Crashworthiness and Sensitivity Analysis of Structural Composite Inserts in Vehicle Structure

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Abstract

This study is focused on identifying influential parameters in numerical analysis of structural composite inserts in vehicle structure. A 3-point bending test of a simplified steel-composite beam structure is conducted to evaluate the crashworthiness of composite insert in steel structure. Empty sections of the beam structure are filled with composite insert and foam filler. From physical 3-point bending tests, it is identified that the two critical behaviors of composite insert and foam filler greatly affect the strength level of steel-composite beam structure. Some influential parameters to achieve an accurate simulation model are studied. Finally, future steps of research work are indicated.

Introduction

As a result of global oil crisis and climate change effects, there has been an increase in demand for developing more fuel-efficient vehicles not only from consumers, but also from governments. In May 2010, the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued new corporate average fuel economy (CAFÉ) and greenhouse gas (GHG) emissions standards to enforce automotive industries to improve fuel efficiency of vehicles [1]. In order to respond this regulation, new advanced technologies and lighter materials have been introduced and investigated.

Structural car body inserts are a well-known 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

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a metal or plastic carrier and high-density structural foam. Figure 1 shows typical applications in the vehicle structure.

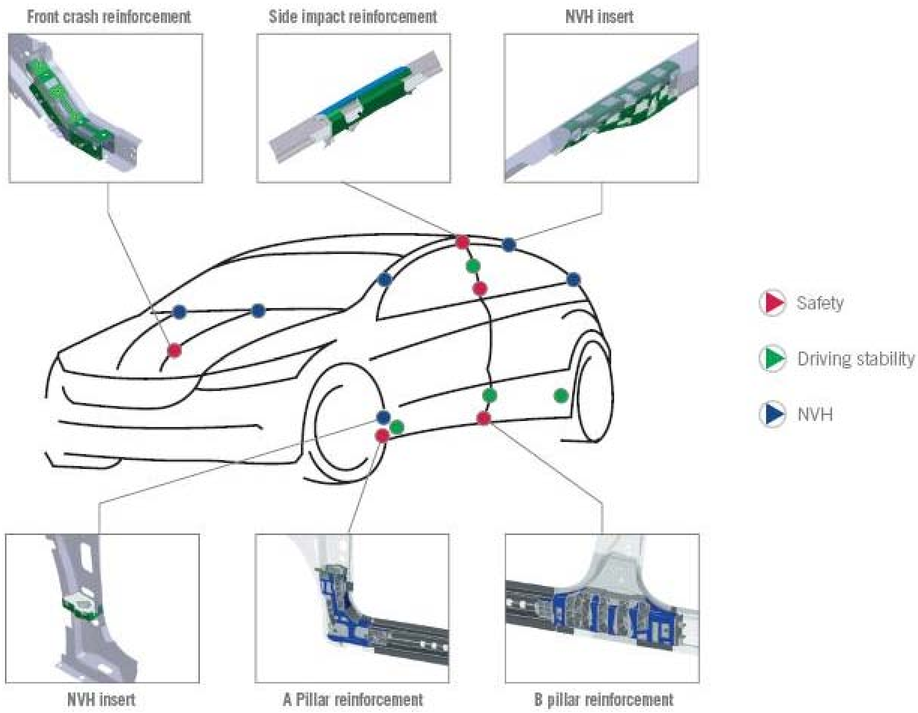


Figure 1. Applications of structural car body inserts [2].

Computer simulations are generally accepted as practical and predictive tools in automotive industry, and widely used for evaluating the crash performance of vehicle structure. Steel is a widely used material in the vehicle structure and its modeling and analysis methods are well understood and developed based on accumulated knowledge and collective experience. However, modeling and analysis of steel-composite combined structures is not as well understood since composite materials have significantly different material characteristics compared to steel. Composite inserts are generally fiber-filled composites which are anisotropic and brittle, where as steel is isotropic and ductile. In addition, the composite material is temperature and strain-rate dependent. Thus, the existing knowledge and experience from analyzing steel-only structures are not sufficient to analyze steel-composite combined structures accurately.

In this study, physical 3-point bending tests were conducted, and later on simulated, and investigated. From the series of tests and simulations, the crashworthiness of composite inserts in vehicle structure is evaluated. Also, influential parameters of steel-composite combined structures are identified to understand composite characteristics in vehicle structure as well as to achieve a well-correlated simulation model. In this paper, the test setup and simulation models are first described, followed by the two critical failure modes seen in the physical tests and their corresponding simulation counterparts. A qualitative explanation for the similarities and differences between the test and simulation results are provided. Finally the future research steps that are needed to improve the correlation are briefly described.

Description of Model

In this study, the composite insert in vehicle structure is evaluated. However, in order to isolate the effect of vehicle geometry and loading conditions, a simplified beam structure was first developed. The steel beam structure shown in figure 2 has double hat-type sections with bottom plate, and the flanges of three components are connected by spot-welds. The beam structure has two empty sections. Two empty sections are filled by composite insert and foam filler to reinforce the beam structure.

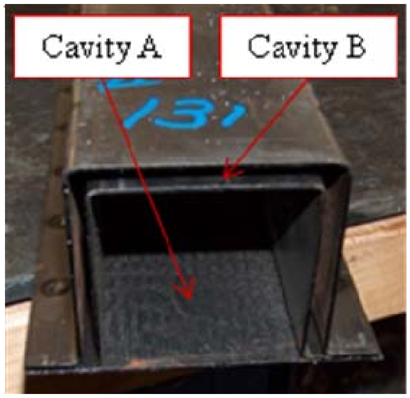


Figure 2. Section of beam structure.

In order to isolate strain rate effects, static 3-point bending tests of a beam filled with composite insert and foam filler were conducted. As shown in Figure 3, the beam is supported at its two endpoints and its middle point is loaded quasi-statically. The LS-DYNA® explicit CAE solver was used for simulating the 3-point bending test. Steel plates and composite inserts are modeled with shell elements and the foam filler is modeled with solid elements.

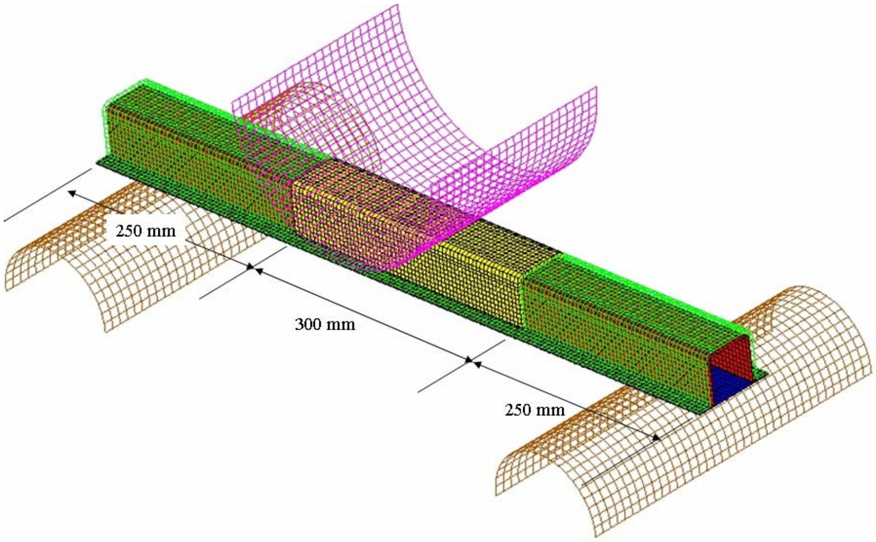


Figure 3. Setup of 3-point bending test.

Model Correlation between Test and Simulation

Based on physical test results, it is identified that two critical physical behaviors of composite insert and foam filler greatly affect the strength level of beam structure. The first is the fracture mode of composite insert. Figure 4 shows the brittle fracture mode of composite insert in the 3-point bending test. The crack is initiated at the bottom point of rib location of composite insert. Then, the crack propagates upward through the rib of composite insert. The second is the debonding of foam filler. The foam filler is injected around composite insert and bonded to surfaces of composite insert and steel plate. During the bending test, the bonding between steel plate and foam filler is failed as shown in Figure 5.

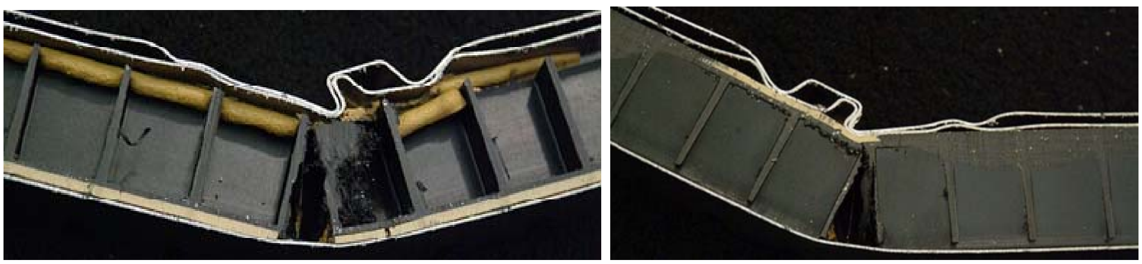


Figure 4. Brittle fracture mode of composite insert.

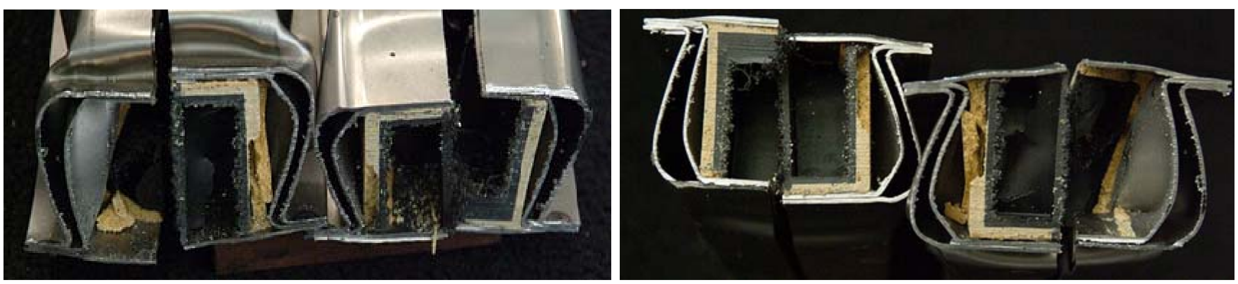
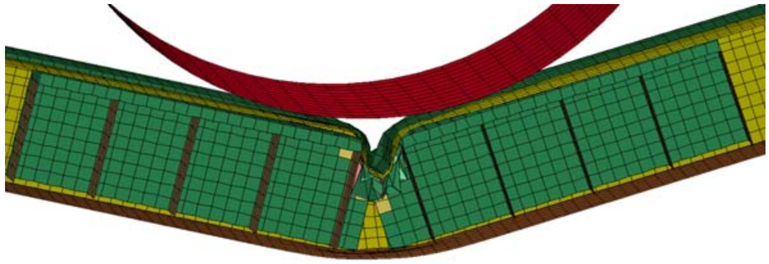
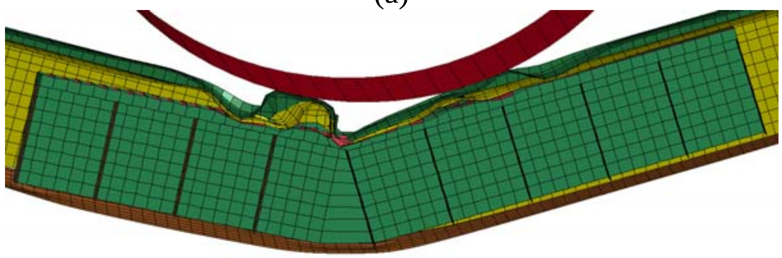


Figure 5. Debonding of foam filler.

In order to obtain an accurate simulation result, a numerical model should be able to simulate those critical physical behaviors properly. Figure 6 shows the simulations of the fracture mode of the composite insert in steel structure. Two material types in LS-DYNA® are studied: material type 24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) and material type 124 (*MAT_PLASTICITY_COMPTESSION_TENSION) [3]. Both materials are an isotropic elasto-plastic material with a stress versus strain curve. A main difference between two materials is that two different stress versus strain curves for compression and tension can be defined in the material 124, but only one curve for both compression and tension can be defined in the material 24. Figure 6(a) shows the fracture mode of composite material using the material 24. The fracture is initiated at the top area of composite insert caused by the steel plate folding, which is dissimilar to the physical test result. Figure 6(b) shows the fracture mode of composite material using the material 124, which is similar to the actual fracture behavior shown in Figure 4. In this case, the scale factor of the stress versus strain curve for compression is set higher than one for tension. Likewise, the bonding and debonding between foam filler and steel plate can be modeled by tie-break contact option in LS-DYNA®. Tie-break contact has two failure options: tensile failure stress and shear failure stress [3].



(a)



(b)

Figure 6. Fracture modes of composite insert with different material type in simulation; (a) MAT24, (b) MAT124.

However, simulating such brittle failure modes, like composite fracture and debonding, is a formidable task since the failure parameters are very sensitive to the result and not clearly understood. In such a steel-composite combined structure, there are many parameters need to be identified whether or not they are influential in simulation. Without understanding influential parameters and their sensitivity, it is difficult to achieve an accurate simulation model which can show good correlation between simulation and test.

In this study, some parameters are selected in three categories: solver, modeling and model setup, and material and boundary conditions. First, the parameters related to solver are implicit or explicit method, the size of time-step, integration scheme and points in elements, and so on. Second, the parameters related to modeling and model setup are element size, corner modeling of beam section, loading point, and so on. Third, the parameters related to material and boundary conditions are material type, contact type, failure parameters, thickness, and so on. Those parameters are studied to identify their sensitivity and interrelationship in the following research.

Overall Scope of Research

The overall scope of this project included the following tasks: experiment, initial model validation, sensitivity analysis and stochastic analysis. First, physical 3-point bending tests were conducted. In the test, strain gages were attached at several locations of composite insert to identify failure strains of composite material in steel structure. Second, a traditional sensitivity analysis was performed to identify influential parameters in a simulation model. A further study of the inter-relationships between the various modeling parameters to explain the complexity of the model was also performed. In addition to the traditional sensitivity analysis, the complexity analysis helped in developing a systematic model validation process. Finally, a stochastic analysis was performed to quantify the robustness of modeling parameters for providing further design guidance. This paper has only focused on the initial stage of the experiment and model validation efforts. The complete report will be posted at the website of National Center for Manufacturing Sciences (NCMS).

Acknowledgements

This research is the NCMS technology transfer project funded by National Center for Manufacturing Sciences (NCMS). The authors would like to express their appreciation to NCMS and Jon Riley, Executive Director, NCMS.

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