A comparison of bending resistance of square thin-walled tubes with different internal reinforcements

Zhongyou Xie
School of Architectural Engineering, Tongling University, Tongling 244061, Anhui, China
Email: zhyxie@126.com

Abstract. Thin-walled structures with light weight are applied widely in some engineering fields, and thin-walled tubes are liable to local deformation under transverse loading. In the paper, six internal reinforced configurations of square thin-walled tubes were presented and their bending resistance was compared with each other based on finite element analysis by ABAQUS code. The numerical results reveal that the internal reinforcement plays significant role on the bending resistance, and some reinforcing strategies have evident advantage over the empty tube without any reinforcement considering the weight specific energy absorption. In addition, the reinforced configurations have more designability than the ordinary empty tube to obtain more specific energy-absorbing capacity.

1. Introduction

Thin-walled structures are widely used in various engineering fields such as automotive engineering, aerial engineering and so on due to their low weight and high energy absorbing performance. A large amount of studies focused on the axial compression behavior of thin-walled tubes. Abramowicz and Jones [1-3] predicted theoretically the static and dynamic axial crushing behavior of circular and square tubes, which showed good agreement with the experimental results. Langseth and Hopperstad [4] conducted static and dynamic crushing tests to study the behavior of square thin-walled tubes, which revealed that dynamic crushing showed a strong inertia effect and different deformation mode from static crushing. Guillow et al. [5] carried out a large range of tests to investigate axial compression of thin-walled circular tubes, which indicated that the ratio of the diameter to thickness of the tubes had substantial effect on the collapse modes and crushing force. Galib and Limam [6] examined the crash behavior of circular aluminum tubes subjected to axial compressive loading by experimental test and numerical simulation, and the influence of some factors was studied.

Bending resistance is one of the most important performance of thin-walled tubes since transverse impact loading is an ordinary case in the real accidental collision events. However, the bending resistance of thin-walled tubes was less investigated than the axial crushing one. Kim and Reid [7] suggested a new theoretic model for the thin-walled rectangular section tubes subjected to bending, and presented an improved analytical solution for the moment-rotation relationship. Zhang et al. [8] studied the bending collapse behavior of thin-walled square tubes with variable thickness, and found that putting less material in flanges and more in the web plates could improve the bending resistance of the tubular beam. Maduliat et al. [9] established an analytical model for the circular hollow sections under pure bending to predict their collapse deformation and energy absorption characteristic, and concluded that the section with lower slenderness ratio had a higher energy absorption capacity.
Thin-walled tubes are apt to generate local deformation especially under transverse concentrated load, which would largely decrease their global bending resistance. Adding internal reinforcement to the thin-walled tubes is perhaps a feasible strategy to constrain local deformation and maintain their bending resistance. The multi-cell cross-sections could be seen as a reinforcing method and their crashworthiness has been severally investigated. Zhang et al. [10] derived a theoretical solution for the mean crushing force of multi-cell square tubes under axial crushing based on the Super Folding Element theory, which demonstrated a good agreement with the numerical results. Tang et al. [11] proposed a type of cylindrical multi-cell tube and found it had high energy-absorbing capacity for its lots of corners in the cross section. TrongNhan et al. [12] studied multi-square tubes under oblique impact loading, and proposed theoretical solutions to the mean crushing force, horizontal force, and bending moment based on a Simplified Super Folding Element theory. Wang et al. [13] investigated the bending resistance of multi-cell square tubes under three-point bending experimentally and numerically, and found that the number of cells had important effect on the bending resistance of the structure.

In the paper, six alternative internal reinforced configurations are suggested to improve anti-indentation capacity of the thin-walled tubes, and general three-point bending tests of thin-walled tubes with the six different cross-sections are modeled using the ABAQUS code to compare their reinforcing effect. The specific loading-carrying capacity and energy absorbing performance relative to the whole structural mass are mainly focused on, and the results may enlighten more novel reinforcing strategy based on grasping the load-carrying and energy-absorbing mechanism of the thin-walled structures.

![Figure 1. Six internal reinforced configurations with identical global cross-section and the same walled thickness called I–VI, respectively.](image-url)
2. Internal reinforcement design and numerical tests
Six internal reinforced configurations with identical global cross-section are presented to compare their bending resistance, see Figure 1. When the tubes have the same material, total depth and wall thickness, the total mass would be dominated by the whole length $l_s$ of the cross-sectional segments, named characteristic mass. For example, the characteristic mass $l_s$ of configuration I in Figure 1 (a) sums up to $5b$ including the four sides and the one reinforced linking segment, and so on.

A typical three-point bending test is set up to investigate the bending resistance of the above sections, as shown in Figure 2. The loading and bearing cylinders have an identical radius, and the loading cylinder is loaded at the middle span.

![Figure 2. Schematic of three-point bending test of thin-walled tubes with identical global cross-section.](image)

3. Numerical modelling
In the present simulations, all the tubes have the same side-length $b=0.2m$, and identical walled thickness $0.01b=0.002m$. The total depth of the tubes is $10b=2.0m$, and the span $L=8b=1.6m$. The loading/bearing cylinders have the same radius $R=0.5b=0.1m$. Due to symmetry about middle-span cross-section, a half of models is established to decrease element amount and calculating time. For simplicity, the sizes in Figure 1 are assigned as follows: $b_1=b_2=b_3=b_4=0.5b=0.1m$; $b_5=b_6=b_7=b_8=0.6b=0.12m$. Now, the characteristic mass $l_s$ of the empty section is 0.8m, and those of the reinforced six cross-sections from I to VI are 1.0, 1.083, 1.2, 1.3656, 1.44 and 1.52m, respectively.

3.1. Part features
In present models, the loading/bearing cylinders are modeled as Analytical Rigid that cannot deform, whose motion is governed by the motion of a single reference node. The thin-walled tubes are simulated using 3D deformable Shell, whose thickness is considered small compared to the width and length.

3.2. Material properties
The loading/bearing cylinders modeled as Analytical Rigid don’t need assigning certain material properties. The tubular walls are modeled using elastic, ideally plastic material with density $7.8\times10^3kg/m^3$, elastic modulus 200GPa and flow stress 600MPa, and they are assigned homogeneous shell section integrated using Simpson's rule where the first section point is exactly on the bottom surface of the shell. In the material module of ABAQUS, the thickness of shell is assigned 0.002m. According to ABAQUS Documentation, a shell made of a single isotropic material with a thickness-to-span ratio greater than 1/15 is considered “thick” shell. If the ratio is less than 1/15, the shell is considered “thin” shell. In present models, the ratio is about 1/100, meeting the condition of “thin” shell.

3.3. Analysis procedure
General static analysis procedure is usually used to calculate static or quasi-static events, but solving convergence is difficult in the case of large distortion. To improve solving efficiency and convergence,
the dynamic explicit one is adopted where the Nlgeom button is opened considering geometric nonlinearities and the time period is assigned 2s. Linear bulk viscosity is included with a default damping coefficient of 0.06 in Abaqus/Explicit, but the influence could be neglected due to present low-speed quasi-static events. In addition, double precision in the Abaqus/Explicit packager and analysis is used to ensure the highest overall execution precision.

3.4. Interaction
All of the interaction is modeled using General contact (Explicit) with a frictionless tangential behavior and hard normal one. The contact domain includes all faces of the tubular walls themselves and the exterior faces of the loading/bearing rigid cylinders with the corresponding exterior faces of the tubes.

3.5. Boundary and loading
The bearing cylinder is fully fixed using Encastre boundary without any displacements, and the middle-span sections of the tubes are enforced the Symmetry boundary about middle-span cross-section. The loading cylinder using displacement loading is only allowed to move vertically downward up to 0.2m, and the average loading velocity becomes 0.2m/2s, i.e. 0.1m/s.

3.6. Meshing and element type
The loading/bearing cylinders modeled as Analytical Rigid don’t need meshing. The tubular elements are modeled using 4-node general-purpose shell, reduced integration with hourglass control, finite membrane strain (S4R). Based on ABAQUS 2016 Documentation, the relationship of the element side-length of shell $l_s$ with the shell thickness $h$ is proposed to satisfy $h/0.6<l_s<15h$, and the shell
4. Results and discussions

4.1. Reaction forces of the loading cylinder

In some cases, the specific load-carrying capacity relative to the whole mass of the construction is most significant. The reaction forces of the loading cylinder of the six reinforced configurations as well as the empty tube without reinforcement divided by their characteristic mass are plotted in Figure 3. It can be observed that the six reinforced configurations show distinctly higher load-carrying resistance than the empty tube. After an elastic deformation peak force, the curve of the empty tubes demonstrates a long descending trend, while those of the six reinforced cross-sections will ascend up to a second peak value after a short drop.

4.2. Energy dissipation by plastic deformation of the tubes

Under quasi-static loading, the external work would dissipate mainly through plastic deformation of the tubes neglecting elastic deformation. The external work or plastic strain energy could be calculated by integrating the reaction force of the loader \( P \) with its displacement \( \delta \)

\[
E = \int Pd\delta
\]  

(1)

When the reaction force is specific as seen in Figure 3, the energy dissipation will become the corresponding specific one relative to the tubular mass. To compare the reinforcing effect, the ratio of specific energy absorption of the reinforced cross-sections to that of the empty one is plotted in Figure 4. It can be seen that all of the specific energy absorption of the reinforced cross-sections is larger than that of the empty one, and especially the ratio of the fifth configuration V up to about 1.9 times is the largest one among them. This may be due to a significant restriction of the inward deformation in the compressive region from the foam filler at the cost of smaller increase of structural weight. In other words, the reinforced configuration strategy plays significant role on the specific energy-absorbing capacity. Superior to the empty cross-section, the reinforced configurations have more designability, and there would be an optimal size, i.e. the value of \( b_1, b_2 \) and so on, for a given reinforcing method.

![Figure 4. The ratio of the specific energy absorption of six reinforced cross-section to that of the empty one without any reinforcement.](image)

5. Conclusions

Light-weight thin-walled structures are widely used in some engineering region, and their mechanical properties including load-carrying and energy-absorbing capacity were extensively studied for several decades. Six square thin-walled tubes with different internal reinforcement are put forward, and their
bending behavior was modeled using ABAQUS code. The numerical results reveal that the internal reinforcements considerably improve the specific bending resistance and energy absorption compared with the corresponding empty tube with identical global size and wall thickness. Of course, the present reinforcing strategies here were presented at random, and not their optimal arrangement through optimization. It is reasonable that higher mechanical properties would be obtained after optimization for a certain configuration. Present investigation would enlighten more superior reinforcing strategies to meet some particular engineering demand.

Acknowledgement
This research was supported by University Natural Science Research Project of Anhui Province (No. KJ2018A0481), which is gratefully acknowledged.

References
[1] Abramowicz W, Jones N 1984 Dynamic axial crushing of square tubes *International Journal of Impact Engineering* **2**(2) 179-208
[2] Abramowicz W, Jones N 1984 Dynamic axial crushing of circular tubes *International Journal of Impact Engineering* **2**(3) 263-281
[3] Jones N, Abramowicz W 1985 Static and dynamic axial crushing of circular and square tubes *Metal Forming & Impact Mechanics* 225-247
[4] Langseth M, Hopperstad O S 1996 Static and dynamic axial crushing of square thin-walled aluminium extrusions *International Journal of Impact Engineering* **18**(7-8) 949-968
[5] Guillow S R, Lu G, Grzebieta R H 2001 Quasi-static axial compression of thin-walled circular aluminium tubes *International Journal of Mechanical Sciences* **43**(9) 2103-2123
[6] Galib D A, Limam A 2004 Experimental and numerical investigation of static and dynamic axial crushing of circular aluminium tubes *Thin-Walled Structures* **42**(8) 1103-1137
[7] Kim T H, Reid S R 2001 Bending collapse of thin-walled rectangular section columns. *Computers & Structures* **79**(20-21) 1897-1911
[8] Zhang X, Zhang H, Wang Z 2016 Bending collapse of square tubes with variable thickness *International Journal of Mechanical Sciences* **106** 107-116
[9] Maduliat S, Ngo T D, Tran P 2015 Energy absorption of steel hollow tubes under bending *Proceedings of the Institution of Civil Engineers-Structures and Buildings* **168**(12) 930-942
[10] Zhang X, Cheng G, Zhang H 2006 Theoretical prediction and numerical simulation of multi-cell square thin-walled structures *Thin-Walled Structures* **44**(11) 1185-1191
[11] Tang Z, Liu S, Zhang Z 2013 Analysis of energy absorption characteristics of cylindrical multi-cell columns *Thin-Walled Structures* **62** 75-84
[12] TrongNhan, Tran, Shujuan, et al 2014 Theoretical prediction and crashworthiness optimization of multi-cell square tubes under oblique impact loading *International Journal of Mechanical Sciences* **89** 177-193
[13] Wang Z, Li Z, Zhang X 2016 Bending resistance of thin-walled multi-cell square tubes *Thin-Walled structures* **107** 287-299