Development of Waja Based CNGDI Passenger Vehicle Rear Platform Component

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Abstract: The development of a compressed natural gas vehicle (CNGV) for passenger car is of interest nationally and worldwide, particularly with the rise in petrol prices. The main components of a CNGV are the body, engine and transmission and fuel storage. For the vehicle body development, many aspects need to be considered. These are the on board fuel storage locations, crashworthiness, strength and vibration characteristics. For petrol vehicle, the shape of the fuel storage can be designed to fit the space available underneath the vehicle body structure. However, for CNGV, the shape of the gas storage is always cylindrical. Hence, the vehicle body structure is to be designed to fit the cylindrical storage tanks underneath the platform as well as the passengers above it. In addition, the ergonomic passenger compartment and crashworthiness need also to be considered. This paper presents the analysis of a rear platform of Waja body to fit the CNG tanks. The result for the crash characteristics of the CNG rear platform is presented. It is compared with that of the corresponding petrol platform and discussed. The effect of the CNG rear platform on the natural frequency and stiffness of the vehicle body is also presented and discussed.

Keyword: Natural Gas Vehicle, Rear Platform, Crashworthiness

NOTATION

E – Young’s modulus
t – time in milliseconds
ν – Poisson’s ratio
σ – direct stress
σy – yield stress
ε – strains
ρ – material mass density
y – displacement
KT – total energy
KE – kinetic energy
KI – internal energy
H – hour glass energy (distortion energy due to deformation without change of volume)

Sij – deviatoric stress tensor (= σij – δijσkk)

δij – Kronecker delta (= 1 for i = j, = 0 for i ≠ j)
k – structural stiffness

de_i^p – incremental plastic strain components

de_e^p – incremental equivalent plastic strain

F – crush force

Subscript
p – plastic
e – elastic
eq – equivalent
INTRODUCTION

The automotive body platform is a complex structure. The platform forms the basic size and shape of the car. Cars of different makes and models can use the same platform and drive train (engine, transmission, and final drive components), suspension and steering. For simplicity of identification, the platform is divided into three parts - engine compartment, front platform and rear platform as shown in Fig. 1 (1). The engine compartment refers to the part covering the engine to the firewall, while the front platform refers to the part from the firewall to the rear passenger seat excluding the firewall and the rear platform is the structure from the rear passenger seat to the rear end. In an attempt to design crash energy absorber for automotive vehicles, many research works on crashworthiness has concentrated on metallic tubes (2), composite tubes and cones (3, 4, 5, 6, 7, 8, 9, 10, 11). These works shows that the crashworthiness and energy absorption depends on the geometry and material properties.

In the design of CNGV platform, the shape of the tank has to be cylindrical. Hence, the platform has to fit the tank. On the other hand, for gasoline vehicle, the shape of the fuel tank is designed to fit the available space. It can be seen that a slightly different approach need to be used. The main characteristics to be determined included static strength, torsion and bending stiffness, first mode vibration natural frequency and crashworthiness analysis (12). There are three methods that can be used; namely closed form analytical, experimental and finite element (3, 4, 5, 6, 7, 8, 9, 10 and 11). The closed form analytical method is normally limited to simple geometry, whereas experimental method is usually expensive and only being carried out for verification. Hence finite element method offers practical alternative to experimental method. In the present work, a CNGV rear platform component without reinforcement (platform B) and with reinforcement (platform C) shown in Fig. 2, is developed based on similar platform for gasoline without reinforcement (platform A) as shown in Fig. 1. Finite element is used for the crash analysis of the rear platform subjected to lateral impact. The results obtained were compared with the platform for gasoline vehicle. The objective of the work is to achieve CNGV platform with similar, if not better, crash characteristics compared with that of gasoline. For this purpose, the internal crash energy absorbed was used as the criteria. In the present work, the CNG platform is considered acceptable when it has similar or better internal energy absorbed compared with the gasoline platform.

THEORETICAL BACKGROUND

In crash analysis, generally it involves impacting an elastic plastic structure of known mass, m, moving with a specified velocity, v, against a rigid object, such as a rigid wall. At the onset of impact, the structure will come into contact with the rigid wall. The kinetic energy, KE of the structures is given by

Eqn. 1

\[ KE = \frac{1}{2}mv^2 \]

This kinetic energy will be transferred into strain energy. At the beginning of impact, only elastic deformation occurs. The stress distribution is often non uniform, especially for complex structures like car platform, and pockets of highly stressed areas may occur. As the crash proceeds, more kinetic energy is released (results in reduction of v) and this cause plastic deformation starting from the high stressed regions. As the crash proceeds further, v will further reduce with time and increases the structural deformation and distortion. To account for distortion without change of volume, hourglass energy, H is used. For most cases, the value of H is small and negligible. Some part of the structure may fail plastically. The total energy in the system becomes:-

Eqn. 2

\[ KT = KE + KI \]

During crash, total energy is conserved and hence:-

Eqn. 3

\[ \frac{1}{2}mv^2 = \frac{1}{2}k_e y_e^2 + k_p y_p^2 + H \]

The plastic deformation only occurs when the yield criteria of the material is satisfied. For the present study, von Mises yield criteria is used. That is yield occur when:-

Eqn. 4

\[ \sigma_{eq} = \sqrt{\frac{3}{2}S_y S_y} = \sigma_y \]

The plastic strain resulting from material yielding is determined from the Prandtl Reuss flow rule, that is
\[ \text{Eqn. 5} \quad \alpha = \frac{3}{2} \frac{\text{de}_{ij}^p}{\sigma_{eq}} S_{ij} \]

Where, \( S_{ij} \) is the stress tensor.

\[ \text{Eqn. 6} \quad \text{de}_{ij}^p = \sqrt{\frac{2}{3}} \text{de}_{ij}^p \]

For analysis involving crash, as in the present case, the elastic displacement \( y_e \) is very small compared with plastic displacement \( y_p \). Also, in the present analysis, a ‘good’ mesh is developed that resulted in \( H \) also very small. Hence, neglecting elastic energy and \( H \), the internal energy expression reduces to:-

\[ \text{Eqn. 7} \quad KI = k_p y_p^2 \]

In integral form, \( \text{Eqn. 7} \) can be written as

\[ \text{Eqn. 8} \quad KI = \int k_p y_p dy = \int F dy_p \]

Where \( F \) is the crush force and is given by

\[ \text{Eqn. 9} \quad F = k_p y_p \]

Hence, from \( \text{Eqn. 8} \) it can be seen that the internal energy can be obtained from the area under the graph of crush force, \( F \) versus plastic displacement, \( y_p \). From \( \text{Eqn. 7} \), it can be seen that \( KI \) is very much dependent on \( y_p \). The crashworthiness of a structure is often represented by a graph of \( KI \) versus displacement. The main objective of the analysis is to achieve maximum \( KI \) in the shortest possible displacement.

**FINITE ELEMENT MODELLING, MATERIALS AND BOUNDARY CONDITIONS**

The shape of the platform under investigation is as shown in Fig. 1. A typical finite element mesh is shown in Fig. 2. The platform is made of mild steel with the properties given in Table 1. The boundary condition used in the present analysis is one of the side is fully restraint while the the other is subjected to a rigid wall impact. The mass of the rigid wall is 950 kg and its initial velocity is 50 km/h (13.9 m/s) in the y (rear to front) direction. For all cases, the analyses were carried out for a maximum time of 100.0 ms. This was to ensure that all the kinetic energy has been completely dissipated. The CNGV is designed with the specification as shown in Table 3.

**RESULT AND DISCUSSION**

**Finite element results**

The crash behaviour is best described by looking at the shape of platform deformation at various time interval from \( t = 0 \) ms to \( t = 100.0 \) ms at time interval of 50 ms. For the rear impact, Fig. 3 shows the variation of crash displacement (mm) with time (ms) for platforms A, B and C. It can be seen that the displacement first increases linearly with time up to 10 ms and thereafter the behaviour becomes nonlinear. Crash initiate at the impacted side with the platform crumple in the direction of velocity. It was found that there is no displacement normal to the platform plane suggesting that crumpling occurs in the same plane as the platform and no intrusion to the passenger compartment as a result of the crash. Crash initiate at the impacted side with the platform crumple in the direction of velocity. It was found that there is no displacement normal to the platform plane suggesting that crumpling occurs in the same plane as the platform and no intrusion to the passenger compartment as a result of the crash. From Fig. 3, it can be said that platform A is superior compared with platforms B or C. The kinetic energy absorbed is shown in Fig. 4. It shows that all the impact energy is fully dissipated within 100 ms. The internal energy absorbed is shown in Fig. 5. It can be seen that platform B achieved the highest energy compared with either platforms A or C. This shows that the reinforcement design is sufficient to absorb higher energy compared with the platform without reinforcement and the base platform. The numerical values of the results are shown in Table 2. From Table 2, platform B with the reinforcement is suitable to be used.

**Experimental results**

From the modelling work and finite element results, the results CNG platform and vehicle was fabricated. The vehicle is shown in Fig. 6. The vehicle was tested by static bending and torsion and its natural frequencies were determined. The values of maximum stress, torsional and bending stiffnesses and natural frequencies were compared with the base Waja values. The results for the bending test is shown in. All other values are given numerically in
Table 4. It can be seen that the performance of the CNGV vehicle is similar to the gasoline base platform. In some cases namely, higher torsional stiffness, higher bending stiffness, lower first 3 modes of natural frequencies. The first mode natural frequency which is 41.9 Hz is within acceptable values and it is torsional which is desirable for handling and stability. Hence, the developed CNGV platform and body is acceptable.

CONCLUSIONS

The objectives of the work has been achieved. The behaviour of rear platform component for CNGV has been carried out. From the results obtained, it can be concluded that, changing the shape of the rear platform do not change the performance of the platform. In some cases the performance is improved. Hence, the newly developed platform for CNGV is suitable for installation of the tanks outside the vehicle and at the same time improves its strength and dynamic performance. Also, the earlier hypothesis that if the shape of a part of the structure is modified and replaced with another part having the same characteristics, the resultant structural characteristics remains the similar.

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REFERENCES

### Table 1  Mechanical property

<table>
<thead>
<tr>
<th>Properties of material</th>
<th>Value of properties</th>
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<tbody>
<tr>
<td>Modulus Young, $E$ (GPa)</td>
<td>200</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>Mass density, $\rho$ (kg/m³)</td>
<td>7830</td>
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<tr>
<td>Yield stress, $\sigma_y$ (GPa)</td>
<td>0.207</td>
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### Table 2 Result of crash analysis

<table>
<thead>
<tr>
<th>Rear platform component types</th>
<th>Characteristics</th>
<th>Lateral impact</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Internal Energy absorption (kJ)</td>
</tr>
<tr>
<td>A</td>
<td>Gasoline tank</td>
<td>8.0</td>
</tr>
<tr>
<td>B</td>
<td>CNG with reinforcement</td>
<td>14.5</td>
</tr>
<tr>
<td>C</td>
<td>CNG without reinforcement</td>
<td>7.8</td>
</tr>
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</table>

### Table 3: Tank specification for 3 Tank model CNG vehicle

<table>
<thead>
<tr>
<th>Bil</th>
<th>Dimension</th>
<th>Location</th>
<th>Tank Weight (kg)</th>
<th>Gas Weight (kg)</th>
<th>Total Weight (kg)</th>
<th>GGE</th>
<th>Range (km)</th>
<th>Ground Clearance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\varnothing$ 280 mm x 594 mm</td>
<td>Boot/luggage compartment (Rear)</td>
<td>14.0</td>
<td>4.63</td>
<td>18.63</td>
<td>1.8</td>
<td>88.57</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>$\varnothing$ 240 mm x 820 mm</td>
<td>Boot/luggage compartment (Middle)</td>
<td>15.0</td>
<td>4.12</td>
<td>19.12</td>
<td>1.6</td>
<td>78.73</td>
<td>180</td>
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<tr>
<td>3</td>
<td>$\varnothing$ 240 mm x 920 mm</td>
<td>Boot/luggage compartment (Front)</td>
<td>16.0</td>
<td>6.43</td>
<td>22.43</td>
<td>2.5</td>
<td>123.01</td>
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<tr>
<td></td>
<td>Total</td>
<td></td>
<td>45.0</td>
<td>15.18</td>
<td>60.18</td>
<td>5.9</td>
<td>290.31</td>
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### Table 4 Experimental results

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Waja Gasoline</th>
<th>CNGV</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>With Glass</td>
<td>No Glass</td>
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<tr>
<td>Bending</td>
<td></td>
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<tr>
<td>Stress point 1 (Mpa)</td>
<td>113.5</td>
<td>135.4</td>
</tr>
<tr>
<td>Stress point 2 (Mpa)</td>
<td>90.7</td>
<td>103.5</td>
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<tr>
<td>Stress point 3 (Mpa)</td>
<td>61.2</td>
<td>62.3</td>
</tr>
<tr>
<td>Stress point 4 (Mpa)</td>
<td>59.3</td>
<td>62.32</td>
</tr>
<tr>
<td>Stiffness (N/mm)</td>
<td>18691.58</td>
<td>11876.98</td>
</tr>
<tr>
<td>Torsion</td>
<td>20237.44</td>
<td>13586.55</td>
</tr>
<tr>
<td>Dynamic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First mode frequency</td>
<td>38.7 Hz, torsion</td>
<td>44.05 Hz, torsion</td>
</tr>
<tr>
<td>Second mode</td>
<td>42.8 Hz, bending</td>
<td>46.02 Hz, bending</td>
</tr>
<tr>
<td>Third mode</td>
<td>84.3 Hz, bending</td>
<td>95.6 Hz</td>
</tr>
</tbody>
</table>
Fig. 1: Design concept for rear CNGV platform (platform C and D)

Fig. 2: Finite element mesh for rear platform (platform E)
Variation of displacement with time, rear platform component, side impact

Fig. 3 Side impact crash analysis results for rear platform

Kinetic energy side impact rear platform component

Fig. 4. Kinetic energy for side impact of rear platform
Fig. 5. Side impact crash results for rear platform

Fig. 6 The CNGV body in white
Fig. 7 Torsional moment versus angular twist for CNGV body in white.