

Crashworthiness and Numerical Analysis of Composite Inserts in Vehicle Structure

Chung-Kyu Park and Cing-Dao Kan
The George Washington University

Steven Reagan
L & L Products Inc.

Balachandra Deshpande
SimaFore Inc.

Pradeep Mohan
The George Washington University

ABSTRACT

The objective of this research is to understand the crashworthiness performance of composite inserts in vehicle structure and to improve the numerical model of steel-composite combined structure for providing better prediction in the design process of composite inserts. A simplified steel-composite combined beam structure is used for three-point bending tests. Epoxy-based structural foam and 33% short glass fiber reinforced nylon composite insert are considered as composite fillers in empty sections of double hat-type steel beam structure. Four cases based on the different combination of composite materials are considered.

In the series of physical three-point bending tests, the force-displacement (F-D) curves and material behaviors are investigated. The test results show that the composite insert greatly contributes to improve the crashworthiness of beam structure as well as to reduce the vehicle weight. Especially, the adhesive failure of structural foam and the brittle fracture mode of composite insert are greatly influential to the resistance force level in the three-point bending test. In the numerical study, a concern is to build a practical FE model, which can be used in full-scale vehicle crash simulation. The parametric study shows that parameters related to material and contact types are critical to simulate the adhesive failure of structural foam and the brittle fracture of composite insert. The final simulation results show good agreement with the physical tests.

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INTRODUCTION

Over the last several years, there has been an increase in demand for developing more fuel-efficient vehicles, not only by consumers, but also by governments. In 2011, US government announced a historic agreement with thirteen major automakers to pursue the next phase in the Administration's national vehicle program, increasing fuel economy to 54.5 miles per gallon for cars and light-duty trucks by Model Year 2025 [1]. In respond to new fuel standards, new advanced technologies and lighter materials have been introduced and investigated. The "mixed material

vehicles" will likely become a norm as new materials and bonding technologies mature. In addition to standard ferrous metals (steel, aluminum, and magnesium), innovative plastics and composites will start finding increasing use in order to meet the proposed fuel efficiency requirements without sacrificing current crashworthiness performance.

Composite structural inserts are a well-known and innovative technology in the automotive industry to improve safety, NVH and fatigue life of vehicles, as well as to reduce vehicle weight and manufacturing cost. In general, structural inserts are light-weighting macro-composites made of a metal or plastic carrier and structural foams made of an epoxy

based, thermosetting adhesive. Figure 1 shows typical applications in the vehicle structure. Typical components of the composite insert are custom designed and developed for the structural needs and geometry of an automotive component for improved safety performance. So, composite inserts must perform their structural safety function in large deformation and high strain-rate crash environments.

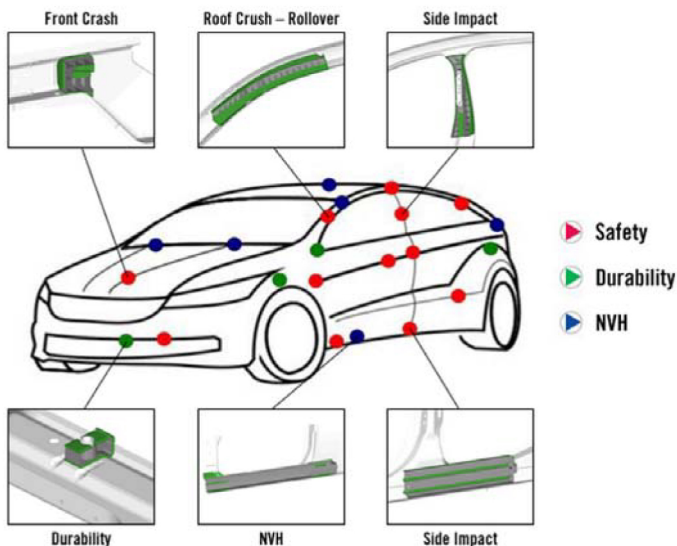


Figure 1. Applications of composite inserts [2].

Steel is a widely used material in the vehicle structure, and its design and analysis methods are well understood and developed based on accumulated knowledge and collective experience. However, design and analysis of steel-composite combined structures are not as well understood since composite materials have significantly different material characteristics compared to steel. Composites are anisotropic and brittle, whereas steel is commonly assumed to be isotropic and ductile. The existing knowledge and experience from analyzing steel-only structures are not sufficient to design and analyze steel-composite combined structures accurately.

The design process of these components includes computer-aided engineering (CAE) simulations where the surrounding structure of the vehicle is modeled along with the composite insert and adhesive, using detailed finite element (FE) analysis. It is known that a key contributor to the overall failure predictability is the mode, severity, and timing of the failure of the composite. Since the failure mechanism of composite components in vehicle structure is quite complex, there are many numerical parameters which affect the crash performance of steel-composite combined structures in the FE analysis.

The objective of this research is to understand the crashworthiness performance of a steel-composite combined structure and to improve its numerical model for providing better prediction in the design process of composite inserts. In this study, a simplified steel-composite combined beam

structure is used for physical three-point bending tests. From the series of tests, the crashworthiness performance of composite inserts in a steel beam structure was evaluated and the resistance force level of a beam and the failure mechanism of composite inserts were investigated [3]. Later on, a sensitivity analysis for a three-point bend CAE simulation was conducted to identify influential parameters in the numerical model of steel-composite combined structures, and to improve the correlation of the simulation with respect to the physical test. In this paper, physical test results are analyzed and influential parameters of CAE simulations of steel-composite combined structures are described.

MODEL DESCRIPTION

In order to isolate the effect of vehicle geometry and loading conditions, a simplified steel-composite combined beam structure is developed. The steel-composite combined beam structure is composed of steel beam, structural foam, and composite insert. The steel beam is composed of three components, an outer hat section, an inner hat section and a bottom plate, as shown in Figure 2. The beam length is 800.0 mm and a gap distance between the outer hat section and the inner section is 4.9 mm. The beam is made from high-strength low alloy (HSLA) steel. The thickness of all three components is 1.0 mm. The flanges of all three components are spot-welded with an interval of 35.0 mm. The beam section has two empty spaces, an outer cavity (Cavity A) and an inner cavity (Cavity B). Those cavities are filled with composite materials for reinforcement of the beam.

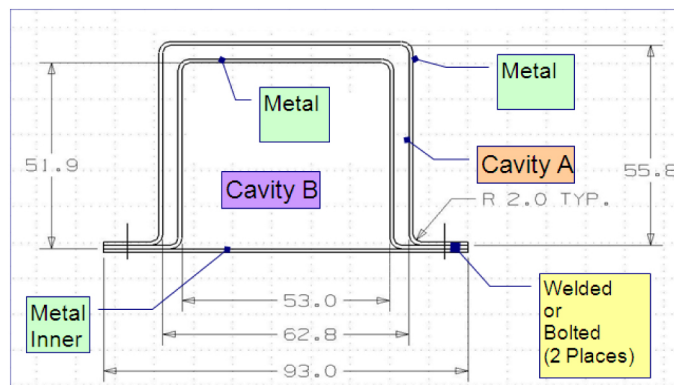


Figure 2. Description of beam section (unit: mm).

The outer cavity is filled with epoxy-based structural foam. The structural foam is injected at the longitudinal center of the outer cavity with a length of 300.0 mm. The inner cavity is filled with a composite insert which is made of 33% short glass fiber reinforced nylon composite. The dimension of the composite insert is 300.0 mm (L) × 43.0 mm (W) × 43.0 mm (H). The composite insert has a grid structure with one vertical rib in longitudinal direction and eight vertical ribs in transverse direction as shown in Figure 3(a). The half of its bottom is covered and the other half of its top is covered as shown in Figure 3(b). The average thickness

of the composite insert is 2.0 mm. The composite insert is located at the section center and the longitudinal center of the inner cavity, and the structural foam is applied to around the composite insert for positioning as well as for reinforcement. The inside of composite insert remains empty.

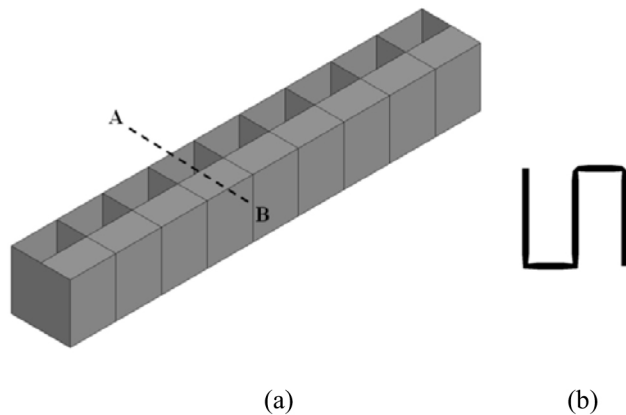


Figure 3. Description of composite insert; (a) composite insert, (b) A-B section of composite insert.

A three-point bending test is adapted to evaluate the crashworthiness of the steel-composite combined beam structure. The test setup is described in Figure 4. The both ends of the beam are supported by rigid supports and the middle of the beam is loaded by a punch with a speed of 5.0 mm/min. Such a quasi-static loading condition can remove rate-effects in the physical test.

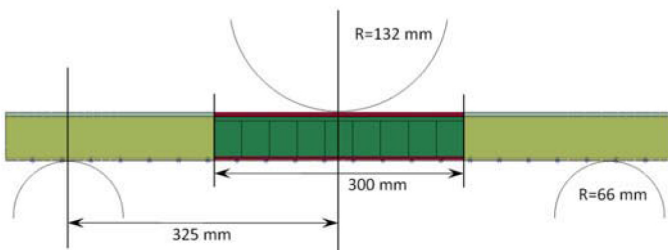


Figure 4. Three-point bending test.

Four different cases are considered by using different combinations of composite materials in two empty spaces of the beam section, so as to observe the effects of composite materials on the crashworthiness of the beam. Four cases are described in Table 1. In Case1, both the outer and the inner cavities remain empty, which represents a baseline beam structure. Only the outer cavity is filled with the structural foam in Case2. In Case3, the composite insert is applied to the inner cavity and the outer cavity remains empty. Case4 is the combined case of Case2 and Case3.

Table 1. Description of cases.

	Cavity A	Cavity B
Case1 (baseline)	empty	empty
Case2	structural foam	empty
Case3	empty	composite insert
Case4	structural foam	composite insert

PHYSICAL THREE-POINT BENDING TEST

Many three-point bending tests with the steel-composite combined beam structure were conducted. The average force-displacement (F-D) curves of three-point bending tests are shown in Figure 5. Depending on the combination of composite materials for the beam sections, there are large differences in peak and residual force levels, initial slope, curve shape of F-D curves, deformation mode and so on. Those differences will be addressed hereinafter.

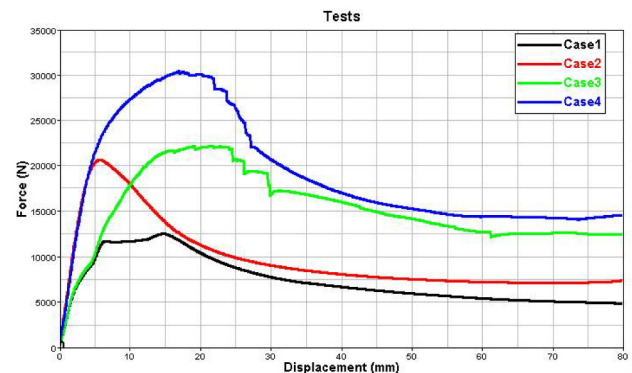


Figure 5. F-D curves of four cases.

In Case1, the steel-only beam structure is used for the three-point bending test. In other words, the F-D curve of Case1 represents the baseline resistance force level of the steel-only beam structure and there is no effect of composite materials. It can be seen that the F-D curve of Case1 in Figure 5 has two-step initial slope, plateau peak range and smooth force decrease which are induced by the changes of the deformation behavior of the beam structure during the three-point bending test. In Case2, the outer section of the beam structure is filled with structural foam and the inner section of the beam structure is empty. Since the structural foam is filled between the outer and inner hat sections, both hat sections are deformed together. So, as shown in Figure 5, Case2 has the stiffer one-step initial slope and higher peak force level than Case1. However, right after the force reaches its peak, it is decreasing down to the similar residual force level of Case1. So, it can be seen that there is large difference between the peak and the residual force levels.

In Case3, the inner empty section of the beam structure is filled with composite insert and the outer section of the beam structure is empty. The structural foam is injected around the