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Modeling of Crashworthiness in Energy Absorbent Shells with Discontinuities

H. Rostami[1,*], M. Mirzaei[2]

[1]MSC graduate, Tarbiat Modares Univ., Tehran, Iran
[2]Assoc. Prof., Tarbiat Modares Univ., Tehran, Iran

*Corresponding author: Hodarostami95@gmail.com

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Abstract

The importance of research in crashworthiness and the post-accident behavior and efforts to improve the behavior of the structure and reduce the accelerations to the occupants with the help of energy absorbers is determined by observing the increasing statistics of vehicle accidents, including cars, trains, and airplanes. In this research, the energy-absorbing behavior of a thin wall with an aluminum rectangular section will be investigated by numerical solution in finite element method and in Abaqus software, and to improve its energy absorption parameters, discontinuities were created on the geometry, which regularized the folding pattern. The primary research approach is to improve the energy absorption behavior without fundamentally changing the geometry. Discontinuities with different geometrical shapes, sizes, and numbers are placed in different places in the model to obtain the best energy absorption behavior. After evaluating and choosing the circular discontinuity among the other geometric shapes, for their proper placement, an initial guess of the location of the discontinuities was considered with the help of similar research. Then, the eigenvalues of the geometry extracted from the buckling solver have been used to place and increase the number of discontinuities. Finally, by examining 43 models with different numbers and placement of discontinuities, a model with a 13% improvement in the CFE criterion was proposed.

Keywords: Crashworthiness, Discontinuities energy absorbent shells, Finite Element, Damage criteria, Crash.

1. Introduction

The basic principles of the system approach in design based on crashworthiness can be described with five factors of creating a survival volume, restraining the passenger in the structure, impact energy management, proper design of the interior space and post-crash factors such as fire [1].

In this research, the impact energy management section is discussed and to absorb the energy caused by crash and deflect the impact force from the passenger to the aircraft body, thin wall energy absorbent structures with a rectangular cross section are investigated.

In 2008, Yuen and Nurick [2] investigated the effect of discontinuities such as grooves and cutting edge on aluminum tubes with circular and square sections on crushing and the maximum crushing force experimentally and numerically. They showed that the creation of discontinuities in the tube, including the creation of cuts and grooves activates the symmetric crushing mode and reduces the maximum force. Simhachalam et al [3] performed numerical and experimental analysis of compression behavior and energy absorbed by aluminum alloys using cylindrical tubes under static and dynamic loading. Sun et al. [8] have given a numerical study to analyze the effect of aluminum profile cross section geometry on energy absorption parameters under dynamic loading. The cross sections used include a polygon with multiple corners. Cheng et al. [4] had an experimental test that compares the energy absorption of models with geometric discontinuity on the walls. Energy absorption in the circular discontinuity has performed best with an improvement of 74.6% compared to the initial model.

Marzbanrad et al. [5] have reviewed energy absorption of five cross-sections of square, rectangle, circle, hexagon and octagon with angle of 0, 15 and 30 degrees. They also studied the location, type (holes or folds) and suitable dimensions of discontinuity on the energy absorber.

Estrada et al [6-9] investigated the effect of discontinuity with different shapes in steel profile on improving energy absorption parameters. In another study they studied the effect of circular discontinuity in aluminum profile on improving energy absorption parameters and then the radius of the circular discontinuity was investigated. In another study, Estrada et al. investigated the twin-walled model. After that, the effect of changing the distance between two walls of the model and height of the discontinuities on the two walls was investigated. In another study, Estrada et al. have investigated the effect of the presence of a wall between the two walls and a multi-cell cross section. Bay et al. [10] investigated the effect of impact angle, thickness, half vertex angle, model diameter, corner cut dimensions and the number of cuts.

The innovation used in this research is that it improves energy absorption parameters without changing the original geometry of the energy absorber and simply by adding geometrical discontinuities.

Effective criteria for improving damage tolerance in thin-walled energy absorbers that have been investigated in this research are maximum impact force (Pmax), average impact force (Pmean), absorbed energy (Eabsorption), specific absorbed energy (SEA) and Impact force efficiency (CFE).

$$P_{max/mean} = a_{max/mean} \times m \qquad (1)[11]$$

$$P_{mean} = \frac{\int_{S_i}^{S_f} P(s)ds}{S_f - S_i} \qquad (2)[11]$$

$$E_{absorption} = \int_{S_i}^{S_f} P(s)ds \qquad (3)[11]$$

$$SEA = \frac{E_{absorption}}{m} \qquad (4)[11]$$

$$SEA = \frac{E_{absorption}}{m} \qquad (5)[11]$$

The permissible acceleration of the body in the direction of crash with an angle of 30 degrees is 36G in the critical state, and this issue is taken into consideration for the design of P_{max} and P_{mean} criteria. The impact speed in this research is based on the minimum impact speed of the requirements of FAR23, FAR25, FAR27 and FAR29, 10 m/s is considered. [1]

2. Validation

In order to measure the validity of the model in this study, the geometry that was modeled in the research of Estrada et al. [9] and Hopatra et al. [12] (two-cell geometry) was used in both numerical and experimental methods.

Based on the folding pattern and the comparison of the displacement force diagram of the model with the corresponding sample in these two studies, it can be seen that the overall validity of the model has been measured and can be valid.

3. FEM Modeling

The geometric dimensions of the model are L=400 mm, W=95 mm, H=68 mm and the thickness is 2.5 mm. The radius of curvature of the corners of the cross section is 7.9 mm.

The type of material is EN AW-7108 T6 aluminum alloy with a density of 2700 kg/m3, elasticity modulus of 70 GPa and a Poisson's ratio of 0.33. For the plasticity properties of the material, the stress-strain diagram has been used for the strain rate of 25. Two types of damage criteria named DUCTILE and SHEAR Criteria have been used in modeling. For damage evolution modeling, a displacement equal to 0.001 has been used.

There is a rigid, shell top and bottom plates and the square two-dimensional element R3D4 with a size of 5 mm is assigned to it. After checking the convergence of the mesh for the aluminum tube and meshing the model with elements between 3 to 18 mm, the shell, homogeneous and two-dimensional element, S4R and S3R, with a size of 5 mm has been selected for the model.

The origin point of the top plate is given an initial velocity of 10 m/s and a mass of 500 kg and a displacement constraint equal to zero in five degrees of freedom other than the direction of movement (y). The degrees of freedom of the origin point of the lower plane are completely closed. In addition, 4 cm of the lower part of the model is separated by partitioning and its degrees of freedom are closed due to the creation of a support.

To model surface contacts in dynamic modeling, a general contact with a hard contact normal property and a penalty tangential property with friction coefficient of 0.15 have been used.

Due to imperfection of the material, geometry, and loads, an imperfection has been entered in the edit keywords section. In this way, it is first implemented with the buckling analysis in the Linear Perturbation solver of Abaqus and specifically for each geometry and by calculating the eigenvalues, the buckling modes of that geometry are obtained. Then it is called in the main model. In this research, the first and second eigenvalues with a factor of 0.0015 have been applied by the following code.

```
IMPERFECTION,FILE=DT-T,STEP=1
1,0.0015
2,0.0015
```

Step time is 0.04 seconds and the number of iterations is 270.

4. Application of geometric discontinuities

In order to change the height of the discontinuities, two circular discontinuities with a diameter of 14 mm have been placed on the opposite sides of the absorber at H equal to 50, 125 and 200.

To change the size of the discontinuity, at a height equal to 50 mm the diameter of two circular discontinuities on the opposite sides of the absorber are changed between numbers 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 30, 36 and 50 mm.

To change the geometric shape of the discontinuity, at a height equal to 50 mm, the geometric shape of discontinuities changes between triangle, square, rectangle, rhombus, pentagon, hexagon, oval, and circle. The area of discontinuities is assumed to be constant and two cases of 531 and 154 square mm have been investigated.

To apply changes in discontinuity position and number, six position and number modes have been investigated for two diameters of 14 and 30 mm. As shown in Figure 1, the number of discontinuities is 6 and 12, and they are placed in two faces and four faces. For the initial guess, the location of the convexity and concavity of the geometry in the buckling solver is used in three eigenvalues and the heights of 50, 160 and 260 mm and the heights of 100, 200 and 300 mm are considered.

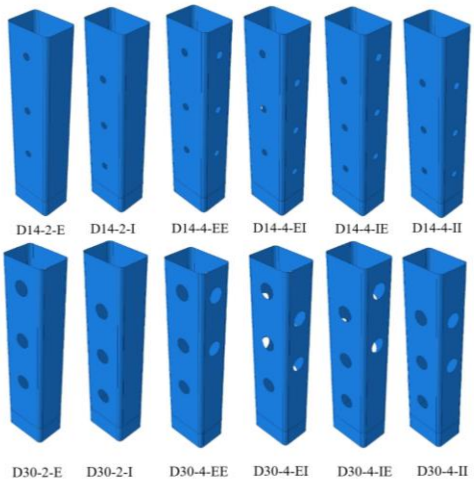

Figure 1. Changes in location and number of discontinuities with diameters of 14 and 30 mm

5. Results and Discussion

Due to the more accurate model of Ductile Damage than Shear Damage, the criterion of Ductile Damage has been used in the modeling.

In the changes in the height of the discontinuities, SEAhas increased by 2.5% and CFE by 3.6%. The best model is for DT-T, where the CFE has increased by 3.6%. It can be seen in sections A and B shown in Figure 2 that this is influenced by the improvement of the folding pattern. In fact, by controlling the folding points, the sharpening of this area and as a result the destruction of the element and its removal have been prevented.

In the effect of changes in the diameter of discontinuities, all parameters of crashworthiness have improved compared to the model without discontinuities.

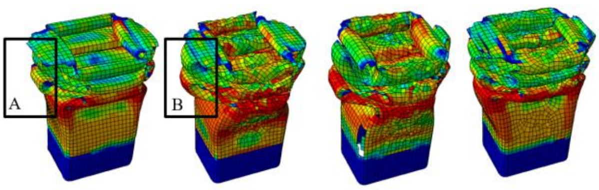

Figure 2. Folding pattern for the model without discontinuity and height of 50, 125 and 200 mm

The SEA for the 14 mentioned models has improved up to 6.7% and CFE up to 9.5% compared to the model without discontinuity. DT-26 to DT-50 models with a height of 50 mm have better performance. Among these four models, the DT-30 model is the best option due to the 5.4% improvement of the CFE and the creation of a more suitable final acceleration.

The DT-30 model has the best performance with 39G maximum acceleration at the end of the model and with an error of 10%, they have an acceptable performance compared to the maximum acceleration of the body.

In the changes in the geometric shape of the discontinuities, among all the models with an area of 154 mm^2, DT-14, which has a circular discontinuity, has a higher CFE. The same thing happens for models that have an area of 531 mm^2. The reason why the circle discontinuity performed the best could be due to the lack of stress concentration.

In the changes in the number and position of discontinuities, folding pattern for an example of these models, i.e., D30-4-IE model, can be seen in Figure 3.

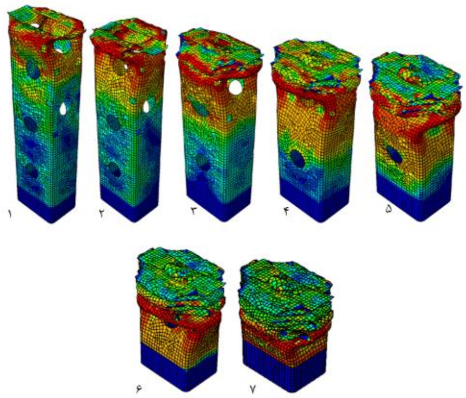

Figure 3. Folding pattern for D30-4-IE model in changes in the number and position of discontinuities

According to Figure 4, the best performance is for the D30-4-IE model, where the CFE has improved by 13%. But the maximum acceleration at the end has increased to 41G, which is 15% more than the allowed acceleration of the body.

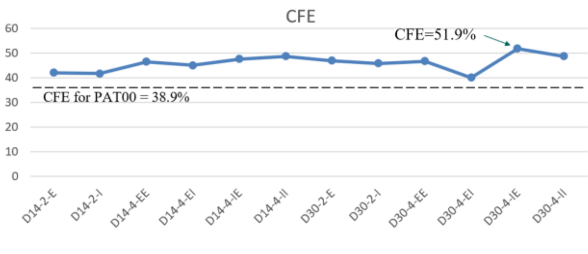

Figure 4. CFE changes in the number and placement of discontinuities

6. Conclusions

The results of this research are as follows:

- By examining two damage criteria, Ductile Damage and Shear Damage, it was found that the Ductile Damage criterion has a better and more accurate damage estimate.
- By examining three heights for the discontinuity of a circle with a diameter of 14 on two facing faces, the highest height, i.e., 50mm height, is the best height. The CFE of model has improved by 3.6%.
- By examining 14 circular discontinuity models with different diameters located on two faces and a height of 50, the best improvement in damage criteria belongs to the model with a diameter of 30 mm. In this model, CFE has improved by 5.4% and SEA has improved by 6.2%. Maximum final acceleration is reduced to 39G, which is 10% off the tolerable body acceleration and improves the prototype by 15%.
- By examining seven other geometric shapes for two area sizes and at a height of 50 mm, the best performance is related to circle and the worst is the small triangular.
- By examining 12 models with different number and placement of discontinuities, the best crashworthy behavior is for 30 mm diameter and 10 discontinuities, so that the longer side of the cross-section is concave and the shorter side of the cross-section is convex. In this case, CFE is improved by 13%. The maximum acceleration in the last 0.01 seconds has an error of 15% compared to the maximum allowed acceleration of the body, but shows an improvement of 6% compared to the initial model.
- Examining the behavior of the total models shows that the improvement of the crashworthiness behavior is due to the prevention of element failure and its removal. This issue has been done by slight changes in the folding pattern and not sharpening the folding points.
- Due to the fact that in this research the main approach is to improve the model and not to change the model, noticeable changes in the absorbed energy are not felt, but the CFE criterion and the accelerations on the passenger have been improved.

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