

Nonlinear Crash Dynamics Simulation of Novel Airbag Based Next Generation Energy Absorbing Barrier

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Abstract

The fatality analysis report system of the National Highway Traffic Safety Administration reported that approximately 42,000 people in the United States are killed annually in motor vehicle crashes. Approximately 30 percent of the fatalities are from run-off-the-road crashes involved in collisions with roadside objects. Energy absorbing barriers (EABs) such as concrete median barriers, guardrails, guardrail end treatments, impact attenuators, crash cushions and bridge rails are designed to absorb and dissipate the kinetic energy of run-off-the-road vehicles efficiently. The main purpose of EABs is to increase vehicle occupant survivability while reducing injury levels by smoothly redirecting an errant vehicle to bring it to a controlled stop and to prevent deadly rollover or crossover accidents. Non-linear, three-dimensional, FEA code LS-DYNA is used to perform realistic and predictive virtual crash simulations for analyzing the large-deformation dynamic responses of elastic or inelastic structures using implicit as well as explicit time integration schemes.

This paper presents a novel airbag technology, fluid-structure interaction effect based patented EAB designed and tested by the researchers at North Carolina A&T State University primarily for high velocity impacts. Simulation and testing have shown marked improvements compared to the current generation of EABs. The analysis consists of a crash deformation profile, acceleration records at different locations, and energy absorptions by different components.

Introduction

Statistics show that an injury occurs every 9 seconds and a death occurs every 13 minutes in the USA as a result of car accidents. Full frontal impact crashes are the most severe in terms of injuries and deaths on the road, as they represent one-fourth of all frontal collisions. A vehicle crash at 40 mph can cause 100G in 100 milliseconds. To place things in perspective, an astronaut in a spacecraft experiences 3G at takeoff and pilots in aircraft tend to pass out at 6G. Thus, the effect of 100G on car drivers can be extremely serious.

General Motors performed early vehicle testing in 1924. This type of testing was focused primarily on the vehicle's structure. Between the years 1920-1964, auto fatality rates doubled and in 1966 auto safety laws were enacted. In 1971, airbag crash tests were performed with human subjects. These were the earliest efforts in safety testing.

Today, agencies such as the National Highway Traffic Safety Administration (NHTSA), the Insurance Institute for Highway Safety (IIHS), the United States Department of Transportation, and the National Crash Analysis Center (NCAC), among others, are responsible for testing vehicles to ensure that there is a reduction in fatalities, injuries, and economic loss resulting from motor vehicle accidents. Setting and enforcing safety performance standards for all motor vehicles is accomplished in this manner.

FEA is an extremely efficient and cost-effective tool to assist in the design of safer highway guardrails, bridge supports, signposts, and other roadside structures. FEA, which can be used to predict the outcome of a crash test, provides the potential to prevent some of the 500,000 human injuries and 13,000 premature deaths resulting from motor vehicles that run off the road and either roll over or are involved in collisions with a roadside object or feature.

Rigid Barrier Research

Bligh [1] researched rigid roadside barriers on the effects of higher speed limits on impact speed and the appropriateness of 25 degrees for the impact angle (under the appropriate test conditions specified in NCHRP Report 350). In his research he suggested (i) maintaining the current test impact speed of 100 km/h (62.2 mph), (ii) maintaining the current impact angle of 25 degrees for test 11 of the length-of-need sections of permanent longitudinal barriers, (iii) reducing the test impact angle from 25 to 20 degrees for test 11 of the length-of-need sections of the temporary longitudinal barriers and (iv) reducing the test impact angle from 25 to 20 degrees for test 21 of the barrier transition sections.

Consolazio et al. [2,3] proposed a new low profile portable concrete barrier system that was developed for use in roadside work zone environments. It was shown that the extensive use of nonlinear dynamic finite element simulation could accomplish several cycles of conceptual design refinement without expensive full-scale crash testing.

Flexible Alternate Material Barrier Research

Botkin et al. [4] coordinated with Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratory, Argonne National Laboratory, and Los Alamos National Laboratory to work in three distinctly different technical areas, one of which was composites material modeling for crashworthiness with the primary use of LS-DYNA. An excellent agreement was found between tube crush simulations and the experiments.

Reid et al. [5] worked on SAFER barrier developments. For many years, containment for errant racing vehicles traveling on oval speedways has been provided through the use of rigid, concrete containment walls placed around the exterior of the tracks. However, accident experience has shown that serious injuries, and even fatalities, may occur as a result of vehicular impacts into these non-deformable barriers. Because of these injuries, the Midwest Roadside Safety Facility at the University of Nebraska-Lincoln was sponsored by the Indy Racing League and the Indianapolis Motor Speedway, and later joined by NASCAR, to develop a new barrier system that could improve the safety of drivers participating in auto racing events. Over the course of the project, several barrier prototypes were investigated and evaluated using static and dynamic component testing, LS-DYNA computer simulation modeling, and a total of 20 full-scale vehicle crash tests. The full-scale crash-testing program included Bogie vehicles, small cars, a full-size sedan, as well as actual IRL open-wheeled cars and NASCAR Winston Cup cars. For the race car impact tests, typical impact speeds and angles ranged approximately from 190 to 245 km/h (120 to 150 mph) and from 20 to 25.6 degrees, respectively. During this research effort, a combination steel tube skin and foam energy-absorbing barrier system, referred to as the SAFER barrier, was successfully developed. Subsequently, the SAFER barrier was installed at the Indianapolis Motor Speedway in advance of the running of the 2002 Indy 500 mile race. From the results of the laboratory-testing program as well as from the accidents occurring with the SAFER barrier during practice, qualifying, and the race, the SAFER barrier was shown to

provide improved safety for drivers impacting the outer walls. An overview of this research effort was provided in this paper. In addition, several possible roadside or highway applications using the new technology were identified.

FEA in Crashworthiness Research

Jiang et al. [6] presented equations for determining the peak impact load of a car crashing into a rigid concrete safety barrier. The equations were validated using full-scale crash tests performed by different research institutions, including Monash University. Comparisons between theory and test results indicated that the equations provided reasonable accuracy when predicting peak impact loads of a car crashing into a rigid concrete barrier for different impact speeds and angles.

Karma et al. [7] evaluated rigid concrete barriers using nonlinear dynamic FEM to analyze vehicle-to-barrier crashes. The underlying challenge was the capability of the constitutive models of concrete to represent a realistic response of the barrier under impact loading. LS-DYNA, a commercial FE code for crashworthiness analysis, offered four major constitutive models for concrete. The performance of each of these models was assessed by comparison between numerical simulations and benchmark stress-strain data obtained from triaxial experiments conducted on plain concrete.

Kelkar et al. [8] researched simulation of the Ford Taurus frontal offset impact on the EEVC fixed deformable barrier.

Kirkpatrick et al. [9] worked on the development of an LS-DYNA Occupant Model for use in crash analyses of roadside safety features. Using the correct combination of deformable and rigid components resulted in an occupant model that was computationally efficient and capable of simulating occupant kinematics in a collision.

Mackerle [10] provided bibliographical review of FEM and simulations of crashes and impact-induced injuries from a theoretical as well as a practical point of view.

Ray et al. [11] assessed how well FEA of a collision event simulated a corresponding full-scale crash test. The method was used to compare a series of six identical crash tests and was also used to compare FEA to a full-scale crash test.

Wekezer [12] presented the research results of a study in which computational mechanics was used to predict vehicle trajectories traversing standard Florida DOT street curbs. Computational analysis was performed using the LS-DYNA nonlinear FEA code. Verification results indicated a good correlation between computational analyses and the full-scale test data.

Motivation for Flexible EAB Research

Large amounts of kinetic energy must be dissipated when a moving vehicle impacts a relatively immovable object like a barrier. The kinetic energy of a moving vehicle is proportional to the square of the velocity; therefore, a car traveling at 50 mph has four times the kinetic energy of the same car traveling at 25 mph ($KE = \frac{1}{2} MV^2$). A crash barrier works by removing the kinetic energy of the moving vehicle. It may accomplish this removal in several ways:

1. **Rigid Barrier:** By being very rigid and strong, this barrier keeps the vehicle from traveling further. This kind of crash barrier is very rigid and it cannot move much, therefore, it does not absorb much energy. The vehicle has to absorb its own kinetic energy by deforming. If the vehicle itself is very strong and rigid, the impact forces can be extremely large.
2. **Soft Impact Barrier:** By soaking up the kinetic energy this barrier acts like a sponge. This means that the EAB does not need to be strong and rigid as it stops the vehicle by a plowing action. In many cases, the vehicle will be almost unharmed, as the barrier does the work. A correctly designed EAB must be relatively weak, as it needs to deform readily to keep the reaction forces low.

Under explosive conditions or crash conditions, an EAB is always better than a rigid barrier. This has been proven by many tests. Rigid barriers will fail under relatively small impact velocities, while EABs will be able to survive much higher velocities.

A majority of the current research work has been in the area of Rigid Barrier development. A minority of the current research work has been in the area of Flexible Barrier development. Major thrusts have been made in the development of cost effective solutions, thereby compromising safety criteria.

Reid et al [5] investigated SAFER Barrier development. During their research, a combination steel tube skin and Polystyrene EAB system was developed. Its purpose was to cushion the effects of force through energy absorption and distribution. Bundles of extruded, closed cell polystyrene were placed between the rigid concrete barrier wall and the steel tubes every ten feet. However, the SAFER barrier is not really a flexible barrier and deforms very little as compared to the Airbag EAB.

The goal of this research is to develop an optimum cost effective novel technology based EAB geared towards safety and security of the vehicle and its occupants. A correctly designed EAB must be relatively weak, as it needs to deform readily to keep reaction forces low.

Analytical Formulation of Flexible EAB



Figure 1. Air-dampened flexible barrier

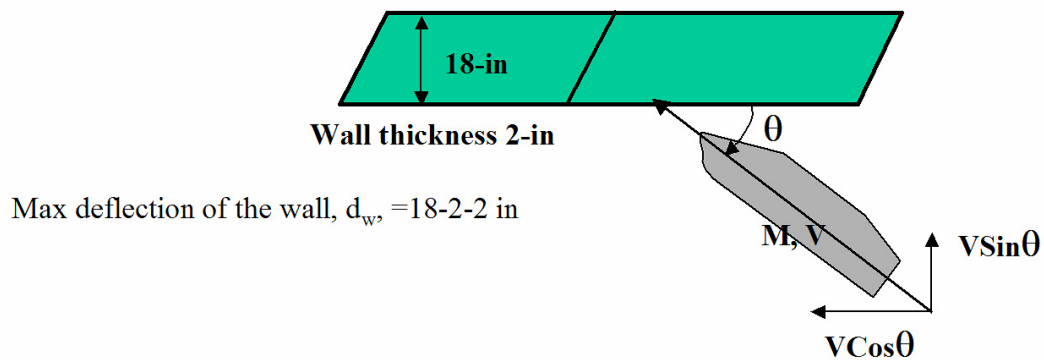


Figure 2. Analytical model of air-dampened flexible barrier

Figure 1 and 2 shows the energy transfer mechanism, which depends on:

- Flexibility and size of the barrier
- Diameter and number of the holes
- Density of the fluid/air
- Car speed and mass

(Assumptions: Wall is highly flexible and instantaneous energy transfer occurs)

Energy Transfer Analytical Equations

$$(KE)_{\text{Impact}} \Rightarrow (PE)_{\text{Fluid/Air}} \Rightarrow (PE)_{\text{Fluid/Air}} \text{ Decreases as the air is expelled}$$

$$(PE)_{\text{Fluid/Air}} @t = (PE)_{\text{Initial}} - (KE)_{\text{lost by the expelling air}}$$

An Excel based spreadsheet program has been created based on the analytical formulation which computes impact force vs. impact angle based on the car mass velocity and angle of impact. Figure 3 shows the “impact force versus impact angle” plots based on the analytical formulation for 4000 lb weight car.

Design Parameters

- Max Wt of the car = 4000 lb
 - Max Velocity = 153 m/hr
 - $g = 32 \text{ ft/Sec}^2$
 - Max deflection of the wall, d_w , 14-in
 - Max deformation of the car, d_c , 4-in
- $d_c = 0$ for rigid car
 $d_c \neq 0$ for non-rigid car

Car deformation

- 4 #s of 2" dia & 0.09 ft. thick
- Length = 5ft
- Axial stiffness $K_a = (4AE/L) = 1.3 \text{ mlb}$
- Transverse stiffness component, $K_c = K_a \sin^2\theta$
- Anticipated impact force about 300 - 600 kips
- Car frame deflection about 1.5" - 3", other deformations 1" - 2.5"
- Estimated maximum deflection about 4"

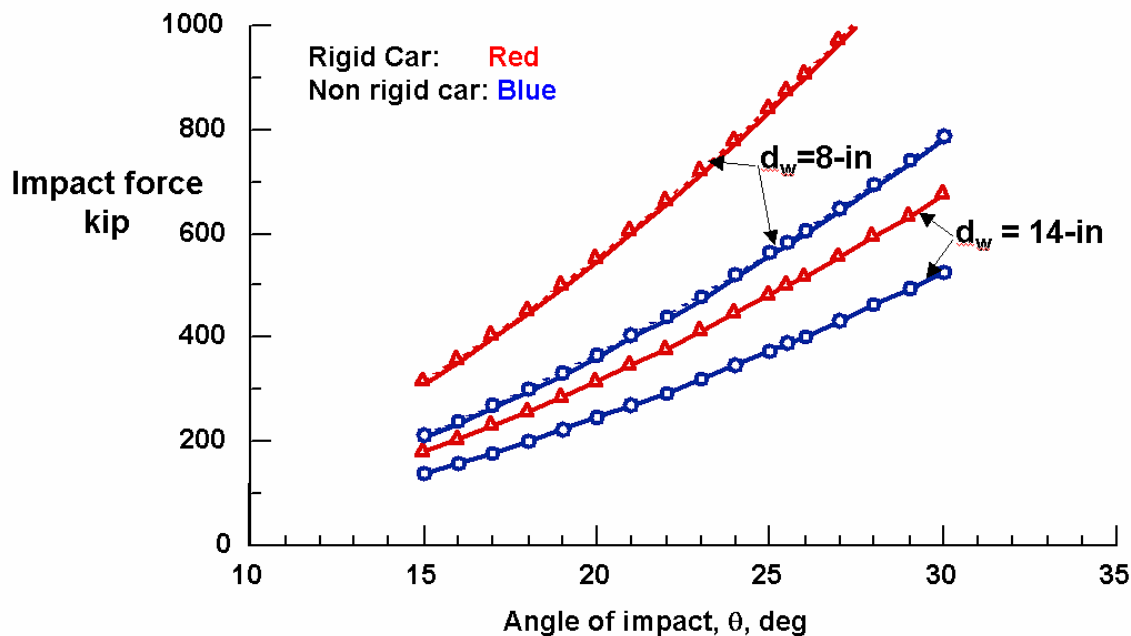


Figure 3. Impact force vs. impact angle (car weight 4000 lb)

Quasi Static Finite Element Analysis

The materials used are:

- 1] UHMW HDPE : Ultra High Molecular Weight High Density Polyethylene
- 2] SCANDURA Laminated Rubber

The material properties of the components were determined experimentally. Figures 4 and 5 show the airbag EAB test model and the samples. Table 1 displays the experimentally determined material properties of rubber and UHMW. ANSYS FEA software (version 8.0) was used for the quasi-static FEA simulation. The patch pressure loading was 672 K lb. Figure 6 shows the patch pressure loading applied to simulate the bumper impact. Figures 7-9 show the VM stress and the displacement plots.



Figure 4. Airbag EAB test model

TESTING OF SCANDURA SAMPLES FOR MODULUS OF ELASTICITY, POISSON'S RATIO AND ULTIMATE STRENGTH									
RAYALON 3-600 MATCHLESS 3/8" X3/32"			USFLEX 440 GIANT 1/4" X 1/8"			USFLEX 116660 MATCHLESS 3/8" X 3/32"			
3-600A	WIDTH	THICKNESS	440 A	WIDTH	THICKNESS	11660A	WIDTH	THICKNESS	
	0.996	0.673		1.092	0.593		0.995	0.724	
	1.003	0.673		1.096	0.59		1.046	0.727	
	1.005	0.667		1.049	0.585		1.074	0.736	
AVERAGE	1.001	0.671	AVERAGE	1.079	0.589	AVERAGE	1.038	0.729	
AREA	0.671671		AREA	0.635531		AREA	0.756702		
3-600B	1.024	0.676	440 B	1.044	0.585	11660B	1.132	0.722	
	1.022	0.673		0.995	0.59		1.137	0.728	
	1.017	0.666		1.001	0.593		1.125	0.735	
AVERAGE	1.021	0.6672	AVERAGE	1.013	0.589	AVERAGE	1.131	0.728	
AREA	0.668611		AREA	0.596657		AREA	0.817304		
ALL VALUES ARE IN INCHES									
3-600			440			11660			

Figure 5. Material property after testing

Table 1. Material property testing result

Material	Modulus E psi	Poisson's Ratio	Ultimate Tensile Strength psi
UHMW - HDPE	145000	0.35	6820
SCANDURA 1	12000	0.04	2736
SCANDURA 2	10000	0.03	2457
SCANDURA 3	10330	0.035	1740

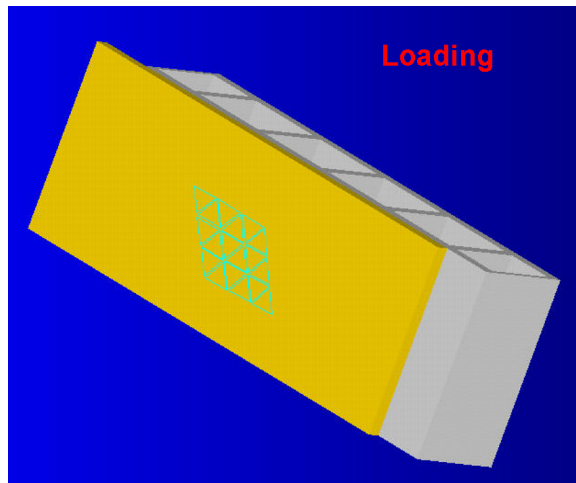


Figure 6. Patch pressure load for airbag EAB

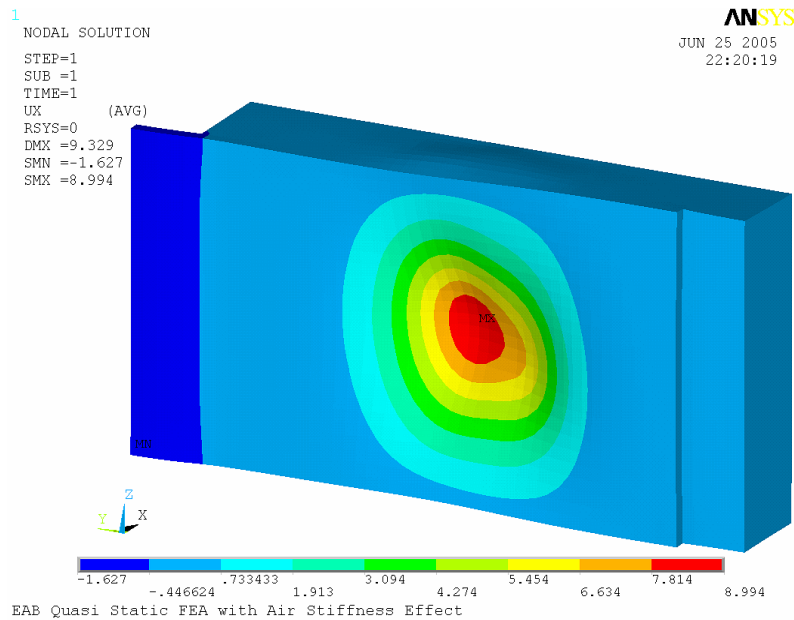


Figure 7. Axial displacement plot of airbag EAB

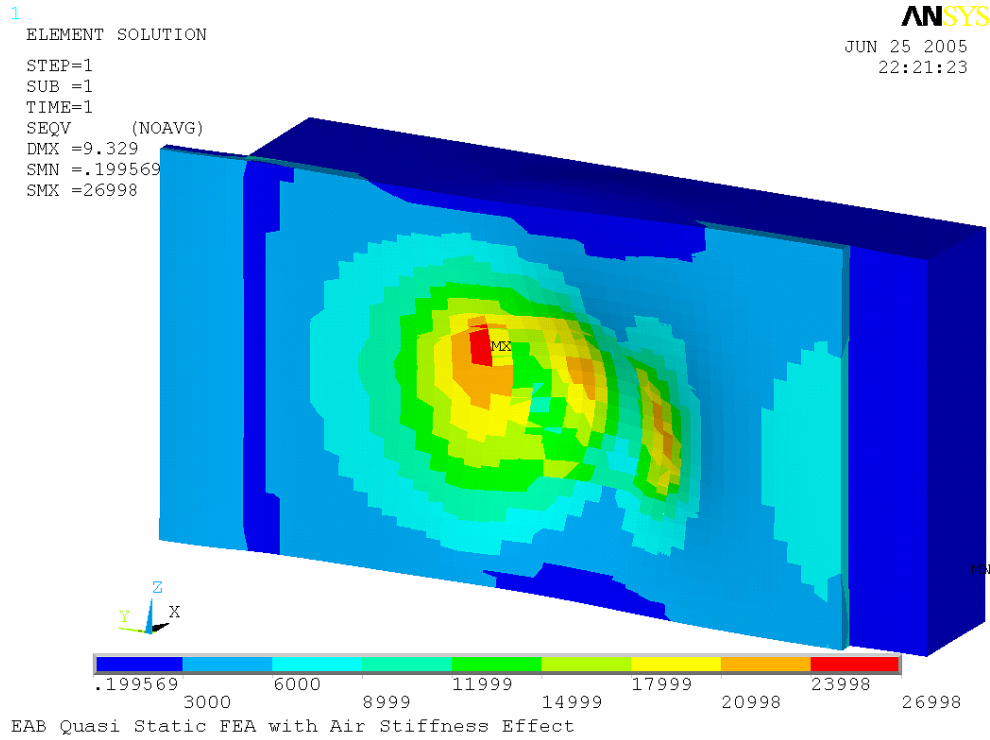


Figure 8. VMS plot of airbag EAB

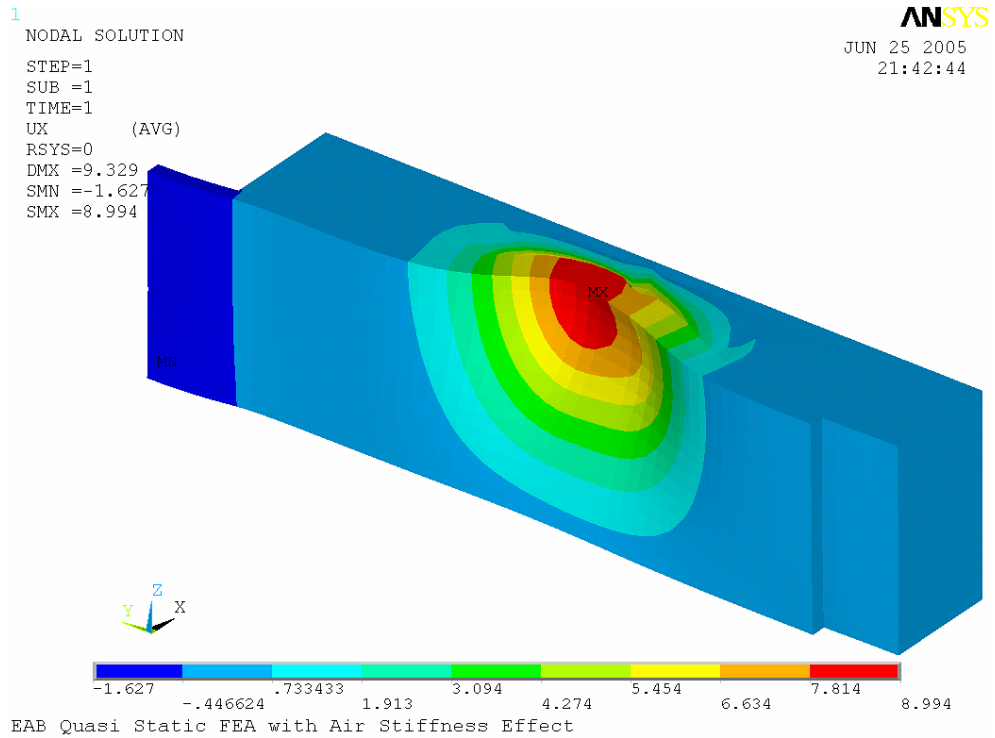


Figure 9. Axial displacement plot of airbag EAB (section view)

Non-Linear LS-DYNA Analysis (Airbag Effect)

LS-DYNA impact simulation is performed on an EAB. The dynamic simulation parameters and results are explained below, and are accompanied by plots.

A rigid car body of 4000 lb weight hits the barrier wall at 90 MPH velocity (car modeled through rigid structure). Simulation is held for 20 ms (0.02 sec). The rib angle is 0 degrees, the car hits at a 25.5° angle. The EAB is wrapped with a 1/8” rubber skin. Tied-Surface-To-Surface contact elements are applied between the front wall and the rubber part and between the rubber skin and the front wall and the rubber part. Automatic surface-to-surface contact elements are applied between the bumper and the front wall and the rubber skin. Airbag control volume with Airbag *MAT_FABRIC properties are applied for the airbags. Automatic surface-to-surface elements are applied between the airbags and the chambers. Automatic single-surface contact is applied inside the airbags.

The back of the rubber wall is fixed. Symmetric Boundary condition has been used at the side edges to simulate a continuous barrier wall. Each unit of the barrier is 96 inches long, 18 inches in depth, and 40 inches in height. Two identical units were laid side by side for the impact simulation (Figure 10).

The plots on the following pages display LS-DYNA based nonlinear dynamic FEA simulation for both the non-Airbag EAB as well as Airbag EAB and present the comparative results summary at the end.

Material Properties

The material properties of the assembly components are given below. Table 2 summarizes the comparative results for the concrete versus flexible EAB (without airbag effect) and flexible EAB (with airbag effect).

- Rigid wall: (simulating 4000 lb car weight) hitting the barrier wall at 90 MPH (initial velocity). LS-DYNA rigid material property was used for this part.
- Front wall: Material Property: Young’s modulus=145,000 psi, Poisson’s ratio=.35
- Rubber compartment: Young’s modulus=12000 psi, Poisson’s ratio=.04.
- Rubber skin (1/8” thick): (wrapped all around wall and rubber compartment barrier): Young’s modulus=12000 psi, Poisson’s ratio=.04.
- Airbags: Fabric material

LS-DYNA Fabric Material Model for Airbag

The LS-DYNA fabric model is a variation on the Layered Orthotropic Composite material model (Material 22) and is valid for only 3 and 4 node membrane elements. This material model is strongly recommended for use in airbags and seatbelts. In addition to being a constitutive model, this model also invokes a special membrane element formulation that is better suited to the large deformations experienced by fabrics. For thin fabrics, buckling (wrinkling) can occur with the associated inability of the structure to support compressive stresses; a material parameter flag is included for this option. A linear elastic liner is also included which can be used to reduce the tendency for these material / elements to be crushed when the no-compression option is invoked.

If the airbag material is to be approximated as an isotropic elastic material, then only one Young's modulus and Poisson's ratio should be defined. The elastic approximation is very efficient because the local transformations to the material coordinate system may be skipped. If orthotropic constants are defined, it is very important to consider the orientation of the local material system and use great care in setting up the finite element mesh.

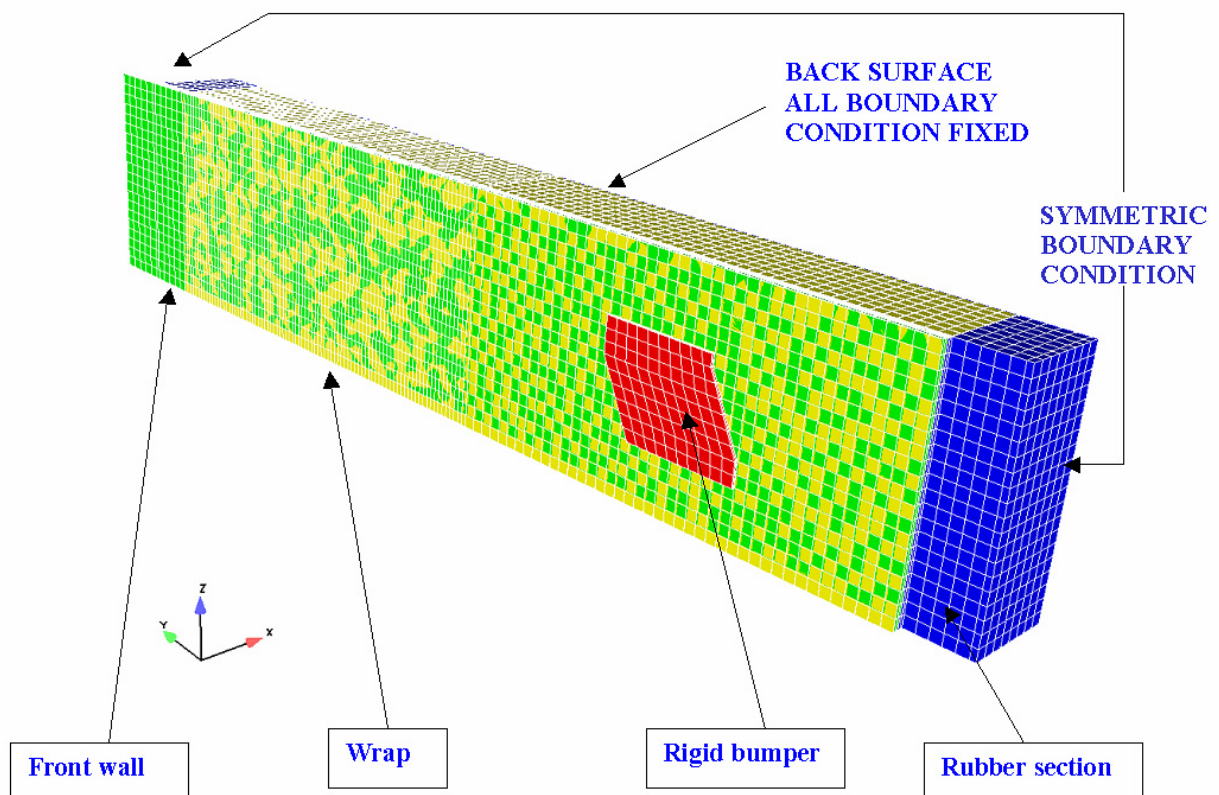


Figure 10. EAB impact analysis: Wall angle 0 Deg: Car hitting at 25.5° angle (Double Unit Block wrapped with 1/8" rubber skin)

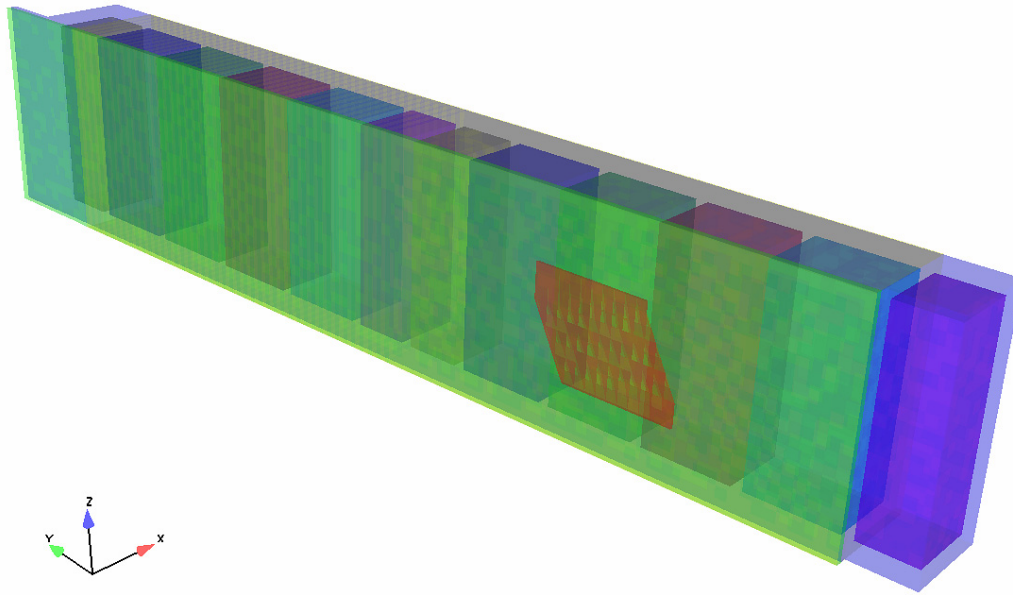


Figure 11. EAB impact analysis: Full model with airbags (Translucent view)

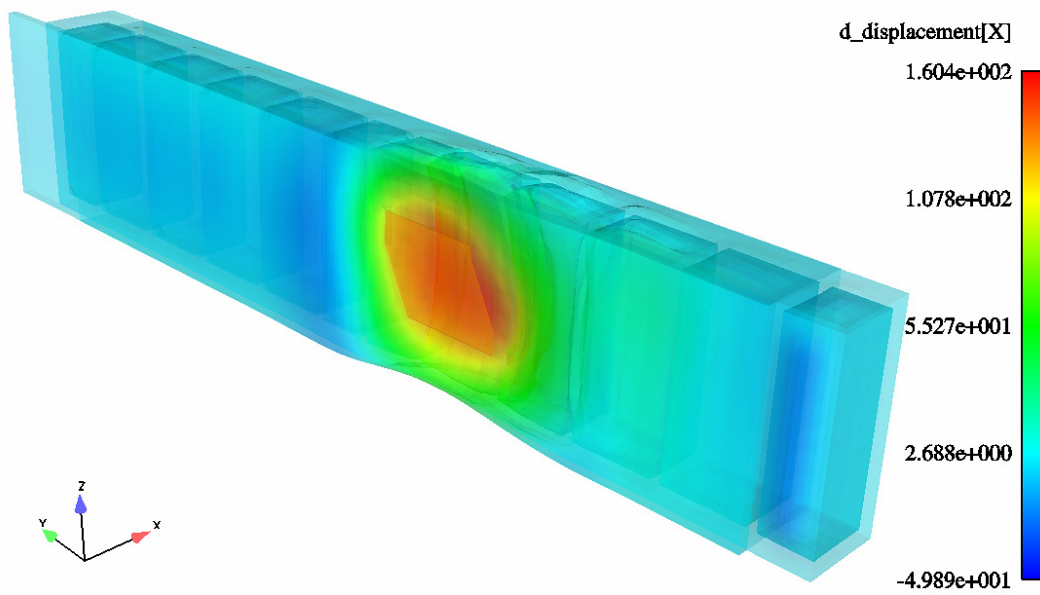


Figure 12. EAB impact analysis: Full model axial deflection (mm)

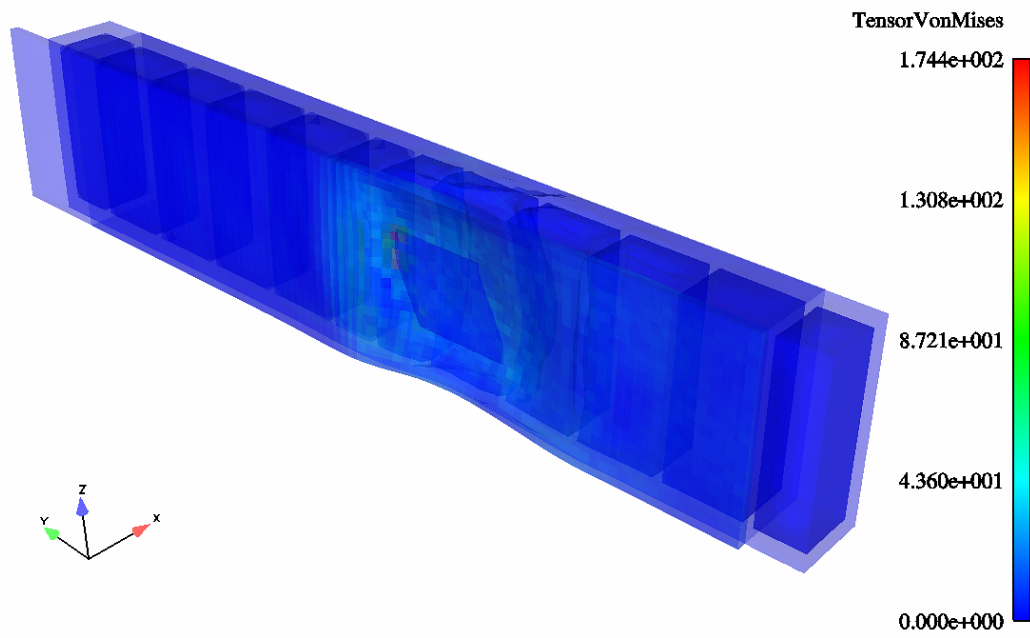


Figure 13. EAB impact analysis: Full body VMS (MPa)

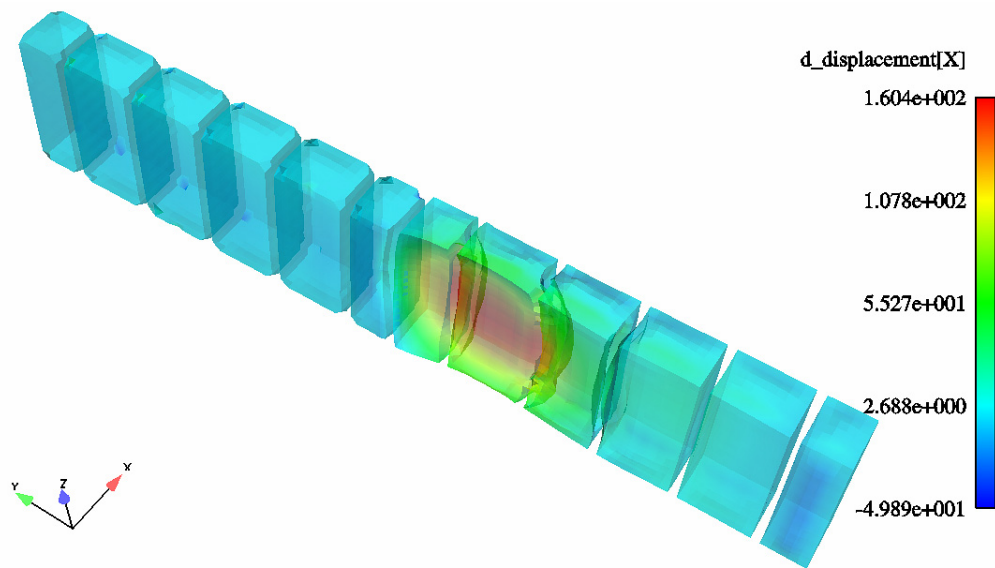


Figure 14. EAB impact analysis: Airbag deformation plot (mm), (ISO view)

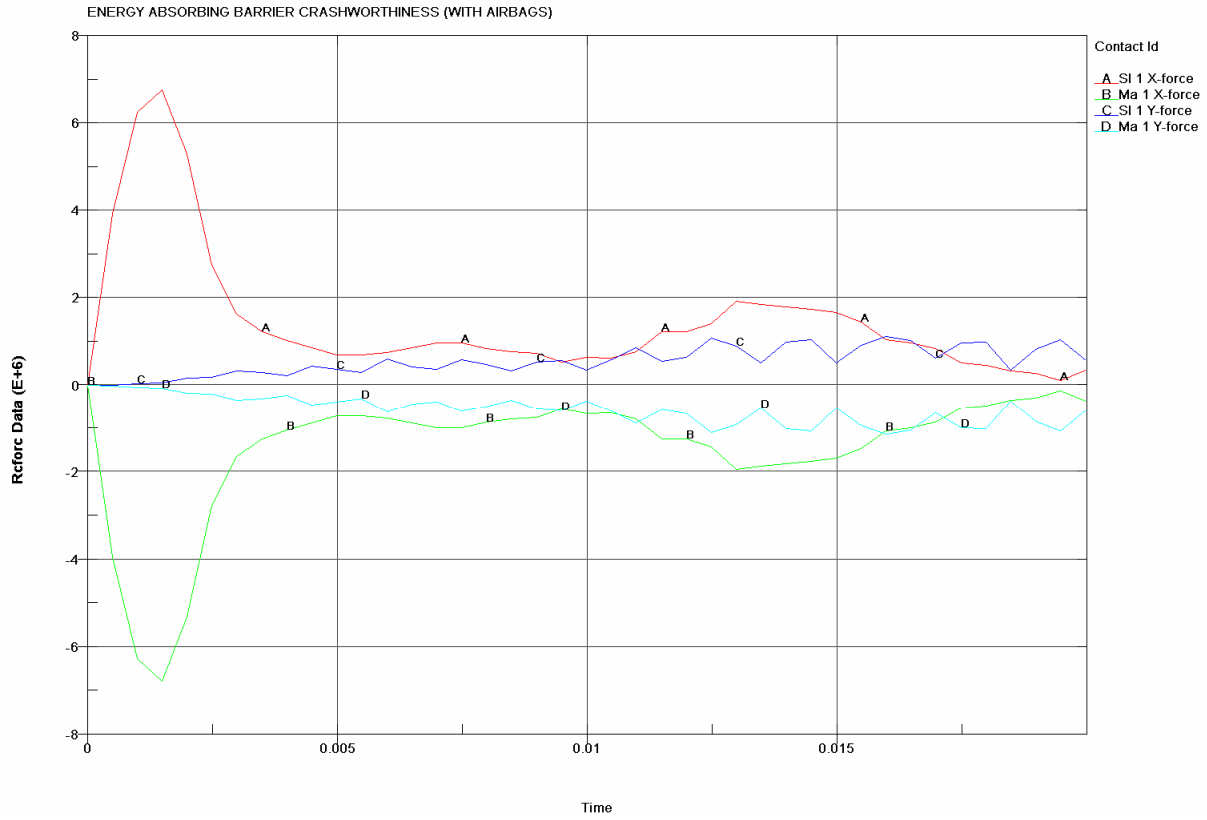


Figure 15. EAB impact analysis: Reaction Force vs. Time

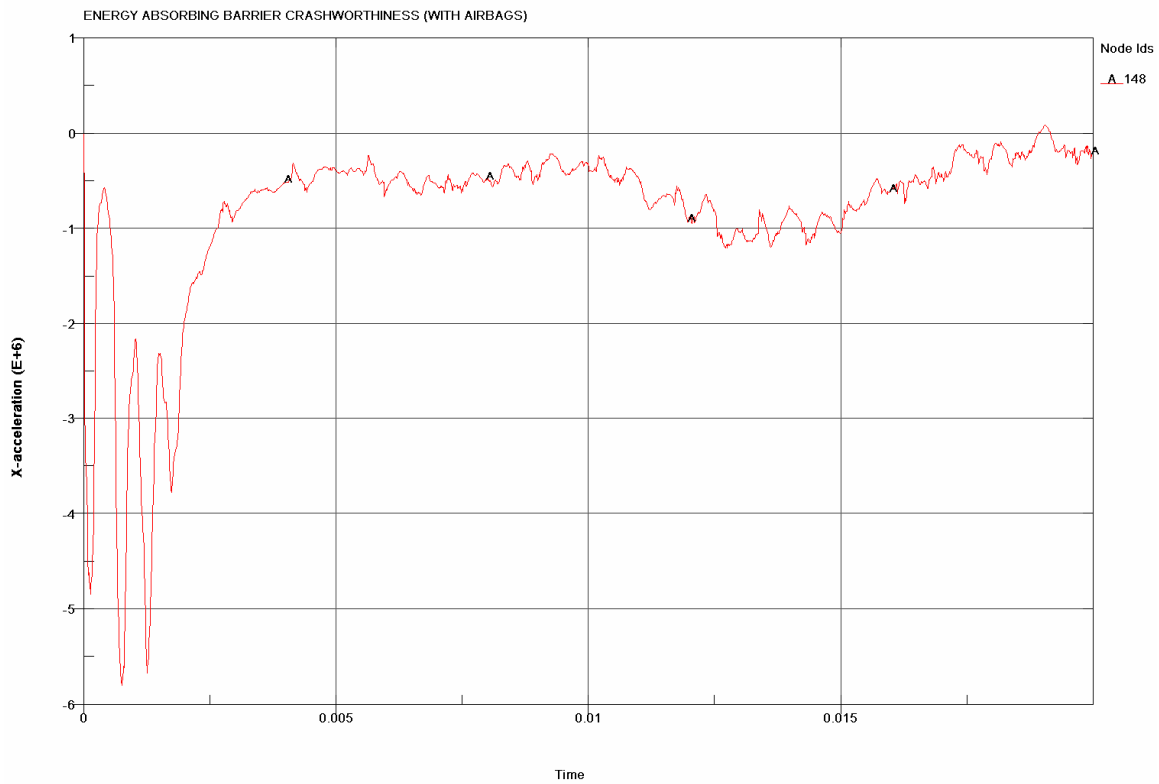


Figure 16. EAB impact analysis: Unfiltered G load vs. Time

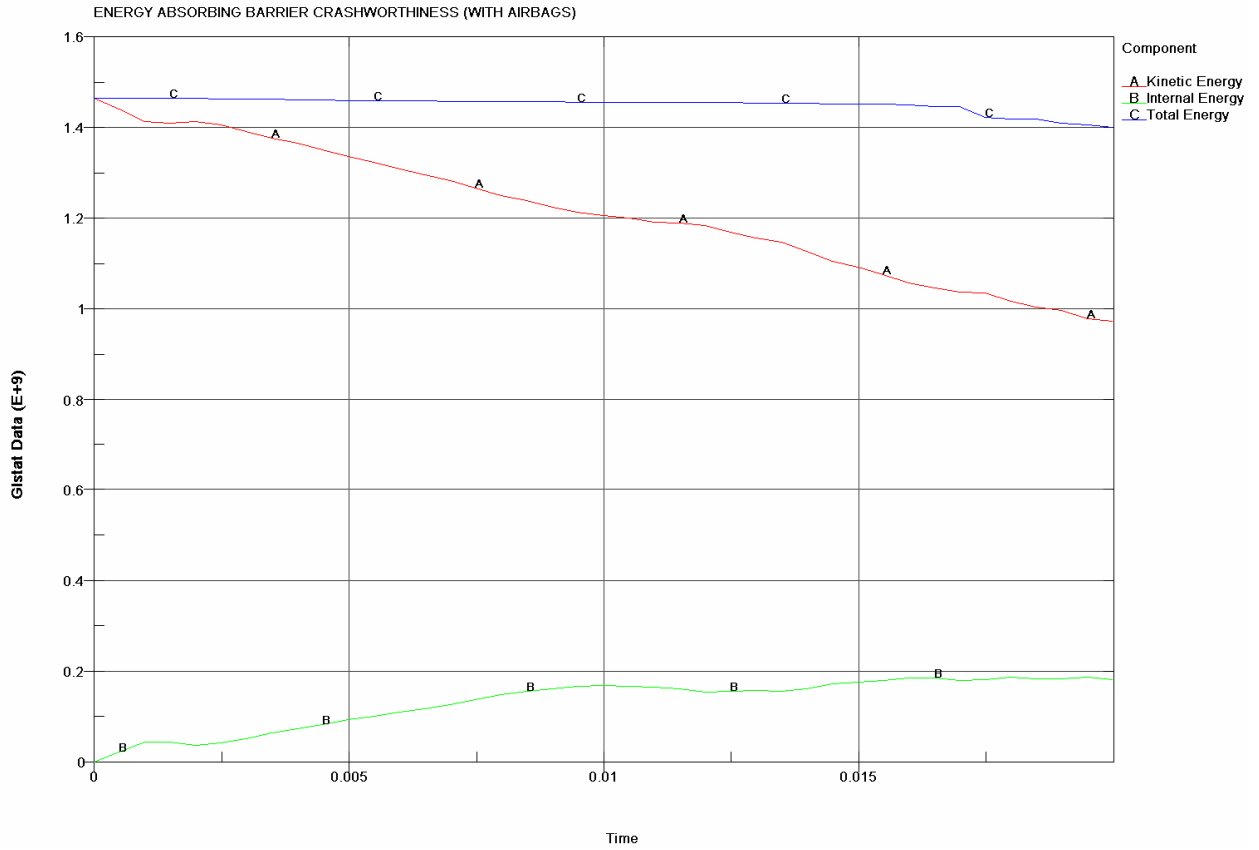


Figure 17. EAB impact analysis: Global Energy vs. Time

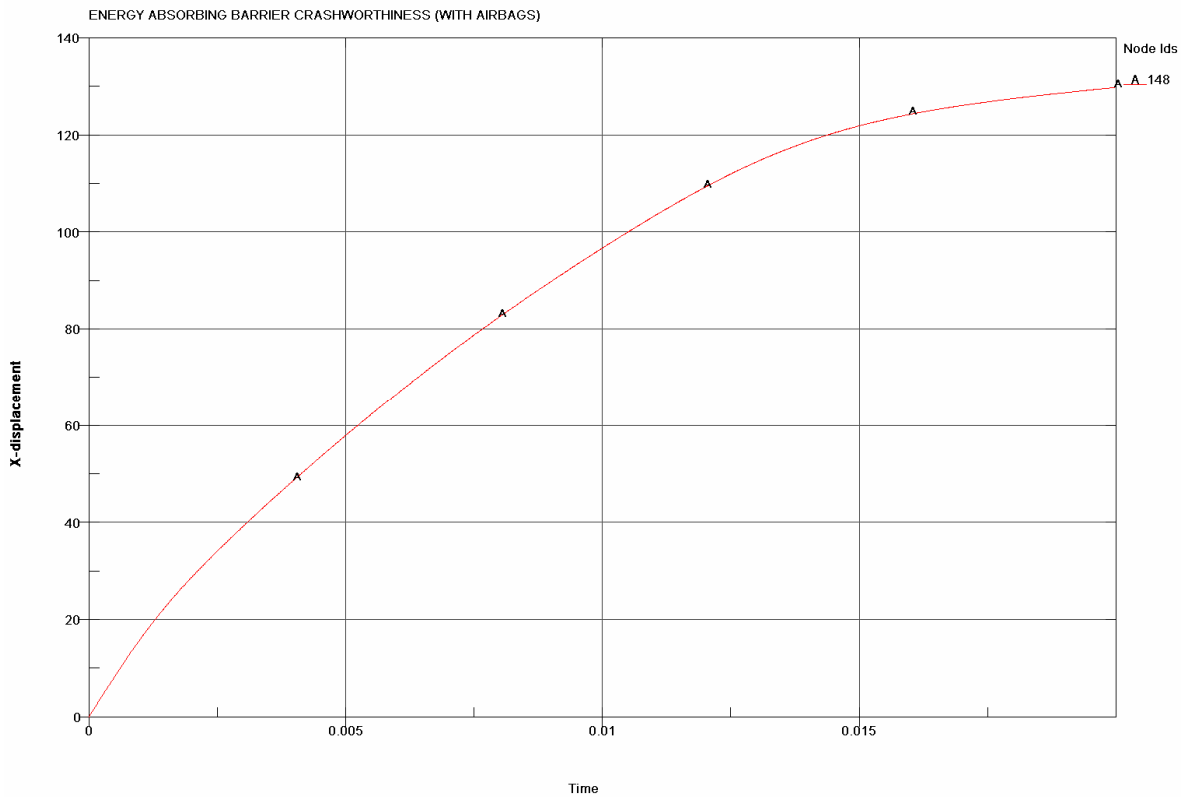
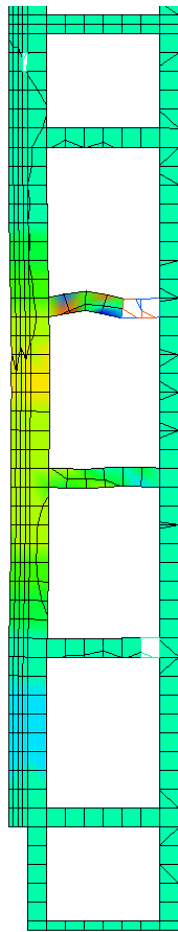
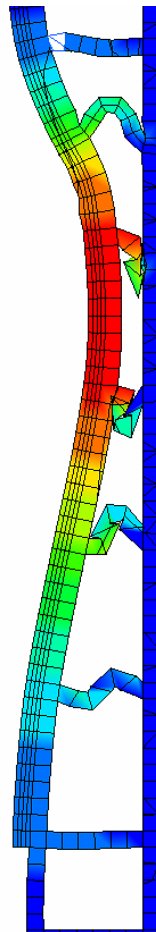


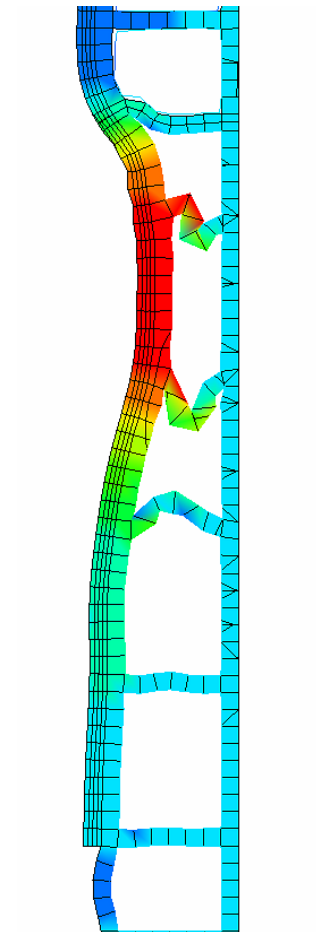
Figure 18. EAB impact analysis: X Displacement vs. Time



[a] Concrete Barrier
Section view @ 3 ms



[b] EAB (without airbag)
Section view @ 20 ms



[c] EAB (with airbag)
Section view @ 20 ms

Figure 19: Concrete Barrier versus Airbag EAB, Impact Performance Comparison

Comparison with Concrete Barrier and EAB

The concrete material property obtained from the web is provided below:
(<http://hyperphysics.phy-astr.gsu.edu/hbase/permot3.html>)

- Density = 2320 Kg/m³ = 2.32 E-9 T/ mm³ = 0.0838 lb/in³
- E = 30 E9 N/m² = 30 E3 N/ mm² = 4.27E7 psi
- Nu = 0.2

Table 2. Summary of 90 MPH impact results (with and without airbag)

	DX (mm)	Impact Force (KN)	VMS (MPa)			Peak G Load (Axial, Unfiltered)
Concrete	13.39	45000	843			3300
			Front Wall	Rubber Wall	Wrap	
Without Airbag	244	3800	131	41	55	480
With Airbag	162	6780	174	35	55	580
UTS			47	19	19	

Discussion Based on LS-DYNA Analysis

Figures 12-14 show the axial displacement and VMS plots. Figures 15-18 show the time dependent plots of reaction force, unfiltered G load, energy and displacement. Figure 19 shows the comparative deformed plots of concrete barrier versus EAB with and without airbag effect. It is clear that the concrete barrier absorbs very little energy and deforms very little compared to the flexible EAB. The peak G load is almost eight times that of the flexible EAB, which translates into extreme damage of the vehicle and extreme injury of the passengers. Nonlinear material property (stress-strain curves) has not been incorporated in the model. The peak VM stress values are higher than the UTS indicating failure of the EAB; however, the linear elastic material properties tend to overestimate the stresses during plastic deformation. The inclusion of nonlinear material properties would lower the VM stresses in the EAB components. Compared to the flexible EAB (no airbag), the EAB (airbag effect) behaves significantly better. The peak axial deformation is 30% lower, the G loading is almost identical and the stresses are higher due to the increased stiffness (airbag effect).

Conclusions Based on LS-DYNA Analysis

- FEA models of airbag EABs are developed to perform racecar crash simulation. These FEA models are used to predict the magnitude of impact forces, G loading, Deformation, Stresses as a function of racecar velocity and the angle of impact.
- Quasi Static FEA over predicted deformation compared to LS-DYNA.
- Peak axial deformation for the EAB with the airbag is 30% lower than the EAB without the airbag effect, while the G loading is almost identical.
- Stresses for the EAB with the airbag are higher compared to those from the EAB without the airbag due to increased stiffness (the airbag effect).
- Nonlinear material property (stress-strain curves) has not been incorporated. The peak VMS values are higher than UTS indicating failure of the EAB. Since linear elastic material properties tend to overestimate the stresses during plastic deformation, the inclusion of nonlinear material properties would lower the VMS.
- Effect of cut-outs on the airbag surface is studied; however, no appreciable change in displacement or stress is noticed for the main parts for small changes in the cutout diameter. This issue needs to be further investigated.
- Worst-case scenario of impact is studied using a rigid bumper.
- Actual racecar would be more flexible and the peak G load and wall deformation would be lower than this research exhibits.

Recommendations Based on LS-DYNA Analysis

- Non-linear material properties should be included in the LS-DYNA simulation.
- Racecar crash simulations should be performed at 153 MPH peak velocity.
- Effect of cutouts on airbag surfaces should be further explored.
- Actual racecar impact could be studied for peak G load and wall deformation.

Acknowledgements

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