FINITE ELEMENT MODELING OF CRASHING BEHAVIOR CONCERNING RECTANGULAR MULTI-LAYERED THIN-WALLED STRUCTURES

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Abstract: Tubular thin-walled structures with different shapes of the cross-sections are widely used in various transportation systems as energy absorbing components to dissipate the kinetic energy during violent collisions and crashes. The aims of this paper are to obtain numerical data on the crashing of thin-walled structures made by multiple layers of steel sheets. A series of finite element calculations was carried out on four different models crashed axially in dynamic conditions by using LS_Dyna V971. The effect of the generated fold depth on the peak load and the mean crashing load of these types of structures were also examined.

Keywords: crashworthiness, specific energy absorption, axial crashing, thin-walled structure, crashworthiness

1. INTRODUCTION

Tubular thin-walled structures with different shapes of the cross-sections are widely used in various transportation systems [1] as energy absorbing components to dissipate the kinetic energy during violent collisions and crashes. The main purpose in thin-walled structures design is to get excellent crashworthiness performance by having high specific energy absorption (SEA) values and low maximum reaction forces during the impact processes [2]. Various types of structures are utilized in the construction of controlled body crashing zones. These elements have different cross-sections like circular, elliptical, square, top-hat, double-hat, polygonal shapes [3]. The top-hat and double-hat structures are mainly studied due to their facile possibility of application in car body construction [4]. Regardless the cross-section shape, one of the most crashworthy parameter is the total energy that a given structure can ultimately absorb. Thus, it depends on many geometric and material parameters as on the folding modes that a great kinetic energy to be absorbed and dissipated properly [5].

It is possible that well known and widely used materials like deep-drawing steels will be discarded [6] in favor of high-strength steels, aluminium or magnesium alloys and various grades of polymeric materials and composites [7]. Many problems are linked to the introduction of new materials because their properties are still not completely known, the technologies usually adopted sometimes fail and new environmental problems can be argued [8]. Additional problems are connected to the joining systems.

Numerical methods are now extensively applied in engineering due to the advances in computing. Of all the numerical methods, the finite element method is the most convenient approach [9], because all types of boundary and loading conditions are easy to implement and it can be used for the analysis of large or complex structures.

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LS_Dyna V971, which in this research is used, is purposely designed and applicable for the transient dynamic analysis of highly nonlinear problems such as impact situations.

In this study, various construction types of square thin-walled structures are researched. Therefore, multiple layers of steel sheets are used to enforce the walls of the dynamically crashed structures. Instead of using expensive tailored welded blanks or specially laminated steel sheets having various thicknesses, additional layers of the same material were used. The need of specific conditions of manufacturing disappears once these layers of materials are bonded together with an adhesive solution which gives good results in impacting thin-walled structures. The impact conditions were carefully reproducing the real impact tests which were examined in previous studies. So, the moving mass was described as a rigid body free to translate only along the z axis with a specific velocity and a certain weight.

The aims of this research are to obtain numerical data on the crashing of thin-walled structures made by multiple layers of steel sheets. A series of finite element calculations was carried out on four different models crashed axially in dynamic conditions by using LS_Dyna V971. The rectangular thin-walled structures were constructed by using four different positions of the additional layers as well as a different number of layers. Also, effect of the generated fold depth on the peak load and the mean crashing load of these types of structures were also examined.

2. FINITE ELEMENT MODELING

2.1. Materials characterization
The material used in the construction of the TWB columns is a SPE-220BH steel grade used in car body manufacturing which in the present study will be referred to as M1. The thickness of the sheet metals used in this research was 0.7 mm. The forming characteristics (Figure 1) of the sheet metals were obtained by Marciniak drawing test. In order to find the stress/strain behavior (Table 1, Figure 2) tensile tests were carried out [10].

Table 1. Mechanical properties of the material.

<table>
<thead>
<tr>
<th>Property</th>
<th>SI</th>
<th>M1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>MPa</td>
<td>245.57</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>432.88</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>GPa</td>
<td>214.6</td>
</tr>
<tr>
<td>Strain hardening index</td>
<td>-</td>
<td>0.157</td>
</tr>
<tr>
<td>Resistance coefficient</td>
<td>-</td>
<td>541.86</td>
</tr>
</tbody>
</table>

![Fig. 1. Forming limit curve for the researched steel grade.](image1)

![Fig. 2. Characteristic stress-strain curve for the researched steel grade.](image2)

2.2. Structural components
In this study, various construction types of square thin-walled structures are researched. Therefore, multiple layers of steel sheets are used to enforce the walls of the dynamically crashed structures (Figure 3).
Instead of using expensive tailored welded blanks or specially laminated steel sheets having various thicknesses, additional layers of the same material were used. There were used three types of structures: simple wall rectangular structure (1RS), double wall rectangular structure (2RS) and three wall rectangular structure (3RS). The side of the enclosed cross sections was 62.5 mm for the rectangular shape. The reason for having these dimensions of the sides is for having 250 mm for both crash box length and cross section perimeter respectively.

### 2.3. Numerical setup

The numerical analysis was conducted through the explicit non-linear finite element platform LS-Dyna V971 R5.0. This application was used in conjunction with the pre- and post-processor LSPrePost V4.0. The strain rate effect was accounted by using the Cowper and Symonds model that scales the flow stress with the factor $1 + \left( \frac{\dot{\varepsilon}}{C} \right)^{1/P}$ [9].

All the structures from these simulations were modelled using Belytschko-Tsay shell elements having five points of integration through the thickness. This element formulation gives greater computational efficiency compared with other shell element formulation [9]. The crashing tool is defined with 1 point of integration. *Mat_Piecewise_Linear_Plasticity material model was used to characterize the sheet metals for the thin-walled structures and rigid elements were used to characterize the crashing tool. The size of the mesh is 2 mm for the structure and 20 mm for the tool. The velocity boundary conditions were applied on the top rigid plane in the axial direction while the bottom was kept into place. According to the impact tests, the impact velocity was established to be equal to 6.5 m/s. Clamped boundary conditions were applied at the bottom of the structure.

### 3. RESULTS AND DISCUSSION

In the case of the collapse mode the folds formation and shape can be clearly characterized. The simulated impact collapse mode in different steps and the load/energy graphs in conjunction with displacement are all depicted in Figures 4-9. Regardless to the construction type, the square structures collapsed into a diamond mode (asymmetric mode) which is characteristic for this type of structures. This is caused by the presence of the corners which affects the characteristic progressive buckling of the square structures.

For all structural types, the folds created due to impact deformation are in contact with each other, which determine by consequence the symmetrical inward and outward formation on opposite walls of these folds. The structure which shows the maximum number of folds is the 1RS structure and the one with the minimum number of the folds is the 3RS structure.

In the presented diagrams, the absorbed energy curve is obtained by surface integration of the space below the load/displacement curve after the termination of the progressive buckling. The general characteristic of the load/displacement curve is described by the fast increase of the loading value caused by the elastic compression of the thin-walled structure. After the first fold is created and the peak load appears, a load reversal cycle during progressive buckling follows. This phenomenon occurs until the end of the deformation.
Fig. 4. Load/displacement and energy absorption response of the single wall structure.

Fig. 5. Folding patterns in impact tests on single wall structures.

Fig. 6. Load/displacement and energy absorption response of the double wall structure.
In order to determine the efficiency of the columns one of the most important coefficients (specific energy absorption) was taken into consideration. As Figure 10 displayed below shows, once the number of layers increased the specific energy absorption increased as well. This fact is very important for structural design in
general, because a high SEA value means that the structure is capable for high energy absorption, there for higher loads. Even if the weight of the structure increases, as more layers of materials are added, the ratio between the weight and the absorbed energy is better (Figure 11). The numeric data extracted from these analyses is presented in Table 2.

As the absorbed energy of the crushed structures is analyzed, an offset to the natural flow of the energy absorption curves is emphasized. These offsets are produced as a result of new layers of material resisting the crash load.

Table 2. Correlation data between the SEA coefficient and the absorbed energy.

<table>
<thead>
<tr>
<th>type</th>
<th>Weight (g)</th>
<th>SEA</th>
<th>Energy (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1RS</td>
<td>214</td>
<td>5.68</td>
<td>1.17</td>
</tr>
<tr>
<td>2RS</td>
<td>321</td>
<td>5.71</td>
<td>1.71</td>
</tr>
<tr>
<td>3RS</td>
<td>428</td>
<td>6.15</td>
<td>2.63</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

Analyzing the presented data it was found that for steel thin-walled structures with rectangular cross-section, the specific energy absorption can be improved by adding multiple layers of material (Figure 10) such as the global inertia of the structure is being reduced to minimum. Due to asymmetric progressive buckling the folding process is maintained consistent regardless the number of layers that the structure has.

Furthermore, by doubling the walls of the structure just on a half of it, the absorbed energy increased by 46.2 % and the value of the SEA coefficient also increased by 0.6 %. A better result is obtained if the structure has three layers of sheet metal similar to structure 3RS, shown in Figure 3. In this case, the absorbed energy increased by 124.8 % and the value of the SEA coefficient, went also up by 8.3 %.

REFERENCES


