

Analysis of Crashworthiness of a Saloon Car Fitted with CNG Cylinder

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Abstract

There is an increase in demand for compressed natural gas vehicles in India. Due to the high gasoline prices and lack of electric vehicle infrastructure in India, compressed natural gas vehicles are the only feasible option. This research work focuses on the crashworthiness of a saloon car fitted with a compressed natural gas cylinder under rear-collision conditions. Four different candidate materials of the same thickness are chosen for the cylinder based on strength and ductility i.e., AA6061, AA2024, mild steel, and A36 steel. The finite element analysis of the crash is performed in LS-DYNA by incorporating the Johnson-Cook material model parameters for the selected materials. The results are obtained from the crash analysis for the variation of the resultant force, kinetic energy, and internal energy, and these results are compared for different materials. The cylinder made of A36 Steel has shown the least absorption of specific energy, and the least deformation is observed in the cylinder compared to other materials.

Keywords: Crashworthiness, Johnson-Cook model, CNG cylinder, saloon car, finite element analysis

INTRODUCTION

In India, CNG is getting popular in various sectors such as industrial, residential, energy, and especially the automotive industry due to its ecological and economical merits. Etienne Lenoir invented the first engine powered by town gas and air late in the 1860s [1]. According to the natural gas vehicle (NGV) global report, there are more than 28.5 million vehicles running on natural gas in 2020. After China and Iran, India comes in the third position when it comes to the number of natural gas vehicles used in transport [2]. Looking at the current scenario in India, a significant number of car customers are trying to shift to electric and CNG vehicles. Still, due to insufficient infrastructure and the high prices of electric vehicles, CNG vehicles are the only economical and viable option left. Thus, there is a drastic increase in demand for CNG vehicles. From the fiscal year 2015–16 to the

fiscal year 2020–21, there has been a change of 0.03 to 0.2% in terms of market share of electric vehicles, whereas 0.1 to 6.2% in CNG vehicles in the same period of time [3]. Thus, the safety of CNG vehicles is a crucial topic and justifies the effort put into crash test analysis.

The CNG cylinder is the main component that makes CNG vehicles different from normal conventional fuel-based vehicles. For the CNG vehicle to have a respectable range, the CNG cylinder needs to be of adequate size. There are some desired properties of CNG cylinders, such as being lightweight as the weight will affect both the stability and the fuel efficiency of the car. Still, the durability and extent of deformation of cylinders

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under load are also important factors regarding the safety of CNG vehicles. Hence, it becomes essential to inspect these properties to know its factor of safety. On the basis of the material, the CNG cylinder can be categorized into four major groups. The first is in which the cylinder is made of forged metal. In the second type, the cylinder is made of metal, but the cylinder is now partially wrapped with a composite such as carbon fibre or glass fibre etc. The metallic cylinder is fully wrapped in the composite in the third type. The fourth type of CNG cylinder is a non-metallic type of cylinder, it has a polymer liner and is wrapped around with a composite all around [4]. In this research work, the main focus is associated with type one i.e., metallic CNG cylinders.

Since the rise in the number of on-road vehicles, there are more crashes that happen on a daily basis. Two methods are often used to determine crashworthiness: the first is to perform an actual crash test, and the second is to utilize simulation software to generate realistic crash results. Further, the researchers cannot test everything in real life since it has a lot of limitations like the number of iterations that can be performed with the same vehicle and by changing material properties; so, it becomes monetarily unreasonable to perform this crash test [5]. Therefore, simulation tools like LS-DYNA are a cost-effective choice that offers a lot of functionality for the researchers to perform these crash tests and achieve results much quicker and more efficiently.

Various models have been developed to study flow stresses in the last few years. These models can be mainly categorized into physically based, empirical, and semi-empirical models [6]. The fact that physically based models require a lot of data related to the material involved in the analysis, thus this model is not a good fit for this particular study. A Johnson cook material model is used for the simulation of a CNG cylinder which falls in the category of the semi-empirical model to give realistic results [7–9]. The Johnson cook model meets the industry standard for dynamic crash test analysis and is used extensively for simulation, incorporating a wide range of temperature and strain rates [10].

The main objective of this study is to observe the properties of CNG cylinders made from four different materials: AA2024, AA6061, mild steel, and A36 steel during the rear-end collision. The CNG cylinder is modelled as a shell cylinder having a thickness of 3 mm. Rear-end collision is set such that one car with a CNG cylinder is kept at rest and the other car collides with the first car from the rear at 56 km/h. The collision is simulated on LS-DYNA software and various results are drawn.

Johnson-Cook Material Model

Johnson-Cook model is extensively used to analyse the dynamic strain rate based on material behaviour, especially for ductile materials; it is a visco-plastic model. The model was first published in 1983 and since then it is used in various applications [11]. The Johnson-cook model is derived from the Mackenzie and Hancock damage models [12]. The Johnson-Cook model is an empirical relationship for flow stress, σ_{flow} , which is represented as:

$$\sigma_{flow} = (A + B \epsilon^n)(1 + C \dot{\epsilon}^*)(1 + (T^*)^m)$$

B = strain hardening coefficient,

C = strain rate sensitivity,

n = strain hardening exponent,

m = thermal softening parameter,

$\dot{\epsilon}^*$ = dimensionless plastic strain rate (reference strain rate, $\epsilon_0=1s^{-1}$), and

T^* = dimensionless temperature defined as:

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}$$

Table 1 gives the material parameters of the Johnson-Cook material model. The corresponding values are taken from various research articles [13–16].

Table 1. Johnson-Cook parameters for different materials.

Material parameters	A36 Steel	Mild Steel	AA2024	AA6061
A (MPa)	286.13	363	352	324
B (MPa)	500.14	792.7	440	114
N	0.228	0.5756	0.42	0.42
C	0.017	0.0054	0.0083	0.002
M	0.917	1.6456	1	1.34
T _{melt} (K)	1773	1798	793	923

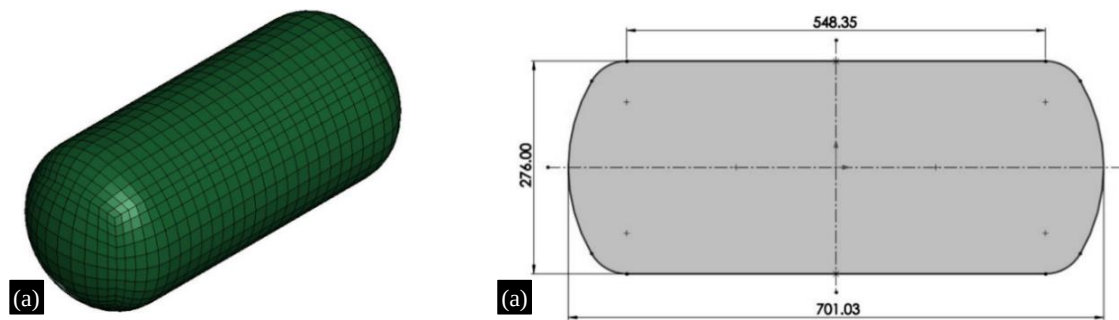


Figure 1. (a) Mesh view of CNG cylinder (b) Dimensions of cylinder model (in mm).

Table 2. Number of nodes, elements and type of mesh in FE models.

FE Model	No. of Nodes	No. of Elements	Mesh Type
Cylinder	1402	1400	Quadrilateral
Dodge Neon	283857	271111	Mixed (Quads-95.79% and Trais-4.21%)

METHODOLOGY

The vehicles used in the rear crash analysis are simulated using Dodge Neon as the test finite element model [17]. The CNG cylinder is modelled using LS-PrePost using a thickness of 3 mm and appropriate dimensions [18]. The mesh view and the major dimensions used to model the cylinder are shown in Figure 1. The Johnson-Cook material model gives different properties to the cylinder for each iteration. The mesh size plays a vital role in the analysis accuracy but also affects the computational time. Therefore, a mesh size of 15 mm for the cylinder is chosen to balance accuracy and computational time. The total number of nodes, elements and the type of mesh obtained from FE simulations are given in Table 2.

To perform the rear crash analysis, two vehicle models are placed in a line. The cylinder is constrained using Constrained Nodal Rigid Body (CNRB) at its two ends where its surface is in contact with the floor bed, inside the trunk of the front vehicle. The front vehicle is kept at rest whereas the other vehicle is moving with a velocity of 56 km/h and strikes the end of the front car. Using LS-DYNA, automatic surface contacts are established between the two vehicles and between the cylinder and the front vehicle.

The worst condition for a cylinder during a crash is when there is no natural gas pressure inside the CNG cylinder. When the CNG cylinder is completely full, the cylinder will behave rigidly and resist more impact against a crash while on the other hand when the cylinder is empty, it can get crushed easily. Therefore, the worst-case conditions are chosen and simulated in LS-DYNA. The termination time for analysis is set as 0.15 sec to observe the complete crash. Figures 2–4 demonstrate the states of collision that are observed in LS-DYNA.

The properties of different materials used to model the CNG cylinder are given in Table 3.

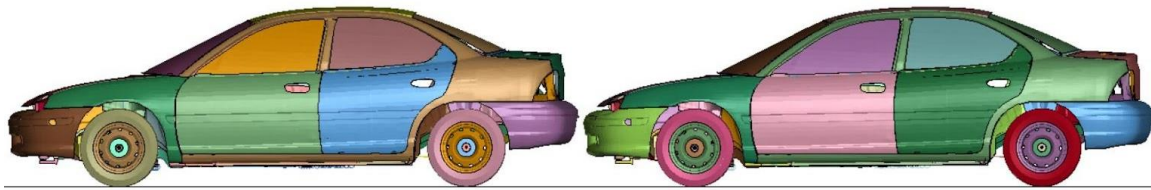


Figure 2. Before collision conditions.



Figure 3. After collision conditions.

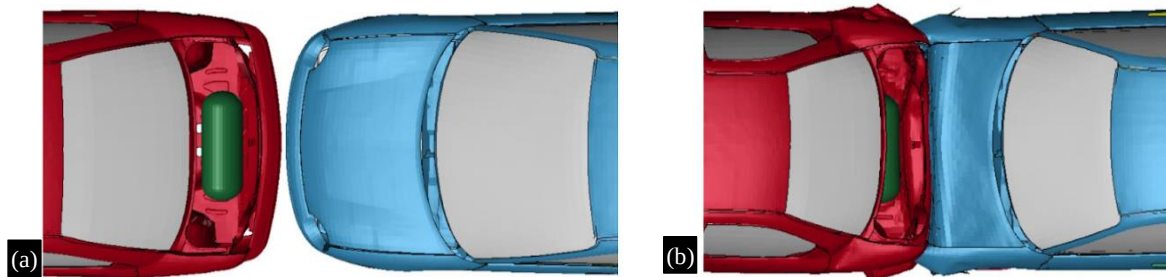


Figure 4. (a) Position of the cylinder before collision (b) after collision.

Table 3. Material properties used for simulation.

Material Properties	A36 Steel	Mild Steel	AA2024	AA6061
Density (kg/m^3)	7850	7860	2780	2700
Young's Modulus (GPa)	200	210	73	69
Shear Modulus (GPa)	76.9	80.58	28	26
Poisson's Ratio	0.3	0.303	0.33	0.33
Specific Heat (J/kgK)	486	400	875	895

RESULTS AND DISCUSSION

The specific internal energy has been taken as a basis for analysing which material performed best during the crash test. Specific internal energy will be affected by the weight of the cylinder as well as the internal energy during the collision.

In a crash, a cylinder goes through a certain amount of impact. The cylinder absorbs some part of the impact energy in the form of internal energy and the other part is converted to kinetic energy, which is used to accelerate the cylinder. The high specific energy of a CNG cylinder during a crash means that more plastic work has been done, resulting in more cylinder deformation. For the cylinder to have the least deformation, the specific energy should also be the least. Therefore, the less the specific energy the better the material of the cylinder performed during the crash.

The kinetic energy in the case of aluminium alloys has been similar to each other and their peak kinetic energy lies in the range of 350–400 J and similarly the same trait can be seen in mild steel and A36 steel whose peak kinetic energy lies in the range of 740–780 J which is much higher than the aluminium alloys. The resultant force on mild steel and A36 steel came out to be significantly higher than on aluminium alloys. The resultant force of 33.8 kN is observed in the case of mild steel which is

the maximum among all the other materials followed by A36 steel. On the other hand, AA2024 shows the minimum resultant force of 19.2 kN.

Figures 5–7 show the variation of the resultant force, kinetic and internal energy respectively with respect to time for each material.

The peak values of all the three parameters are given in the Table 4.

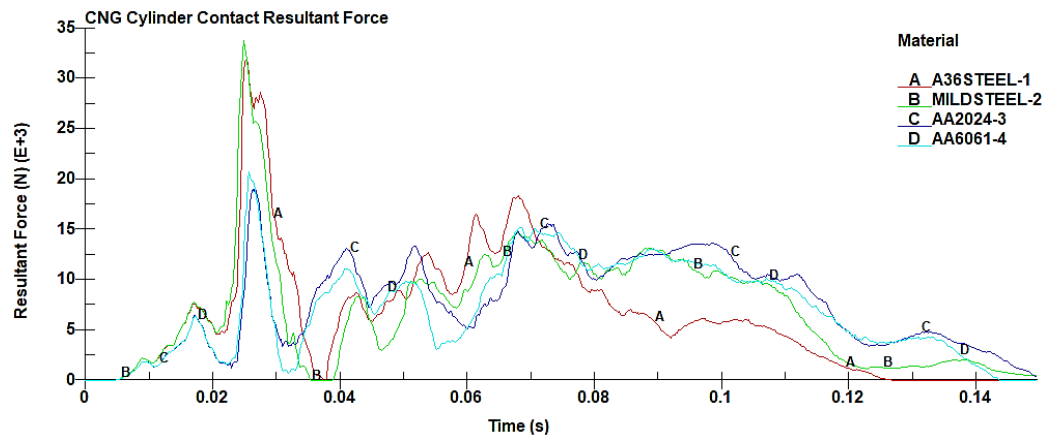


Figure 5. Variations of resultant force vs. time on CNG cylinder.

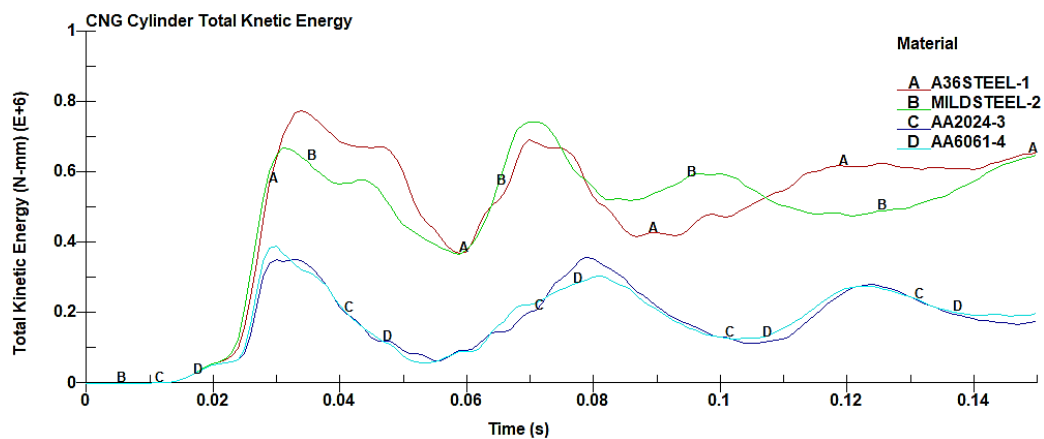


Figure 6. Variations of total kinetic energy vs. time on CNG cylinder.

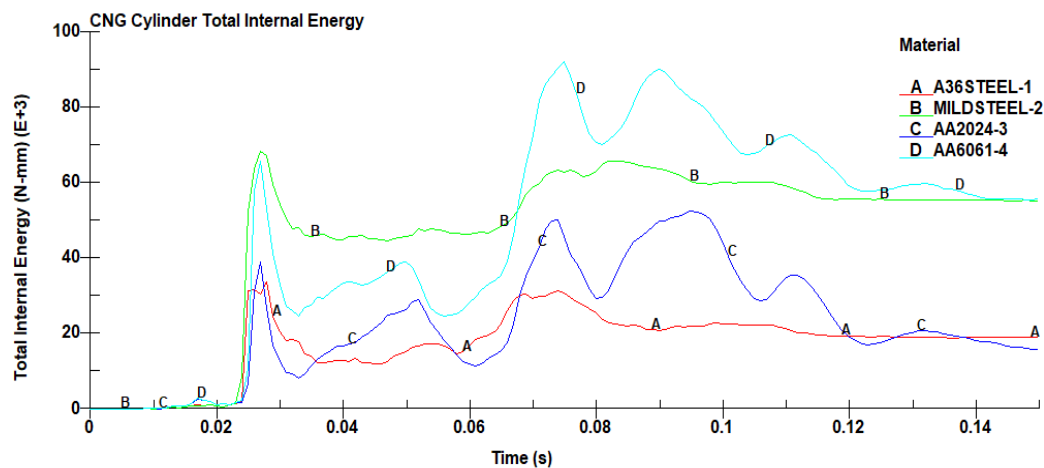


Figure 7. Variations of total internal energy vs. time on CNG cylinder.

Table 4. Peak values of the resultant force, kinetic energy, and internal energy.

Output (on cylinder)	A36 Steel	Mild Steel	AA2024	AA6061
Peak internal energy (N-mm)	33.917×10^3	68.384×10^3	52.687×10^3	92.387×10^3
Peak kinetic energy (N-mm)	7.7764×10^5	7.4443×10^5	3.5805×10^5	3.9042×10^5
Peak resultant force (N)	3.1940×10^4	3.3821×10^4	1.9297×10^4	2.0761×10^4

Table 5. Specific internal energies for cylinders of different materials.

Cylinder material	Mass of cylinder (kg)	Peak internal energy of cylinder (J)	Specific internal energy of cylinder (J/kg)
A36 Steel	16.64	33.917	2.038
Mild Steel	16.66	68.384	4.104
AA2024	5.894	52.687	8.939
AA6061	5.724	92.387	16.140

When comparing the results of all five materials, it is observed that AA6061 has the highest internal energy, followed by mild steel, AA2024, and A36 steel, respectively. The specific internal energy for all the materials is calculated and given in Table 5.

Observing the specific energy of the cylinders in the Table 5, A36 Steel has the least specific energy and therefore performed the best among all the materials during the crash. Among the aluminium alloys, AA2024 performed better in comparison to AA6061.

Initially when the crash takes place, both the resultant force and internal energy rise. Before 0.07 sec, the material has acquired the momentum to get collapsed but after 0.07 sec, the strain density increases, and the development of stains take place in the cylinder and the material strength is increasing to resist further deformation.

CONCLUSIONS

Crash test analysis is vital to ensure passengers' and fuel cylinder safety to prevent any fatalities. CNG vehicles with Type-1 metallic cylinders generally use material that can resist deformation and absorb less energy from the impact to prevent any leakage of CNG which can burst and can cause accidents. Looking at the specific energy results, it can be clearly concluded that A36 Steel performed best during the crash due to its ability to absorb less impact energy whereas, aluminium alloys absorbed maximum impact energy which resulted in more deformation than steel and steel alloy. The resultant force and kinetic energy developed by the mild steel and A36 steel are higher than that of aluminium alloys i.e., aluminium alloys transformed the total impact energy, more into internal energy than it used kinetic energy during the impact.

It can be concluded that in the Type-1 cylinders i.e., metallic cylinders, Steel and steel alloys are the best material in terms of safety. On the other hand, they are also very cost-efficient compared to aluminium alloys. Due to high deformation and high energy absorption in aluminium alloys, they are generally not considered a good fit for Type-1 metallic cylinders. However, due to their lighter weight, they can be used as a liner material in Type-2 and 3, i.e., composite cylinders.

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