PROTECTING SMALL CARS AND MITIGATING SEVERE CRASHES – SMART STRUCTURE SOLUTION

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ABSTRACT

Designers of frontal car structures are faced with conflicting requirements of the full, offset, severe and moderate crashes. These conflicts impose a trade off between stiff structure to reduce intrusion and softer structures to prevent violating the G-limit of the passenger compartment. Requirements for smart structures to adapt to various crash conditions have been demonstrated.

This research seeks to extend the deformation properties of the frontal structure by introducing 'hydraulic smart structures' within the front part of the main longitudinal members. This allows the smart structure to increase its energy absorption capacity, change its deformation properties and adapt to varying collision conditions.

It is shown that Smart Structures is capable of reducing agressivity of large vehicles towards small cars. It is also shown that Smart Structures provides further protection to the occupants incase of more severe crashes. A Smart Vehicle involved in head-on collision with standard passive vehicle produces significantly lower intrusions than that of the partner passive vehicle. Smart Structures proved superior to the traditional passive structures by absorbing more energy for the same crush zone distance, speed sensitive and controllable structure.

INTRODUCTION

Fatal or serious injuries inflicted in frontal crashes have been the focus of the research community for decades. This has been the case because frontal collisions represent the majority of real world crashes involving occupants with fatal or serious injuries. The problem is further exacerbated with severe frontal impacts due to higher impact speeds, offset impacts and agressivity of large vehicles towards smaller cars.

Occupants of small cars risk more severe injuries than those of larger vehicles when involved the two incompatible cars are involved in head-on collision. The occupants of the small car see more severe crash than with larger vehicles of higher mass and stiffer frontal structure. Offset crashes are other type of crashes that usually result in more critical injuries. Crash type and severity are two major and critical parameters behind higher injury risks resulting from frontal crashes.

Design compromise is often necessary to cope with conflicting requirements of broad crash conditions mainly in terms of crash type and severity. To optimize crash performance in these cases frontal structure need to adapt to crash conditions. Ideally, stiffer structure is required on the impact side or with severe crashes, and softer structure on the other side or with moderate crashes.

The ideal material needs to have controllable yield characteristics in order to adapt to changing impact speed and type. The ideal structure for frontal collisions needs to maximize the deformation zone, and adapt to impact conditions by stiffening at severe impacts and softening otherwise. Smart hydraulic structures are proposed to meet these ideal requirements. Full simulations of various scenarios of frontal head-on crashes were investigated. Significant reduction in the intrusion injury risk is expected with the integral use of "Smart structures" within the front part of the longitudinal members of the smart vehicle. The simulation investigations covered variation of crash severity in terms of mass, speed and overlap ratio incase of offset crashes.

The above requirements set the need to optimize the energy absorbing rails so that they perform under all crash conditions. Using passive structures, optimization is proved to be only possible under specific crash conditions[12] . Smart Structures that has the controllable yield characteristics and crash length that can adapt to crash conditions offer a better potential for optimized crash performance under broad crash conditions. Earlier attempts to employ hydraulic structure in vehicle front end was doomed to failure because of attempting to replace the two longitudinals completely with old technology resulting in high penalty of added mass and space[15].

A novel system of Smart Structures is introduced to support the function of the existing passive structure. The proposed Smart Structures consist of two independently controlled hydraulic cylinders integrated with the front-end rails. Smart Structures proved superior to the traditional passive structures by absorbing more energy for the same crush zone distance, stiffening the impacted side and stiffening the structure at more severe impacts. The results are reduced injuries for severe crashes and structurally in-compatible crashes while maintaining the permitted G-level.

Deployable Smart Structures have not been considered in this paper as this scenario was covered in previous publication (9).

CRASH COMPATIBILITY

Mass and stiffness incompatibility are major parameters behind the higher injury risks of occupants of smaller cars when involved in head-on collision with larger vehicles. There is not much that can be done about mass incompatibility apart from designing for geometric compatibility. The solution does not lie in the small car design, but in the larger vehicle design by reducing its aggressivity towards smaller cars. Stiffness agressivity of the larger vehicle may be reduced by softer primary stiffness with longer crumple zone [8]. Fixing primary frontal structure of heavy vehicles with soft stiffness is not a viable option. Soft primary frontal structure in heavy vehicles can only be viable with adaptable structure to adjust crush characteristics to suit crash conditions and improve compatibility with smaller cars.

Smart Structures can detect crash severity in case of incompatible impact and adapt its deformation characteristics to the instantaneous crash conditions, thus maximizing energy absorption within allowable G-levels. This will effectively shape the crash pulse so that the smart structure stiffens at a slower rate with small partner vehicle than the case with larger partner vehicle.

CRASH SEVERITY

Crash severity is characterized by higher energy absorption. This is usually either due to higher impact speed or partial overlap offset impacts where energy absorption is concentrated on one side of the car, the impacted side. Excessive intrusion and higher risk of injuries result from offset crashes. Structural reinforcement has been used to control intrusion in a soft offset impact without raising any concern of exceeding passenger compartment pulse requirement [1]. These constraints impose a trade-off solution between full and offset crash requirements, thus, making an adaptive solution an absolute necessity to optimize performance in both full and offset crashes.

As conventional passive structures have fixed deformation characteristics, impacted side and non-impacted, sever crash and non-sever crash are expected to offer the same crush behavior. Smart Structures can adapt its deformation characteristics to crash conditions and thus optimse energy absorption within allowable G-limits. This will effectively shape the crash pulse according to crash conditions and thus reduce injury risks to occupants. The shaping process requires thorough understanding of the relationships between biomechanics of collision injury, the crash pulse and the deformation characteristics of the vehicle structure (3).

SMART STRUCTURES

Smart Structure is a term used to denote a structure that can adapt its deformation characteristics to impact conditions. This is best achieved by use of hydraulic devices utilizing liquid jet flow through orifice. The basic idea was first tested by Rupp(7) in 1974. Rupp utilized hydraulic buffers to obtain velocity-sensitive force-deflection characteristics. Crush distance in excess of that provided by the hydraulic buffers was provided by a crushable passive structure supporting the buffers. Rupp’s study was aiming at mitigating high-speed frontal impacts. Five different strokes were used ranging from 9” to 16”. Rupp concluded that the 14” buffer was the preferred configuration for a 45 mph frontal impact.

This is the actual control of the Smart Structures in order to optimize its response to the particular crash condition. An intelligent control is required to vary the dynamic/stiffness characteristics to adapt to all possible collision circumstances. Smart Structures can achieve these adaptive deformation characteristics by integrating a hydraulic cylinder and a piston with each of the front part of the longitudinal lower rails of the structure.

The proposed Smart Structures consist of two independently controlled hydraulic cylinders packaged in the front section of the longitudinal rails. The hydraulic cylinder walls can be crushable to facilitate hybrid front structure system combining passive and smart structures. Smart Structures proved superior to the traditional passive structures by absorbing more energy for the same crush zone distance, stiffening the impacted side and stiffening the structure at high-speed impacts.

SIMULATION MODEL

Ten degrees of freedom spring mass model of two head-on colliding vehicles was developed. Each vehicle in the model includes center mass, engine/transmission mass and the body mass. One of the vehicles has conventional primary and secondary spring stiffness, while the second car includes hybrid smart/passive primary stiffness and conventional spring secondary stiffness. The model allows adjustable partial overlap and assumes axial movement of the vehicle's body. A schematic configuration of the model is shown in Figure 1.

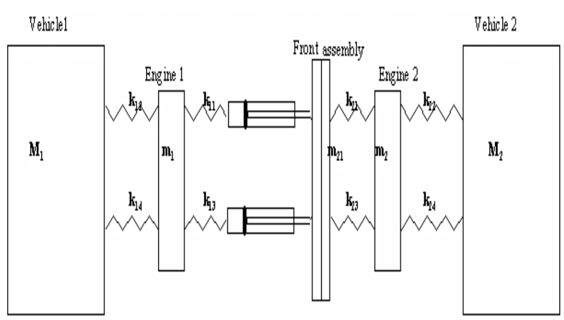

Figure 1, Schematic diagram of the simulation model of offset head-on crash

Ten second-order differential equations were solved to simulate head-on crashes involving smart structures. The input parameters considered in the simulation are:

1. Speed of both vehicles
2. Offset overlap ratio of the crash
3. Mass of the two colliding vehicles

The model is capable of capturing deformation displacement of the front and backup rail at the impacted and non-impacted sides independently. The model assumes that the two colliding structures geometrically interact with each other. The front-end structure deformation characteristics are represented by a Smart Structure on the primary structure (front of engine block) and a simplified trapezoid for the secondary structure (rear of engine).

INJURY RISK CRITERIA

The main injury criterion of interest in this research is the intrusion criterion. Other injury criteria have been considered like acceleration level of the passenger compartment. Various criteria have been used by different researchers [11],[13] depending on the required accuracy and application. These criteria range from simplified one based on the crush dynamics to sophisticated criteria involving occupant's dynamics. This work does not simulate occupant's dynamics, thus the criteria must be readily available in the simulation model.
Two criteria have been identified as most relevant for this purpose:
i) Intrusion injury criterion measured as the maximum length of deformation sustained by the secondary part of the rail.
ii) Acceleration injury criterion measured as the average dynamic acceleration pulse sustained by the passenger compartment during the crash.

SIMULATION RESULTS

Two sets of simulation runs involving two vehicles in head-on collision are used to compare results. The first set uses 'smart' vehicle fitted with Smart Structures for vehicle 1, while the second vehicle uses 'standard' vehicle fitted with passive structure for vehicle 2. The second set uses two identical 'standard' vehicles with passive structures.

The objectives of this approach are to compare the results of the two sets and assess the performance of adopting Smart Structures in the first test compared with that of conventional passive structure.
Each test results have three curves in one figure:

1. Curve 1: parameter of smart vehicle in collision with standard vehicle - suffix 1. This curve indicates the actual performance of Smart Structures when compared to curve 3.
2. Curve 2: parameter of standard vehicle in collision with smart vehicle - suffix 2. This

curve is presented to indicate any aggressivity of the smart vehicle upon its partner vehicle.

3. Curve 3: parameter of standard vehicle in collision with standard vehicle - suffixes 01, 02. This curve is presented as a reference for comparison with curve 1.

PROTECTING SMALL CARS

Occupants of smaller cars are disadvantaged when involved in head-on collision with larger vehicles. Fundamental issues of Mass/stiffness incompatibility prevent any solution in terms of the structural design of the small car. Smart structures fitted to the partner large vehicle involved with small car in head-on collision offer a potential solution. Figures 2,3 show simulation results of two head-on impacts. The first is large vehicle with smart structure and stiff control versus small car with conventional structure. The second is the same large vehicle but with conventional structure versus the same small car.

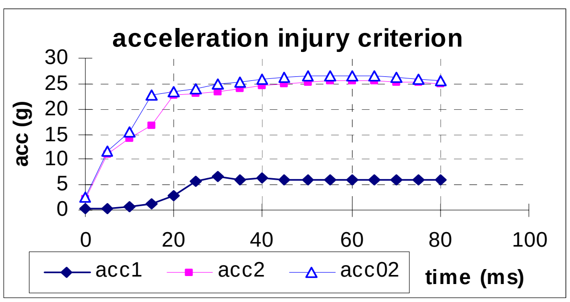

Figure 2, Average acceleration signature

Mass: 12,000 kg versus 1500 kg. Speed 30 mph

Figure 2 shows results of the impact using Occupants compartment acceleration as injury criterion. No improvement is clearly demonstrated.

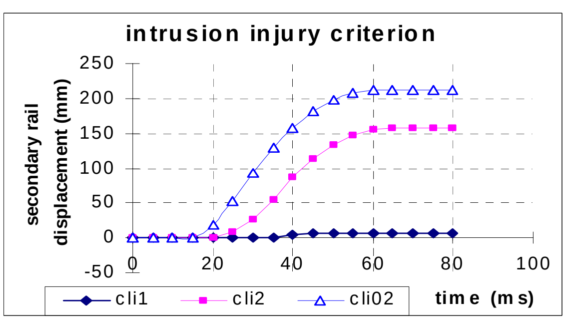

Figure 3, Secondary rail displacement

Mass: 12,000 kg versus 1500 kg. Speed 30 mph

A clear improvement in intrusion injury risk displacement is demonstrated in Figure 3.

Figure 4 is a repeat of the same test shown in figure 3, but using softer control of the smart structure. A slightly improved intrusion injury risk is indicated. The acceleration criterion is not shown as it offered no change compared with that indicated in Figure 2.

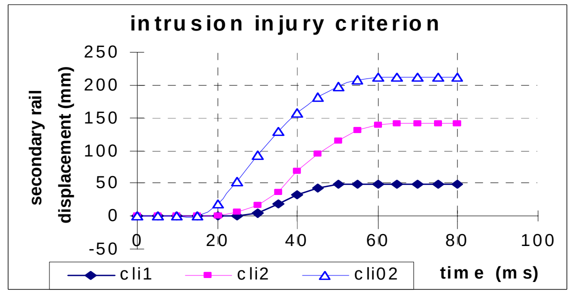

Figure 4, Secondary rail displacement

Mass: 12,000 kg versus 1500 kg. Speed 30 mph

SEVERE CRASHES – HIGH SPEED

As the Smart structure is speed sensitive, its response presents ideal solution to severe crashes. Crash severity conditions was investigated with 35 mph and 40 mph collision speeds using head on collision between smart vehicle and conventional vehicle in comparison to another collision of two identical conventional vehicles.

Figure 5 shows results for acceleration criterion indicating a clear instantaneous response to speed at first contact with a peak of 30g settling down to an average of 25 g. This peak may be shaped or even eliminated by applying more sophisticated control of the orifice. Once again the average acceleration show no particular advantage of smart structures.

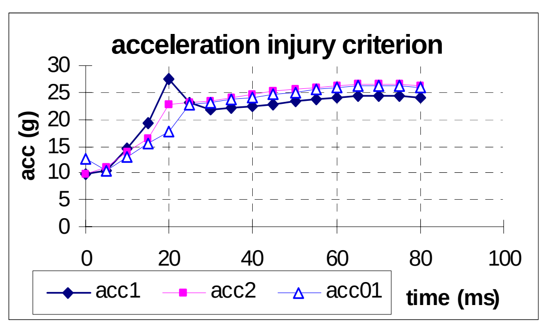

Figure 5, Average acceleration signature

Mass: 1500 kg versus 1500 kg. Speed 35 mph.

Figure 6 shows results for intrusion injury criterion indicating a clear reduction in the secondary rail deformation of the smart vehicle.

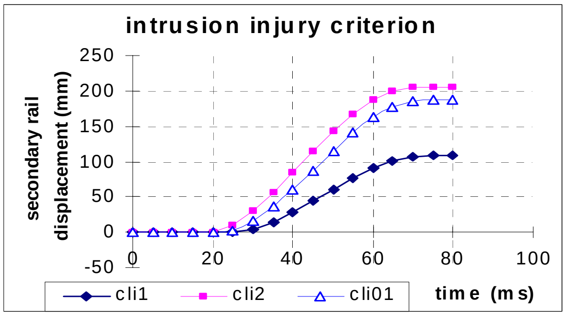

Figure 6, Secondary rail displacement

Mass: 1500 kg versus 1500 kg. Speed 35 mph

Figures 7,8 show results for both acceleration intrusion injury criteria respectively. These tests are repeats of Figures 5, 6 but with higher impact speed of 40 mph. Figure 7 indicates a more severe peak due to higher impact speed. Figure 8 shows greater reduction in the secondary rail deformation of the smart vehicle.

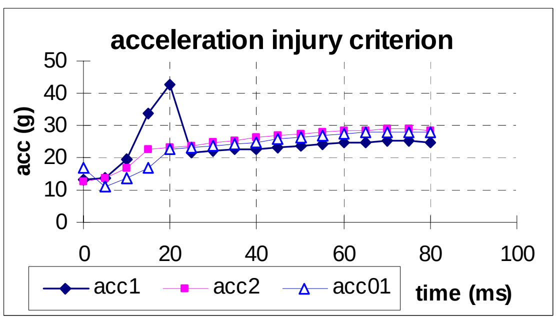

Figure 7, Average acceleration signature

Mass: 1500 kg versus 1500 kg. Speed 40 mph.

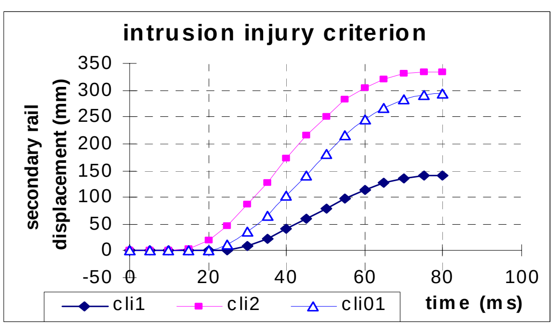

Figure 8, Secondary rail displacement

Mass: 1500 kg versus 1500 kg. Speed 40 mph

The impact of collision speed on intrusion injury risk is far greater than that of acceleration injury criterion. This is mainly because of the sensitivity of Smart Structure to speed. As evident from Figures 6, 8 the secondary deformation of standard passive vehicles colliding against each other increases from 200 mm to 330 mm when the collision speed is increased from 35 mph to 40 mph. In the case of smart vehicle colliding against 'passive' vehicle the secondary deformation of the smart vehicle increases from 110 mm to 140 mm. This amounts to about 50% of improvements, when averaging intrusion in smart and standard vehicles, in secondary deformation distance at high collision speeds.

SEVERE CRASHES - OFFSET

Crash severity is most crucial on the impacted side of an offset crash. The impacted side of an offset crash takes provide a path to most of the impact load. Many simulations were carried out to test response of the smart structures to offset crashes at various crash conditions particularly impact speed. One sample of offset crash simulation results is presented here.

Figures 9 and 10 show acceleration signature and intrusion injury displacement of a 30 mph set of offset impacts using soft smart hydraulic control. The overlap ratio was taken to be 60%. The acceleration pulse of the Smart Vehicle shown in Figure 9 presents no blip in the acceleration of the smart vehicle because of moderate speed and soft control. The average accelerations show no difference between the smart vehicle and conventional vehicle.

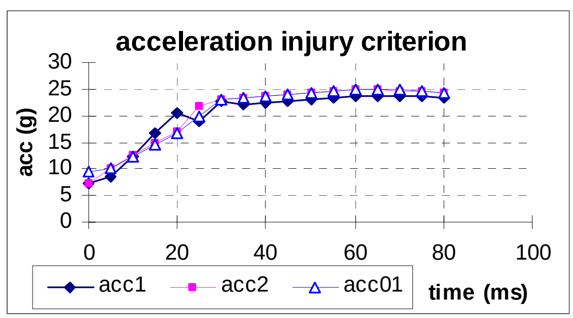

Figure 9, Average acceleration signature (offset)

Mass: 1500 kg versus 1500 kg. Speed 30 mph

The intrusion injury displacement shown in Figure 10 indicates clear reduction in intrusion displacement from 180 mm to 130 mm. This reduction in intrusion of the impacted side of the smart vehicle is made by stiffening the impacted side, thus diverting the load path towards the non-impacted side.

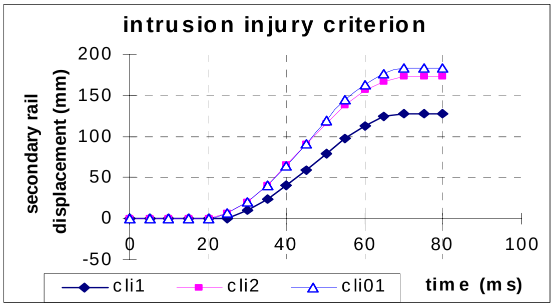

Figure 10, Secondary rail displacement (offset)
Mass: 1500 kg versus 1500 kg. Speed 30 mph

Figures 11 and 12 show acceleration signature and intrusion injury displacement of a 35 mph set of offset impacts using the same soft smart hydraulic control as in Figures 9, 10. The overlap ratio was taken to be 60% again. The acceleration pulse of the Smart Vehicle shown in Figure 11 indicates very small blip in the acceleration of the Smart Vehicle due to higher impact speed. This is well within the simulation limit.

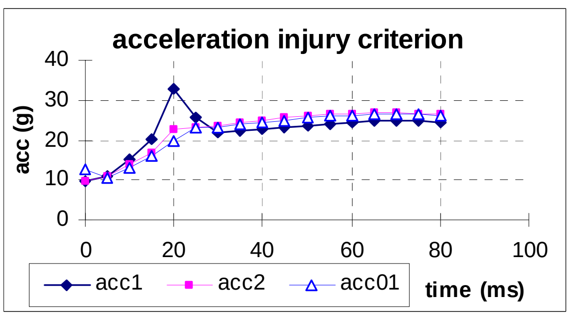

Figure 11, Average acceleration signature (offset)
Mass: 1500 kg versus 1500 kg. Speed 35 mph

The intrusion injury displacement shown in Figure 12 indicates a clear reduction in intrusion displacement from 300 mm to 180 mm. The corresponding reduction of intrusion injury at 30 mph is from 180 mm to 130 mm as shown in Figure 10. This amounts to about 50% of improvements, when averaging intrusion in smart and standard vehicles at both impact speeds.

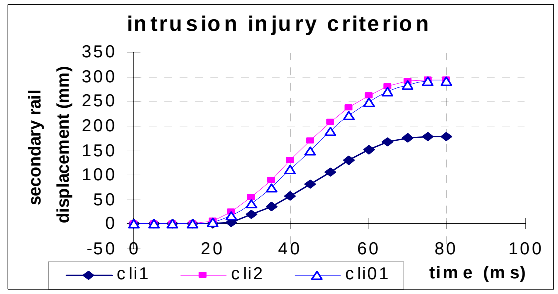

Figure 12, Secondary rail displacement (offset)
Mass: 1500 kg versus 1500 kg. Speed 35 mph

DISCUSSION

The superiority of “ hydraulic smart structures” over passive structures is based on three fundamental characteristics of the “ hydraulic smart structures”:

1. Energy absorption capacity
2. Speed sensitivity
3. Load controllability

1. Energy absorption

The ability of “Smart Structures” to use more distance available for crush, which is otherwise occupied by the folded material of the passive structure, makes it higher capacity of energy absorption than passive structures. This feature is clearly demonstrated by noting the lower intrusion displacement of the “smart vehicle” compared with that of the “standard vehicle”. The reason behind this reduction in intrusion is that the front hydraulic section absorbs higher proportion of the impact energy leaving the backup section of the structure to absorb less energy and produce lower intrusion.

2. Speed sensitivity

As shown in Figures 5, 6, 7 and 8, the collapse load of Smart Structure is speed sensitive. The load is expected to increase proportional to the square of the impact speed. This feature is very important with offset crashes where the impacted side suffers higher local collision speed than the non-impacted side. The implication in an offset frontal impact scenario is that the impacted side produces higher resistance or collapse load than the non-impacted side. The results are diverted load path to the non-impacted side and lower intrusion of the impacted side.

3. Controllability of "SMART STRUCTURES"

The Smart Structure is controlled by orifice(s) of adjustable sizes. The smart features are introduced due to adjustment of orifice size as a function of deformation distance and/or time, pressure or other relevant parameters. The results is tailored or shaped deformation characteristics of the Smart Structure according to crash conditions or scenario. The function of the orifice size in terms of the deformation distance can be tailored to any particular application. For the purpose of demonstrating the principle of controllability, a straight-line orifice variation with crush deformation distance has been assumed in this investigation. The initial total orifice size was assumed to be 500 mm^2 and dropping down at a rate of 0.6 mm^2 per 1.0 mm of deformation distance for soft control, and 1.2 mm^2 per 1.0 mm of deformation distance for stiff control. This variation of orifice size with deformation distance must clearly be optimized to conceivably produce a fine-tuned deformation curve. No such optimization is attempted in this paper. This is the subject of further research in this area.

CONCLUSIONS

It is shown that Smart Structures employing two hydraulic cylinders integrated within the front longitudinal members is capable of reducing agressivity of large vehicles towards small cars. It is also shown that Smart Structures provides further protection to the occupants incase of more severe crashes. A Smart Vehicle involved in head-on collision with standard passive vehicle produces significantly lower intrusions than that of the partner passive vehicle.

These objectives are achieved because of three fundamental features of Smart Structures:

- Absorbing more impact energy for the same crush distance and for the same maximum load level compared with passive structures.
- Speed sensitivity of the Smart Structures
- Controllability of the Smart Structures

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