








# On the Use of Carbon Fiber Composites for the Enhancement of the Rollover Resistance of Steel Buses

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**Abstract.** The increasing use of composites in vehicles in recent years is one of the current trends in the automotive industry. In particular, fiber composites are being used as reinforcements for the main structural elements of vehicles, due to their outstanding specific mechanical properties and low weight. When combined with metal parts, fiber composites can significantly enhance the crashworthiness of vehicle structures, by increasing their energy absorption capabilities and resistance to plastic deformations and permanent damage. This work presents CFRP reinforcements as a case study for enhancing the bending collapse behavior and crashworthiness of bus structures. The required calculations are based on a simplified “concept model” that includes the bending collapse behavior of the structural components, based on theoretical models calibrated with experimental results. The results demonstrate that the use of CFRP reinforcements improves the rollover crashworthiness of a bus structure, and need not be applied to the entire structure, but only to the critical parts where bending collapse is most likely to occur in a rollover accident.

**Keywords:** Carbon fiber composites · vehicle structures · bending collapse · concept modelling

## 1 Introduction

Design of lightweight structures often considers the full load capacity of a material instead of the yield strength [1]. This implies working in the plastic range of a material, which can be advantageous in applications with energy absorption and dissipation requirements. For instance, automobiles require that their structures absorb the kinetic energy of an impact accident, so it does not reach the passengers. On the other hand, weight reduction is required to reduce material and manufacturing costs, as well as fuel consumption. This means that the crashworthiness design needs be done with weight and manufacturing in mind.

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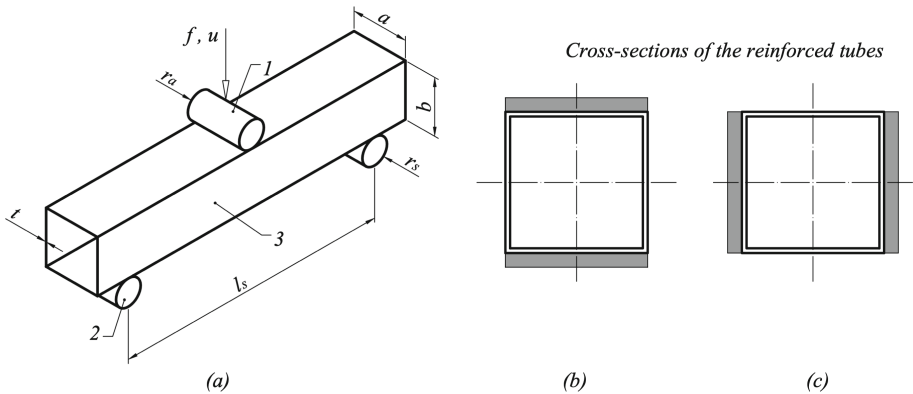
Additionally, rollover of buses is an extremely dangerous scenario. Although rare, circa 3% of all accidents, they are known to be particularly lethal [2]. For this reason, several efforts have been devoted to avoiding and preventing rollovers [3, 4], as well as to mitigate the potentially deadly effects, mainly by improving the bending collapse behavior of the steel tubes used [5–11]. Regulations and design rules have also been implemented internationally, with the UN/ECE R66 [7] being the most used. This regulation requires the characterization of the bending collapse of the tubes that form the structure.

In this study, previously developed localized reinforcements and collapse theories implemented in [12, 13] are employed and introduced into a “concept model” representative of a bus structure in a rollover test. It is noteworthy that although this is not the first-time concept models have been used to analyze structures in plastic regimes, it is one of the first times for multimaterial systems: steel structures reinforced with composite materials.

## 2 Methodology

### 2.1 Bending Collapse Experimental Setup

In order to characterize the bending collapse, three-point bending experiments are performed on a universal testing machine, following the schemes shown in Fig. 1.



**Fig. 1.** (a) Three-point bending test scheme aimed to produce failure in the middle of the test specimen. (1) force applicator, (2) fixed support cylinders, (3) test specimen. (b) Cross-section of tube with reinforced flanges or UD reinforcements. (c) Cross-section of tube with reinforced webs or LR reinforcements.

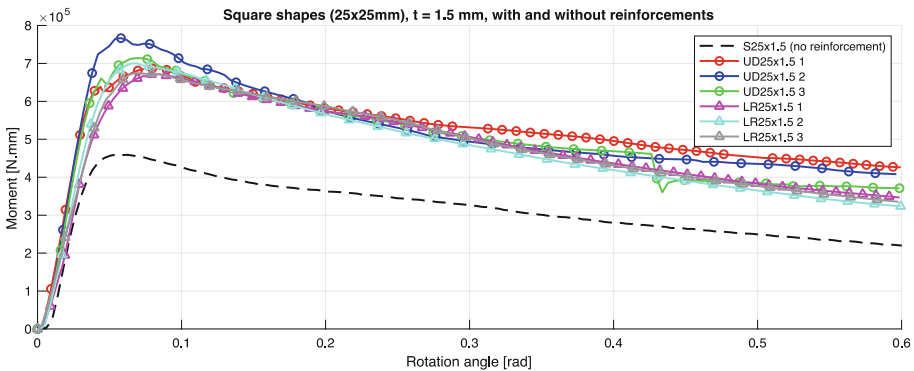
The test specimens are based on tubes of S275 steel. The reinforcements are made from carbon fiber reinforced polymer (CFRP), based on bidirectional carbon fiber weave and epoxy resin as polymer. Hand layup is used to prepare CFRP plates, which are then cut to the size of the steel tubes. Both materials are then joined with an epoxy-based structural adhesive Sikapower 1277.

Once specimens are ready, three sets of bending experiments are performed:

1. Specimens without reinforcements (steel tubes). The results of this set are used as a baseline to evaluate the influence of the reinforcements.
2. Specimens with Up-Down reinforcements (UD), shown in Fig. 1(b), cover the flanges of the tube.
3. Specimens with lateral or Left-Right reinforcements (LR), shown in Fig. 1(c), cover the webs of the tube.

## 2.2 Concept Modeling of the Structure

The results of the bending tests are used to calibrate the theoretical models developed by the authors [12, 13]. The output of these tests is moment – angle ( $M - \theta$ ) curves, as shown in Fig. 2. Note that during these tests, the influence of the reinforcements is readily apparent.



**Fig. 2.** Example of experimental  $M - \theta$  curves for a tube of 25 mm and thickness of 1.5 mm. S25x1.5 represents a tube without reinforcements. Results based on [12].

The structure itself is modeled as beam line elements (see Fig. 3), and the zones prone to bending collapse are modeled as non-linear springs with the  $M - \theta$  curves as their constitutive law; as this method provides accurate results [14–16].

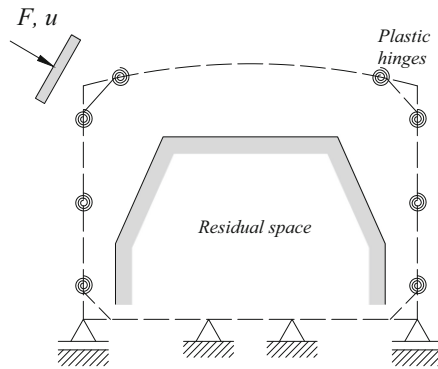
Additionally, to simulate a rollover event, quasi-static loads are applied through a rigid inclined plane, which represents the ground. The calculation is carried out until contact between the residual space and the structure is detected. The residual space is modeled as a rigid surface fixed to the ground. In this calculation, the measured or observed quantities are the force ( $F$ ) and displacement ( $u$ ) of the rigid inclined surface (see Fig. 3). Therefore, the absorbed energy ( $E_{abs}$ ) by the structure can be calculated as

the area under the curve  $F$ - $u$  as shown in Eq. 1:

$$E_{abs} = \int_0^{u_{max}} F \cdot du \quad (1)$$

To obtain a complete vision of the influence of the reinforcement and tube sizes on the crashworthiness, ten different dimensions for the structural loop of the concept model are tested. These dimensions are defined using Latin Hypercube sampling and allow to have a complete vision of the influence of every parameter. Furthermore, similarly to the bending tests, three sets of simulations are performed:

1. Rollover of the concept model of a steel structure.
2. Rollover of the concept model of a steel structure with UD reinforcements.
3. Rollover of the concept model of a steel structure with LR reinforcements.

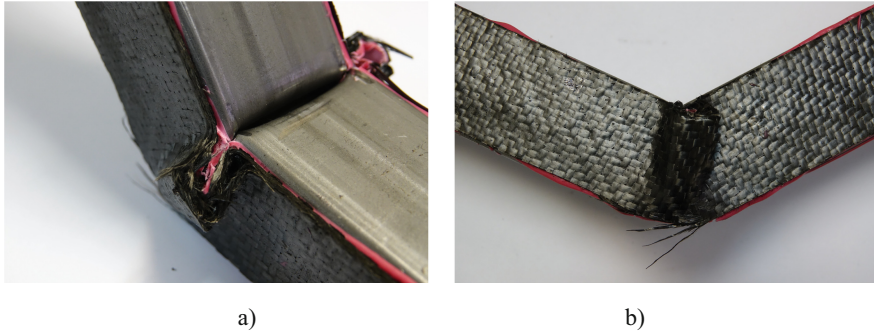


**Fig. 3.** Concept model of the bus structure. The springs are defined with a non-linear curve obtained from the bending collapse theoretical models.

### 3 Results

Three-point bending tests reveal important details about the failure modes, some exemplified in Fig. 4. As expected, steel shapes concentrate the plastic deformations in the “bulges”. Reinforced shapes also show damaged composites due to delamination in the zones near the “bulge”, with the rest of the composite seemingly showing no damage. Since damage is only restricted to the collapse zone (see Fig. 4), then the reinforcements only need to be applied in the critical zones, and thus significant savings in CFRP manufacturing can be achieved when applied to a large structure.

Furthermore, the bus structure simulations show that most of the tested sizes benefit from the composite reinforcements, regardless of the variant, as shown in Table 1. Additionally, the UD reinforcements can provide in general a better enhancement in crashworthiness than the LR reinforcements, which can be explained by the larger increase in the moment of inertia of the cross section. On the other hand, by comparing shapes of



**Fig. 4.** Plastic deformation produced by bending collapse on a tube with LR reinforcements. Failure and delamination of the composite is restricted to the collapse zone. The CFRP does not suffer damage outside the collapse zone.

similar thickness, it can be inferred that the addition of any type of localized reinforcement can have a similar effect than increasing the thickness of the steel base shape. By increasing the thickness of a shape, the whole structure grows in weight, since shapes are produced with a constant thickness. However, if the CFRP reinforcements are applied only to the critical zone, the crashworthiness is enhanced without a significant increment in weight.

**Table 1.** Results of the rollover calculations of structures with base tubes of different sizes and different reinforcements. The percentages are taken using the steel structure as reference.

ID	Height b [mm]	Width a [mm]	Thickness t [mm]	UD reinforc		LR reinforc	
				Fmax %	Eabs %	Fmax %	Eabs %
1	62.5	32.5	2.6	+18.9	+2.8	+18.7	+2.4
2	52.5	72.5	1.6	+60.5	+64.5	+27.2	+34.0
3	32.5	77.5	3.9	+8.7	+0.0	+8.5	-0.4
4	77.5	57.5	3.8	+18.7	+1.7	+18.7	+1.2
5	57.5	62.5	3.1	+36.6	+16.6	+28.9	+14.6
6	37.5	37.5	3.4	+6.5	-2.7	+6.3	-3.4
7	47.5	42.5	2.9	+19.4	+6.1	+19.2	+5.6
8	42.5	52.5	2.1	+39.1	+24.0	+29.5	+20.9
9	67.5	47.5	2.4	+38.9	+21.0	+28.4	+18.0
10	72.5	67.5	1.9	+45.5	+55.2	+27.5	+32.3

## 4 Conclusions

This study explores the impact of adding composite material reinforcements, specifically CFRP, on the rollover resistance of a bus. The results show that partial local reinforcements, located in the areas prone to bending collapse, have a positive effect on the structure's rollover resistance (up to 64% increase) and increase the absorbed energy (up to 60% increase) in the event of an accident, without significant weight penalties (up to 15% increase). The use of recycled composite materials is also a possibility, which extends the composite's lifespan and makes it an environmentally friendly alternative [17, 18]. However, covering an entire metal structure with composite material can be costly, so incorporating composite materials only in areas that are prone to localized failure is a more cost-effective solution. This method is not only applicable to new designs but also existing structures that need repair or reinforcement to comply with current and newer regulations and standards.

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