Axial Crashing of Folded Thin-Walled Tubular Structure with Various Cross-Sectional Shapes

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Abstract. Many thin-walled tubular structures have been widely applied to absorb the impact energy during vehicle crash accidents. Literatures prove that the energy absorption performance of the tubular structure is closely associated with its cross-sectional shape. Here in this paper, a series of folded tubular structures that have various cross-sectional shapes, including triangle, square, hexagon and circle, are proposed, and the crashworthiness characteristics of these structures are compared and analyzed based on finite element simulation. It is found that folded tubular structure with more cornered cross section has better energy absorption performance. The parametric analysis results also indicate that the energy absorption performance of the folded tubular structure improves with bigger thickness.

1. Introduction

Thin-walled (TW) tubular structures, which have sound crashworthiness and light weight, are widely used in automotive industries to absorb energy during vehicular crash accidents and the corresponding study has become increasingly attractive in recent years [1].

Generally speaking, the thin-walled tubular structures realize energy absorption through progressive plastic deformation during the axial crashing processes. The energy absorbing capacity of the structures is greatly influenced by the cross-sectional configurations. The traditional thin-walled tubular structures usually have very simple single-celled cross-sectional shapes, such as the plain circular tubular structure [2, 3] and square tubular structure [4]. They are all proved to have acceptable energy absorption performance. Besides, Fan et al. [5] studied the axial crushing behavior of square tubes with cross-section of 12-sided and 16-sided stars, respectively. The tube with 12-side star shaped cross-section is proved to have better energy absorption characteristics than that of the traditional pure square tubular structure.

In addition to the simple single-celled tubular structures we mentioned above, many efforts have also been made to investigate the energy absorption performance of the tubular structures with multi-cell closed sections in recent years. For example, Zhang et al. [6] analyzed the axial compressive performance of multi-cell square tubular structures with various cross sections and it was found that the energy absorption efficiency of the thin-walled tubular structure is significantly increased with the
number of multi-cell columns. Tang et al. [7] also investigated the energy absorption characteristics of some new cylindrical multi-cell tubes. Results showed that this new cylindrical multi-cell structures have better energy absorption performance than the square multi-cell structure. The difficulty for using this kind of tubular structure with multi-cell closed sections is to find the proper manufacturing technology since the commonly used electrical discharge machining wire cutting method may change the materials’ properties.

From the perspective of easy processing for the tubular structure, the structures with multi-cell open sections are also proposed and the corresponding crashworthiness performance is investigated through numerical simulation or experiments by the team of Zhang et al. They [8] studied the energy absorption characteristics of thin-walled tubes fabricated by folding of metal plates with square cross sections. The energy absorption efficiencies of the folded tubes are quite comparable with that of the traditional square tube. And it is believed that the folded tubes have great application potentials in various engineering fields since they are easily prepared and cost-effective for small-scale production. Recently, our group [9] also proposed one folded thin-walled tubular structure with spiral cross section, and the geometric information and energy absorption performance are analyzed. This spiral thin-walled tubular structure is proved to be a promising structure for energy absorption.

Even though the folded thin-walled tubular structures have acceptable energy absorption performance, the specific energy absorption behavior is closely restricted by the specific folded cross-sectional shape. So it is necessary to find the optimal folded tubular structure with the specific cross-sectional shape. Here in this paper, the axial crashing performance of the folded thin-walled structures with various cross-sectional shapes, including triangle, square, hexagon and circle, are compared and analyzed based on numerical simulation and the optimal folded tubular structure are obtained. In addition, the influence of the geometric parameter on the crashworthiness performance of the tubular structure is also investigated.

2. Numerical study

2.1. Geometric shape description of various folded thin-walled tubular structures
The folded thin-walled tubular structure can be easily manufactured by bending the blank along the specific solid mold. Here in this study, four kind of cross-sectional shapes are adopted and compared, namely, triangle, square, hexagon and circle.

The geometric description of the circular tubular component can be referenced from our previous published paper [9]. For this study, the number of the folding circles is 3, and the inner diameter and the outer diameter are 30mm and 36mm, respectively. Similarly, taking the case with the square one as one example, the folding situation is shown in Fig 1. As can be seen from the figure, the geometric dimension of the structure can be easily calculated. The cases with both triangle and hexagon follow the folding principle shown in Fig. 1.
2.2. Material properties
The material used for this study is aluminum extrusion AA6061 T4. The material properties of this material are listed as follows. Young’s modulus is 70GPa, Poisson’s ratio is 0.28, and yield strength and ultimate strength are 103MPa and 213MPa, respectively.

2.3. Finite element modeling study
At present finite element simulation is commonly used to evaluate the deformation behavior of metal plates during axial crashing process in a much more effective way. Here in this study, the numerical simulation method based on the general finite element software is used to analyze the whole axial crashing process for aluminum alloy AA6061 T4.

The numerical simulation model is composed of 1 folded blank sheet, 1 moving tool and 1 stable tool. The length and the thickness of the folded blank are 100mm and 0.5mm, respectively. The cross-sectional geometrical dimension of the folded blank is the same as that referenced in Fig 1. During the simulation, the elastic-plastic model and the rigid model are used to describe the mechanical behavior of the folded sheet and the tools, respectively. The stable tool is fixed and the moving tool moves down along z-axis to press the blank with an impact velocity of 10mm/s. The whole simulation process for the case with square cross section is shown in Fig. 2. It can be seen that the collapsing deformation begins from the top of the folded sheet and incrementally spreads to the bottom of the folded sheet.

![Image](image_url)

**Figure 2.** Axial crushing process of the folded square thin-walled tubular structure.

3. Results and discussion
Fig. 3 shows the final deformation state of the folded thin-walled tubular structures with various cross-sectional shapes when the compressive depths are 65mm. For the case with triangular cross section, the deformation slightly inclines to one side. However, for other three cases, all the blank sheets develop inextensonal model as that developed for the traditional tubular structure with plain square cross section.

![Image](image_url)

**Figure 3.** Final deformation state of the folded thin-walled tubular component with various cross-sectional shapes (compressional depth=65mm).
The crushing force versus displacement curves for the four cases are shown in Fig. 4. It can be seen that all the four curves follow the similar rules. That is, the crushing force increased first due to elastic deformation and then fluctuated along the specific platform, and lastly, the crushing force increased greatly to realize densification. However, the initial peak force and the mean crushing force varied with the specific cross-sectional shape as listed in Table 1. It should be noted that, for the case with triangular cross section, the calculation is not stable when the crushing depth is more than 80 mm, so the predicted force after that increased greatly as shown in Fig. 4.

![Figure 4. Force-deformation curves of folded tubular structure with various cross-sectional shapes.](image)

**Table 1.** Crashing force information of the four sections with various shapes.

|         | triangle | square | hexagon | circle |
|---------|----------|--------|---------|--------|
| initial peak force/kN | 13.5     | 16.3   | 17.7 | 19.4 |
| mean crushing force/kN | 3.4     | 4.6    | 7.2   | 8.5   |

Actually, the value of the crashing force is closely related with the specific cross-sectional area. So in order to more accurately evaluate the crashworthiness performance of the tubular structures with the four various cross-sectional shapes, the average force on each cross section should be compared. Table 2 listed the circumference and cross-sectional area for the four cases and Fig. 5 shows the average pressure versus displacement curves obtained based on the data shown in Table 2. Results show that the tubular structure with more cornered cross section has better energy absorption performance and thus the circular cross-sectional tubular component is the best choice if the number of the folding circles and the circumscribed diameter for each circle are constant.

**Table 2.** Geometric information of the four sections with various shapes.

|         | triangle | square | hexagon | circle |
|---------|----------|--------|---------|--------|
| circumference/mm | 223.12   | 260.12 | 283.44 | 313.93 |
| cross-sectional area/mm² | 111.56 | 130.06 | 141.72 | 156.96 |
As for the circular cross-sectional tubular structure, the crashing worthiness performance is also determined by many factors, including the number of the folding circles, the circumscribed diameters and the thickness of the tubular structure. In our previous literature, the influence of the folding circle number and the circumscribed diameters on the crashing force is analyzed, so here in this paper, the influence of the thickness on the crashworthiness performance of the tubular structure will be investigated.

Fig. 6 shows the crushing force versus displacement curves for the circular cross-sectional tubular structure with three thicknesses. It can be found the one with bigger thickness has larger energy absorption capacity. This conclusion can also be validated by the average pressure versus displacement curves for cases with different thickness shown in Fig 7. From the simulation results shown in Fig 6 and Fig 7, the circular cross-sectional tubular structure is very suitable for energy absorption in many industries.

**Figure 5.** Pressure-deformation curves of folded tubular structure with various cross-sectional shapes.

**Figure 6.** Force-deformation curves of folded circular tubular structure with various thicknesses.
Figure 7. Pressure-deformation curves of folded circular tubular structure with various thicknesses.

4. Conclusion
Here in this study, the thin-walled tubular structures with various cross-section shapes are proposed and the crashworthiness performance of these tubular structures is investigated and analyzed based on finite element simulation. The key conclusions can be summarized as follows:

1) The folded structure with more cornered cross section have larger energy absorption capacity, so circular cross-sectional folded structure and the triangular cross-sectional folded structure have the best and the worst crashworthiness performances respectively if the geometric parameters are the same.

2) The energy absorption performance of the folded tubular structure improves with bigger thickness.

Generally speaking, the folded tubular structures are easy to fabricate and the crashworthiness performance is satisfactory, so this novel tubular structure has great application potential in various industries.

Acknowledgments
The authors would like to express their gratitude to Shenzhen Key Laboratory Project (ZDSYS201707271637577) and CAS-HK Joint Laboratory of Precision Engineering for the financial assistance to this study.

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