Off-Axis Crushes Simulation of Thin-Walled Tapered Tubes Inserted with Foam-Filled Structures

A. Othman\textsuperscript{a,*} and Azrol Jailani\textsuperscript{b}

\textsuperscript{a}Mechanical Engineering Department, Port Dickson Polytechnic, KM. 14 Jalan Pantai, 71050 Si Rusu, Port Dickson, Negeri Sembilan.
\textsuperscript{b}The Association of Ledang Community Youth, 152 Jalan Puteri 1/6, Bandar Baru Tangkak, 84900 Tangkak, Johor.

Abstract

In this study deal with numerical analysis of the impact dynamic effects of crush performance of the tapered cross-section tubes, containing straight, single taper, double taper, taper triple and fourth tapered lightweight polyurethane foam filled alloy steel thin-walled tube. Foam-filled thin-walled tubes have been examined numerically. Off-axis angle load dynamic effects in front of crash were examined at an angle of 0, 5, 10, 15 and 20 degrees. Numerical analysis has been verified by experimental studies in place to validate the data. The results show that the energy absorption capacity has been significantly affected tube with various oblique angle, impact velocity and wall thickness. It was found that the foam filling in a thin-walled tubes increase the amount of energy absorbed compared with empty tubes.

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1. Introduction

The crushing behavior of thin-walled sheet metal tubes under axial compression has received considerable attention over the past 25 years. Early investigations were conducted in order to understand the capabilities of rail coach body shells to withstand impact conditions [1]. Tests have also been conducted on scale models of both rail coaches and motor coaches in which the details of openings etc. were included. Later investigations were carried out to assess the load-compression characteristics of metal tubes of various cross-sections under impact loads in order to obtain their energy absorbing capacities for use in a variety of applications including

* Corresponding author. Tel.: +6-017-709-1560; fax: +6-06-662-2000
E-mail address: akbar.othman@gmail.com
the arrest of dropped fuel elements in nuclear reactors and improving the crashworthiness of vehicles [2]. In
the latter context attempts have also been made to improve the energy absorbing capacity of metal tubes
fabricated from sheet metal by using filler materials such as polymeric foams [3]. A brief review of the
literature on the various aspects of the axial crushing of empty metal tubes referred to above and foam-filled
sheet metal tubes has been given in a companion [4]. That paper show experimental data have been provided
on the behavior of empty and foam-filled spot-welded sheet metal tubes of uniform square and rectangular
cross-sections. It was noted that relatively thin-walled tubes show non-compact plastic crushing behavior, i.e.
during the first phase of deformation a series of plastic folds are formed which are separated by relatively
undeformed panel sections [5].

1.1. Finite Element Model

A finite element model was developed to analyze the axial and oblique dynamic crushing responses of
polyurethane foam-filled tapered tubes [6]. A specific mass was assigned to the moving rigid body to simulate
the mass of impacting device. The geometries of thin-wall tube and foam material were meshed by four-node
axisymmetric continuum elements, which are suitable for large plastic deformation. To find the adequate
element size, a sensitivity analysis was carried out to obtain accurate results within a reasonable
computational time [7].

![Finite element model of tapered tube]

The total work done (W) during the axial crushing of the cones are equal to the area under the
load/displacement curve and is evaluated as:

\[ W = \int Pds \]  \( (kJ) \)  \( (1) \)

where, \( P \) is the force acting on the column. Therefore the specific energy absorption per unit mass, \( E \) is
recognized as:

\[ E = \frac{W}{m} \]  \( (kJ/kg) \)  \( (2) \)
1.2. Material Models And Properties

The types of models were analyzed in this study is polyurethane foam straight and tapered tube under off-axis loading. The square models were arranged as tubular ones, material of mild steel was used to determine the crushing behavior and having of 70 x 70 mm width fixed in bottom section and 1.0, and 2.0 mm wall-thickness were studied. The straight and tapered tube models were carried out from two tubes having shell element as a material mild steel profile and solid element as a foam filler profile. All sections had a length of 200 mm shown in Table 1. The straight and tapered tube sections were tested as filled with the polyurethane foam, Fig. 2 illustrates typical test model geometry, whereas Fig. 2 presents tensile stress-strain data curves of the used materials. In this study the velocity dynamic of impact was applied at 10, and 20 m/s axially and obliquely onto the frontal crash flat plate analytical rigid surface.

![Dynamic Off-axis Loading Curve](image)

Fig. 2. Dynamic off-axis loading of deformation curve of straight polyurethane foam mild steel tube (Wall-thickness = 1.0 mm; Velocity = 10 m/s)

Table 1 Finite element dimension straight and tapered tube modeling

<table>
<thead>
<tr>
<th>Type (tube)</th>
<th>Straight</th>
<th>Single Tapered</th>
<th>Double Tapered</th>
<th>Triple Tapered</th>
<th>Fourth Tapered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Width (outer) (mm)</td>
<td>70 x 70</td>
<td>70 x 70</td>
<td>70 x 70</td>
<td>70 x 70</td>
<td>70 x 70</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>10, 20</td>
<td>10, 20</td>
<td>10, 20</td>
<td>10, 20</td>
<td>10, 20</td>
</tr>
<tr>
<td>Polyurethane Foam Density (kg/m³)</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.0, 2.0</td>
<td>1.0, 2.0</td>
<td>1.0, 2.0</td>
<td>1.0, 2.0</td>
<td>1.0, 2.0</td>
</tr>
<tr>
<td>Angle of Taper θ</td>
<td>0, 5</td>
<td>0, 5</td>
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<tr>
<td>Angle of Loading α</td>
<td>0, 5, 10, 15, and 20</td>
<td>0, 5, 10, 15, and 20</td>
<td>0, 5, 10, 15, and 20</td>
<td>0, 5, 10, 15, and 20</td>
<td>0, 5, 10, 15, and 20</td>
</tr>
</tbody>
</table>

2. Result and Discussion

2.1. Effect of load angle on the tube response

Initially the effect of the load angle on the response of the straight and tapered tubes was studied. Results in this section are compared for baseline tube geometry with undeformed until final collapse, while the impact
velocity of V is 10 and 20 m/s, which are typical of that, encountered in automobile crashworthiness applications. The effect of the load angle is significant for both straight and tapered tubes, as can be seen from the dynamic load deflection curves shown in Fig. 3 to 5. Fig. 3 showed the both of axial and oblique dynamic load-deflection curves for both straight and tapered tubes. For axial loading, the mean load displays an initial peak corresponding to the initiation of buckling at the impacted end of the tube. However, as introduced a taper side of tube, this initial peak reduces in magnitude, such that the mean load up to a given deflection also decreases shown in Fig. 3. An important observation is that as the loading goes from axial loading, the reduction in dynamic load becomes less significant as the number of tapers increases.

Fig. 3. Dynamic off-axis loading of deformation curve of tapered polyurethane foam mild steel tube (Wall-thickness = 1.0 mm; Velocity = 10 m/s)

The deformation pattern of straight and tapered tube clearly shown in Fig. 4, wall-thickness of 1.0 mm velocity of 10 m/s. The thin-walled rectangular straight tapered tubes have shown that the all model fail via global collapse, progressive folding and mode of crumpling on their surface throughout final deformed of total length of 150 mm. The energy absorption is sensitive to the wall thickness and number of tapers under axial and off-axis impact loading.

Fig. 4. Dynamic loading of deformation pattern of polyurethane foam straight and four tapered mild steel tube (Wall-thickness = 1.0 mm; Velocity = 10 m/s)
2.2. Dynamic mean load and absorbed energy deflection response

Fig. 5 compares the straight and tapered tubes under off-axis loading. An important observation from Fig. 5 is that the mean load-deflection response for each tube under off-axis loading is almost constant due to the progressive deformation of the tubes. On the other hand, the mean load for each tube under off-axis loading decreases with deflection after the onset of global collapse, due to the reduced energy absorption capacity of each tube. Moreover, the initial peak loads predicted by the finite element model compared well with the corresponding numerical results for each combination of tube geometry and load angle. From Fig. 5 also it appears that the mean load is less sensitive to load angle for tapered tubes than for straight tubes. It can be seen that both the initial peak and mean loads decrease more for the straight tube than for the tapered tube as the load angle increases from 0 to 20.

3. Conclusions

A numerical simulation procedure was developed to analyze the axial crushing of polyurethane foam-filled straight tapered tubes considering the nonlinear response due to large deformation, contact boundary conditions, work hardening and strain rate effects on material behavior. Based on the numerical results obtained for each modeling tubes, it was shown that the numerical method predicts the buckling and post buckling responses with a reasonable accuracy. The comparison of deformation modes in polyurethane foam straight and tapered tubes reveals that the performance of absorbed energy was significantly increase the capability in term of absorbed energy. The numerical studies conclude the following characteristics: The mean load and energy absorption decrease significantly as the angle of applied load increases, due to a change in the failure mode.

References


