Elastoplastic Quasi-Static and Impact Load Response of Steel Structure Sub-Assemblage with CFRP Strips

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Original Publication Citation

Al Aloosi, A., & Razzaq, Z. (2023). Elastoplastic quasi-static and impact load response of steel structure sub-assemblage with CFRP strips. *European Journal of Engineering and Technology Research*, *8*(2), 13-15. https://doi.org/10.24018/ejeng.2023.8.2.2968

Elastoplastic Quasi-Static and Impact Load Response of Steel Structure Sub-Assemblage with CFRP Strips

Ali Al Aloosi and Zia Razzaq

Abstract — **Presented in this paper is the outcome of an experimental investigation of the elastoplastic quasi-static and impact load response of a steel sub-assemblage constructed using a pair of hollow square section members with or without Carbon Fiber Reinforced Polymer (CFRP) strips. The sub-assemblage consists of a long structural member welded to a short member, thus representing a typical combination of a column and a beam on the face of a multi-story steel building frame. The column is subjected to a lateral quasi-static or impact load. Tests are conducted on four separate steel sub-assemblages. The first two tests are conducted with a gradually increasing flexural load applied at the midspan of the column up to the collapse condition without and with CFRP strips, respectively. Additional two tests are performed with a flexural impact load applied at midspan of the column also both without and with CFRP strips, respectively. The results of the study show that CFRP strips substantially increase the quasi-static collapse load of the sub-assemblage. However, when subjected to an impact load, the steel structure sub-assemblage with CFRP strips developed smaller strains in comparison with those without the CFRP strips. The post-impact time-dependent strains also became considerably smaller for the sub-assemblage with CFRP strips.**

Keywords — **Elastoplastic, Quasi-Static, Impact Load Response, Steel Structure Sub-Assemblage, Carbon Fiber Reinforced Polymer (CFRP) Strips.**

I. Introduction

Research related to the impact load response of multi-story steel buildings gained considerable importance after the well-known 9/11 events in New York city causing catastrophic collapse of the World Trade Towers [1]. In addition, the need for finding means of strengthening structures to better resist such a loading condition also became apparent. Whereas the strengthening methods utilizing Carbon Fiber Reinforced Polymer (CFRP) strips and sheets have been evolving over the past decade for quasi-static loading conditions, studies on its effectiveness under dynamic or impact loading conditions, however, are far from few. Galal and El-Sawy [2] investigated three retrofitting strategies for enhancing the response of existing steel moment resisting frames designed for gravity loads. The response of the damaged frames was evaluated when retrofitted with Fiber-Reinforced Polymer (FRP) composites. Wen *et al.* [3] proposed a quasi-static procedure based on the principle of virtual work for estimating the dynamic plastic response and failure of clamped metal beams subjected to a low velocity impact at any point on the span by a heavy mass. Liu and Jones [4] conducted a series of tests on clamped metal beams struck by a mass at various impact points and observed tearing and shear failure modes. Majid, Wu, and Cunningham [5] used finite element modelling of CFRP-strengthened steel columns under impact and found a significant improvement in their performance. The present study is focused on both quasi-static and impact load response of a building steel structure sub-assemblage both with and without the use of longitudinal CFRP strips.

II. Problem Statement

The focus of the study presented is on comparing the experimental performance of a two-member steel structure sub-assemblage when subjected to a gradually increasing or quasi-static load up to the structural collapse condition as well as under impact loading both without and with the use of CFRP strips. Laboratory test results on scaled-down steel structure models are presented herein, Specifically, the load versus deflection relations under quasi-static loading up to collapse are generated to determine the influence of the CFRP strips. For the impact load tests, steel strain versus time relations is generated in order to observe the performance of the sub-assemblage both without and with CFRP strips.

III. Experimental Investigation

Fig. 1 shows a schematic of the steel structure sub-assemblage and consists of a long structural member BT welded at T to a short structural member RS at its midspan. The end B is attached to a support frame providing a partially restrained end condition. Member RS has its ends partially restrained. Each of the two members is a 2 × 2 × 0.125 in. square steel tube. The length L of the long member BT is 66 inches, and the length RS of the short member is 30 inches. Although the sub-assemblage is shown in Fig. 1 in a horizontal plane, it represents a portion of the vertical face of a typical steel building, with BT as a 'vertical column' and RS as the beam welded to the 'top' end T of the column.

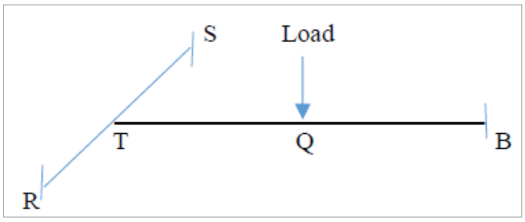

Fig. 1. Schematic of steel structure sub-assemblage.

Submitted on December 29, 2022
Published on March 14, 2023
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The "Load" shown in Fig. 1 represents a flexural quasi-static, or an impact load. Accordingly, the laboratory tests are conducted on the steel sub-assemblage mounted in a horizontal plane whereas the applied loading is vertical. The test setup also made application of the impact load simpler which was achieved by vertically dropping a solid steel cylinder at the midspan point Q of member BT. Fig. 2 shows the sub-assemblage with a hydraulic jack to apply the midspan quasi-static load. Fig. 3 shows the test setup for the impact load application.

Fig. 2. Sub-assemblage setup for quasi-static load test.

Fig. 3. Sub-assemblage setup for impact load test.

Fig. 4 shows the characterization of end spring stiffnesses for the structural sub-assemblage in which the torsional and flexural stiffnesses of the member RS are depicted by spring constants k_T and K_{spr}, respectively. The spring constant at B is k_B. The values of k_T, K_{spr}, and k_B are 1.5 × 106 kip-in/rad, 6.0 × 106 kip-in/rad and 34.0 × 103 kip/in., respectively. A quasi-static test was first conducted on the sub-assemblage without any CFRP strips. A gradually increasing load was applied at midspan location indicated by the point Q in Fig. 1 and Fig. 2 until the sub-assemblage collapse occurred. Next, a quasi-static sub-assemblage load test was conducted with CFRP strips bonded to the entire length of the member BT at its bottom surface as shown in the cross-sectional view in Fig. 5. The Young's modulus values for steel and CFRP material are 30,000 ksi, and 20,000 ksi, respectively. The yield stress of steel was found to be 62 ksi, and the ultimate strength of CFRP strips was measured as 255 ksi. The dynamic (impact) tests were performed on two additional sub-assemblages, namely, without and with CFRP strips, respectively. Impact loading was applied by a dropping a 400-lb solid steel cylinder of 5 ft. length at the point Q of the sub-assemblage shown in Fig. 1. The steel cylinder was lifted to a six-inch clear height above the top of the member BT at Q and then dropped.

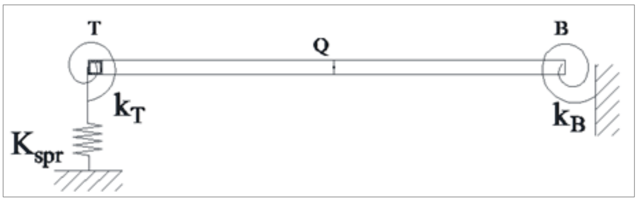

Fig. 4. Characterization of end spring stiffnesses.

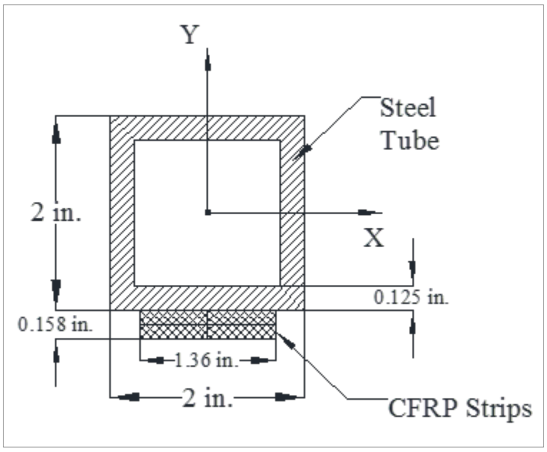

Fig. 5. Cross-section of member BT with CFRP strips.

IV. Results

Fig. 6 compares the load-deflection relations at Q for the sub-assemblage both with and without CFRP strips. The comparison shows a substantial increase in both the stiffness and the ultimate load-carrying capacity of the sub-assemblage when CFRP strips are used. Fig. 7 shows a comparison of the dynamic strain-time relations at Q due to impact load. The strain readings are recorded using electrical-resistance strain gauges mounted at the bottom face of the member BT at Q. It is seen that both with and without the CFRP strips, the sub-assemblage performed in a very similar manner up to about t = 0.075 seconds, whereas the peak strain was nearly 14 percent higher when no CFRP strips are used. Furthermore, the 'residual natural vibration' performance of the sub-assemblage with CFRP strips is superior to that of the sub-assemblage without CFRP strips in that the former developed substantially lower strains. It should be noted that after about t = 0.075 seconds, the impactor was resting on the sub-assemblage at location Q while the sub-assemblage was still vibrating.

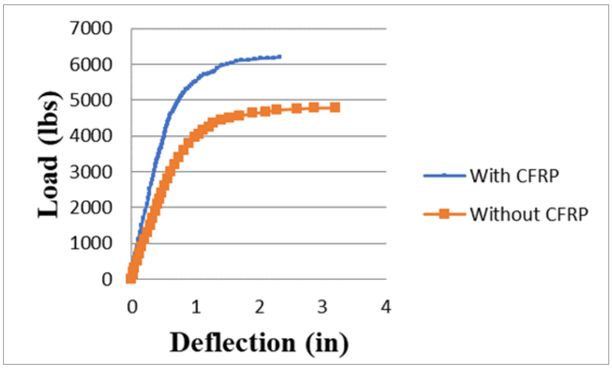

Fig. 6. Quasi-Static Load-deflection Relations at Q.

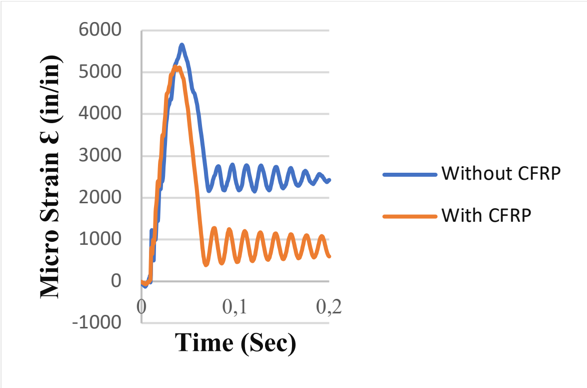

Fig. 7. Dynamic strain-time relations at Q due to impact load.

V. Conclusions

The study shows that the addition of CFRP strips increased the quasi-static collapse load of the sub-assemblage by about 26 percent. When subjected to impact load, the use of CFRP strips reduced the peak strain by nearly 14 percent as compared to that measured in the sub-assemblage without the CFRP strips. In addition, the post-impact time-dependent strains are found to be substantially smaller in the sub-assemblage with CFRP strips.

Conflict of Interest

Authors declare that they do not have any conflict of interest.

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