Lumped Parameter Model for Design of Crash Energy Absorption Tubes

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Abstract

Crash safety is an important domain in the field of automotive engineering. Finite Element Analysis (FEA) and Lumped Parameter Model (LPM) are two most widely used methods for determining the crashworthiness characteristics of a car. When compared to FEA, LPM is less accurate in predicting the exact dynamics of crash. However, LPM has been widely used in industry since 1970 to predict crash performance during development stages.

An attempt is made in this paper to develop an LPM representation of crash energy absorbing structure for frontal crash. After validating FEA results of axial crushing of a square tube with the experimental results, LPM model for the same tube was created using the stiffness characteristic of the tube obtained from FEA analysis results.

Next, two configurations, one with two and another with five square tubes, were analysed using FEM and LPM. For developing LPM, first, crush characteristics of a single square tube was obtained using FEA.

Results from use of LPM model were compared with the FEA results and it was found that LPM is capable of predicting crash phenomenon when the stiffness is obtained from software simulation instead of experiments. The results of crushed distance and force-displacement characteristics from FEA and LPM were found to match well. CPU time required of LPM was a fraction of that for FEM.

Key Words: Crashworthiness, Lumped Parameter Model

1. INTRODUCTION

Safety of the occupants of automobiles has always been a priority in automobile design. Earlier efforts in this direction were focussed on developing systems and components for preventing accidents. The next stage of development was to create a safer surrounding for restrained occupants. Post 1960, with legislated safety regulations, crashworthiness of automobile structure became focus of attention. Downsizing of automobiles further necessitated development of novel structural designs to enhance occupant safety.

One of the structural designs used prominently for controlling deceleration and energy absorption consists of thin walled tubes oriented in the longitudinal direction. In the event of a frontal crash, these tubes, subjected to compressive axial loading, fail through crippling of the walls and corners. Energy dissipated in this process helps reduce kinetic energy of the vehicle, and ultimately brings it to a stop. Post-crippling kinematics of the tube and resisting load generated by it depends on geometric dimensions of the cross-section and yield strength of the material. A typical tube deformation pattern and corresponding load-time characteristics for a crush under dynamic loading is shown in Figure 1.1.

Deceleration of the vehicle depends on this force. Since potential of injuries to occupants, either because of restraint force or impact with the interior, is directly proportional to vehicle deceleration, limiting magnitude of this force is a key goal in design.

Design of these tubes involves proper proportioning of two sides of rectangular cross-section, wall thicknesses and corner geometry and non-linear properties of the material. With no simple analytical solution available for this complex problem, in earlier years, designers depended heavily on testing to come up with required tube designs. This was a long, tedious and expensive process prototypes testing.

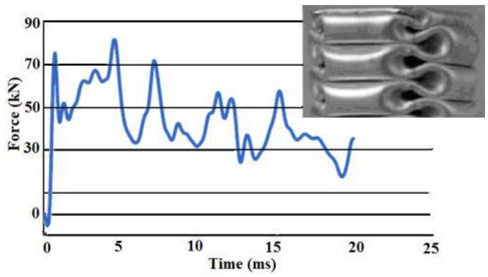

Fig. 1.1 Progressive buckling failure of a rectangular tube and its Force-Time history

A pioneer in developing analytical methods for such problems, Alexander [1] related average crushing force for concertina (axi-symmetric) deformation mode of circular tube to its diameter and wall thickness and material yield strength of a rigid plastic material. Following researchers [2-5] extended this approach to multi-cornered tubes. Based on the observed symmetric and asymmetric crush modes, concept of Super Folding Element (SFE) was developed [6, 7]. Its use made it possible to predict average crush force for polygonal cross-sections. Abramowicz and Wierzbicki [7] incorporated the effect of strain rate on material properties using the work of Calladine and English [8] and Symonds [9]. Based on this work, CRASH-CAD [10], a computer aided design package was developed. It allowed users to assess energy absorbing characteristics of axially impacted tubes with polygonal cross-section.

Computers in 60s and 70s, though not very powerful, allowed designers to include more complexity of the tube crush phenomenon in simulations. Not able to model, in full detail, the geometry and time-dependent deformation, they used Lumped Parameter Models (LPM) [11–13]. This methodology utilises rigid masses connected by springs with negligible mass for modelling structural elements. Using experimentally obtained mass, stiffness and damping characteristics, these models, despite their approximations, were able to predict structural behaviour fairly accurately (Fig. 1.2)

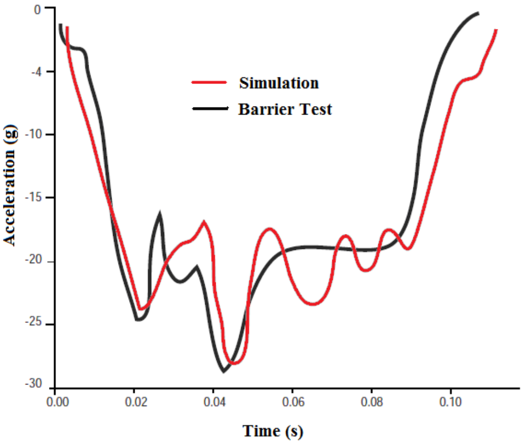

Fig. 1.2 Crash pulse predicted by LMS model and actual crash test [13]

With increasing computation power being made available in the following decades, it was possible to analyse more detailed models for better accuracy. A concise summary of these developments can be found in [14].

Advent of non-linear transient dynamic simulation software like LS-Dyna and PAM-Crash in late 1980s made it possible to analyse response of full structures subjected to impact loading [15]. Even though these simulation packages allow analysis of complete structures, these require substantial computing resources and simulation time.

That is why Lumped Parameter Models (LPM) still find considerable use, at least in the initial stages of design when it allows designer to carry out parametric study and evaluate numerous alternative designs. In this situation, LPM offers a viable quick and economical alternative to full fledged FE analysis [16, 17].

2. PROBLEM STATEMENT

In current designs of automotive structures, a single tubular member is used for absorption of crash energy. This limits designers' options of controlling deceleration characteristics of the vehicle. Use of multiple tubes for this purpose will allow designers to fine tune the design.

Use of multiple tubes in the design allows a designer to alter geometry and placement of tubes. With increased number of parameters, assessing various design alternatives in full detail can become very time consuming. In the work presented, an attempt has been made to develop a methodology using LPM to facilitate this design assessment activity in reduced time.

The main outcome of the work is a methodology to represent axial crush behaviour of tubular structures using a spring element. Using such spring elements, structural configurations with multiple tubes can be analysed using finite element approach.

3. LPM MODEL FOR AXIALLY LOADED THIN WALLED TUBE

As discussed above, deceleration of the vehicle is a key parameter influencing safety of the occupants. This deceleration is directly related to the Force-Displacement (or Force - Time) characteristics of tubes being used. Hence, in designing the tubes, Force-Displacement characteristics is one of the parameter that needs to be assessed. This characteristic can be obtained either through tests or through finite element simulations.

Since both these approaches become economically and temporally unviable for design involving multiple components, development of LPM that can simulate this characteristic has been developed.

In this case since the deformation of the overall tube is that of axial crush, a 1-D LPM, a spring with non-linear stiffness behaviour, can be used. But before such an element can be used in simulation, its stiffness characteristic has to be defined. In early days of simulation this characteristic was obtained through tests. This approach still required considerable time and cost. With the currently available simulation capability, in the current work, it was used to obtain stiffness characteristic of a tube under axial loading.

3.1 Development and Validation of LPM

For development of LPM, results of experimental and simulation work on crushing of rectangular tubes reported in [18] were used. A 310 mm long tube with 80 mm square cross-section and 3.5 mm wall thickness was used. Finite element model of the tube, as shown in Fig. 3.1, was created using Belytschko-Tsay four node shell elements of size 4 mm. Nodes on one end of the tube were fixed in all degrees of freedom to model rigid support and the tube was impacted with a rigid wall of mass 55.9 kg moving with a velocity of 15.6 m/s. A 0.05 mm deep buckle initiator (trigger) was used on the impacted end of the tube to simulate the experimental condition.

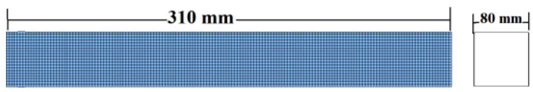

Fig. 3.1 FE model of square section tube used for developing LPM

For the material, elastic-plastic material model for Aluminium alloy A-6060-T4 (Fig. 3.2) was used.

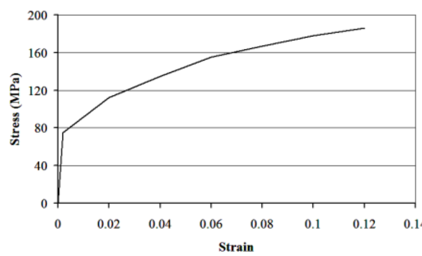

Fig. 3.2 Stress-Strain curve for A-6060-T4

3.2 Validation of LPM

Comparing results from this simulation with those reported in [18] it was found that the maximum crush distance obtained was within 1.5% of reported results. Stiffness characteristic (Force-Displacement curve) of the simulated configuration was not available in the reference. However, the trend was compared with experimental result and was found to be matching it quite well (Fig. 3.3).

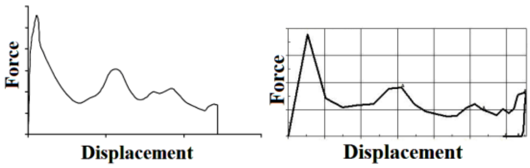

Fig. 3.3 Force-Displacement characteristics from experiment and simulation

LPM for this tube was created in LS-Dyna using a 1-D spring element with its non-linear stiffness defined using the Force-Displacement characteristic obtained from simulation of axial crush of the tube. Response of this spring subjected to same dynamic loading as was applied on the tube was simulated. LPM was able to model the Force Time history response of the full tube model very closely (Fig. 3.4). Some discrepancy was observed close to the end of crush, which is not the most critical part of the total deformation.

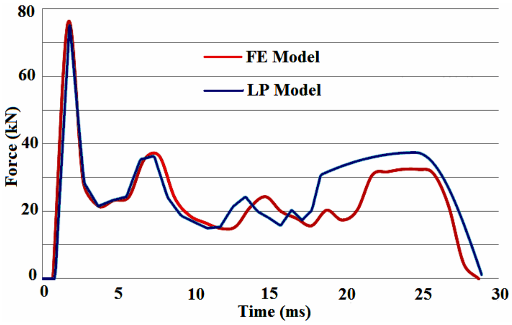

Fig. 3.4 Force – Time history for axial crush of single tube – FEA and LPM

Similar match was found for tubes of different sizes subjected to different dynamic load.

In this validation exercise, simulation time required in FEA and LPM approaches were monitored. It was found that the full FEM takes about 8 times (~120 s) simulation time compared to LPM (~15 s). This difference may vary based on the complexity of the model. But it clearly illustrates the advantage of using LPM to cut down analysis and design development time.

4. LPM FOR MULTITUBE CONFIGURATION

Next step in the development of approach for using LPM in complex designs was to assess its performance for designs with multiple tubes in different configurations.

4.1 LPM for Two-tube Configuration

First, the ability of LPM in modelling two tube configuration was checked using two of the same tubes connected together (Fig. 4.1). Apart from the configuration of the tubes, the rest of the FE model was created the same way as described in Section 3.1.

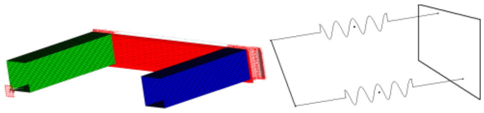

Fig. 4.1 Two tube configuration – FE and LPM

For LPM model also same stiffness characteristic as obtained earlier were assigned to both the spring elements.

In this configuration, a very close match was found between force histories for full tube and LPM models through the full crush of tubes (Fig. 4.2).

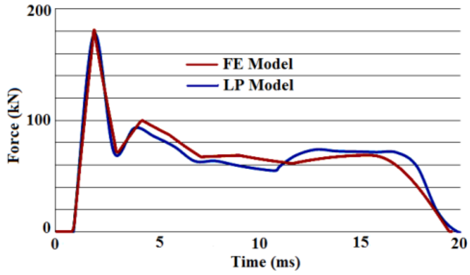

Fig. 14.2 Force history for axial crush of two tubes –FEA and LPM

Displacement histories for the two also were within 5% of each other throughout the crush event (Figure 4.3). From these two results, force and displacement time histories it can be concluded that even for two tube configuration, LP is able to model the stiffness characteristic correctly.

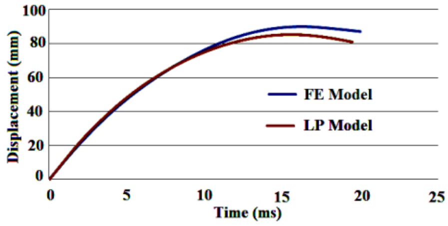

Fig. 4.3 Displacement – Time history for axial crush of two tubes – FEA and LPM

4.2 LPM for five-tube configuration

Next, axial crush of five tubes arranged in a configuration over an area (Fig. 4.4) was simulated.

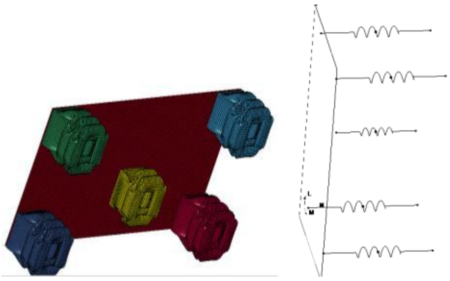

Fig. 4.4 Five tube configuration – FE and LP models

For this model also, in the initial critical stages, results of force history from two models agree well with each other (Fig. 4.5). However at about 60% of total deformation, results from the two start deviating.

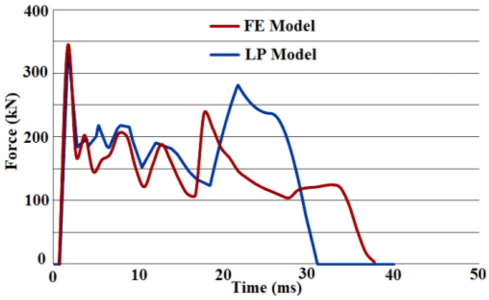

Fig. 4.5 Load history for axial crush of five tubes – FEA and LPM

5. CONCLUSIONS

Based on the work presented, the following conclusions can be drawn.

- For simulation of axial crush of thin walled tubes using finite element method, it is possible to use 1-D spring element to capture the deformation characteristic under dynamic loading instead of modelling the full 3-D configuration.
- 1-D representation of tubes can be used for a single or multiple tubes in any configuration.
- Accuracy of the model using 1-D representation of tubes is of acceptable level (within 5% of experimental and analysis results from detailed FEA) during the critical initial duration of crash. For large crush distance, results start deviating – in some cases substantially. Hence, these results should be used with caution if phenomenon of importance occurs close to end of crush.
- Use of LPM result in considerable reduction in model development and simulation time. for a single component simulation time was found to be approximately 1/8th of simulation time for FEM. This advantage will increase further for multi-component assemblies.
- With reduced time for computation, using a library of LP models for tubes of typical sizes, different designs of crush energy absorber systems with different number of tubes of different sizes and lengths can be speedily assessed in the initial phase of design development.

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