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Formation of a square tube having a middle circular section for axial crushing

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\textbf{ABSTRACT}

A new forming method for the tapered square tube is demanded. In this study, a four-stage forming process for a square tube having a circular section in the middle from a seamless round pipe is developed. The transitions between the square and the circular sections form the tapered walls for the reduction in initial peak load. The height of the circular section is minimised to increase the number of folds per unit length of the tube. In the first and the second stages, about half length the pipe is expanded into a circular section before compressing it into a square section. The square section is formed by pushing the expanded circular section through a square die with a square punch. This process is repeated at the opposite site of the pipe in the third and fourth stages to form the square tube. Both finite element simulation and experiment are performed to evaluate this process. A square tube having a circular middle section is successfully obtained from both the simulation and experiment. The corner radii of the square section reduce when the diameters of the circular dies in the first and third stages are increased. However, the wall thickness distribution of the square section becomes small and uneven. The height of the circular middle is reduced to around 10 mm by increasing the punch strokes in the first and third stages. A quasi-static axial compression test is performed on the square tube. The compressive load has an initial peak value of 250 kN. The crush force efficiency of the square tube, i.e. the ratio of its average load to the initial peak load is about 54\%, much higher than the one for the plain straight tube which is usually around 30\%.

\textbf{1. Introduction}

Energy absorbers are commonly used in a variety of impact loading applications such as in automotive structures, trains, energy-absorbing barriers and as arrestors at the base of lift shafts. Square or circular tubes are the common types of energy absorber owing to its low cost, efficient and easy to fabricate. Thin-walled square tubes are usually used as
energy absorbers in the industries owing to its low cost and high foldability in the crash. However, the high initial peak load of the plain straight square tube during the crash has limited its application in the industries. Although its initial peak load can be reduced by having tapered side walls, the fabrication process involves high material loss and detailed calculation of the blank size and the folding lines. The structure of the tubes is optimally designed for better absorption of the impact energy by controlling the deformation mode of the tubes during the crash. Various types of trigger geometries have been implemented on the tube to control the deformation mode. These geometries are the weakest part of the tube and a localised failure area is initiated as a result of stress concentration. The failure area extends and finally leading to the collapse of the tube. The tube collapses and absorbs energy preventing the initial peak load from being transmitted to the essential components of the vehicle and its occupants. Trigger holes have been used to control frame crush modes in automotive and aircraft structures. The crush performance of a frontal rail is significantly affected by the trigger hole sizes rather than its hole shapes or orientations.[1,2] The influence of bump-type triggers on the axial crushing of top hat thin-walled sections have been studied numerically.[3] Tapered tubes are more likely to provide a desirable constant mean crush load–deflection response under axial loading.[4] Tapered tubes have one or more side walls oblique to the longitudinal axis. Formation of the tapered tube requires detailed calculation of the blank size and folding lines and it also involves high material loss. The energy absorption response between the straight and the tapered thin-walled rectangular tubes under quasi-static axial loading for variations in their wall thickness, taper angle and number of tapered sides has been compared.[5] The initial peak load decreased when the taper angle is increased. The energy absorption characteristics of longitudinally grooved square tubes under axial compression have been studied numerically.[6] When grooves are introduced on the side walls, the specific energy absorption of conventional tubes was increased and the peak force was reduced. The effect of introducing grooves to circular steel tubes under axial crushing has been experimentally studied.[7] It was found that the corrugations or grooves could control the energy absorption of the tubes to some extent and improved the uniformity of the load–displacement curve.

In this study, a four-stages forming process of a square tube having tapered side walls in the middle is developed. In this process, two square sections are formed at the both ends of a seamless round pipe. The length of the circular section is minimised by increasing the height of the both square sections. The transition between the square and the circular sections, i.e. tapered side walls forms the trigger geometry for the axial compression.

2. Forming method

The cross section view for the two-stage forming process of a square end from a seamless round pipe is illustrated in Figure 1. The pipe measures 48 mm in outer diameter, 3.5 mm in initial wall thickness and 80 mm in length. Seamless pipe was used in this study as welded pipes might crack during expansion due to poor weld quality. The burring at the both ends of the pipes is removed before the test. In the first stage, the pipe end is expanded into a circular section having a tapered transition. In the second stage, a square punch with a cone end holds the tapered transition of the tube and pushes it into a tapered square die. The clearance between the punch and the die is set at 14.3% less than the initial wall thickness to flatten the side wall of the square section. This process is repeated at the opposite end
to form another square end using a pipe measuring 130 mm in length. A small portion of circular section in the middle is needed to allow the setting of the tapered square die before the squaring process begun.

3. Conditions for experiment and FEM simulation

The detailed dimensions of the tools for the two-stage forming process are shown in Figure 2. The diameters of the circular die are set at 61 or 63.2 mm. The conical angles for both the circular die and square punch are set at the same angle of 30°. The entry and escape angles of the tapered square die are 25° and 10°, respectively, to reduce the forming load during squaring. All the tool surfaces are induction hardened to above HRC55 to avoid galling. All the contact surfaces between the tools and the tube are well-lubricated with commercial

Figure 1. Cross section view for two-stage forming process of square end from round pipe. (a) first stage; (b) second stage.

Figure 2. Detailed dimensions of tools. (a) Circular die; (b) Square punch; (c) Tapered square die.
deep drawing oil except the interface between the square punch and the tapered transition of the tube is kept dry. A dry contact ensures the punch completely pushing the expanded section into the square die without sliding. The target side lengths of the square are set at 51 mm following the dimension of the tapered square die. The diameter of the circular die is set almost equal to the diagonal length of the target square, i.e. 61.2 mm to avoid stretching of the corners resulting in poor square look.[8]

The 1/4 FEM simulation models for the two-stage and the four-stage forming processes of the single and double square ends are shown in Figure 3. ABAQUS Standard Ver. 6.10 was employed in the simulation. All the tools are modelled as discrete rigid except the pipe is modelled as deformable solid and is assumed to be homogenous and isotropic. Penalty frictions of 0.1 are assumed at all contacting surfaces between the tools and the pipe except the dry contact surface is set at 0.6. In Figure 3(b), the first square end is formed by the tools with label (1) and the second square end is formed by the similar tools with label (2).

The experimental set-up for the two-stage forming process is shown in Figure 4. A 600 kN universal testing machine is used in the experiment at a constant test speed of 10 mm/min.
The tapered square die is placed on top of a die holder in the second stage to allow the square punch moving inside the square die without hitting the base.

### 4. Results and discussions

#### 4.1. Increase in diameter of circular die from \( \phi 61 \) to \( \phi 63.2 \) for reducing corner radii

The comparison of the square bottom ends between the tube formed with a circular die measuring \( \phi 61 \) and the one measuring \( \phi 63.2 \) is shown in Figure 5. Although the corner radius for \( \phi 63.2 \) is about 40% smaller than the one for \( \phi 61 \), its wall thickness distribution is not even, particularly at the side wall. The compressive strength of the square tube reduces when the side wall thickness becomes less and uneven. Hence, the circular die measuring \( \phi 61 \) in diameter is used to form the square tube for axial crushing.

The tubes formed with circular dies measuring \( \phi 61 \) and \( \phi 63.2 \) mm for \( S = 50 \) mm obtained from the simulation and experiment are shown in Figure 6. The tube for \( \phi 63.2 \) has higher amount of plastic strains around the expanded circular bottom and the square corners in the first and the second stages when compared to the former one due to large...
amount expansion and compression when the diameter of the die is increased. Tapered transitions are formed between the circular and the square sections after the squaring process.

Wall thickness distributions around the square bottom trimmed ends for \( \Phi 61 \) and \( \Phi 63.2 \) obtained from the experiment are shown in Figure 7. The increase in wall thickness around the corners is attributed to the flow of the materials towards corners due to compression. The wall thickness distribution for \( \Phi 63.2 \) is not uniform as the circumference of expanded circular end is larger than the perimeter of the target square, resulting in folding of the side walls during the flattening process. The side wall thickness for \( \Phi 63.2 \) is less than the one for \( \Phi 61 \) due to the larger expansion ratio in the first stage.

Forming loads in the first and the second stages obtained from the experiment and simulation for \( \Phi 61 \) and \( \Phi 63.2 \) when \( S = 50 \) mm are shown in Figure 8. In the first stage, forming loads for both cases increase when the punch displacement is increased due to the continuous expansion of the tube end into a cone section. The amount of increase for \( \Phi 63.2 \) becomes large after about 20 mm of punch travel when the bottom of the tube passes through the die shoulder. The increase in the tube expansion ratio from 1.49 to 1.54 when the diameter is increased has resulted in the difference in the maximum forming load between the two cases. In the second stage, the compression
of the curled side wall of the circular section into a square end has resulted in a bell-shaped load–displacement profile. Since the diameter of the expanded circular section for $\emptyset 63.2$ is larger than the one for $\emptyset 61$, the maximum forming load is higher than the later one. The calculated results are in good agreement with the experimental results for all cases.

4.2. Increase in punch stroke, $S$ in first stage

The photos of the tubes for different punch strokes, $S$, in the first stage obtained from the experiment are shown in Figure 9. The height of the square section increases when the punch stroke in the first stage is increased, whereas the dimensions of the tapered transitions remain the same. The flow of the materials towards the corners during compression has resulted in the formation of protrusions around the corner ends. Hence, the bottom end is uneven. The protrusions are trimmed off in the later process before forming the opposite end. The uncompressed expanded cone during the squaring process in the second stage form tapered side walls between the square and the circular section.

The maximum forming loads in the 1st stage for different punch strokes, $S$, are shown in Figure 10. The maximum forming load in the 1st stage slightly increases when $S$ is increased from 50 to 64 mm. In tube end forming processes, buckling might occur around the circular section due to excessive compressive loads. Since the amount of increase in load is not significant when $S$ is increased, there are still rooms for the increase in punch stroke to increase the height of the square section.

Figure 9. Photos of tubes for different punch strokes, $S$ in first stage.

Figure 10. Maximum forming loads in first stage for different punch strokes, $S$. 

(a) $S = 56$ mm  (b) $S = 60$ mm  (c) $S = 64$ mm
4.3. Forming of square tube having a middle circular section for axial crushing

The calculated equivalent plastic strains distribution in the four-stage forming process of the square tube for Ø63.2 with $S_1$ and $S_3 = 60$ mm is shown in Figure 11. In the first stage, the amount of plastic strains uniformly increases towards the bottom end of the expanded section. Hence, the wall thickness around the bottom end is small. In the second stage, high plastic strains are observed around the middle of side walls and the square corners. Since the wall thickness of the expanded section is thick in the middle compared to the bottom, the thick portions are ironed out in the second stage resulting in high plastic strain. The materials tend to flow towards the corners during the squaring process in the second stage leading to increase in wall thickness. In the third stage, the circular section in the middle remains undeformed. In the fourth stage, the length of the circular section slightly reduced when the square punch is pushed through the die. The height of the circular section is successfully minimised using a large punch stroke in the first and third stages. Further
reduction in height of the circular section might lead to the square punch sliding through the tube without forming the square section.

Dimensions of the square tubes for difference punch strokes, $S$, obtained from the experiment are shown in Figure 12. The total tube length and the height of the circular section reduce when $S_1$ and $S_3$ are increased.

5. Axial crushing of square tubes

5.1. Crushing load profiles

The comparison of crushing load profiles between the experiment and the simulation is shown in Figure 13. The square tube for $\odot 61$ formed with $S_1$ and $S_3 = 60$ mm obtained from the experiment is compressed with the 600 kN universal testing machine at a constant rate of 6 mm/min for a crushing distance, $d = 60$ mm. The initial peak load is 250 kN with an average crushing load of around 150 kN. In the simulation, a plain straight square tube and a double-ended tube are modelled in full scale with shell deformable elements. The inner side lengths of the squares for both cases are set at 45 mm $\times$ 45 mm with initial tube lengths of 120 mm and constant wall thickness of 3 mm. Both tubes are constrained at one end and compressed with a rigid flat punch at another end. The initial peak loads obtained from simulation for the straight square tube and the double-ended tube are 316 and 190 kN, respectively. About 40% reduction in initial peak load is successfully obtained from the simulation with the double-ended tube when compared to the straight one. However, the experimental initial peak load for the double-ended tube is 31.6% higher than the calculated one. The difference is mainly due to the variation in wall thickness at the tapered transition and strain hardening of the tube.

5.2. Collapse behaviour

The collapse behaviour of the square tube for $\odot 61$ formed with $S_1$ and $S_3 = 60$ mm obtained from the simulation is shown in Figure 14. The crushing load hits the first peak value of 190 kN when the lower tapered transition started to collapse. The load hits the second peak value of 175 kN when the lower transition has completely collapsed and the deformation
of the upper transition is started at $d = 23$ mm. The load sharply increases to the third peak value of 250 kN when the upper transition has completely collapse and the lower square section is in contact with the upper one at $d = 37.6$ mm. Finally, the folding of the upper square begins with the behaviour similar to straight square tubes. The reduction in initial peak load is successfully obtained from the simulation by having tapered transitions in the middle of the square tube.

### 6. Summary

In this study, a four-stage forming process for a square tube having a circular section in the middle from a seamless round pipe is developed. Based on the results from simulation and experimental work about 40 and 21% reduction in the initial peak load during quasi-static compression are successfully obtained, respectively, with the middle-tapered square tube when compared to the straight one.

### Disclosure statement

No potential conflict of interest was reported by the author.

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