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ENERGY ABSORPTION CHARACTERISTICS OF A CARBON FIBER COMPOSITE AUTOMOBILE LOWER RAIL: A COMPARATIVE STUDY

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ABSTRACT

Composite materials have emerged as promising materials in applications where low weight and high strengths are desired. Aerospace industry has been using composite materials for past several decades exploiting their characteristics of high strength to weight ratio over conventional homogenous materials. To provide a wider selection of materials for design optimization, and to develop lighter and stronger vehicles, automobile industries have been exploring the use of composites for a variety of components, assemblies, and structures. Composite materials offer an attractive alternate to traditional metals as designers have greater flexibility to optimize material and structural shapes according to functional requirements. However, any automotive structure or part constructed from composite materials must meet or exceed crashworthiness standards such as Federal Motor Vehicle Safety Standard (FMVSS) 208. Therefore, for a composite structure designed to support the integrity of the automotive structure and provide impact protection, it is imperative to understand the energy absorption characteristics of the candidate composite structures. In the present study, a detailed finite element analysis is presented to evaluate the energy absorbing characteristics of a carbon fiber reinforced polymer composite lower rail, a critical impact mitigation component in automotive chassis. For purposes of comparison, the analysis is repeated with equivalent aluminum and steel lower rails. The study was conducted using ABAQUS CZone module, finite element analysis software. The rail had a cross-sectional dimension of 62 mm (for each side), length of 457.2 mm, and a wall thickness of 3.016 mm. These values were extracted from automobile chassis manufacturer's catalog. The rail was impacted by a rigid plate of mass 1 tonne (to mimic a vehicle of 1000 Kg gross weight) with an impact velocity of 35 mph (15646.4 mm/s), which is 5 mph over the FMVSS 208 standard, along its axis. The simulation results show that the composite rail crushes in a continuous manner under impact load (in contrast to a folding collapse deformation mode in aluminum and steel rails) which generates force-displacement curve with invariable crushing reactive force for the most part of the crushing stroke. The energy curves obtained from reactive force-displacement graphs show that the composite rail absorbs 240% and 231% more energy per unit mass as compared to aluminum and steel rails. This shows a significant performance enhancement over equivalent traditional metal (aluminum and steel) structures and suggests that composite materials in conjunction with cellular materials/configurations have a tremendous potential to improve crashworthiness of automobiles while offering opportunities of substantial weight reductions

INTRODUCTION

The past several decades have seen an increasing growth in the interest of lighter vehicles for improved fuel efficiency. This need for lighter vehicles has posed challenges on keeping up with the safety standards and survivability of the vehicles' occupants in an event of an accident. Extensive research has been aimed at reducing weight of vehicles without compromising crashworthiness of the vehicle. A large portion of this research has been aimed at new materials [3-6, 11, 14] with the need to characterize their deformation under crash loading conditions. These materials are composite materials and possess certain characteristics that offer great advantages over conventional materials typically aluminum and steel for use in structural and non-structural components.

Typically the front rails of the vehicle are candidates for optimization as they are responsible for absorbing the frontal impact in a controlled manner and without excessive deceleration, which could cause injury to the occupants [15-16]. Mostly in current use are metallic thin walled components which accomplish this controlled deformation by progressive folding of sidewalls due to the gross plastic deformation. In case of composite materials, this impact energy is dissipated and absorbed by following damage mechanisms: 1) micro-structural damage of the material, 2) formation of continuous fronds in combination with transverse tearing, and 3) progressive folding similar to that exhibited by metallic tubes [1-3, 7, 10-11].

Research in characterizing the deformations of composite tubes of simple cross sectional geometries has been extensively covered experimentally in literature. A.G. Mamalis et al 1996 studied the crush behavior of thin-walled circular and frusta fiber glass composite subjected to dynamic axial compression. Their studies were centered on the effects of the geometry and loading rate on the energy absorption efficiency and the mechanics of the crumpling process on a macro-mechanical level. Although in typical cases, stable and unstable collapse could occur, the authors reported only stable collapse of the tubes in their experiments. They classified these stable collapse modes into 2 sub-categories, Mode Ia, and Mode Ib. Mode Ia was characterized by its initiation at one end as the progressive delamination along the tube occurred, with the inner layers of the shell inverting inwards, and the outer layers inverting outwards. . In contrast to the Mode 1a, the Mode Ib tube walls inverted inwards only. This occurred mainly for higher semi apical angles. They observed that for the frustum cylinders, the critical semi apical angle for the dynamic loading was 15°and 20° under static loading conditions. They also observed a decrease in the specific energy with increasing semi-apical angle and the mean post crushing load increased with increasing wall thickness [1]. A.G Mamalis et al 1997 extended their work to square tubes of fiberglass composite material. Here the authors reported four distinct collapse modes, sub-classified as Mode I-IV. Typically these modes were dependent on the number of layers or thickness of the tubes. Mode I deformation was similarly to that reported by the authors in reference [1]. Mode II was described by the cracking of the corners of the frustum. Mode III was described by extensive brittle fracture exhibited by the tube around the tube circumference. The fracture unlike in other cases occurred approximately at the mid length of the tube. The force-displacement curves in this case showed a sharp drop after the initial force peak and thereafter poor crushing characteristics. The Mode IV progressive folding mode of the collapse was characterized by the formation of progressive folds or fracture hinges. The deformation was similar to the collapse exhibited by thermoplastic metal thin-walled tubes under axial loads. The force-displacement curve for Mode IV collapse showed large fluctuations in the peak forces and exhibited small average collapse load.

Despite the reported stable progressive crush behavior and higher specific energy absorption reported by researchers [1-2, 7, 10] for composite materials, there are two factors that affect their use in vehicles: 1) high material and manufacturing costs, and 2) lack of numerical models capable of accurately predicting their response [3]. Attempts to accurately model the deformation have been made by various researchers more recently [3, 9, 11-14, 17].

This paper presents our analysis on the energy absorption characteristics of carbon fiber composite tube for application in vehicle front rails. The analysis is conducted using ABAQUS, finite element package. Here we present comparisons with conventionally implemented materials (steel and aluminum) and assess the improvements in the energy absorption capacity under standard crash testing conditions

FINITE ELEMENT MODELING

The study was conducted using ABAQUS, commercial finite element analysis software, and a special add on module, CZone. This module allows simulating crush behavior of composite materials under impact.

The rail was 457.2 mm long. It had a square cross-section of 62 mm side length and a wall thickness of 3.016 mm. These values were extracted from automobile chassis manufacturer’s catalog. The rail was impacted by a rigid plate of mass 1 tonne (to mimic a vehicle of 1000 Kg gross weight) with an impact velocity of 35 mph (15646.4 mm/s), which is 5 mph over the FMVSS 208 standard, along its axis. A total of 8 carbon fabric/epoxy plies were defined. The material properties assigned to each ply of the composite rail are shown in Table 1:

TABLE 1: IN-PLANE PROPERTIES OF COMPOSITE FABRIC

Longitudinal modulus, E_1 (MPa)	Transverse modulus, E_2 (MPa)	Major Poisson’s ratio, ν_{12}	Shear modulus, G_{12} (MPa)
51500	51500	0.05	3000

The material damage initiation was implemented through Tsai-Wu damage initiation method. This method utilizes tensile and compressive stress limits in the orthotropic material directions and the maximum shear strength to define the onset of damage. The parameters defined in the present study are listed in Table 2.

TABLE 2: IN PLANE MATERIAL CONSTANTS FOR TSAI-WU DAMAGE

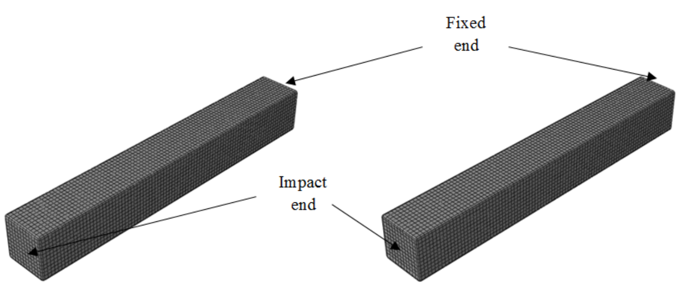
Tensile stress in longitudinal direction, F_{1t} (MPa)	770
Compressive stress in longitudinal direction, F_{1c} (MPa)	600
Tensile stress in transverse direction, F_{2t} (MPa)	770
Compressive stress in transverse direction, F_{2c} (MPa)	600
Shear strength, F_6 (MPa)	110
Interaction term, *f*	0.5

The contact conditions were defined using penalty contact and general contact method. The rail was meshed using hour glass controlled, 4 node, and reduced integration shell elements. The impact plate was discretized using 4 node rigid shell elements. A total of 4953 and 32 elements were generated for composite rail and rigid impact plate, respectively.

RESULTS

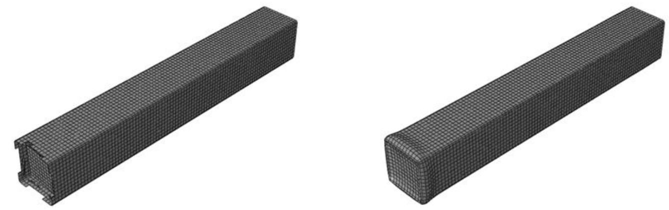
DEFORMATION MODES

Figures 2 to 5 show side by side deformation of composite and aluminum rails. The aluminum rail deforms in a typical Mode I and/or Mode II folding mode [15], which repeats itself as the deformation progresses. The composite rail shatters initially and then crushes in a continuous manner for the rest of the deformation stroke



(a) **(b)**

FIGURE 2: THE MESHED FINITE ELEMENT MODELS. (A) COMPOSITE SQUARE RAIL. THE MATERIAL MODEL HAS 8 WOVEN PLIES MADE OF CARBON FIBER-EPOXY, AND CRUSHING PROCESS WAS SIMULATED USING TSAI-WU FAILURE CRITERION; (B) ALUMINUM SQUARE RAIL. THE MATERIAL IS 6063 ALUMINUM ALLOY (COMMONLY USED IN AUTOMOTIVE INDUSTRY FOR HIGH STRENGTH TO WEIGHT RATIO APPLICATIONS).



(a) **(b)**

FIGURE 3: DEFORMATION AFTER 0.5 MS OF INITIAL IMPACT (A) DEFORMATION OF COMPOSITE RAIL; (B) DEFORMATION OF ALUMINUM RAIL

(a) **(b)**

FIGURE 4: DEFORMATION AFTER 5MS OF INITIAL IMPACT (A) DEFORMATION OF COMPOSITE RAIL; (B) DEFORMATION OF ALUMINUM RAIL

(a) **(b)**

FIGURE 4: DEFORMATION AFTER 5MS OF INITIAL IMPACT (A) DEFORMATION OF COMPOSITE RAIL; (B) DEFORMATION OF ALUMINUM RAIL

Applying same boundary and loading conditions, analysis was conducted on steel rail, and a similar folding deformation mode was observed as in the case of aluminum rail. The material assigned to the rail was HSLA A36 steel, which is commonly used in automobile chassis in the US.

FORCE-DISPLACEMENT CURVES

Figure 5 depicts the reactive force-displacement pulse extracted from the impacting plate. For aluminum, the initial crushing force and average force to maintain crushing is 53.2 kN and 35.6 kN, respectively. The corresponding values for composite rail are 58.2 kN and 55.4 kN, and for steel, the values are 179.8 kN and 107.4 kN. It may be noted that a well-defined reactive force plateau regime is established past 15 mm displacement in composite rail, which is attributed to its continuous crush mode.

ENERGY PLOTS

The area under the curve represents the energy absorbed by each structure. The total energies absorbed by aluminum, steel, and composite rails are 13.4 kJ, 39.69 kJ, and 24.5 kJ, respectively, as shown in Figure 6.

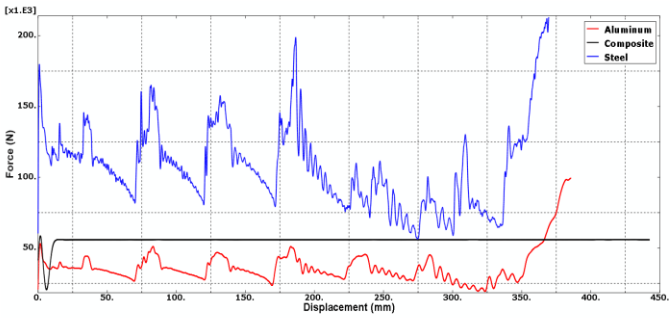


FIGURE 5: FORCE VS. DISPLACEMENT CURVE OF EACH RAIL

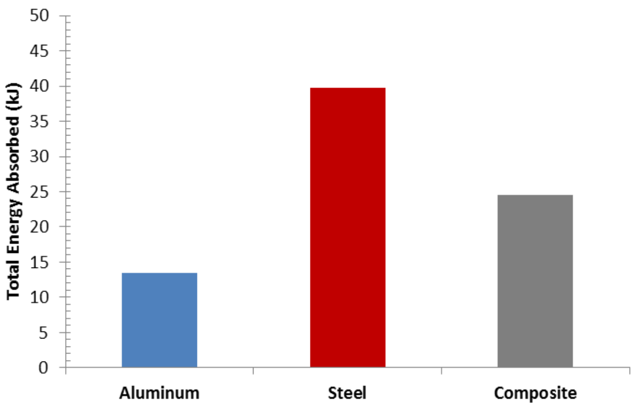


FIGURE 6: TOTAL ENERGY ABSORBED BY EACH RAIL

A comparison of weight for each structure is depicted in Figure 7. The total weights of aluminum (based on 2.7x10^{-6} Kg/mm^3 density), steel (based on 7.8 x10^{-6} Kg/mm^3 density), and composite rails (based on 1.45 x10^{-6} Kg/mm^3 density) are 9.17 N, 26.46 N, and 4.93 N , respectively

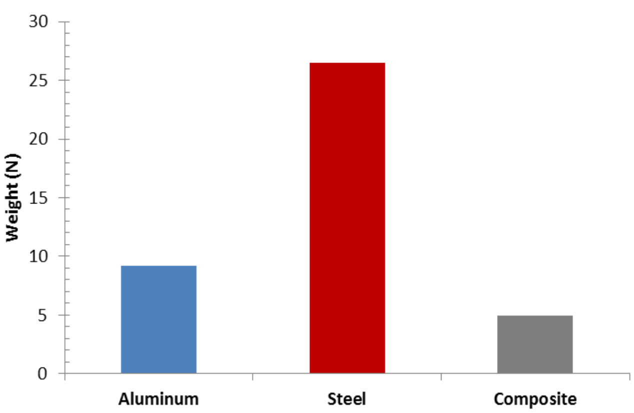


FIGURE 7: WEIGHT OF EACH RAIL

A useful comparison of energy absorbed is conducted by comparing specific energy which is defined as a ratio of total energy absorbed by a structure to the mass of the structure. The specific energies of aluminum, steel, and composite rails in this case are 14.32 kJ/kg, 14.7 kJ/kg, and 48.7 kJ/kg, respectively, as shown in Figure 8. It is evident that the composite rail outperforms aluminum and steel rails. A high value of specific energy means greater flexibility in controlling design and weight of the composite rail and more room for its performance optimization.

In future, a parametric study will be performed on tubes of various sizes and wall thicknesses coupled with composite materials parameters such as matrix, fiber, and ply stacking sequence. The mathematical expressions for predicting crush stress and total and specific energy absorbed will be developed using regression analysis and some other data analysis techniques.

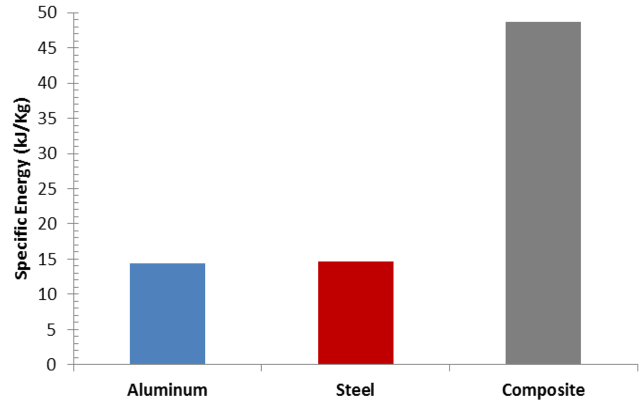


FIGURE 8: SPECIFIC ENERGY OF EACH RAIL

CONCLUSIONS

Energy absorption characteristics of a (fiber reinforced polymer) composite lower square (automobile) rail are studied in comparison with aluminum and steel rails of same geometry. The composite rail crushes in a continuous manner under impact load (in contrast to a folding collapse deformation mode in aluminum and steel rails) which generates force-displacement curve with invariable crushing reactive force for the most part of the crushing stroke. The composite rail absorbs 240% and 231% more energy per unit mass as compared to aluminum and steel rails. This shows a significant performance enhancement over equivalent traditional aluminum and steel structures and suggests that composite materials have a tremendous potential to improve crashworthiness of automobiles while offering opportunities of substantial weight reductions.

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