

Experimental Investigation of Deformation Behaviour of Thin-Walled Circular and Square Crash Tubes Under Axial Compression

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Abstract—Thin-walled metallic structures are widely used in automotive crash management systems because of their excellent energy absorption capability during collision events. These structures are designed to undergo controlled deformation so that the kinetic energy generated during impact can be dissipated safely without causing severe damage to the main structural components of the vehicle.

Crash tubes or crash boxes are typically placed between the bumper beam and the vehicle chassis. These components act as sacrificial elements that absorb impact energy by progressive deformation during a crash event. The ability of these structures to absorb energy depends on several factors including material properties, cross-sectional geometry, wall thickness and structural reinforcement.

The present work experimentally investigates the deformation behaviour of thin-walled circular and square crash tubes subjected to axial compressive loading. Tubular specimens fabricated from commercially available materials such as mild steel, galvanized iron, aluminium and stainless steel were tested using a hydraulic compression setup available in the laboratory.

In addition to plain tubular specimens, reinforced mild steel tubes were also fabricated by inserting an internal reinforcement plate inside the tube. The objective of introducing reinforcement was to examine whether structural reinforcement can improve deformation stability and energy absorption capability.

Experimental observations revealed that mild steel specimens exhibited stable progressive folding behaviour whereas galvanized iron specimens showed folding and crumpling patterns. Aluminium specimens experienced localized deformation due to their lower yield strength. Stainless steel specimens were included mainly to observe deformation behaviour where circular tubes exhibited crumpling while square tubes experienced buckling and cracking due to stress concentration at the corners.

The results highlight the influence of material properties and

tube geometry on the crashworthiness performance of thin-walled energy absorbing structures.

Index Terms—Crashworthiness, Thin-Walled Tubes, Energy Absorption, Axial Compression, Experimental Study

I. INTRODUCTION

Thin-walled structures are widely used in modern automotive engineering due to their ability to absorb large amounts of impact energy through plastic deformation. During vehicle collisions, specially designed structural components known as crash tubes are used to reduce the forces transmitted to the vehicle frame.

These crash tubes act as energy absorbing devices that deform progressively when subjected to compressive loading. The deformation process helps dissipate impact energy and improves overall passenger safety. Thin-walled metallic tubes are widely preferred in crash energy management systems because they provide high strength to weight ratio and excellent deformation characteristics under compressive loading. The deformation behaviour of these tubes depends on several parameters including tube geometry, wall thickness, material properties and loading conditions.

Circular and square cross sections are commonly used in crash energy absorption structures. Circular tubes generally deform through axisymmetric folding patterns, while square tubes tend to experience corner initiated buckling due to stress concentration effects. These deformation

patterns significantly influence the energy absorption capability of the structure.

Understanding the deformation characteristics of these tubes is essential for improving crashworthiness performance in automotive structures. Experimental studies provide valuable insights into real deformation behaviour and help in evaluating the effectiveness of different materials and geometries.

II. EXPERIMENTAL METHODOLOGY

The experimental investigation was conducted to study the deformation behaviour of thin-walled circular and square crash tubes subjected to axial compressive loading. The tests were performed using a hydraulic compression setup available in the laboratory.

Tubular specimens were fabricated using commercially available materials including mild steel (MS), galvanized iron (GI), aluminium (Al) and stainless steel (SS). These materials were selected due to their availability and their widespread use in structural and automotive applications. All specimens were prepared with similar geometric dimensions in order to maintain consistent testing conditions. The tubes were cut to the required length using precision cutting tools and their edges were carefully finished to remove burrs and surface irregularities.

Proper dimensional accuracy of the specimens was verified before conducting the compression tests. Maintaining uniform geometry ensured that the observed deformation behaviour was primarily influenced by material properties and tube geometry.

A. Specimen Geometry

The geometry of the crash tube plays an important role in determining its deformation behaviour under compressive loading. In the present investigation, both circular and square tubular specimens were selected in order to compare their deformation characteristics.

Circular tubes provide uniform distribution of stress along the circumference and generally exhibit stable progressive folding behaviour during compression. Square tubes, on the other hand, possess sharp corners which act as stress concentration points that may initiate buckling during loading.

The specimens were fabricated with identical wall thickness to ensure uniform comparison between different materials and geometries.

B. Material Characteristics

The mechanical behaviour of the tube during compression

strongly depends on the material used for fabrication. Mild steel specimens are known for their high ductility and good energy absorption capability.

Galvanized iron specimens exhibit similar deformation characteristics but may experience additional surface deformation due to the presence of zinc coating. Aluminium specimens possess lower density and yield strength compared to steel materials, which results in early localized deformation.

Stainless steel specimens typically possess higher strength compared to mild steel, but the deformation behaviour may vary depending on geometry and loading conditions.

C. Reinforcement Configuration

In addition to plain tubular specimens, reinforced mild steel tubes were also fabricated in order to study the influence of reinforcement on deformation behaviour. Reinforcement was introduced by inserting a flat steel plate inside the mild steel tube along its central axis.

The reinforcement plate had a thickness of 2 mm and was securely welded to ensure proper attachment inside the tube. The objective of introducing reinforcement was to increase the structural stiffness of the tube and to observe whether reinforcement improves deformation stability during compression. Reinforced structures are often used in practical crash management systems because they can delay the onset of buckling and improve energy absorption capability. By comparing reinforced and plain tubes, the influence of structural modification on deformation behaviour can be better understood.

III. EXPERIMENTAL SETUP

The compression tests were performed using a hydraulic press machine available in the laboratory. The hydraulic press consists of a rigid structural frame, hydraulic actuator, pressure gauge and compression plates used to apply load on the specimen.

During the experiment, the tubular specimen was placed vertically between two rigid steel plates. The lower plate remained fixed while the upper plate moved downward when hydraulic pressure was applied. The compressive load was gradually

increased until noticeable deformation occurred in the specimen.

The pressure applied through the hydraulic system was monitored using a pressure gauge attached to the hydraulic press. As the load increased, the deformation behaviour of the tube was carefully observed and recorded.

Proper alignment of the specimen was ensured before each test in order to avoid eccentric loading conditions. This ensured that the applied load remained predominantly axial and that the deformation patterns observed were due to compressive loading.



Fig. 1. Hydraulic compression testing setup

The experimental setup allowed controlled application of compressive force on the specimens. The deformation behaviour including folding, buckling and crumpling patterns was visually inspected during the compression process.

A. Testing Procedure

Before conducting each experiment, the specimen was carefully positioned between the compression plates. The alignment of the specimen was verified to ensure that the load would be applied uniformly across the cross section.

Once the specimen was properly aligned, hydraulic pressure was gradually applied using the hydraulic system. As the load increased, the tube began to deform and various deformation patterns were observed.

The compression process continued until significant deformation occurred in the specimen. After completion of the test, the deformed specimen was removed and visually inspected in order to analyse the deformation pattern.

Photographs of the crushed specimens were taken in order

to document the deformation behaviour of different materials and geometries.

IV. RESULTS AND DISCUSSION

The experimental investigation revealed different deformation behaviours depending on the material properties and tube geometry. During the compression tests, the tubes underwent various deformation modes including progressive folding, crumpling, localized buckling and cracking.

A. The deformation patterns were carefully observed after each compression test. These observations provide useful insight into the energy absorption behaviour of thin-walled crash tubes subjected to axial loading.
Deformation Behaviour of Circular Tubes

Circular tubes generally exhibited progressive folding behaviour during compression. This type of deformation is considered desirable for energy absorbing structures because the folds form sequentially along the tube length and help dissipate energy effectively.

Mild steel circular tubes demonstrated stable progressive folding patterns. Multiple folds were formed along the length of the tube as the compressive load increased. The deformation occurred in a relatively uniform manner, indicating good ductility and structural stability of the material.

Galvanized iron circular tubes also exhibited folding behaviour, but the deformation was accompanied by slight crumpling patterns. The folds formed during compression were less uniform compared to mild steel specimens.

Aluminium circular tubes displayed localized deformation at the initial stages of compression. Due to the lower yield strength of aluminium, the tube walls began to buckle early in the compression process.

Stainless steel circular tubes exhibited crumpling behaviour during compression. The deformation occurred in irregular patterns compared to mild steel specimens, indicating different mechanical characteristics of the material.



Fig. 2. Deformation pattern of circular crash tubes after compression

The observed deformation patterns indicate that material ductility plays an important role in determining the folding behaviour of circular tubes. Materials with higher ductility tend to produce more stable folding patterns during compression.

B. Deformation Behaviour of Square Tubes

Square tubes exhibited deformation patterns that were significantly different from circular tubes. Due to the presence of sharp corners in square geometry, stress concentration occurs at the corners during compressive loading.

These stress concentrations often initiate buckling at the corners which leads to irregular deformation patterns compared to circular tubes.

Mild steel square tubes showed relatively stable folding behaviour although slight corner buckling was observed during compression. The folds were formed along the edges of the tube as the compressive load increased.

Galvanized iron square tubes displayed moderate buckling behaviour along the tube walls. Aluminium square tubes experienced early buckling due to lower structural strength.

Stainless steel square tubes exhibited buckling followed by cracking at the corners during compression. This behaviour is mainly attributed to stress concentration effects in square geometries.

C. Energy Absorption Behaviour

Energy absorption capability is one of the most important characteristics of crash energy management structures. The ability of a tube to absorb energy depends on its material properties, cross-sectional geometry and deformation mode during compression.

Structures that exhibit stable progressive folding behaviour generally demonstrate higher energy absorption capability

compared to structures that fail through sudden buckling or cracking. Progressive folding allows the structure to dissipate energy gradually as multiple folds are formed during compression.

Mild steel specimens demonstrated the most stable deformation patterns during the experiments. The formation of sequential folds allowed the tube to absorb compressive energy effectively. This behaviour indicates that mild steel is well suited for crash energy absorption applications.

Galvanized iron specimens also exhibited energy absorbing behaviour through folding and crumpling patterns. However, the deformation stability was slightly lower compared to mild steel specimens.

Aluminium specimens showed lower resistance to compressive loading due to their relatively lower yield strength. As a result, localized deformation occurred earlier during compression which reduced the overall energy absorption capability of the tube.

D. Behaviour of Reinforced Tubes

Reinforced mild steel tubes were tested in order to examine the influence of structural reinforcement on deformation behaviour. The reinforcement plate inserted inside the tube increased the stiffness of the structure and helped delay the onset of buckling.

During compression, reinforced tubes showed more stable deformation patterns compared to plain tubes. The reinforcement provided additional support to the tube walls and helped maintain structural integrity during loading.

The presence of reinforcement improved deformation stability and reduced the likelihood of sudden structural collapse. Reinforced tubes exhibited more controlled folding behaviour which contributes to improved energy absorption performance.

E. Comparison of Deformation Behaviour

A comparison of the deformation patterns observed in different materials indicates that both geometry and material properties play a significant role in determining crashworthiness performance. Circular tubes generally produced smoother folding patterns while square tubes exhibited corner-initiated buckling



Fig. 3. Deformation behaviour of reinforced mild steel crash tube behaviour. Reinforced specimens demonstrated improved deformation stability compared to plain tubes.

TABLE I OBSERVED DEFORMATION BEHAVIOUR OF TESTED SPECIMENS

Material	Geometry	Deformation Behaviour
Mild Steel	Circular	Progressive folding
Mild Steel	Square	Stable folding
Galvanized Iron	Circular	Folding and crumpling
Galvanized Iron	Square	Moderate buckling
Aluminium	Circular	Localized deformation
Aluminium	Square	Early buckling
Stainless Steel	Circular	Crumpling and folding
Stainless Steel	Square	Buckling and cracking

F. Effect of Geometry on Deformation Behaviour

The cross-sectional geometry of a crash tube significantly influences its deformation characteristics under compressive loading. In the present experimental investigation, both circular and square tubes were examined in order to compare their structural response during compression.

Circular tubes generally exhibited more uniform deformation patterns during testing. The circular geometry allows stresses to distribute evenly around the circumference of the tube, which leads to axisymmetric folding behaviour. This type of deformation is considered favourable for energy absorbing structures because it promotes gradual energy dissipation.

Square tubes, on the other hand, possess sharp corners that act as stress concentration points during loading. When compressive force is applied, these corners tend to initiate buckling which leads to irregular deformation patterns. As

the load increases, the buckling propagates along the edges of the tube resulting in structural instability.

The experimental results obtained in the present study confirm that geometry plays a crucial role in determining deformation behaviour. Circular tubes exhibited smoother folding patterns whereas square tubes demonstrated corner initiated buckling behaviour.

G. Effect of Material Properties

Material properties also have a strong influence on the deformation characteristics of thin-walled crash tubes. The

ability of a material to undergo plastic deformation without fracture determines how effectively it can absorb energy during compression.

Mild steel specimens demonstrated stable progressive folding behaviour during the experiments. The high ductility of mild steel allows the material to undergo significant plastic deformation before failure occurs. This property makes mild steel a suitable candidate for energy absorbing structures.

Galvanized iron specimens also showed folding behaviour although the deformation patterns were less uniform compared to mild steel specimens. The presence of a zinc coating on galvanized iron may influence the deformation behaviour under compressive loading.

Aluminium specimens displayed localized deformation during the early stages of compression. Due to their relatively lower yield strength compared to steel materials, aluminium tubes experienced buckling earlier during the loading process. Stainless steel specimens exhibited comparatively higher strength but the deformation behaviour varied depending on the tube geometry. Circular stainless steel tubes showed crumpling patterns whereas square tubes experienced buckling followed by cracking at the corners.

H. Practical Relevance in Crashworthiness Applications

Understanding the deformation behaviour of thin-walled tubes is essential for designing efficient crash energy management systems in automotive structures. Crash tubes are intended to deform in a

controlled manner so that impact energy can be absorbed without causing severe damage to the vehicle frame.

Experimental studies such as the present investigation provide valuable insights into real deformation patterns that occur during compression. These observations can help engineers design safer and more efficient crash absorbing components for automotive applications.

I. Overall Experimental Findings

The experimental investigation conducted in this study provided valuable insights into the deformation behaviour of thin-walled crash tubes under axial compressive loading. Different deformation patterns were observed depending on the material type and tube geometry.

Mild steel specimens consistently demonstrated stable progressive folding behaviour during compression. This type of deformation is highly desirable in crash energy absorbing structures because it allows the structure to dissipate impact energy gradually. The formation of multiple folds along the tube length indicates effective plastic deformation of the material.

Galvanized iron specimens exhibited folding behaviour accompanied by crumpling patterns. Although the deformation behaviour was similar to mild steel, the stability of the folds was slightly lower. This may be attributed to differences in material composition and surface characteristics.

Aluminium specimens showed localized deformation at the early stages of compression. Due to the relatively low yield strength of aluminium, the tube walls began to buckle earlier compared to steel specimens. As the compressive load increased, the deformation propagated along the tube length leading to structural collapse.

Stainless steel specimens displayed distinct deformation patterns depending on the tube geometry. Circular stainless steel tubes exhibited crumpling behaviour during compression, whereas square stainless steel tubes experienced buckling followed by cracking at the corners. The cracking behaviour is mainly caused by stress concentration at the sharp corners of the square geometry. The reinforced mild steel specimens demonstrated improved deformation stability compared to plain tubes. The internal reinforcement plate provided additional stiffness to the structure and helped delay the onset of buckling. As a result, reinforced tubes showed more controlled folding behaviour during compression.

J. Discussion on Experimental Observations

The experimental results clearly indicate that both material

properties and tube geometry significantly influence the crashworthiness performance of thin-walled tubes. Materials with higher ductility such as mild steel tend to exhibit stable folding patterns which improve energy absorption capability.

On the other hand, materials with lower ductility or lower yield strength may exhibit localized deformation or premature buckling. Similarly, tube geometry affects the distribution of stresses during compression. Circular tubes distribute stresses more uniformly whereas square tubes tend to develop stress concentration at the corners.

These experimental observations highlight the importance of selecting appropriate materials and geometries when designing crash energy absorbing components in automotive structures.

V. CONCLUSION

An experimental investigation was carried out to study the deformation behaviour of thin-walled circular and square crash tubes subjected to axial compressive loading. The tests were performed using a hydraulic compression setup on tubular specimens fabricated from mild steel, galvanized iron, aluminium and stainless steel.

The experimental observations revealed that deformation behaviour is strongly influenced by both material properties and tube geometry. Mild steel specimens exhibited stable progressive folding patterns which indicate good ductility and effective energy absorption capability.

Galvanized iron specimens also showed folding behaviour accompanied by crumpling deformation patterns. Aluminium specimens experienced localized deformation due to their relatively lower yield strength, which resulted in early buckling during compression.

Stainless steel specimens were included mainly to observe deformation characteristics. Circular stainless steel tubes exhibited crumpling behaviour whereas square tubes experienced buckling followed by cracking at the corners due to stress concentration effects.

Reinforced mild steel tubes demonstrated improved deformation stability compared to plain tubes. The presence of the internal reinforcement plate increased structural stiffness and helped delay the onset of buckling during compression.

Overall, the study highlights the importance of material selection, structural reinforcement and tube geometry in improving the crashworthiness performance of thin-walled energy absorbing structures used in automotive applications.

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