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Efficiency of Reinforcement Materials on Bus Frame Stability

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Abstract: This paper presents the results of an experimental investigation of the CFRP and epoxy foam's effect on bus frame stability. As part of the research, a series of quasi-static tests were conducted to analyze the behavior of the test specimen in four experimental scenarios. Initially, the steel structure was tested, followed by reinforcement with carbon fiber on one post, then extending the carbon fiber reinforcement to both the crossbar and side posts. The final scenario involved filling the steel structure with epoxy foam, excluding carbon fiber. Generally, according to the results obtained, the reinforcing materials have a significant impact on the structural stability of the specimen structure. Namely, the deformation energy in the case of foam and CFRP reinforcement decreased by about 15 %.

Keywords: bus frame; reinforcement materials; structural stability; deformation.

1 Introduction

Bus accidents occur frequently worldwide. In Europe, approximately 150K individuals sustain injuries, while 150 lose their lives annually due to such incidents [1]. In the United States, according to the National Highway Traffic Safety Administration's report, there were 16K injuries and fatalities resulting from bus crashes, with over half of the fatalities arising from non-collision accidents [2]. Consequently, prioritizing the safety of bus passengers has become a critical issue in the bus industry, reflecting the escalating safety challenges seen in the automotive sector. Safeguarding the physical safety of bus passengers isn't solely a matter of marketing; it's also a duty aligned with international standards.

Currently, one of the most promising methods of increasing the structural stability of passenger vehicles is the application of carbon fiber-reinforced polymer (CFRP) and epoxy foam [3-5]. A large number of different studies have been devoted to this issue. However, the reinforcement process is usually adapted to the specific characteristics of each structure, resulting in a customized investigation of each experimental case.

2 Test Configuration and Measuring Equipment

Experimental investigations were conducted at the Dynamic Testing Laboratory of the Research and Testing Institute in Pilsen s.r.o. (Czech Republic). The primary focus of the study was to assess the effectiveness of various reinforcing materials on the structural stability of the frame in passenger transport, specifically in the event of a bus rollover accident. In such situations, the roof and sidewalls undergo significant deformation, which can lead to a critical reduction in safe space, resulting in injury to passengers.

In the current study, a standard bus frame section was used as the test specimen. The experimental plan included conducting a series of quasi-static tests to analyze the behavior of the test specimen across four experimental scenarios. Initially, the investigation focused on a structure comprising solely of steel. After that, in the second scenario, the frame received reinforcement by carbon fiber exclusively on one side. Moving on to the third case, carbon fiber reinforcement (CFRP) was extended to cover both posts and the crossbar of the frame. It is crucial to note that in this configuration, the upper reinforcing lamella was positioned between welds. Finally, the fourth scenario involved filling the steel structure with epoxy foam, without adding carbon fiber.

Figure 1 illustrates the organization of the test bench for assessing the structural stability of the specimen under various scenarios. Classically, a hydraulic cylinder has been applied to simulate the force load on the frame, modeling conditions similar to those that occur when a bus rolls over. One end of the cylinder was attached to a separate base positioned at half the height of the frame, while the other end was linked to the upper corner of the segment via a load cell HBM S9M 20kN. Consequently, when the hydraulic cylinder exerted force, the load cell recorded the force characteristics at which the specimen deformed. It should be noted that in all experimental scenarios, a force of 10 kN was applied at 22 degrees relative to the horizontal plane.

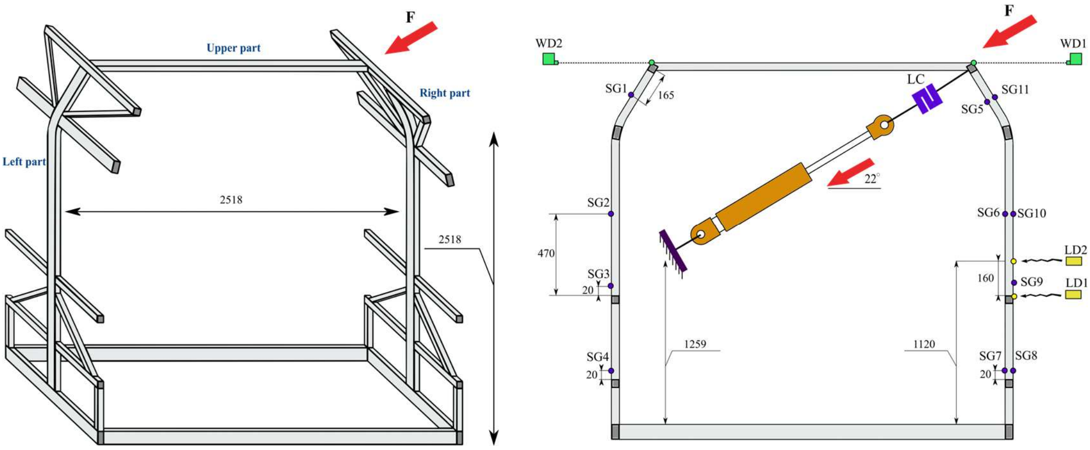

Fig. 1: Experimental setup, there a test specimen sketch on the left and a test bench on the right. Where SG - strain gauges, WD - wire digital sensors WDS-1000-P60, LD - laser distance sensors HG-C1200, LC - load cell HBM S9M/20kN.

Fig. 2: Practical implementation of the test bench and the placement of measuring sensors.

To quantify the deformation pattern of the specimen, a variety of measurement sensors were employed. Figure 2 depict the practical implementation of the test bench and the placement of measuring sensors. To assess the displacement of the specimen construction under load, two digital wire sensors WDS-1000-P60, were positioned at the upper corners of the frame. Moreover, two laser distance sensors, namely the HG-C1200, were strategically placed in the window area of the bus, where the gap between the frame and passengers is minimal. Therefore, in the event of extraordinary situations such as bus rollovers, the reduction of this space becomes critical for ensuring passenger safety. Furthermore, eleven strain gauges were used on both frame supports to evaluate the effect of different reinforcing materials on the structural stability of the specimen. Specifically, on the post where the deformation force was applied, seven sensors were positioned on both the inner and outer sides. Conversely, on the opposite spots, only four strain gauges were situated, exclusively on the outside. Experimental data were gathered and analyzed using the Catman software environment, with data collected at a frequency of 600 Hz from all the aforementioned devices.

3 Experimental Results

The experimental results in Fig. 3 show that in all test scenarios, the external load causes clear localized deformation zones that resemble bulges at the joints of the upper and side frame elements. It is notable that the orientation of the bulges differs depending on the side of the specimen. Specifically, the bulge on the right side displays a downward curvature, whereas on the left side, it curves upward. This contrast is attributed to the compression applied by the hydraulic cylinder on the right side. As a result, the greatest stress and subsequent plastic deformation of the structure are observed in this area. However, depending on the type of specimen reinforcement, the resulting bulges differ.

In the scenario involving the unreinforced frame (see Fig. 3), bulging occurs at distances of 22 mm and 41 mm from the right and left posts, respectively. However, in the case of carbon fiber reinforcement solely on the left side (see Fig. 4), the bulge shifts away from the right posts by 55 mm while remaining 41 mm from the left one. Whereas, in the foam reinforced scenario, the bulges appear symmetrically on both specimen sides at the mounting hole’s location at 51-55 mm (see Fig. 5). Moreover, the local concentration of significant stresses in this area leads to the appearance of cracks.

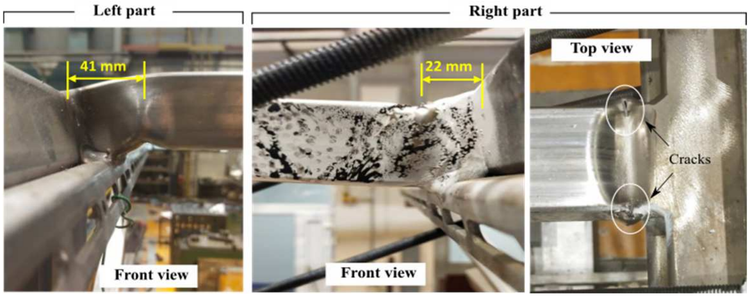

Fig. 3: Local deformation of the unreinforced specimen.

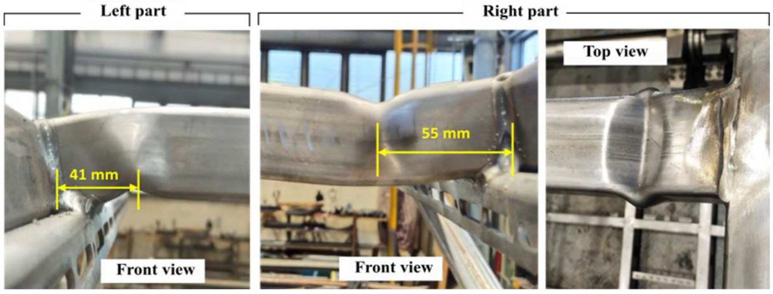

Fig. 4: Local deformation of the reinforced specimen with carbon fiber on one side.

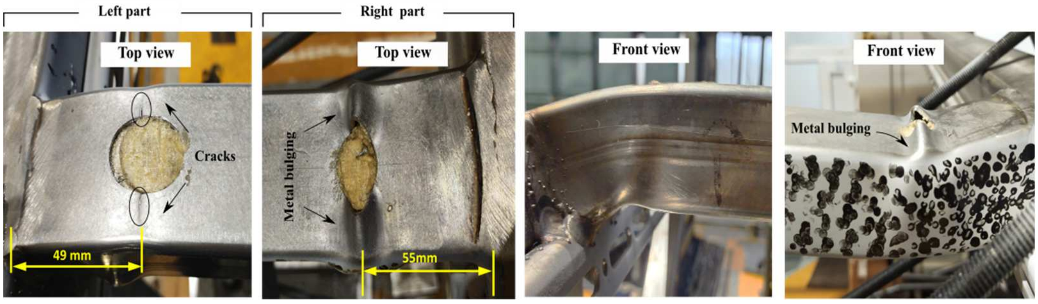

Fig. 5: Local deformation of the foam reinforced specimen.

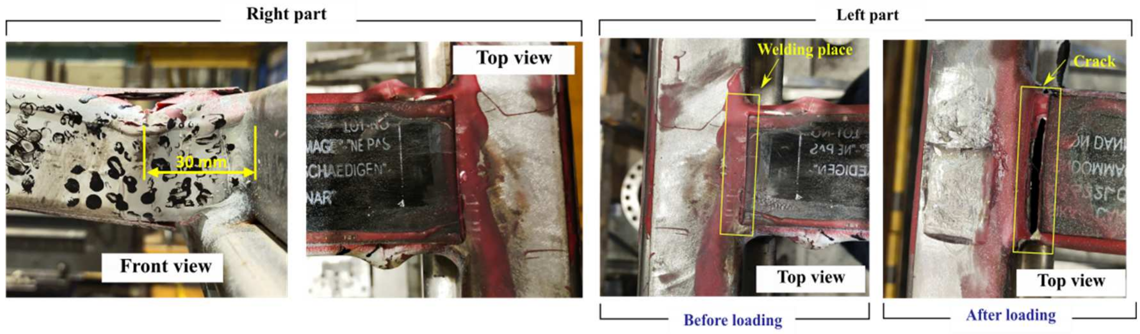

Fig. 6: Local deformation of the specimen reinforced with carbon fiber on both the crossbar and side posts.

The most pronounced impact of reinforcement becomes evident in the scenario involving the carbon fiber reinforcement of the crossbar and side posts. In particular, as a result of the effective stress redistribution in the specimen structure, a welded joint between the crossbar and the left post ruptured (see Fig. 6). It should be noted that this phenomenon was not observed in other test cases. Thus, in this scenario, the bulge is observed only on the right side, at a distance of 30 mm from the post.

As depicted in Fig. 7, the maximum displacement of the specimen construction across all experimental scenarios reached approximately 600 mm. This trend occurs because the applied deforming load of 10 kN exceeds the frame's ability to withstand deformation. Additionally, variations in maximum displacement between experimental cases are explained by tightening or loosening the connection between the hydraulic cylinder and load cell. The plateau observed on the graph indicates the stage of complete compression.

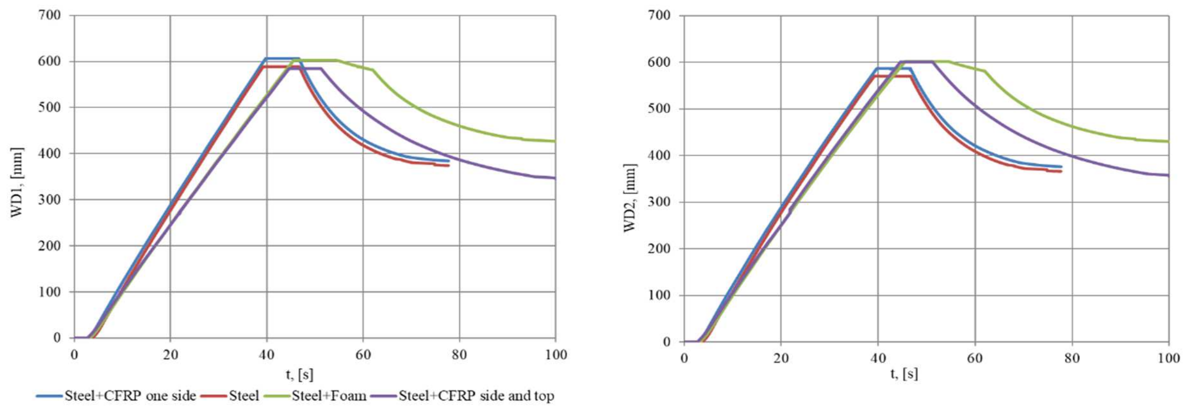

Fig. 7: Specimen displacement across different experimental scenarios. The left and right graphs correspond to the sides of the frame.

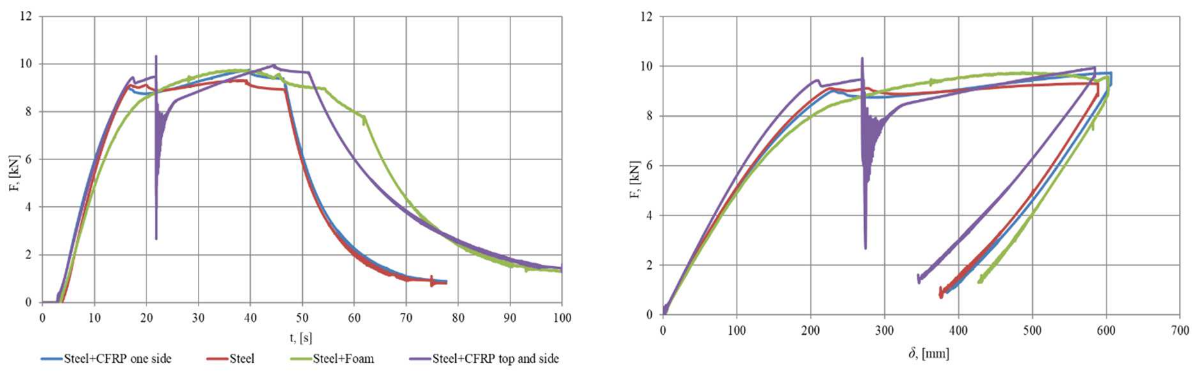

Fig. 8: Force-deformation dependence for all experimental scenarios.

Figure 8 depicts the force-displacement relationship for all experimental scenarios. Notably, the maximum deformation force is evident for specimen reinforced with carbon fiber on both the crossbar and side posts. Additionally, the obtained results exhibit a significant data perturbation at 22 seconds, which is attributed to the weld failure. It's worth noting that for all experimental cases, except for epoxy foam, the deformation curves exhibit clearly defined yield points. That indicates the elastic behavior of the specimen construction in this case. In contrast, in the foam scenario, a more pronounced plastic behavior is observed.

Additionally, the elastic deformation energy of the specimen was estimated based on the obtained data, considering the type of reinforcement. Calculation data in Fig. 3 showed that in the cases of epoxy foam and carbon fiber reinforcement on the crossbar and side posts, the deformation energy decreased by approximately 15%. Consequently, under these conditions, the frame requires less energy to maintain its shape under external loads. This achieved due to the higher strength of the structure, which efficiently absorbs and distributes energy during deformation, thus reducing energy losses attributed to elastic processes.

However, the data in Fig. 10 indicate that the carbon fiber reinforcement case is also characterized by the largest displacement of the structure. This contradiction is explained by the peculiarities of the stress distribution within the specimen construction. In a typical case, for an unreinforced specimen, a substantial portion of the external load energy rapidly converts into plastic deformation of the upper part of the frame. Meanwhile, the residual energy results in only a small displacement of the construction.

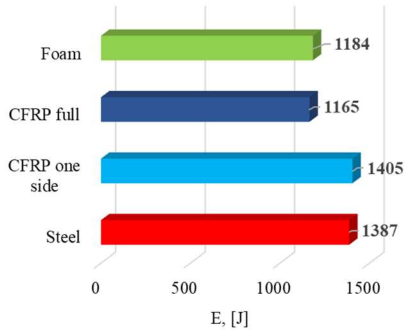

Fig. 9: Elastic deformation energy depending on the bus frame reinforcement type.

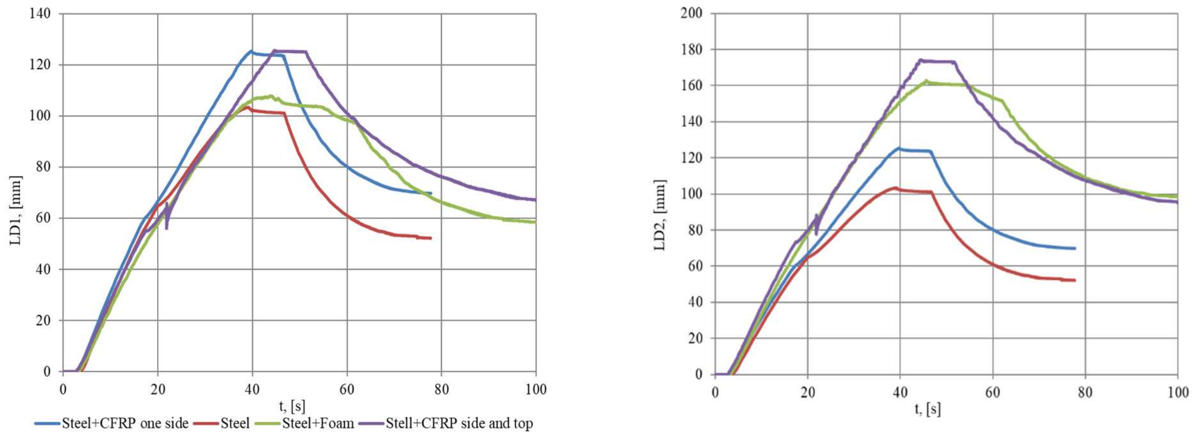

Fig. 10: Specimen displacement across different experimental scenarios.

In general, reinforcing materials have a significant impact on the structural stability of the sample structure. This effect is particularly evident in Fig. 11, which shows the strain estimation at measurement point 9. It can be observed that the foam and carbon fiber reinforcement led to approximately a 65% and 48% reduction in strain, respectively. Unfortunately, as already mentioned, in the case of carbon fiber on the crossbar and side posts, the data is only reliable up to 20 seconds due to structural weld failure.

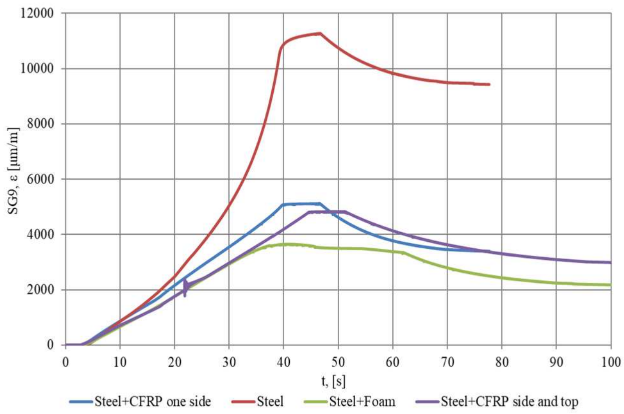

Fig. 11: Strain-time distribution at measurement point 9 depending on type reinforcement.

4 Conclusion

In the classical case of a frame without reinforcement, the structure undergoes significant plastic deformations due to the applied load. In contrast, the epoxy foam acts as an absorber of the deformation energy and helps to effectively distribute the resulting stresses evenly throughout the frame structure. Therefore, the plastic deformation on both sides of the frame is similar. This statement is also confirmed by the configuration of the resulting bulges, which are much wider than in other reinforcement test cases. At the same time, carbon fiber reinforcement increases the stiffness of the frame by effectively redistributing the stress state of the structure. However, it is important to emphasize that, unlike epoxy foam, carbon fiber does not absorb energy, but only redistributes it. This distinct feature causes a localized concentration of significant stress at the welded joints of the frame. Consequently, this concentration leads to the failure of the welded joint outside the carbon fiber reinforcement. Generally, it can be concluded that carbon fiber and foam reinforcement are effective approach to improving the stability of bus frame structures. Namely, their application reduced the deformation energy by almost 15%.

Acknowledgement

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References

[1] P. Albertsson, T. Falkmer, Is there a pattern in European bus and coach incidents? A literature analysis with special focus on injury causation and injury mechanisms, Accident Analysis and Prevention 37(2) (2005) 225–233, https://doi.org/10.1016/j.aap.2004.03.006.

[2] K. Kyoung-Tak et al., Design of a composite roll bar for the improvement of bus rollover crashworthiness, Composites Part B: Engineering 43 (2012) 1705–1713, http://dx.doi.org/10.1016/j.compositesb.2012.01.072.

[3] A. Pawlak et al., The Use of CFRP for Structural Reinforcement-Literature Review, Metals 12 (2022) 1470, http://dx.doi.org/10.3390/met12091470.

[4] R. Sen, L. Liby, A. Mullins, Strengthening steel bridge sections using CFRP laminates, Composites Part B: Engineering 32 (2001) 309–322, http://dx.doi.org/10.1016/S1359-8368(01)00006-3.

[5] J.G. Teng et al., Behaviour and strength of FRP-strengthened RC structures: A state-of-the-art review, Proceedings of the Institution of Civil Engineers-Structures and Buildings 156 (2003) 334–335, http://dx.doi.org/10.1680/stbu.156.3.334.37862.