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High strength steels, stiffness of vehicle front-end structure, and risk of injury to rear seat occupants

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ABSTRACT

Previous research has shown that rear seat occupant protection has decreased over model years, and front-end stiffness is a possible factor causing this trend. In this research, the effects of a change in stiffness on protection of rear seat occupants in frontal crashes were investigated. The stiffness was adjusted by using higher strength steels (DP and TRIP), or thicker metal sheets. Finite element simulations were performed, using an LS Dyna vehicle model coupled with a MADYMO dummy. Simulation results showed that an increase in stiffness, to the extent it happened in recent model years, can increase the risk of AIS3+ head injuries from 4.8% in the original model (with a stiffness of 1000 N/mm) to 24.2% in a modified model (with a stiffness of 2356 N/mm). The simulations also showed an increased risk of chest injury from 9.1% in the original model to 11.8% in the modified model. Distribution of injuries from real world accident data confirms the findings of the simulations.

1. Introduction

Use of high strength steels in vehicle structures has potential in weight reduction and improving certain safety features. As a result, the vehicle stiffness in all directions may increase. A higher stiffness of the vehicle structure can have safety benefits to occupants by decreasing the intrusion to the occupant compartment. However, it can also affect the crash pulse of the vehicle and the accelerations transmitted to the occupants. Front seat occupants are protected against such elevated crash pulses by advanced airbags and force limiting, pretentioning seatbelts. Safety features for rear seat occupants, however, have not changed by any measurable means since introduction of three-point belts in the rear seat. Therefore, the net effects of an elevated crash pulse on protection of rear-seat occupants needs to be fully understood.

Earlier studies showed that rear seat occupants were protected better than front seat occupants in the older model years of vehicles (Berg et al., 2000; Evans and Frick, 1988; Kuppa et al., 2005; Sahraei et al., 2009; Smith and Cummings, 2004). Perception of safety in the rear seat might even weaken incentives for use of seatbelts by rear seat occupants, as only 60% of rear seat occupants in tow-away crashes were reported to be belted (Parenteau and Viano, 2003). However, the protection of rear seat occupants has decreased in recent model years (Sahraei et al., 2009, 2010; Sahraei and Digges, 2009). Consequently, adult occupants seem to be less protected in rear seats compared to the right front seat (Bilston et al., 2010; Sahraei et al., 2010; Smith and Cummings, 2006). The relative reduction in protection of rear seat occupants compared to front seat occupants is often explained to be a result of emergence of advanced safety features and improved protection for the front seat occupants (Beck et al., 2009; Kent et al., 2007). However, the absolute increase in risk of injury to rear seat occupants (Sahraei and Digges, 2009) could not be a function of advanced airbags or force-limiting belts in the front seat.

It is reported that front-end stiffness of vehicles have increased over model years (Sahraei et al., 2011; Swanson et al., 2003) and such an increase in stiffness could be the cause of a decrease in protection of rear seat occupants (Sahraei et al., 2013). In the present study, finite element modeling was used to isolate the effect of an increase in stiffness from other changes in platform and safety features of vehicles, and to quantify the changes in risk of injury to rear seat occupants due to change in stiffness. In an earlier publication from this research, it was shown that scaling the strength of steel, changing the mass of the vehicle, or thickness of load bearing structure can change stiffness and affect head and chest accelerations (Sahraei et al., 2011). In this paper, a more thorough validation of the model was performed to make sure the model can predict risk of injury to head, chest, and neck of the occupant. In addition to revisiting the effect of change in stiffness by former methods, change of stiffness due to using DP and TRIP steels in the front

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structure was studied. Also, the effects of a change in stiffness in a lower speed crash, and an angle impact were evaluated. Another factor that was considered to affect protection of rear seat occupant and was studied in this research was the space available for the rear seat occupant and relative distance to the back of the front seat.

2. Finite element models of vehicle, dummy and the seatbelt

National Crash Analysis Center has a library of finite element models of vehicles developed in LS-Dyna for crashworthiness studies (NCAC, 2008). The Ford Taurus FE model is one of the most detailed models of a medium size passenger car in that library. This vehicle model was validated at NCAC against NHTSA full frontal crash test 3248. The available model was improved by adding a seat cushion in the rear seat and, also, by increasing the floor thickness by 0.2 mm to account for mats and floorings not included in the original model.

The model was to be used for evaluating the protection of rear seat occupants. Therefore, an actual crash test performed using a Ford Taurus at National Highway Traffic administration which had dummies in the rear seat was used to validate the model (Test 5143). The initial speed of the vehicle was set to 56 km/h. The test set-up was according to New Car Assessment Program (NCAP) settings. The actual crash test had two 5 percentile female Hybrid III dummies in the front seats, however, as those dummies were not to be used for this study, only their mass (50 kg each) was added to the vehicle front seats. Locations of accelerometers were adjusted to be exactly similar to NHTSA crash test 5143. The FE vehicle model had 972,148 elements and 921,937 nodes. Out of this total, 837,673 were shell elements (705 shell parts), 134,459 solid elements (82 solid parts), 4 beam elements (2 beam parts), 12 discrete elements (5 discrete parts), and 124 mass elements.

The rear seat dummy in the NHTSA test was a 5 percentile female Hybrid III dummy. In the simulations, the rear seat dummy was modeled using MADYMO multi-body dynamics software. MADYMO dummies are validated against component tests as well as sled type simulations. After an initial evaluation of both the facet model and the ellipsoid model, the results showed that the ellipsoid model was not as reliable as the facet model for our purpose. Therefore, the facet dummy was used for this study.

The dummy model was coupled with the vehicle model using LS Dyna-MADYMO coupling tools. A settling simulation was performed to make sure the dummy was positioned correctly on the seat cushion and the seat cushion was deformed to the contour of the dummy. The deformed shape of the seat and the residual stresses in the foam elements of the seat were then extracted from this simulation and input into the vehicle model. Dummy joint positions after settling were also extracted and imported into the dummy model to reflect the correct positioning of upper and lower limbs relative to the seat. The FE mesh for the three-point belt was developed using MADYMO and Hypermesh. The D-ring and retractor were added using LS Dyna seatbelt elements. The fabric model was based on properties of the Automotive Occupant Restrains Council (AORC) received from Livermore Software Technology Corporation (LSTC), and the lock acceleration was 0.7*g* according to Federal Motor Vehicle Safety Standard (FMVSS) 209.

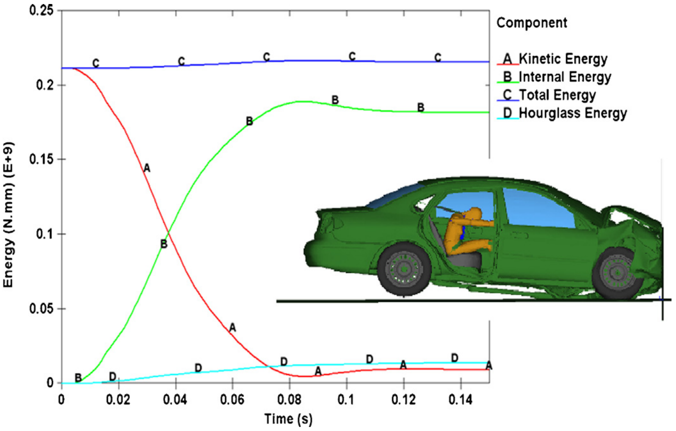

Fig. 1. Balance of energies through the finite element simulation.

Our previous coupled vehicle–dummy–belt models were validated for head and chest acceleration, but the dummy chest deflection was not validated. In this study, as the risk of AIS3+ injury had to be calculated, there was a need to have proper representation of the chest deflection. A proper contact between the LS Dyna belt and the MADYMO dummy chest and neck is essential to model chest deflection correctly. None of the MADYMO contacts alone simulated the chest, neck, and belt interactions correctly. The node to surface contact allowed for some penetration of the belt into the chest, and the surface to surface contact resulted in slipping of the belt over the thorax. However, the use of two contacts (node to surface + surface to surface) at the same time solved this problem. Proper simulation of the belt/dummy interactions affected accelerations of head and chest of the dummy, as well. Therefore, a full validation was required to make sure that the updated model represents the actual crash test.

2.1. *Validation of the model*

A Ford Taurus NCAP test was used for comparison with the simulated Ford Taurus vehicle. The two models were similar in terms of model year (2004 versus 2001), mass (1739 kg versus 1740 kg), length (5025 mm versus 5022 mm), width (1865 mm versus 1853 mm), and location of the center of gravity from front axle (1156 mm versus 1070 mm).

At the first step the model balance of kinetic, internal, hourglass and total energies was reviewed, see Fig. 1. The kinetic energy drops as the vehicle hits the rigid wall, and the internal energy increases as the deformation progresses. The hourglass energy is less than 10% of the total energy through the simulation, and the total energy remains almost constant.

To quantify the validation of the simulation against the test, a method suggested by Ray (1996) was used. Ray studied the repeatability of crash tests and provided criteria for validating simulation results. He reported that repeating crash tests of exactly similar vehicles in standard conditions using the same equipment and procedures can still produce some variability in the measured accelerations. The differences in crash pulse of two identical tests can be associated with the variations in vehicle characteristics caused by different construction materials or imprecise construction methods. Small variations in impact condition and experimental errors in data collection also contribute to variations in crash pulse. Ray demonstrates that even two independent measurements of one crash test can show differences between time history results. He also provides a quantifiable criterion to judge the similarity of a crash test with a simulation above and beyond subjective comparison. In this method, the difference between the simulated acceleration and the test acceleration is calculated in each instant of the time, and it is assumed that these residuals are results of random experimental errors. The criteria suggest that the average of these residuals should be less than 5% and the standard deviation less than 20% of the peak acceleration. If these conditions are met, the simulation is considered the same event as the crash