Crashworthiness of Aluminium Structures - An Illustration Through Scaled Model

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Abstract
The use of aluminium in aerospace structures is predominantly high for being one of the best candidates to achieve light weight with sufficient crashworthiness characteristics. This paper supports the study of aluminium-based vehicle crashworthiness through an aluminium space frame scaled model. Within the limitations of the availability of the extruded tubes, the current study reports about correlation of physical testing and simulation practice along with the visualisation of the crush behaviour of scaled model. An in-house Impact Testing Machine (ITM) is used for testing of the scaled vehicle model. The use ITM is justified using an extruded aluminium tube impact testing and its correlation with finite element simulation. With this confidence the same procedure was used for carrying impact test on scaled vehicle model. The results from physical test and simulation were correlated satisfactorily supporting the simulation procedure. The test results also helped in visualising the crush space behaviour of the vehicle side structure and the impact force paths. These insights were further used in full vehicle design and simulations practice. Thus a vehicle structure designed similar to that of the scaled model could indicate aluminium as good candidate for light weight crashworthy vehicle design application. Finally, this paper summarises a systematic procedure of gaining insights from the testing and simulation scaled models to full scale structural design.

1. INTRODUCTION

Aluminium has a low tensile strength in its purest form, but with thermo-mechanical processing, aluminium alloys display a sufficiently good mechanical properties, especially when tempered. Aluminium alloys form vital components of aerospace systems as a result of their high strength-to-weight ratio. Aluminium readily forms alloys with many elements such as copper, zinc, magnesium, manganese and silicon (e.g., duralumin). Today, almost all bulk metal materials that are referred to loosely as “aluminium”, are actually alloys. The use lightweight structures in transportation vehicles have significant advantage in terms of energy efficiency. Structural components made from aluminium and its alloys are vital to the aerospace industry and are very important in other areas of transportation and building. Though aluminium is lighter than steel by approximately 3 times but is inferior to steel in terms of strength. A balanced design with right selection of aluminium alloys and its tempering technique would result in an aluminium-based crashworthy light weight structure. With this assumption authors have reported aluminium alloys as suitable materials for design of light weight transportation vehicles whilst satisfying the structural strength requirements [1–3]. Importance of reduction in mass is paramount especially in design of electric and hybrid vehicles. In current paper a scaled model of aluminium space frame vehicle [3–4] designed with an electric drive is studied for structural crashworthiness. In this paper a practical approach for analysing the crashworthiness of this vehicle is illustrated with help of insightful physical testing and Computer Aided Engineering (CAE) simulation techniques. In order to get an initial confidence level in the tubular vehicle structural design a scaled model of the vehicle is tested using an in-house Impact Testing Machine (ITM). This paper also reports aluminium tube crush using the same testing machine to establish confidence in the testing and simulation practices.

A full scale model [3–4] is made of predominantly extruded aluminium members bent into desired shapes wherever necessary and welded at joints to form a space frame grid. Aluminium body panels are riveted to the space frame members. Within the scope of building such a prototype of aluminium space frame electric vehicle the physical testing of the vehicle was not possible. In order to gain initial confidence in vehicle structural design and the simulation procedure of this new vehicle structure, a scaled model of it is tested and simulated. This gave insights into the crush space and modelling procedures for aluminium structural model. Further the studies on full scale model simulation were reported in [8].

2. ALUMINIUM TUBE AXIAL IMPACT

As mentioned already, before proceeding for impact analysis of the aluminium space frame vehicle, confidence in simulation of crushing of aluminium components is gained by comparing simulation results against test data for impact of a circular aluminium tube. Authors in [3] have reported the satisfactory weld strengths of the space frame tube members. The energy absorption of aluminium extrusions were extensively studied by [6], and reported that they are good candidates for impact energy absorption. In the current study, the impact test has been carried out in an ITM which has an impactor of mass 120 kg. The impactor in ITM is guided and free-fall can be controlled with variable heights for different impact energy scenarios such that it strikes a specimen placed on a rigid base at the bottom of the machine. A picture of the ITM in Product Safety Laboratory, CPDM, Indian Institute of Science is given in Figure 2. The ITM is equipped with a high speed data acquisition system which can acquire data from a load cell as well as an accelerometer. A finite element model of the impactor striking a circular tube is shown in Figure 1 and Figure 3 (a) shows its dimensions. The analysis results are reported for a mesh of 2.5 mm element size based on a convergence study in which the modelled tube was meshed with coarser (element size > 2.5 mm) and finer (element size < 2.5 mm) elements. The type of shell elements used for modelling the aluminium tube is Belytschko-Lin-Tsay which is based on a co-rotational formulation [7]. The impactor and its base are modelled with 8-node brick elements. The contact interactions between different entities in the FE model are modelled by an automatic surface to surface algorithm approach [7].

The impactor is dropped from a height of about 1 m on the circular tube held securely on the rigid base using fixtures. The striking velocity of the impactor as obtained from the data acquisition system is 3.42 m/s. The material properties of the tube used in the LS-DYNA model are given in Table 1.

A comparison of the time histories of force obtained through test using the ITM and simulation using LS-DYNA are given in Figure 4. The peak impact forces of finite element simulation and the

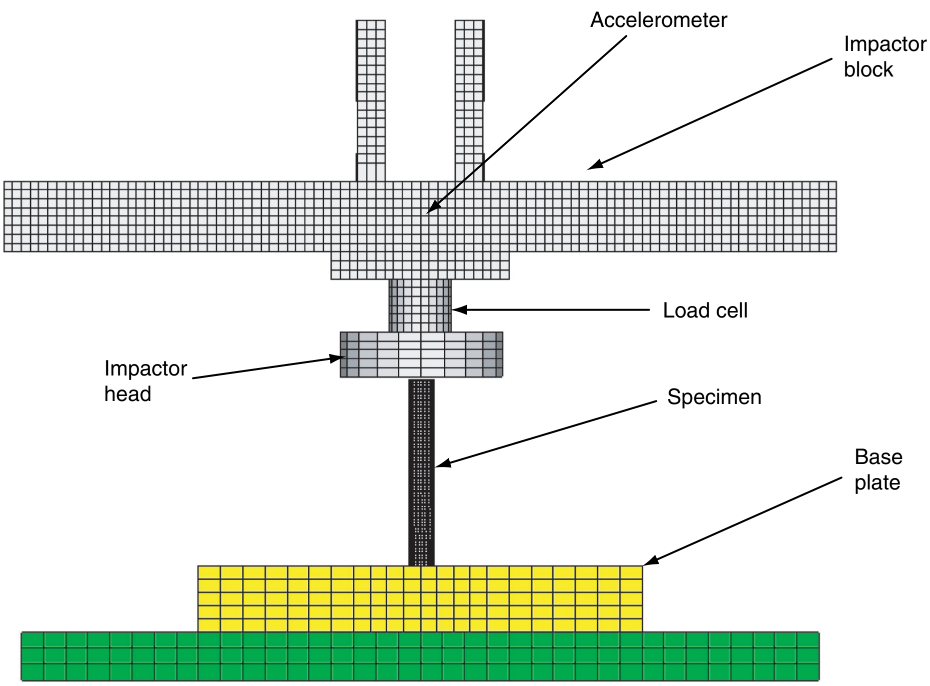


Figure 1. Finite element model of axial impact of a circular tube in ITM.

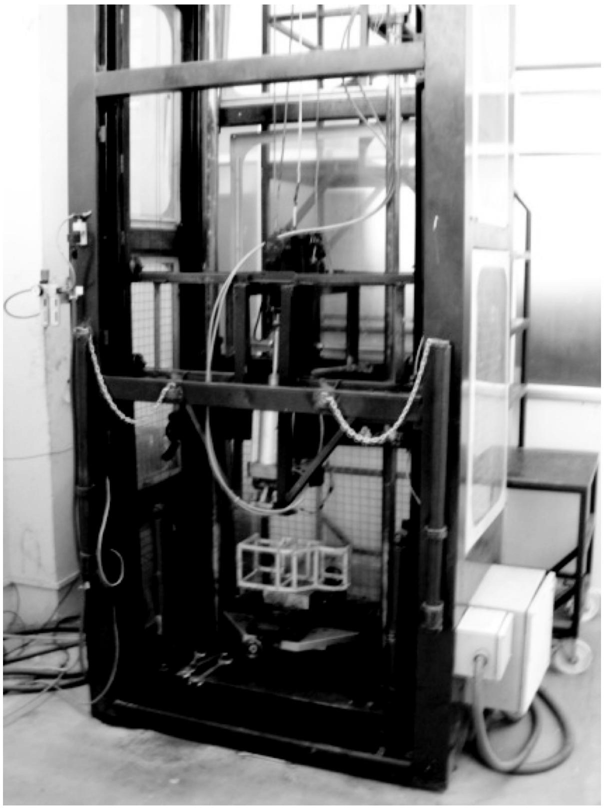


Figure 2. Lower half of impact testing machine (ITM).

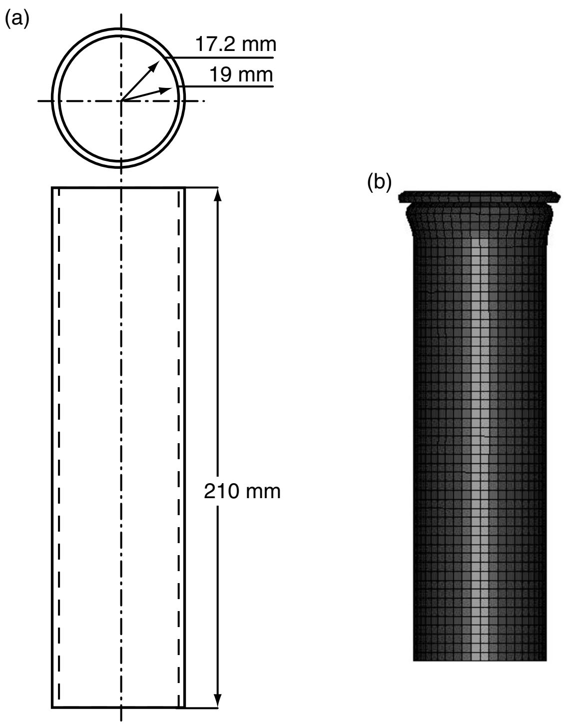


Figure 3. (a) Geometric details of circular tube (b) Deformed shape of circular tube after impact analysis.

Table 1. Material properties of finite element model of aluminium tube

Density (ρ)	$2.7 \times 10^3\ kg/m^3$
Young's modulus (E)	$7 \times 10^{10}\ Pa$
True yield stress (σ_y)	$1.7 \times 10^8\ Pa$
True failure stress (σ_u)	$2.09 \times 10^8\ Pa$
Failure strain	**0.11**
Tangent modulus	$2.08 \times 10^8\ Pa$
Material model used	***MAT_PIECEWISE_LINEAR_PLASTICITY (Material type 24)**

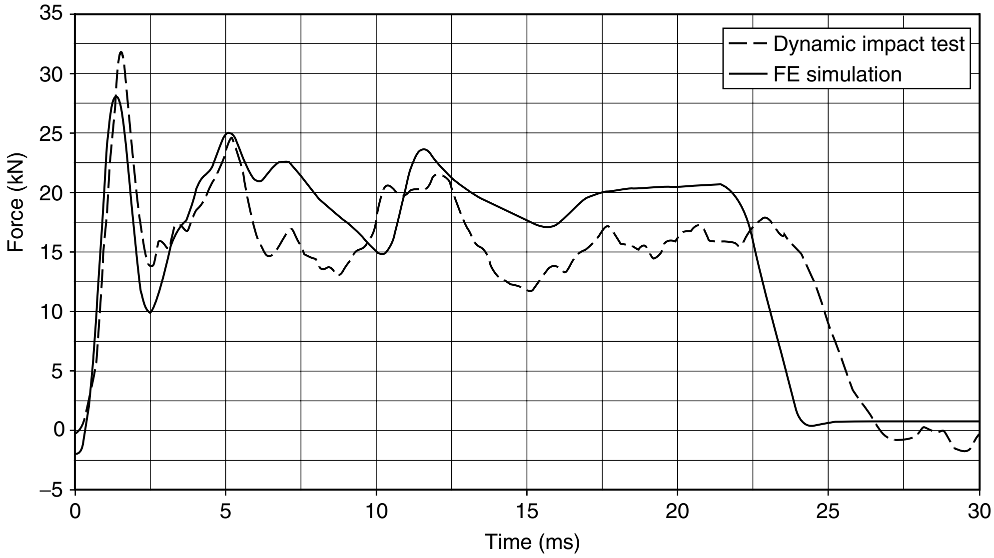


Figure 4. Force time histories of circular aluminium tube under axial impact.

impact test are 28.2 kN and 33.19 kN respectively. The mean forces for finite element simulation and impact test are calculated as 18.8 kN and 17.3 kN respectively. The overall correspondence between the test and simulation results can be considered as good as the mean forces compare closely and the primary and secondary peaks occur at nearly the same instances of time. The time at which the force peaks in force-time histories happen in test and simulation are very close. These peaks correspond to the number of crush folds in the tube. Thus a satisfactory correlation of the test and simulation were observed. These insights and the procedure are further used to test and simulate the scale model.

3. SCALED MODEL OF ALUMINIUM SPACE FRAME VEHICLE

A space frame vehicle structure consists of steel or aluminium tubular pipes welded at joints forming a three-dimensional grid. It is an inherently rigid design and can efficiently meet NVH (noise, vibration and harshness) and other body attribute targets. Body panels (such as roof and quarter panels) can be attached to the space frame using one or a combination of techniques such as riveting, adhesive bonding, welding, etc. Space frame architecture for passenger vehicles with steel members is, however, less suitable for high volume production and is restrictive in terms of styling. A battery-powered aluminium space frame vehicle has perhaps better prospects than its steel counterpart and a prototype [4] with a DC motor was developed. In order to enhance confidence in the simulation procedures for side impact assessment of this vehicle, a scaled prototype of the basic space frame design has been made and tested for lateral impact in the ITM used earlier for the tube crush tests. The actual full scale space frame vehicle is part of electric car project in Centre for Product Design and Manufacturing (CPDM) in Indian Institute of Science. Within the scope of the project there was no provision for carrying out crash impact tests as it is built for demonstration of the new aluminium-based electric car concept. In order to achieve sufficient confidence in the full scale vehicle structure without doing direct crash testing, the current scaled model testing was carried out. The test for this scaled model is carried in ITM and similar finite element modelling procedure as that of tube crush reported earlier was adopted.

3.1. Prototyping of a scaled model

In the current study a 1:8 scaled model of the aluminium space frame car of [3 and 4] is tested and correlated with simulation results in order to provide design insights and confidence in simulation of full scale model. It may be noted that the scaling is applied only to the body dimensions (length, width and height) and spacings between the extruded members. The cross-sections of the various members have been chosen as 12.5 mm × 12.5 mm as smaller sized specimens are not easily available in market and would be difficult to weld. Based this consideration the scaling is not applied to the cross-sections of the extruded members. The thickness of the extruded hollow sections in used in scaled model is 1 mm which is based on availability in the market. A physical prototype of the scaled model is made using TIG welding to join the extruded aluminium tubes as shown in Figure 5. For ease of fabrication, the curved left and right shotguns in CAD model shown in Figure 6 are replaced with piecewise straight shotguns as indicated in Figure 5. This change, however, is unlikely to have any effect on the side impact performance of the physical scaled prototype relative to its CAD version.

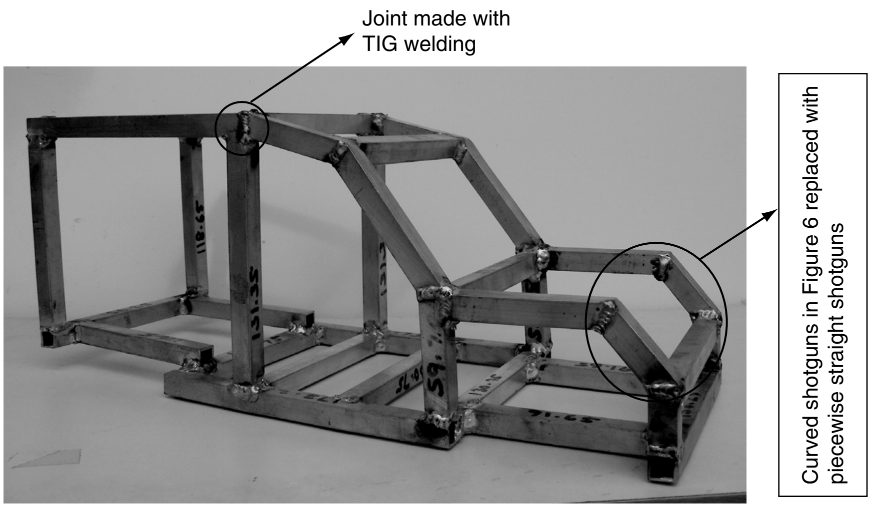


Figure 5. Physical prototype of 1 : 8 aluminium space frame model.

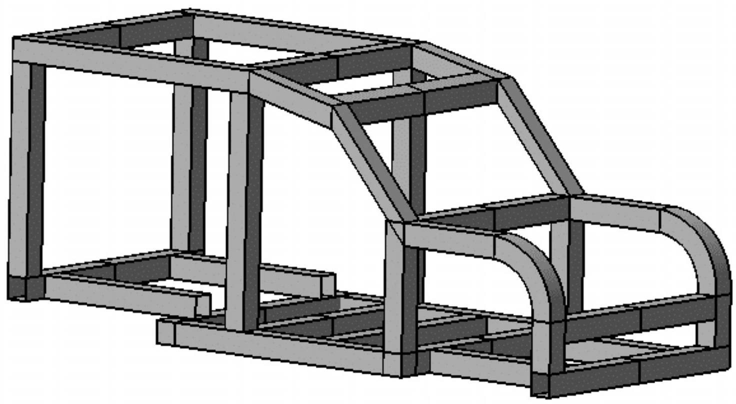


Figure 6. CAD model of 1 : 8 aluminium space frame.

3.2. Testing and finite element simulation

The CAD model as shown in Figure 6 is exported in IGES format and is imported into a finite element pre-processor. After geometric clean-up of the model, it is meshed using 4-node shell elements of size 2.5 mm. The resulting finite element model is shown in Figure 7. The element type used is Belystschko-Lin-Tsay which is based on a co-rotational formulation [7]. In co-rotational formulation local co-ordinate system is used. All element strains and stresses are calculated in a local reference system that follows the element normal and the element 1–2 side. This ensures objectivity in the sense that no spurious strains and stresses are calculated if the element is subjected to large rigid body rotational motions. This element formulation is based on uncoupling of membrane and bending effects. The Belytschko and Tsay co-rotational elements are used in vehicle crash analysis for computational efficiency and the results were promising [5]. The material properties of the extruded aluminium sections in the scaled model are obtained from uniaxial tensile tests of coupons cut from the walls of the tubes. Details of material modelling of the aluminium tubes are given in Table 2. The meshing especially at joints is manually checked to avoid spurious results. As the scaled model is relatively thin and made of small members, the meshing of the model was thoroughly checked before using it for simulation. The strain rate sensitivity is an important factor in most of the vehicle crash simulations but in the present case aluminium is the structural member not steel as in most commercial vehicle and strain rate sensitivity effects can be ignored in aluminium-based material behaviour [9]. The finite element model with impactor of the ITM and the scaled vehicle model is shown in Figure 8. The scaled model is placed on one of its sides on the ITM base so that the impactor strikes it in its lateral direction. The impactor is modelled with rigid solid elements.

The positioning of the impactor relative to the vehicle in the finite element model is such that it will correspond to the position of the test impactor just before it strikes the scaled prototype of the aluminium space frame vehicle. In the actual test set-up shown in Figure 2, the impactor is placed at a given height above the test specimen so that it reaches the desired velocity at the time of impact. In the analysis model, the impactor is given an initial velocity which corresponds to the observed velocity of the test impactor in Figure 2 immediately before it strikes the vehicle specimen.

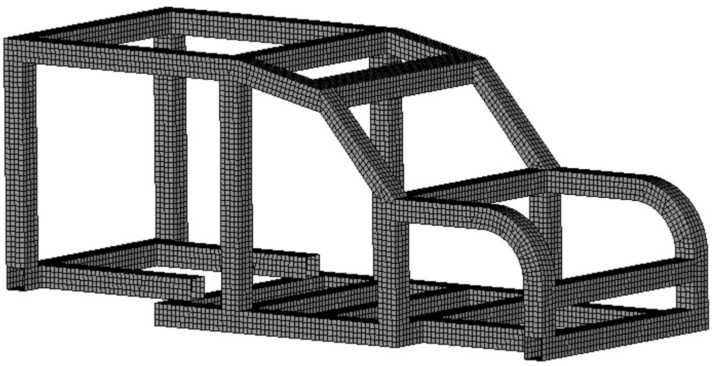


Figure 7. Finite element model of the scaled specimen.

Table 2. Details of material modelling of scaled space frame vehicle

Density (ρ)	**2.7×10^3 *kg / m*^{3}**
Young's modulus (E)	**7×10^{10} *Pa***
Poisson's ratio	**0.3**
True yield stress (σ_y)	**8×10^7 *Pa***
True failure stress (σ_u)	**1.4×10^8 *Pa***
Failure strain	**0.14**
Tangent modulus	**4.28×10^8 *Pa***
Material model used	***MAT_PIECEWISE_LINEAR_PLASTICITY (Material type 24)**

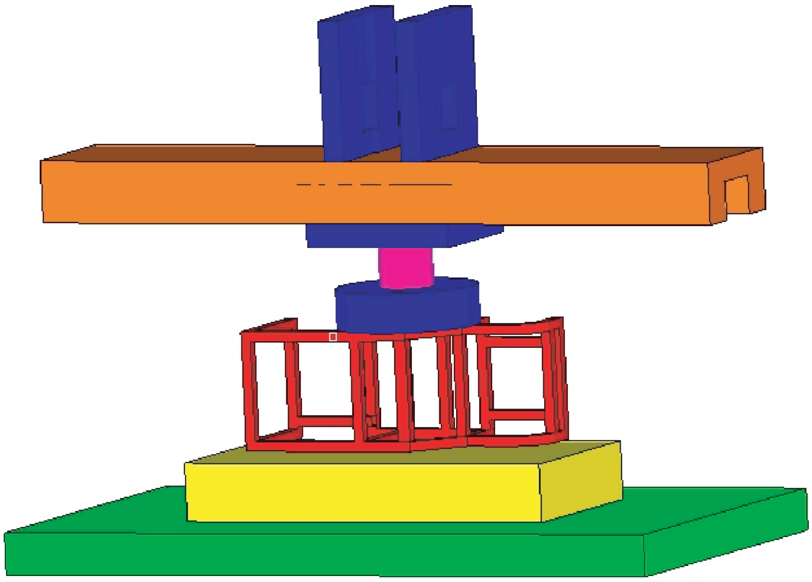
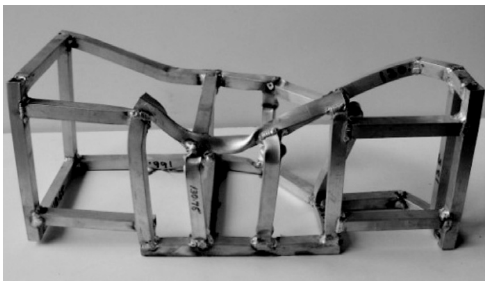


Figure 8. Impactor position in finite element simulation.

The deformed shapes of the scaled physical model after test and that from simulation are shown in Figure 9 and a good correlation in terms of deformations between the two is seen. The maximum lateral intrusion in the test specimen is 32 mm which is rather close to the corresponding value of 35 mm obtained in the analyzed model. The deformed shapes shown in Figure 9 not only indicate a good correlation but also give design insights in terms of the spacing between the lateral members. An analogy of the scaled model with full scale model with respect to the crush space can be analysed using this scaled model. Based on the observation of the crush after test the space frame design of the vehicle similar to scaled model could be give similar way of crush where the impact energy is mostly taken by the lateral members and after crush the interior space gives indication for a promising protection in the event side impact for full scale model. Though this gives good design insights, in the current study the scaled model is scaled for over all dimensions only but not for cross-sections, mass and impact energy. Given the mass of the impactor, velocity of impact and constrained vehicle boundary these design insights were further considered in development of full scaled prototype.

A comparison of force-time histories of physical test and simulation is given in Figure 10. It is observed that the peak impact forces and the time at which they occur close. This peak force corresponds to the initial collapse of the structure in lateral direction. The small peaks or variations in the force-time history correspond to the bending and collapse of the lateral members. The same is observed in Figure 9 where it can be observed that some extruded members are subjected to bending and collapse. In real case physical test of full scale model these corresponds to the members like B-pillars and lateral members between the B-pillars. A similar kind of crush behaviour in full scale vehicle structure would help to protect the passenger compartment by taking more impact load. As

(a)



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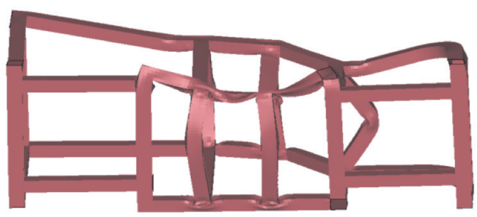

Figure 9. Deformed shapes of scaled model after impact in (a) actual test and (b) finite element analysis.

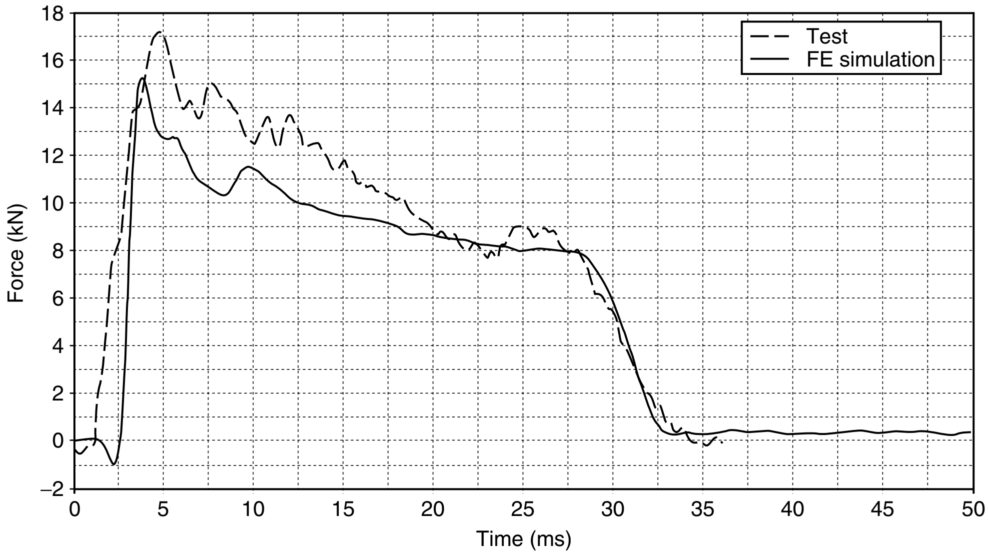

Figure 10. Force time histories from actual impact test and simulation for the scaled model.

seen in the Figure 10, the peak test-based load of 17.18 kN is about 10% higher than the computed value of 15.5 kN. In both physical test and simulation, the impact forces have similar loading and unloading behaviour. This indicates a good finite element modelling approach for the impact simulation. With this confidence the structural design and finite element simulation procedure the full scale vehicle was made and studied for its side impact crashworthiness as reported in [8].

4. CONCLUSION

In the current paper a systematic procedure for testing aluminium-based vehicle scaled structural frame is demonstrated to study crashworthy behaviour and gain confidence in simulation procedure. This was necessary as the prototype of full scale vehicle model could not tested and the kind of vehicle structure is new i.e., made up of aluminium space frame where very little literature was available. An inbuilt Impact Testing Machine was used to carry the experiment and which is further correlated with simulation results. This test on the scaled model is different from the tests that would be generally carried out on the actual vehicles. The actual tests in side impact the vehicle is free to move after taking the impact load where as in the test scenario of the present scaled model, the physical model is taking the entire energy of impact without any rigid body motion. The inner space of the scaled model, which typically a representation of occupant space in the actual vehicle remains intact after impact, thus proving a similar kind space frame would be good for crashworthy vehicle structure. The processing of welding for full scale space frame vehicle and the scaled model were same. The test not only suggests aluminium space frame design for new vehicle design in terms of it ability to absorb impact energy but also proves the current vehicle structural design and the welding process used. The impacted energy is absorbed through bending and crushing of the space frame members. The correlation between simulation and tests can further used to carry out further design changes virtually and analyse them using simulation. A similar approach could be used in aerospace domain in the initial stages of design where it is very expensive to carry out physical test of actual components or systems.

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