steel structures is a major concern in order to resist the dynamic loads resulted from earthquakes. This report investigates the potential for the use of Carbon Fibre Reinforced Polymer (CFRP) to strengthen the rigid steel frame under a real earthquake load. This research will be undertaken using Strand7, a finite element (FE) analysis software. To validate the accuracy of this research, the finite analysis results have been compared to the available experimental study by the Authors. First, both FE models of a five-story bare steel frame and CFRP strengthened steel frame has been developed. Then the predicted numerical results of bare steel frame and CFRP strengthened steel frame under earthquake excitation are compared. The results indicated an increase in the seismic performance of the steel structure due to the strengthened with CFRP. The CFRP strengthened steel frame showed 15% less tip deflection compared to bare steel frame. Further analysis on the strengthening capabilities of higher thickness CFRP was performed to assess the effect of the thickness of CFRP and the higher thickness CFRP showed better seismic performance compare to normal thickness CFRP by reducing 34.38% of tip deflection.

Introduction

One of the most destructive natural disasters, earthquake, have caused a huge amount of destruction to both property and casualties. 1.87 million people died because of the earthquake in 20th century. In the period between 1990 – 2010, a mean of 2052 deaths per earthquake has been recorded [1]. An extensive amount of steel structures has been built within the regions of high seismic risk. However, now the fracture failures of structural elements that have been subjected to seismic loadings because of seismic excitations have induced a significant concern. Steel frames located onshore and offshore are both susceptible to the extensive destruction caused by earthquake [2]. In addition, massive amount of steel structures are addressed with structural deficiency as the live loads increases, effect of design error, environmental factors and deterioration of material properties. Hence, researchers are looking for alternative ways and its effectiveness, to strengthen or rehabilitate of steel frames in order to sustain greater cyclic loads within seismic zones.

Originally, additional steel plates are welded as a method to rehabilitate a steel structure. This method results in more dead load to the structure and the stress distribution can be affected because of the heat that caused in the welding process, structures such as steel bridge would be critically affected as those structures are exposed to fatigue loads. Furthermore, welding would create a weak spot against corrosion resistance in steel structures. Massive machinery and scaffolding are needed in general for this method of welding, they also require a long period of time to construct [2]. In contrast, carbon fibre reinforced polymer (CFRP) can be applied to strengthen and rehabilitate steel structure while withstanding the drawbacks of the welding method, also it enables various advantages to the steel structure such as better strength-weight ratio and improves tensile strength [3]. As well as higher corrosion resistance. Moreover, CFRP utilizes a simpler construction process, which makes it more adaptable to different environments, as well as higher flexibility that can be adjusted to other shapes as required, which makes CFRP a cost-effective material. There is research that found CFRP strengthening technique able to increase the member's moment capacity [4]. Also, CFRP able to absorb and resist higher impact [5]. Moreover, CFRP strengthened structures' local buckling has been delayed [6]. Also, achieve higher energy absorption capacity as steel members are strengthened by CFRP reinforcement [7]. Additionally, CFRP strengthening technique is fatigue strengthening for steel joints which considerably an advantage to the structure [8]. Based on above literature, a study with comprehensive numerical study has been conducted with the purpose of upgrading seismic performances in rigid steel frame. This study is expected to be useful for rehabilitating steel members of high importance level structures that are located within seismic regions with CFRP strengthening technique.

The seismic responses of CFRP strengthened steel structures have not been widely studied. Thus, a knowledge gap emerges about the lack of information of effectiveness of CFRP strengthened steel frames that are subjected to earthquake. The focus of this study is to analyse and predict the behaviour of CFRP strengthened steel frames under seismic loading based on numerical simulation approaches in FE analysis software named Strand7 [9]. The FE modelling technique has been validated by comparing the predicted results that came from the available experimental tests by Authors [10]. Next, the comparison between bare steel and CFRP strengthened steel frames are conducted. Earthquake excitation from the 1994 Northridge earthquake was chosen for the seismic excitation. Furthermore, the effect of CFRP thickness has been investigated by varying the thickness of CFRP.

FE Modelling and Validation

FE computing software Strand7 of R2.4.4 version [9] was used for seismic simulation. In Strand7, the experimental bare and two layers of CFRP strengthened two-story frame (SF2) (for experimental details [10]) were developed by using the same as the experimental material properties (Table 1) [10]. The mesh convergence study was performed. First, the steel structure was created by jointing the basic nodes using Hexa8 brick elements. The node-node connection was developed to ensure the rigidity between steel column and beam. To replicate the experiment, the fixed restrained in each direction were applied in the bottom nodes. The adhesive and unidirectional CFRP has been created by using the ply material function. Then the CFRP and adhesive composite were developed with laminate function where CFRP weave directions were defined according to the experiment and applied in steel frame. The transient dynamic solver has been used to simulate the experimental seismic excitation. The accuracy of FE modelling technique can be confirmed with good matching between the experimental and FE simulated results in Fig.1 and Fig. 2.

Table 1: Properties of materials [10]

Property	Steel	Adhesive	CFRP
Elastic modulus (GPa)	200	2.028	125
Tensile strength (MPa)	-	25	3800
Density (kg/m^3)	7850	-	1700
Poisson's ratio	0.25	0.32	0.28

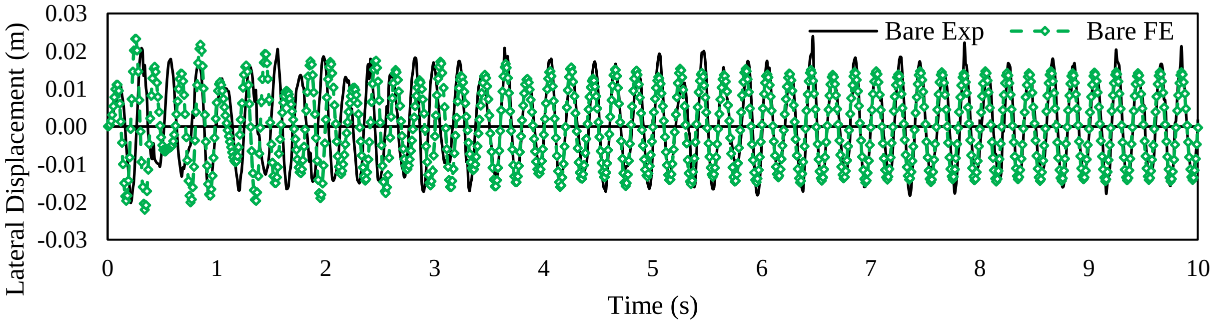


Figure 1: Tip lateral displacement comparison of bare specimen

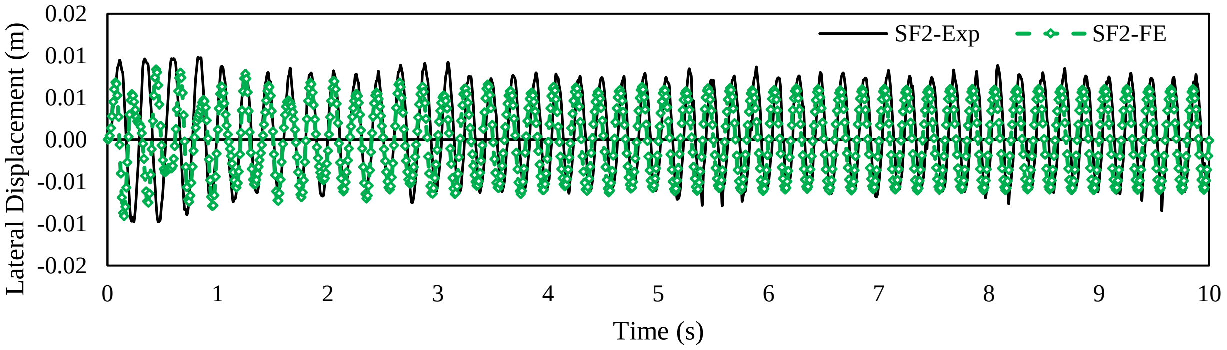


Figure 2: Tip lateral displacement comparison of CFRP strengthen specimen

Seismic Simulation of Full-scale Steel Frame

In the present study, the FE models of full-scale single-bay five-story bare and CFRP strengthened steel frames are created by following the previous section validated numerical technique. Real size W310x118 and W610x82 sections were used as column and beam respectively. The external and internal loads are calculated as per CAN/CSA-S16 [11]. The plastic hinge region (span length/16) of beams, one-fourth of column height of columns and the whole of the joint has been wrapped by CFRP [12]. Fig. 3 shows the details of FE models for bare and strengthened single-bay three-story steel frames. Earthquake data from the 1994 Northridge Earthquake shown in Fig. 4 was chosen for the seismic excitation to be applied to the finite models created [13].

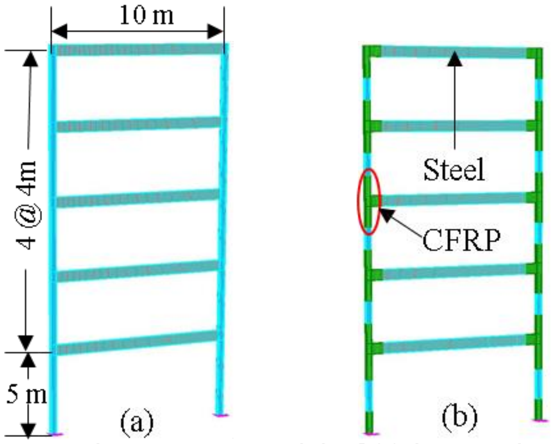


Figure 3: FE model of (a) bare and (b) CFRP strengthened steel

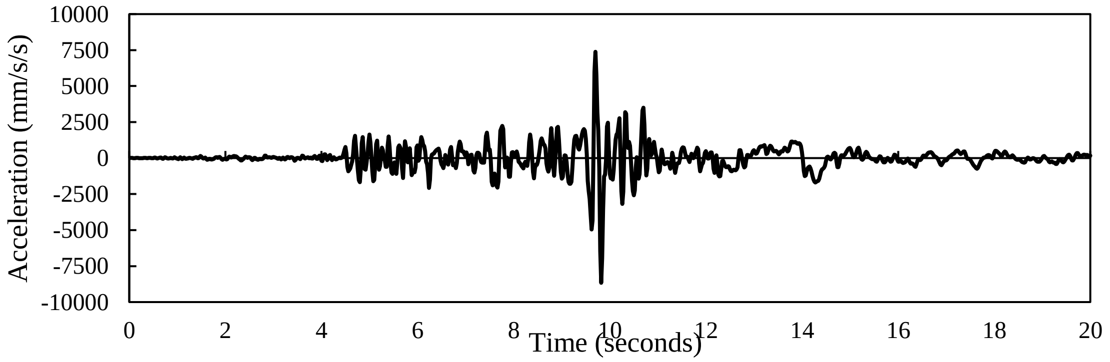


Figure 4: Ground acceleration vs time data for Northridge 1994 Earthquake [13].

Seismic Simulation Results

Natural frequency analysis has been performed to simulate the modal properties of the bare and CFRP strengthened steel frames and provided in Table 2. The tip lateral displacement comparison of bare and CFRP strengthened steel frame is shown in Fig. 5. The maximum lateral displacement and inter-story drift at each story comparison of bare and CFRP strengthened steel frame are shown in Fig. 6(a) and Fig. 6(b) respectively. It can be concluded from these results that the CFRP strengthening technique is very effective to enhance the seismic performance of the rigid steel frame. The tip lateral displacement of the bare and the CFRP strengthened steel frame are 343.9 mm and 292.5 mm. Hence, after strengthening with CFRP, the tip lateral displacement of five-story steel frame has been decreased by 15%. Therefore, the seismic strengthening of the rigid steel frame with CFRP is a very effective technique.

Table 2: Modal properties of the bare and CFRP strengthened steel frames

Frame	Mode	Frequency (Hz)	Frame	Mode	Frequency (Hz)
Bare Frame	1st	0.0814	CFRP Strengthened Frame	1st	0.0834
	2nd	0.1473		2nd	0.1519
	3rd	0.3687		3rd	0.3748
	4th	0.4908		4th	0.4983

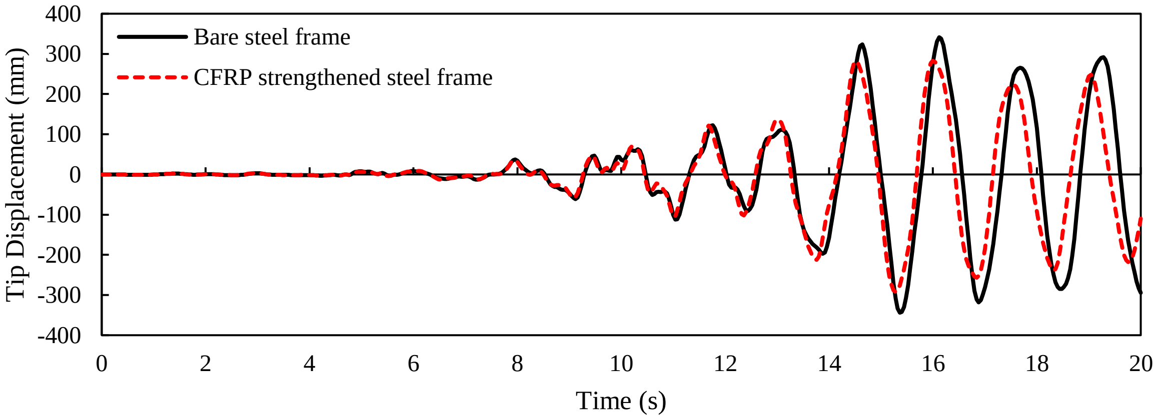
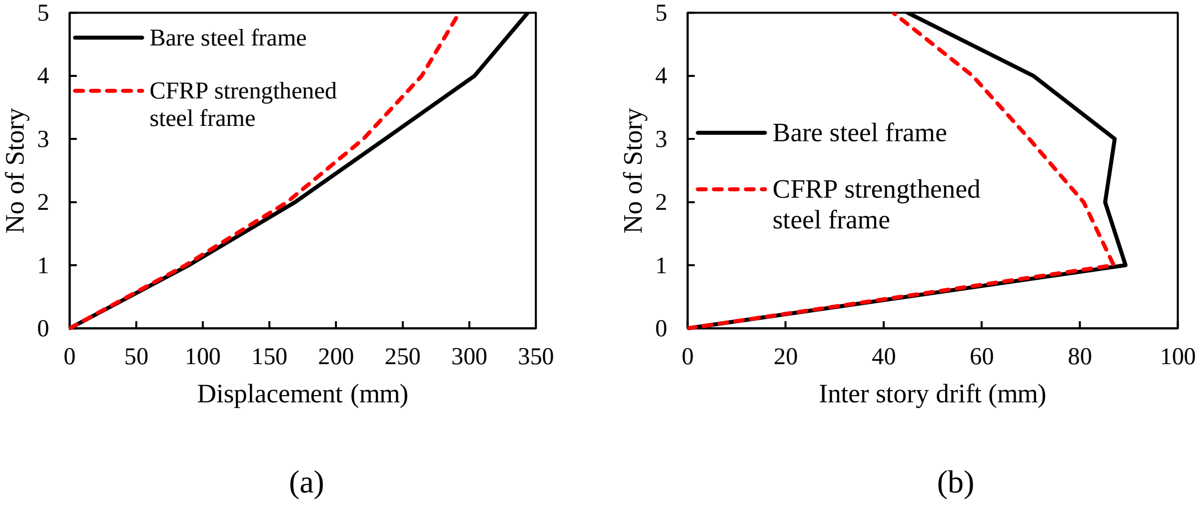


Figure 5: Tip lateral displacement comparison of Bare and CFRP strengthened steel frame



(a) (b)

Figure 6: (a) Lateral displacement and (b) inter story drift at each story comparison of Bare and CFRP strengthened steel frame

Effect of CFRP Thickness

The thickness of CFRP has been varied in the present study to evaluate the effect of CFRP thickness on the seismic responses of CFRP strengthened rigid steel frame. The FE model of five-story steel frame retrofitted with three layers of normal thickness CFRP and high thickness CFRP has been developed. The same unidirectional MBrace CF130 of 0.176 mm thick CFRP of previous section with same mechanical properties as Table 1 is used as normal thickness CFRP. In addition, unidirectional QuakeWrap TU27C of 0.524 mm thick CFRP is used as high thickness CFRP. QuakeWrap Australia has manufactured the TU27C CFRP and provided the mechanical properties. The modulus of elasticity, tensile strength and density of TU27C are 231 GPa, 3800 MPa and 1800 kg/m^3 respectively. Hence both normal thickness CFRP and high thickness CFRP have almost same mechanical properties except the thickness which is required to predict the effect of the CFRP thickness. The same adhesive used in previous section is considered here as well with the same mechanical properties shown in Table 1. Then the normal thickness and high thickness CFRP strengthened steel frames were simulated under the same Northridge 1994 earthquake excitation.

The modal properties, simulated by natural frequency analysis, of the steel frames strengthened with normal and high thickness CFRP are provided in Table 3. The tip lateral displacement comparison of normal and high thickness CFRP is shown in Fig. 7. The maximum lateral displacement and inter-story drift at each story of steel frame strengthened with normal and high thickness CFRP are shown in Fig. 8(a) and Fig. 8(b) respectively. It can be concluded from those figures that the high thickness CFRP has better seismic performance compared to normal thickness CFRP. After strengthening with high thickness CFRP, the tip lateral displacement of five-story steel frame has been decreased by 34.38%, while for normal thickness CFRP that is 15%. For strengthening the rigid steel frame high thickness CFRP is more effective contrast to normal thickness CFRP. A similar outcome has been concluded in the previous study as well [12].

Table 3: Modal properties of the steel frames strengthened with normal and high thickness CFRP

Frame	Mode	Frequency (Hz)	Frame	Mode	Frequency (Hz)
Normal thickness CFRP	1st	0.0834	High thickness CFRP	1st	0.0867
	2nd	0.1519		2nd	0.1595
	3rd	0.3748		3rd	0.3847
	4th	0.4983		4th	0.5107

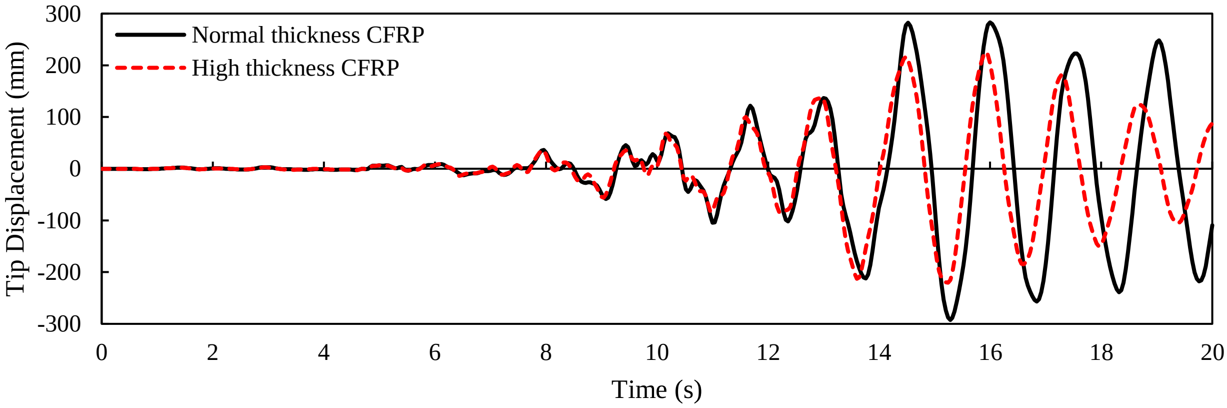
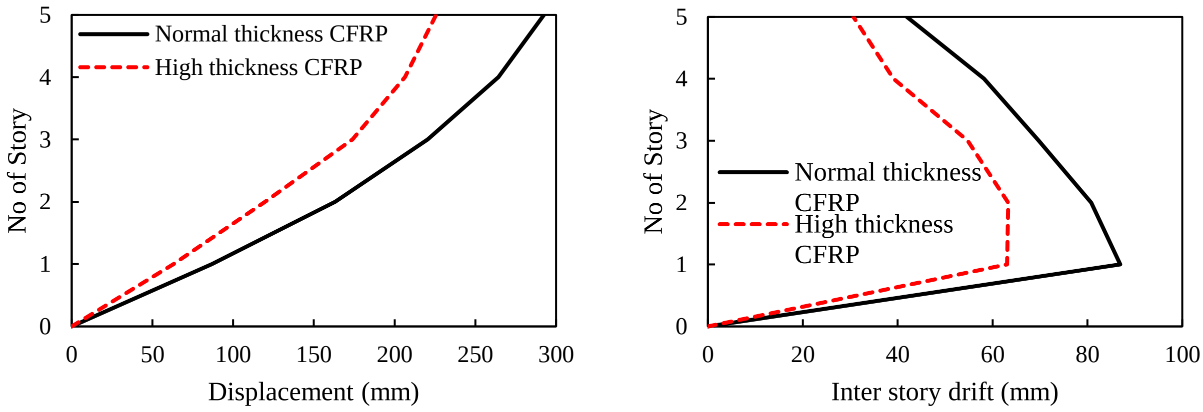


Figure 7: Tip lateral displacement comparison of normal and high thickness CFRP



(a) (b)

Figure 8: (a) Lateral displacement and (b) inter story drift at each story comparison of steel frame strengthened with normal and high thickness CFRP

Conclusion:

The seismic responses of bare and CFRP strengthened steel frame has been evaluated through numerical study. At the beginning of the validation, the FE simulation technique was performed by comparing the results with available experimental results. The good matching between FE simulated and experimental results confirmed the accuracy of FE modelling technique to simulate the seismic behaviour of bare and CFRP strengthened steel frame. Then the seismic responses of full-scale single-bay five-story bare and CFRP strengthened steel frames were investigated. From where it is clear that the CFRP strengthening technique is very effective to enhance the seismic performance of rigid steel frame. After strengthening with CFRP, the tip lateral displacement of five-story steel frame has been decreased by 15%. Furthermore, the thickness of CFRP has been varied to evaluate the effect of CFRP thickness on the seismic responses of CFRP strengthened rigid steel frame. It can be concluded that the steel frame strengthened with high thickness CFRP has shown better seismic performance compare to normal thickness CFRP. After strengthening with high thickness CFRP, the tip lateral displacement of five-story steel frame has been decreased by 34.38%, while for normal thickness CFRP that is 15%. For strengthening the rigid steel frame high thickness CFRP is more effective contrast to normal thickness CFRP.

References:

[1] Guha-Sapir D, Below R, Hoyois P. EM-DAT: International disaster database. Cathol Univ Louvain Brussels, Belgium 2015.

[2] Seica M V., Packer JA. FRP materials for the rehabilitation of tubular steel structures, for underwater applications. Compos Struct 2007;80:440–50. doi:10.1016/j.compstruct.2006.05.029.

[3] Batuwitage C, Fawzia S, Thambiratnam DP, Tafsirojjaman T, Al-Mahaidi R, Elchalakani M. CFRP-wrapped hollow steel tubes under axial impact loading. Tubul. Struct. XVI Proc. 16th Int. Symp. Tubul. Struct. (ISTS 2017, 4-6 December 2017, Melbourne, Aust., CRC Press; 2017, p. 401.

[4] Tafsirojjaman T, Fawzia S, Thambiratnam D, Zhao XL. Behaviour of CFRP strengthened CHS members under monotonic and cyclic loading. Compos Struct 2019;220:592–601. doi:10.1016/j.compstruct.2019.04.029.

[5] Alam MI, Fawzia S, Tafsirojjaman T, Zhao XL. FE modeling of FRP strengthened CHS members subjected to lateral impact. Tubul. Struct. XVI Proc. 16th Int. Symp. Tubul. Struct.

(ISTS 2017, 4-6 December 2017, Melbourne, Aust., CRC Press; 2017, p. 409.

[6] Fernando ND. Bond behaviour and debonding failures in CFRP-strengthened steel members. The Hong Kong Polytechnic University, 2010.

[7] Alam MI, Fawzia S. Numerical studies on CFRP strengthened steel columns under transverse impact. Compos Struct 2015;120:428–41. doi:10.1016/j.compstruct.2014.10.022.

[8] Xiao Z-G, Zhao X-L. CFRP repaired welded thin-walled cross-beam connections subject to in-plane fatigue loading. Int J Struct Stab Dyn 2012;12:195–211.

[9] Strand7. Strand7 Finite Element Analysis System 2007.

[10] Tafsirojjaman, Fawzia S, Thambiratnam D. Enhancement Of Seismic Performance Of Steel Frame Through CFRP Strengthening. Procedia Manuf 2019;30:239–46. doi:10.1016/j.promfg.2019.02.035.

[11] Association CS. CAN/CSA-S16. 1-M89. Limit States Design of Steel Structures. Association canadienne normalisation; 1990.

[12] Tafsirojjaman T, Fawzia S, Thambiratnam D, Zhao XL. Seismic strengthening of rigid steel frame with CFRP. Arch Civ Mech Eng 2019;19:334–47. doi:10.1016/j.acme.2018.08.007.

[13] Ranf RT, Eberhard MO, Berry MP. Pacific Earthquake Engineering Research Center. Univ California, Berkeley 2001.