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STUDY OF VEHICLE CRASHWORTHINESS APPLYING COMPOSITE MATERIALS (FRONTAL AND OFFSET IMPACT)

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ABSTRACT

The automotive industry is faced with an unprecedented challenge, to produce lighter vehicles with less fuel consumption and pollution without sacrificing internal roominess and passenger safety. Therefore , new materials other than steel are being considered . This study presents the usage of composite materials instead of steel in certain parts (main rail, bumper, hood, fenders, wheel housing and doors) of the vehicle to improve its performance by studying of vehicle crashworthiness (frontal and offset impact). A finite element model of a 1994 Chevrolet C-1500 pick-up truck was modified and used for this purpose with the aid of the multi-purpose finite element code LS-DYNA . The results showed that, the usage of composite materials in vehicle frame (or all parts together) gives higher percentage of weight reduction and higher percentage of absorbed energy , than in the case of steel .

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INTRODUCTION

Automotive industry is one of the leading industries in the world . One of the goals of automotive industry is a lighter and safer vehicle, with more miles per gallon and fewer pollutants . Many factors are considered and the vehicle structure is the main dominating one .

A key factor in the structural engineering design, is the impact protection for vehicle occupants. A lighter vehicle means lighter weight materials which should fulfill the requirements of safety. So, new materials other than steel are being considered in the fabrication of vehicle's structural parts such as composite materials. The composite materials give the solution for these problems in design and can be tailored to satisfy the required needs.

Several approaches were investigated in order to achieve the goal of producing a lighter and safer vehicle. One approach was to downsize the vehicle ; after 1973 [1]; another approach was to substitute conventional structural materials with innovative materials [2] , which give the same or better performance (but with less weight). Almost every part of the vehicle structure was investigated by replacement with another one made from non-conventional material . For example vehicle frame was replaced with another frame made totally from reinforced aluminum by Ford Corporation [3]. Moreover , the steel body was replaced by a reinforced aluminum one in a model of Audi's cars [3] . The objective of this work is to study the vehicle structural mechanics and the possibility to replace the conventional materials with composite ones in automotive structural parts (main rail, bumper, hood, fenders, wheel housing and doors) separately and as a combination, to improve the performance of the vehicle (decrease the vehicle weight, increase the power to weight ratio and improve the absorbed energy).

The LS-DYNA Chevrolet C-1500 model [4] , [5] was modified to fulfill the above objectives . The modified model was validated by comparing the results with that of the tests and models of the National Crash Analysis Center (NCAC).

THEORETICAL STUDY

LS-DYNA [6] is a general purpose finite element code for analyzing the large deformation and dynamic response of structures. It uses a displacement-based, Lagrangian, central-difference finite element formulation to solve the dynamic response of nonlinear structural problems. The formulation makes use of Cauchy's first law of motion and the principle of virtual work to determine the potential energy equation for the general three-dimensional problem [6] , [7]:

$$-\int_V \rho\, \ddot{x}_i\, \delta x_i\, dV - \int_V \sigma_{ij}\, \delta\varepsilon_{ij}\, dV + \int_V \rho\, b_i\, \delta x_i\, dV + \int_{S_t} t_i\, \delta x_i\, dS = 0$$

where $\delta\varepsilon_{ij}$ is the virtual strain tensor attributed to the virtual displacement δx_i for a three-dimensional body located in a fixed (Lagrangian) space. The body is subjected to traction forces $t_i(t)$ (forces per unit area) over a portion of its outer surface S_t, prescribed displacements $d_i(t)$ over a surface S_d, and external body forces $b_i(t)$ (forces per unit volume) over its entire volume *V* , *σij* denotes Cauchy's stress tensor, *ρ* is the material current density, and $\ddot{x}_i$ is the current acceleration of the particle .

The potential energy equation is first discretized in space through the finite element mesh and shape functions. It is then discretized in time through the explicit central difference method to derive the dynamic equations of motion .

MODELING

A finite element model was developed by the NCAC , (using LS-DYNA code) , for a 1994 chevrolet C-1500 pick-up truck as a regular- cab, fleet side long-box with a total length of 5.4 meters and a wheelbase of 3.34 meters. The engine is a 4.3 liter Vortec V6 with electronic fuel injection coupled to an automatic transmission with a rear wheel drive configuration [4] , [5] . This model was in static condition (zero impact velocity) with no wall or floor . To use this model in the present study , it was necessary to be modified by :

1- Using impact velocity 35 mph (56.3 km/hr) .
2- Changing the material behavior of the main rail from piecewise linear plasticity to composite damage .
3- Adding wall and floor .

The modified model results were compared with those of the crash test and crash simulation conducted by the NCAC and was found adequate [8-9] .

MODEL RESULTS AND ANALYSIS

It is important to analyze the energy absorption by the different components in the vehicle. This can be obtained in the simulation by computing the material internal energies in the model. The internal energy of the materials is the sum of the plastic strain energy and the elastic strain energy.

Frontal Impact :

Table 1 shows the percentage of the total energy absorbed through the different components [4] , [5] . From this table , it is obvious that , the main rail, bumper, hood, fenders, wheel housing and doors are the effective parts in crashworthiness and have the maximum values of absorbing the internal energy. A comparison is made for (displacement, velocity and internal energy) curves for the chosen parts before and after changing their materials to composite materials and aluminum alloy .

Frontal impact is studied for each of the chosen parts and for all the chosen parts together at node 16154 under the driver on the frame and at node 81 on the middle of the pumper because they represent the driver location and the total deformation during the crash test as shown in Fig (1) .

Tables (2), (3) and (4) show the properties of steel [3-5] , kevlar/epoxy [2] , boron /Al [2] and aluminum alloy materials [3-5] . Tables (5) and (6) show the chemical composition of aluminum alloy and volume fraction of kevlar/epoxy and boron /Al materials.

Table (1). Material internal energy for a 56 km/hr frontal impact into a rigid wall (before changing materials) [4-5] .

Material Parts	Internal Energy (KJoules)	Percentage
Whole Vehicle	214	100%
Rails and its matching structures	93.20	43.55%
Bumper and its matching structures	26.10	12.20%
Engine and its matching structures	23.00	10.75%
Radiator and its matching structures	21.80	10.19%
Toepan and front floor	15.20	7.10%
Hood	10.70	5.00%
Fender	9.80	4.58%
Wheelhouse	1.65	0.77%
Remaining components	12.50	5.84%

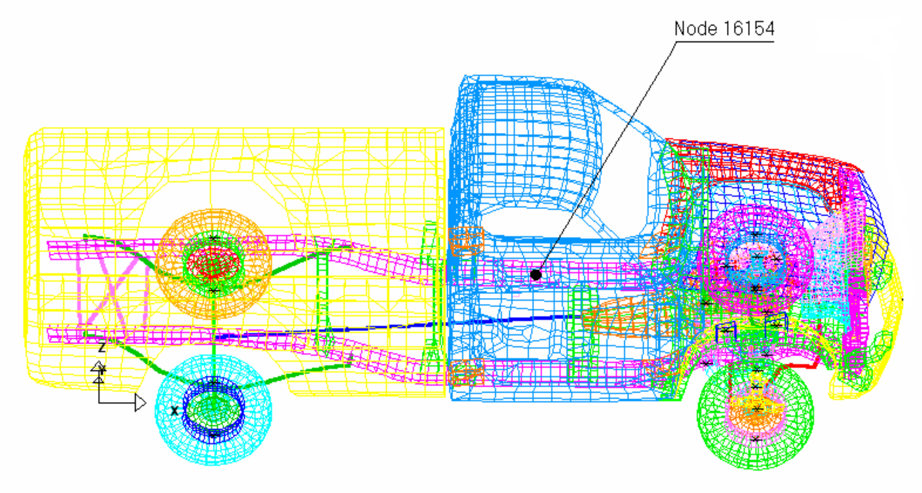

Fig. (1). Position of the node 16154 on the model.

Table (2) The properties of steel material [3-5].

Density	7.85 ($10^3 Kg/m^3$)
Young's Modulus	210 (GPa)
Poisson's Ratio	0.3
Yield Stress	215 (MPa)

Table (3) The properties of aluminum alloy material (2024-T4) [3-5].

Yong's Modulus (GPa)	Poisson's Ratio	Ultimate Stress (MPa)	Yield Stress (MPa)	Density (10^3Kg/m3)
74.5	0.33	470	320	2.77

Table (4) The properties of composite materials (boron/aluminum and kevlar/epoxy) [2].

	Boron /Al	Kevlar /Epoxy
Density	2.65E-09 (ton/mm^3)	1.38 E-09 (ton/mm^3)
Axial Young's modulus	227 (MPa)	76.8 (MPa)
Transverse Young's modulus	139 (MPa)	55 (MPa)
Poisson's ratio υ_{12}	0.24	0.34
Poisson's ratio υ_{23}	0.36	0.37
Shear modules G_{12}	57.6 (MPa)	2.07 (MPa)
Shear modules G_{23}	49.1 (MPa)	1.4 (MPa)

Table (5) The chemical composition of aluminum alloy material [3-5].

(Al) %	Others Total %	(Ti) %	(Zn) %	(Cr) %	(Mg) %	(Mn) %	(Cu) %	(Fe) %	(Si) %
Remainder 93.05-90.75	0.15	0.15	0.25	0.1	1.2-1.8	0.3-0.9	3.8-4.9	0.5	0.5

Table (6) The volume fraction of kevlar /epoxy and boron / aluminum materials [2].

(Epoxy) %	(Kevlar) %	(Al) %	(Bo) %
31.6	68.4	0.85	0.15

The resulting curves are plotted in the longitudinal direction (x direction) only , because the car does not rotate significantly around the z-axis even after the max. deformation point is reached . Thus , the variations in the y and z directions are neglected. Figure (2) shows two images of the vehicle before and after the frontal impact test [8].

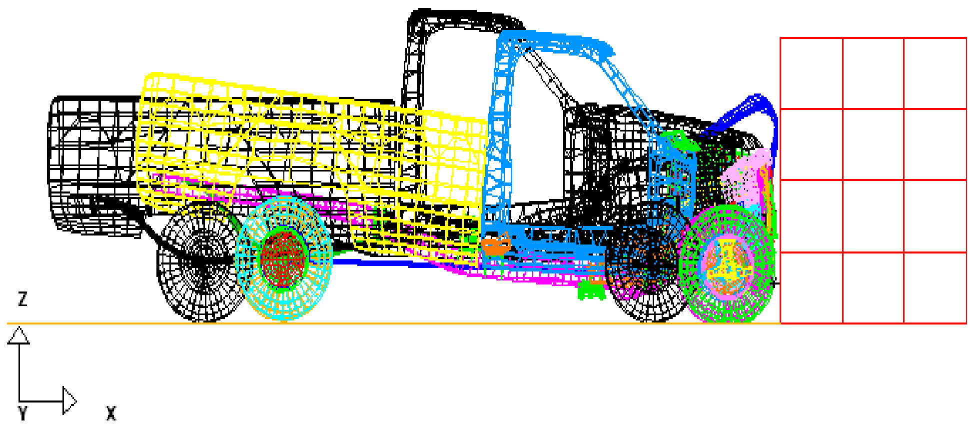

Fig. (2) Vehicle before and after the frontal impact test [1].

Figure (3) shows that the Boron/Al applied on main rail provides displacement (1.3 times steel) . The max time at which velocity reaches zero is shown in Fig. (4). The max. internal energy (6 times steel) is shown in Figure (5).

Changing the bumper material, Fig. (6) shows that the displacement resulting value of the Boron/Al is located between the steel and the aluminum alloy (1.07 times steel). The max time at which velocity reaches zero is shown in Fig. (7) . The internal energy has the max. value (90 times steel) as shown in Fig. (8).

In the case of changing of (hood, fenders, wheel housing and doors) material by Boron/Al, Fig. (9) shows that Boron/Al provides the max. displacement (1.07 times steel). The max time at which velocity reaches zero is shown in Fig. (10) . The max. internal energy (90 times steel) is shown in Fig. (11).

In case of changing of the all parts materials together, Fig. (12) shows that Boron/Al provides the max. displacement (1.24 times steel) . The max time at which velocity reaches zero is shown in Fig. (13). The max. internal energy (6.2 times steel) is shown in Fig. (14).

The Main Rail Test

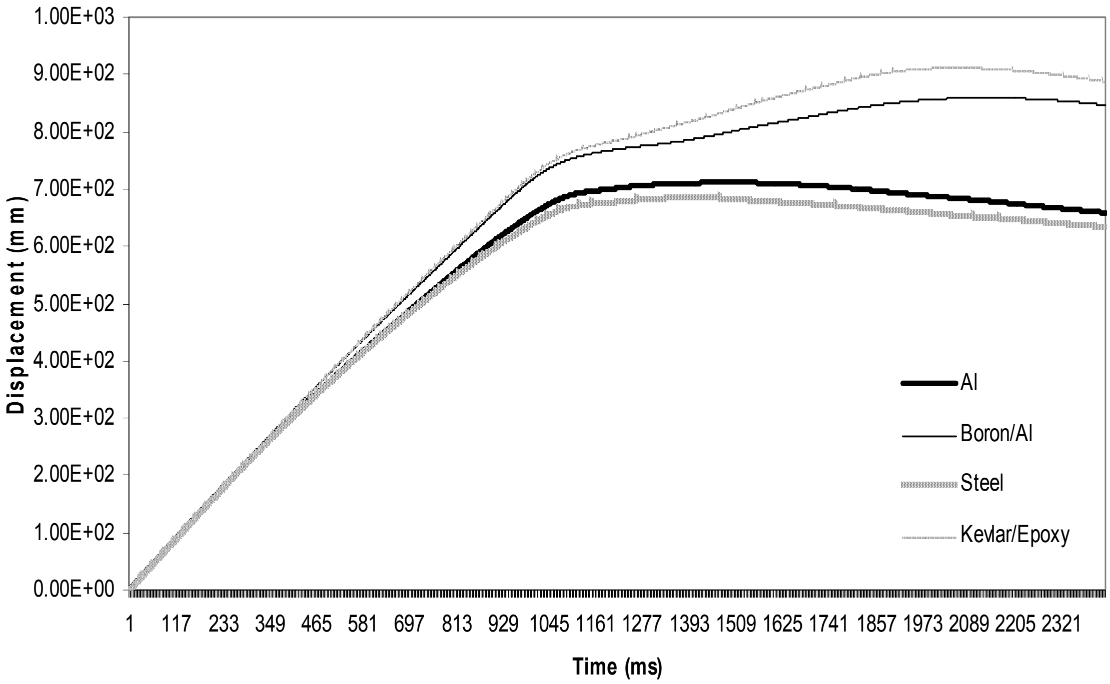

Fig. (3) Displacement of node 16154 due to frame material changing.

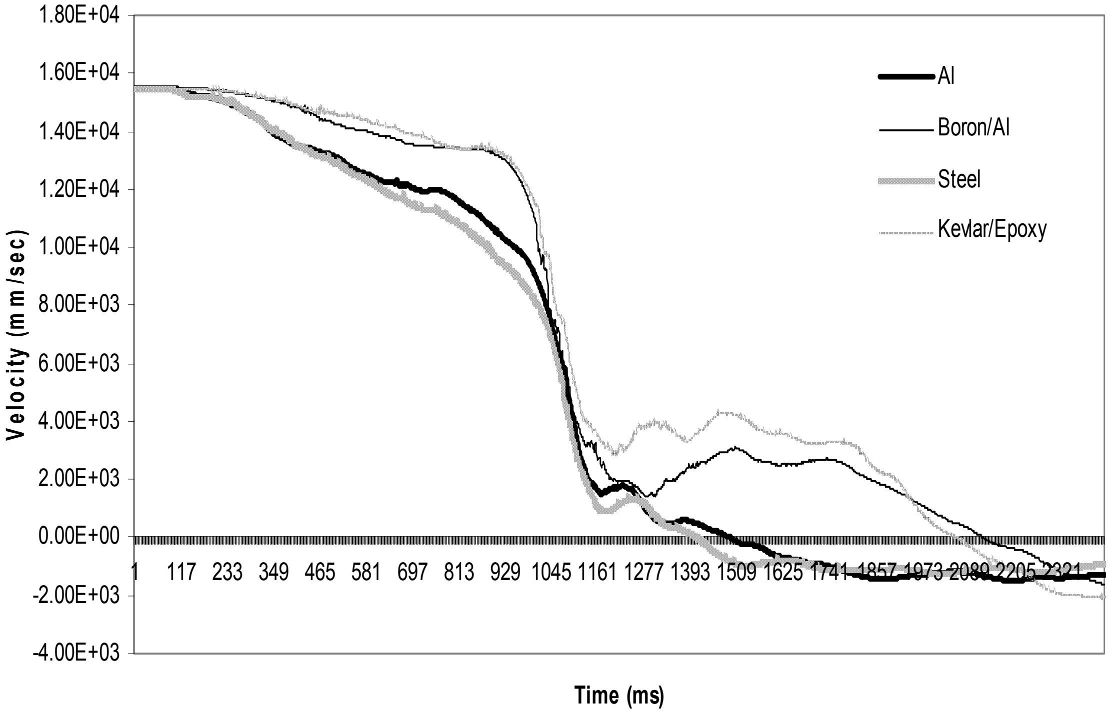

Fig. (4) Velocity of node 16154 due to frame material changing.

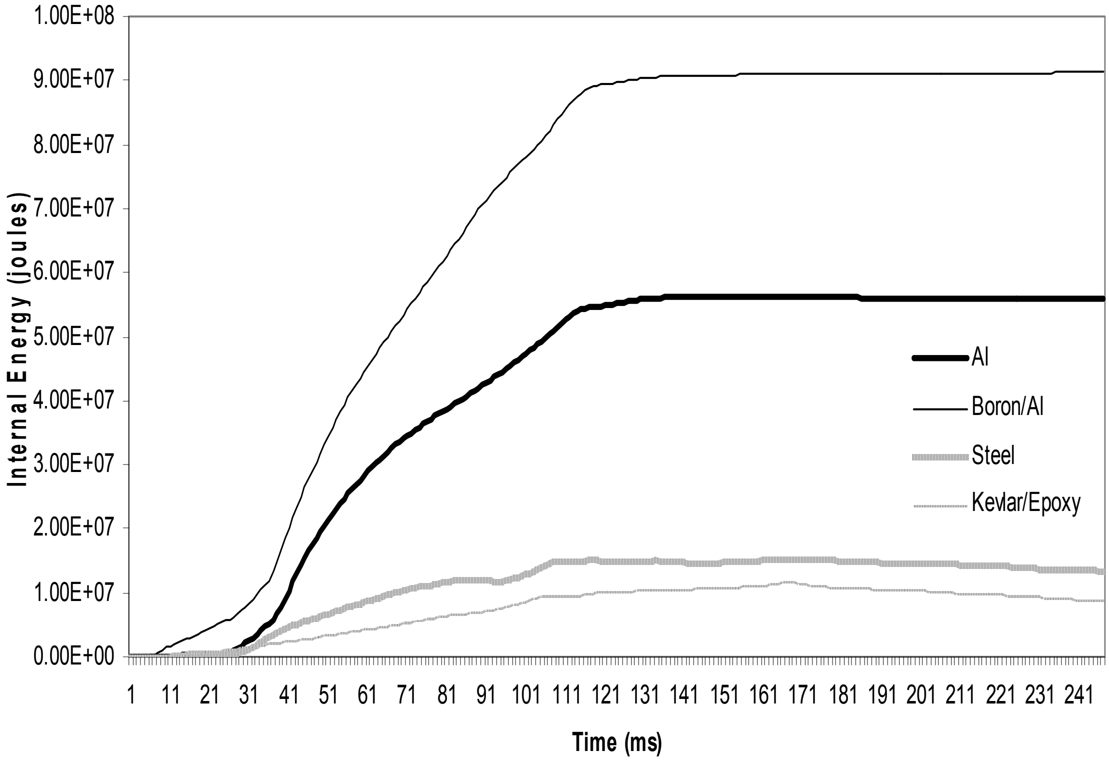

Fig. (5) Internal energy of frame due to material changing.

The Bumper Test

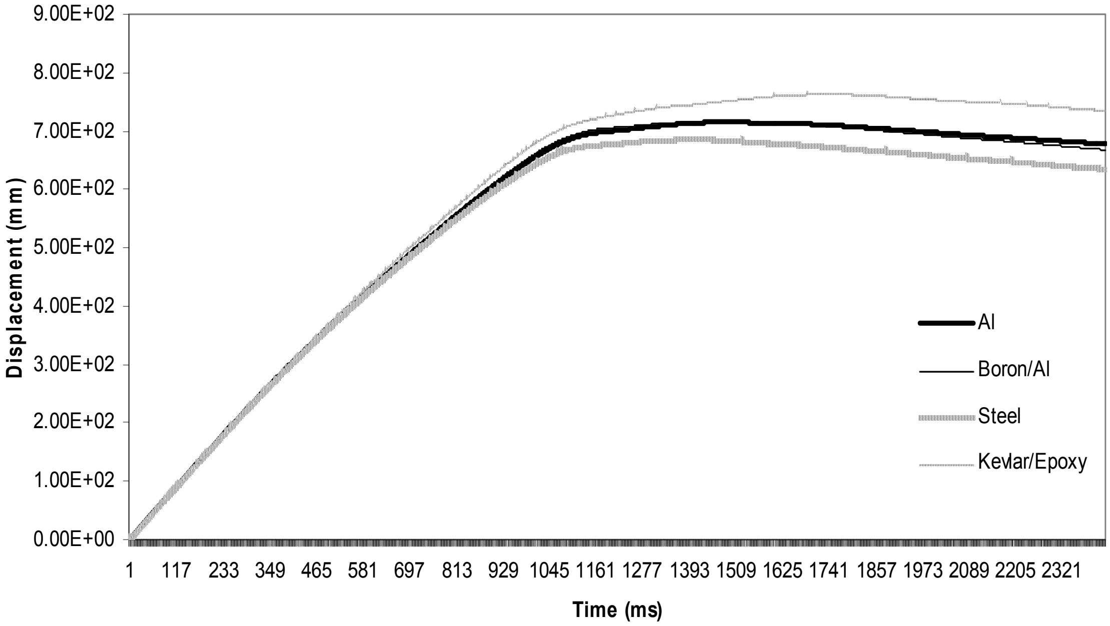

Fig. (6) Displacement of node 16154 due to bumper material changing.

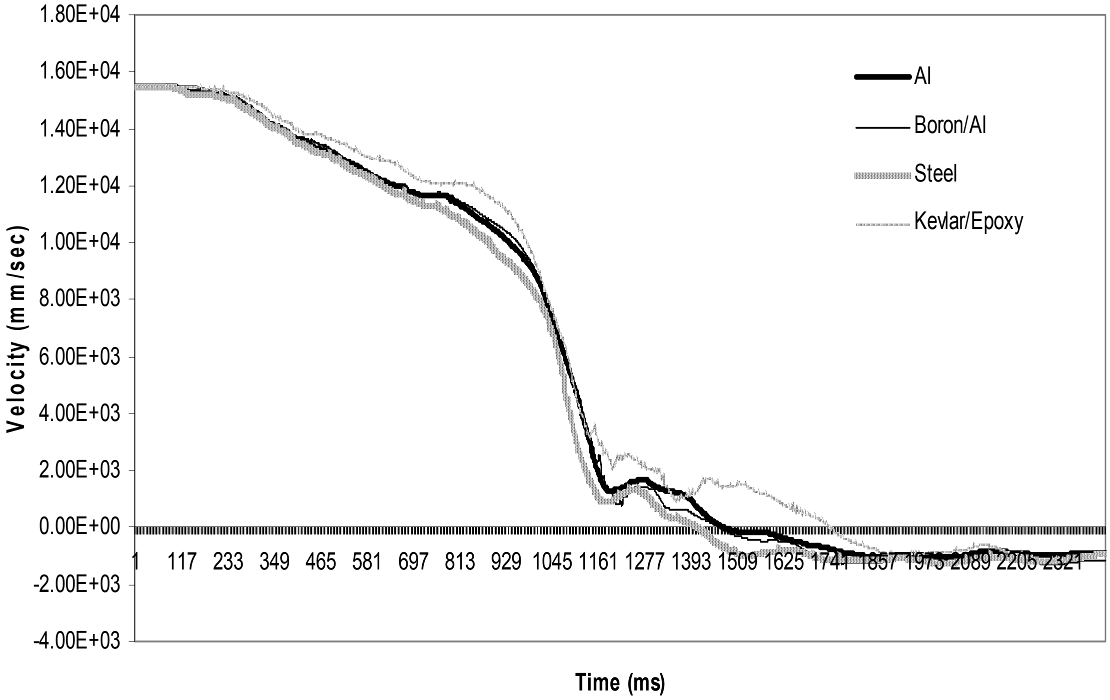

Fig. (7) Velocity of node 16154 due to bumper material changing.

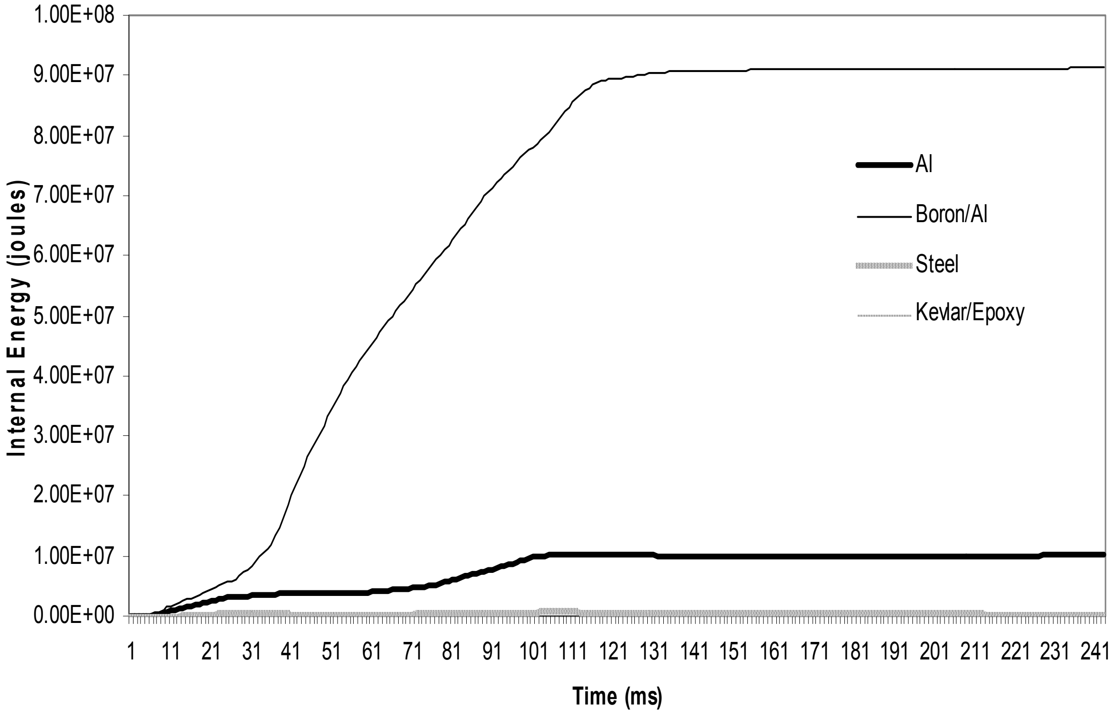

Fig. (8) Internal energy of bumper due to material changing

Hood, Fenders, Wheel Housing and Doors Test

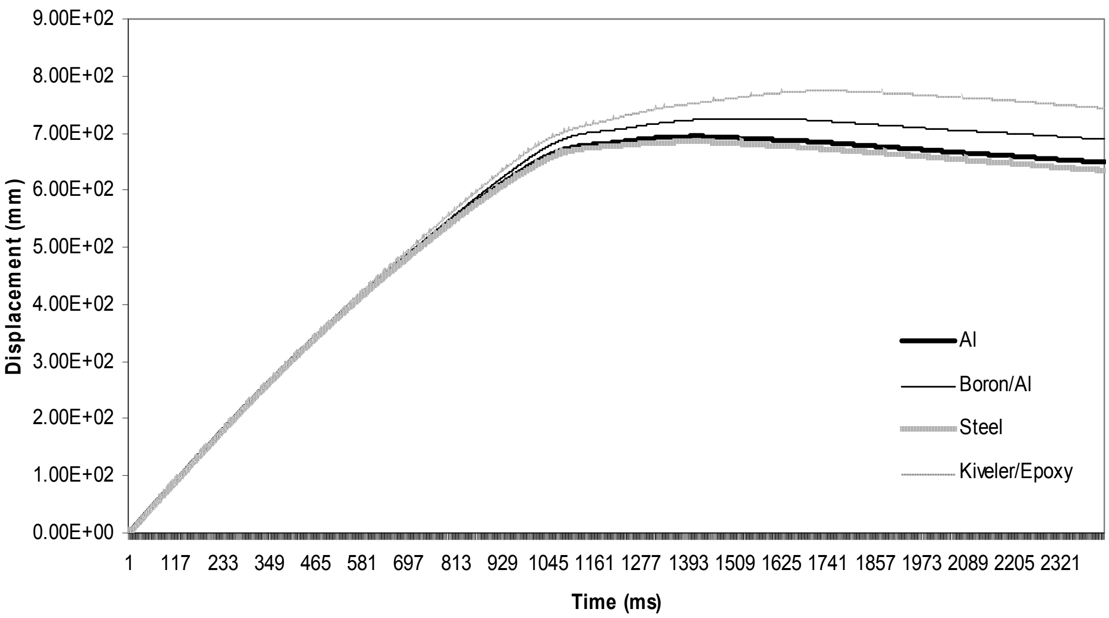

Fig. (9) Displacement of node 16154 due to hood, fenders, wheel housing and doors material changing.

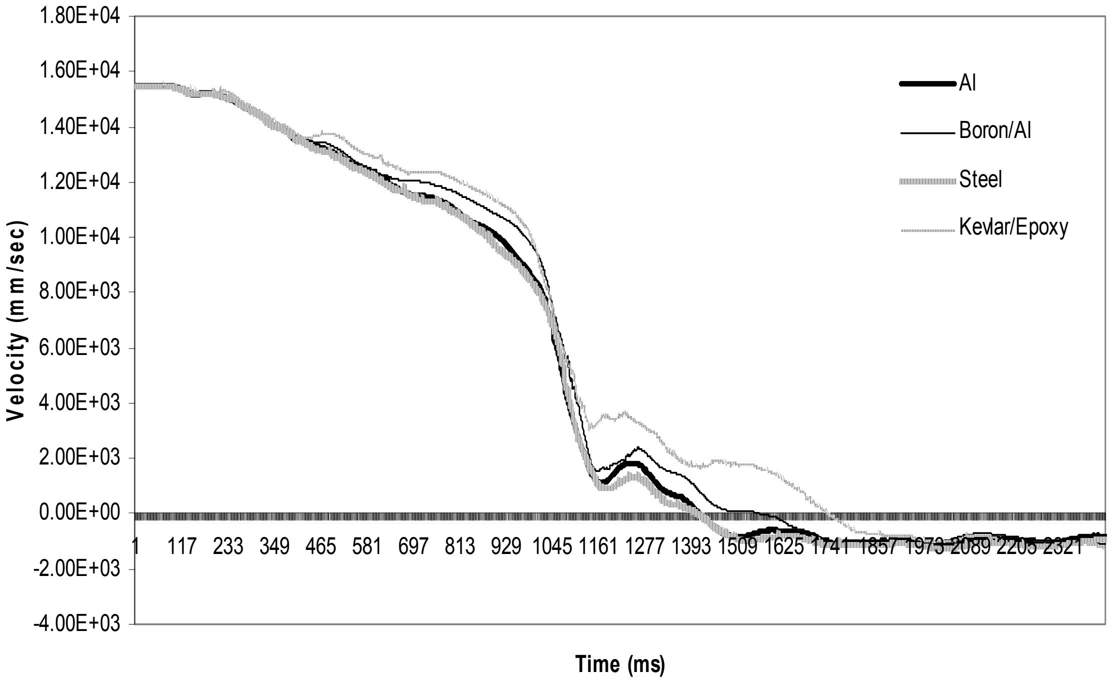

Fig. (10) Velocity of node 16154 due to hood, fenders, wheel housing and doors material changing.

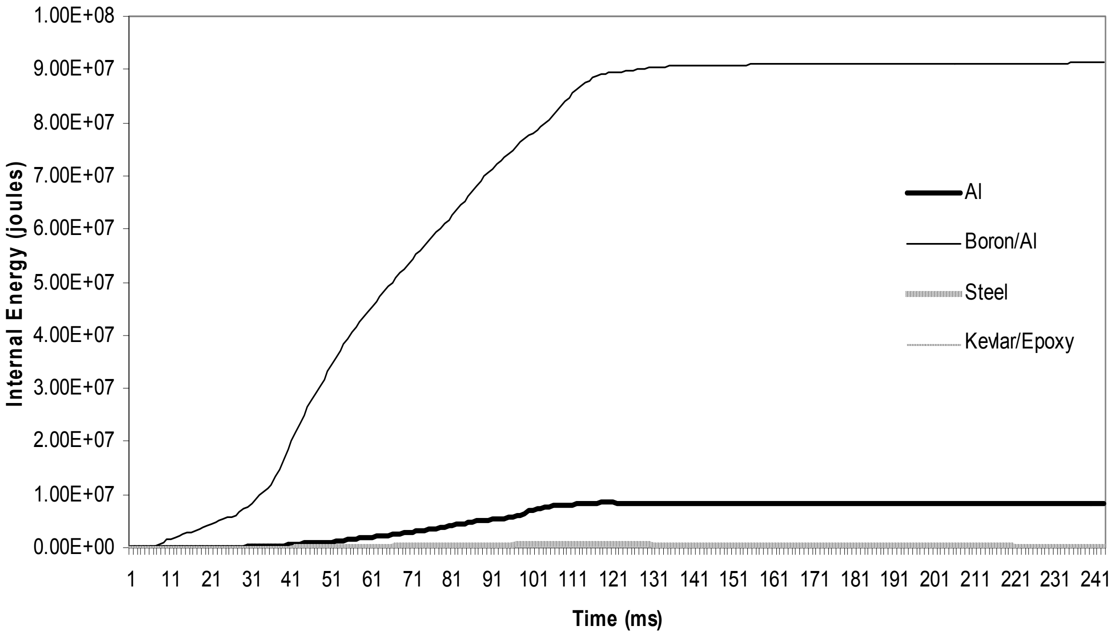

Fig. (11) Internal energy of hood, fenders, wheel housing and doors due to material changing

All Parts Test

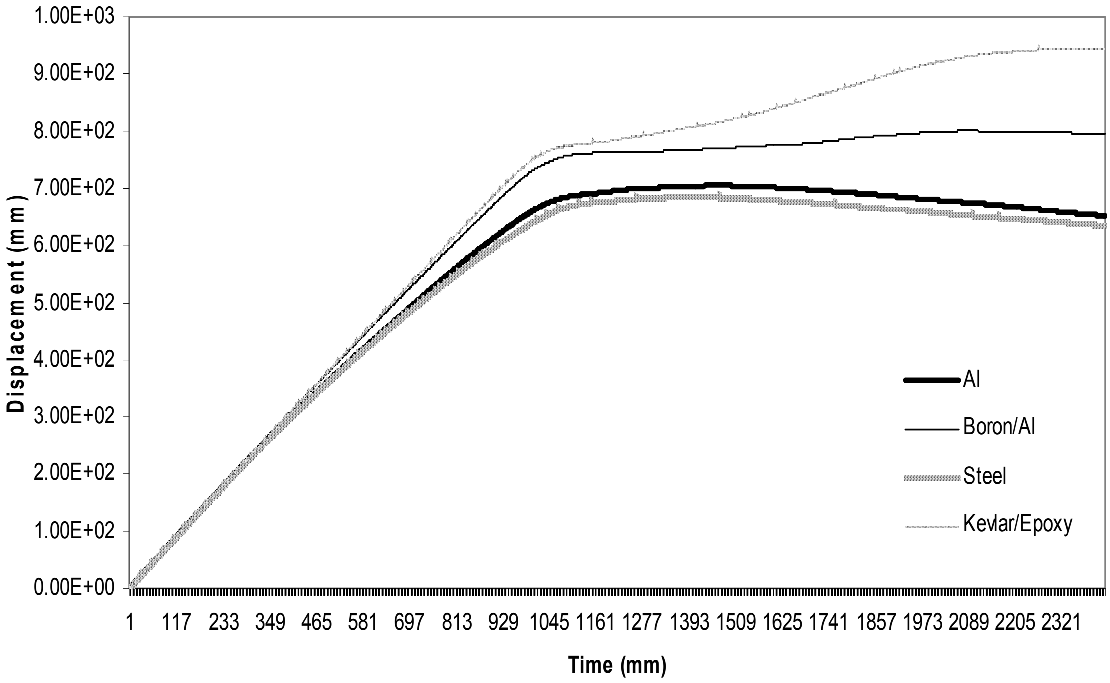

Fig. (12) Displacement of node 16154 due to all parts material changing.

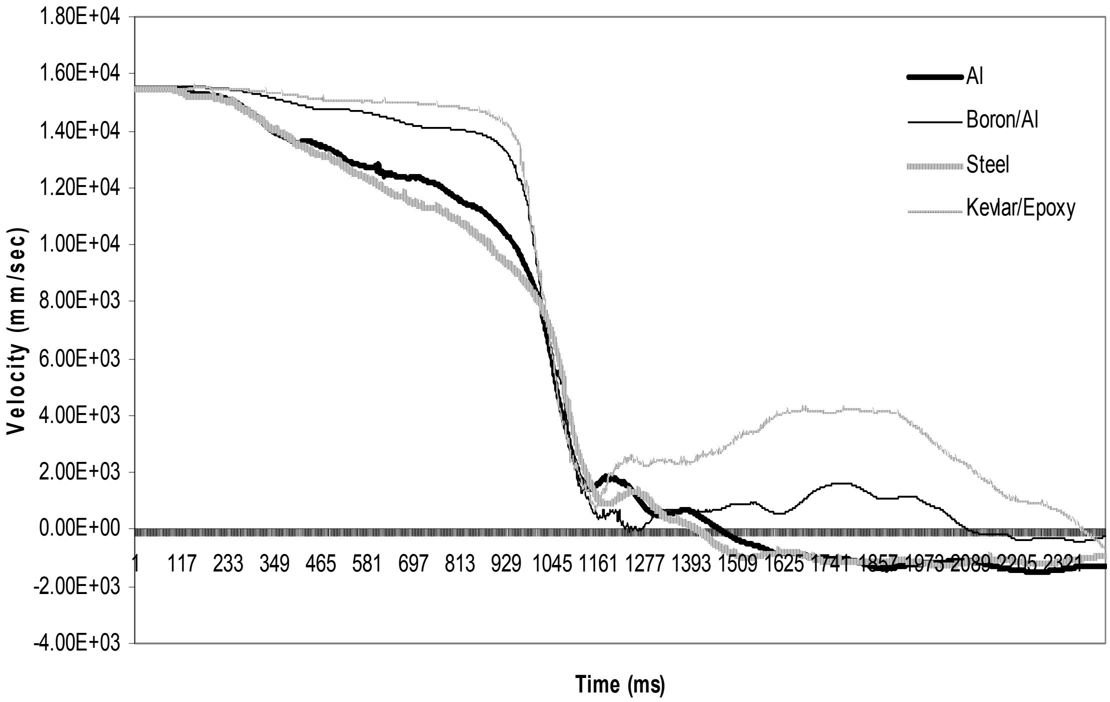

Fig. (13) Velocity of node 16154 due to all parts material changing.

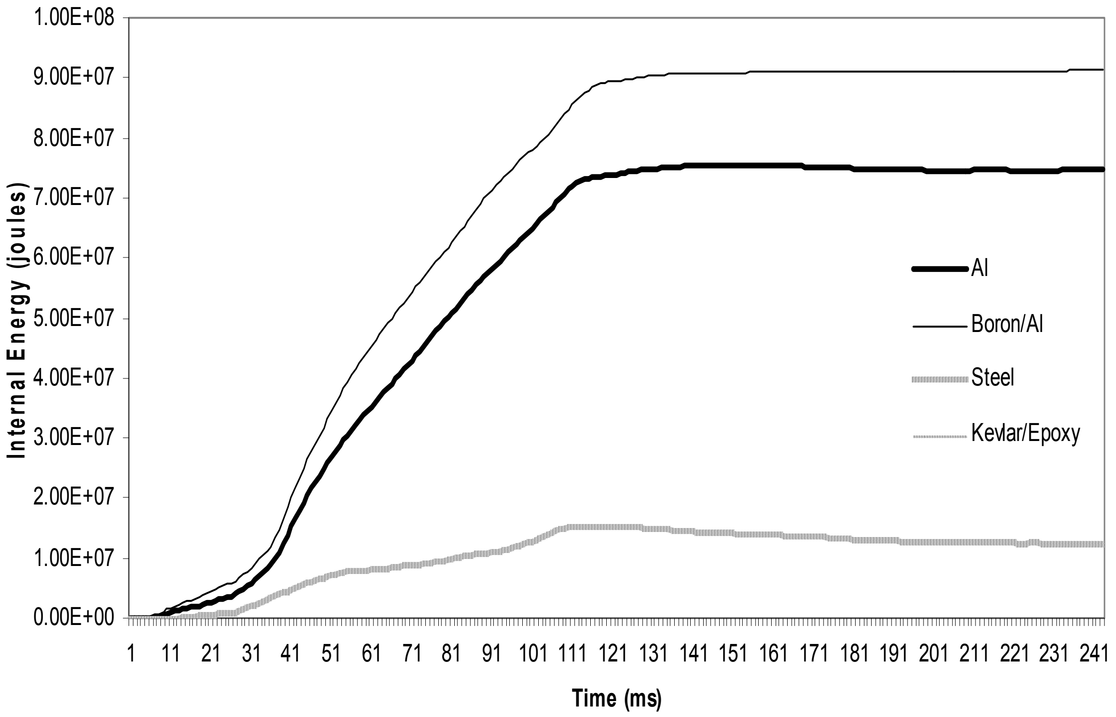

Fig. (14) Internal energy of all parts due to material changing.

The previous results are summerised in Table (7) .

Table (7) Frontal impact summary (driver node 16154).

	Frame			Bumper			Hood, Fenders,…etc			All		
	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.
Boron/Al	3	1	1	2	3	1	3	2	1	3	2	1
Kevlar/Epoxy	4	2	4	4	1	3	4	1	4	4	1	4
Al Alloy	2	3	2	3	2	2	2	4	2	2	3	2
Steel	1	4	3	1	4	4	1	3	3	1	4	3

where 1:Best … 4: Weak.

The same work was done in frontal impact but at the bumper node 81 , and the results are summerised in Table (8).

Table (8): Frontal impact summary (bumper node 81)

	Frame			Bumper			Hood, Fenders,…etc			All		
	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.
Boron/Al	3	1	2	2	2	1	3	2	1	3	2	1
Kevlar/Epoxy	4	2	1	4	1	4	4	1	4	4	1	4
Al	2	3	3	3	3	2	2	4	2	2	3	2
Steel	1	4	4	1	4	3	1	3	3	1	4	3

Tables (7) and (8) show that Boron / Al is the best material to absorb energy whish is the most important factor in crashworthiness (then comes velocity and displacement results) . However , Kevlar / Epoxy gives the weakest results especially in internal energy than the others (Al Alloy , Boron / Al and Steel), therefore , the Kevlar / Epoxy will be excluded .

Offset Impact :

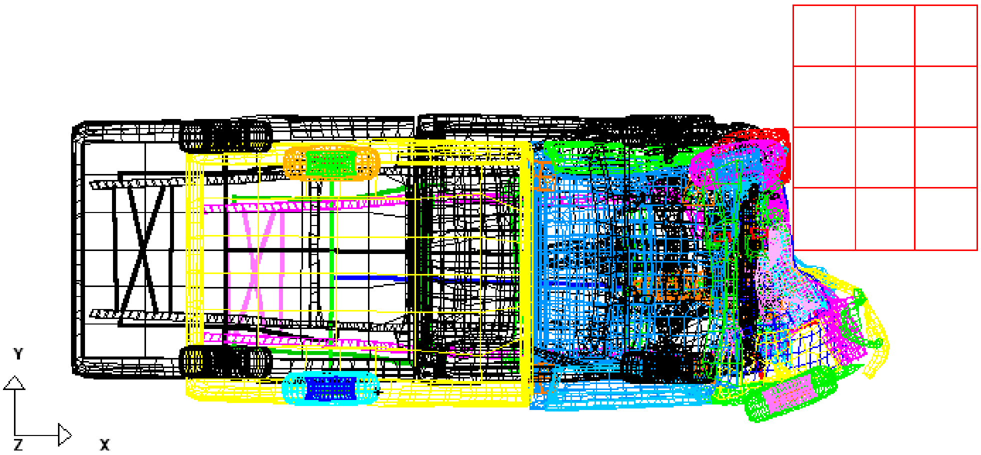

Fig. (15) Vehicle before and after the offset impact test.

Similarly, the above work was repeated but for the offset impact at the same mentioned nodes [8] . The results are summarised in Tables (9) and (10).

Table (9): Offset impact summary (driver node 16154).

	Frame			Bumper			Hood, Fenders,…etc			All		
	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.
Boron/Al	3	1	1	3	1	1	2	3	1	3	1	1
Al	2	2	2	1	3	2	3	1	2	2	2	2
Steel	1	3	3	2	2	3	1	2	3	1	3	3

Table (10): Offset impact summary (bumper node 81).

	Frame			Bumper			Hood, Fenders,…etc			All		
	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.	Dis.	Vel.	I.E.
Boron/Al	3	1	1	3	1	1	2	3	1	3	1	1
Al	2	2	2	1	3	2	3	1	2	2	2	2
Steel	1	3	3	2	2	3	1	2	3	1	3	3

Tables (9) and (10) showed the same behavior as in frontal impact .

CONCLUSIONS

From both frontal and offset impacts results , it is clear that replacing steel by Boron/Al is the best choice to improve the vehicle performance (weight reduction) and to fulfill the requirements of safety (higher energy absorption).

The choice of the part to be replaced is also important . Therefore , the results of parts replacement by (Boron/Al) for displacement, velocity and internal energy for both frontal and offset impacts are recalled .

The frontal impact study showed that the main rail material change provides the maximum displacement, maximum time of velocity to reach zero and maximum internal energy .

The offset impact study showed that all parts material change provides the maximum displacement and maximum time of velocity to reach zero , but for internal energy the main rail material change is the best .

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