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# Crush response of variable thickness distribution inversion tubes under oblique loading

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A B S T R A C T

Crush response of Variable Thickness Distribution (VTD) tubes subjected to oblique loading are investigated for external inversion process. Crashworthiness performance and benefits of VTD tubes compared with their Uniform Thickness (UT) equivalents. Furthermore, in order to find detail verification about crush process of VTD tubes, at first Finite element (FE) models established and then validated by experimental tests to ensure that they can accurately predict the responses of VTD inversion tubes. Our study shows that tube thickness distribution, die radius, and coefficient of friction between die and tube have great influence on the responses of VTD tubes inversion. The results demonstrated that different loading angles have different requirements on geometries of VTD inversion tubes. The outcome of this paper gives new design ideas to improve crashworthiness performance of inversion tubes under oblique loads.

## 1. Introduction

There has been considerable activity on crush of thin walled tubes during the past decades. Increased interest in vehicle safety and crashworthiness has led to comprehensive research on the crush response of energy absorbers. A significant part of this effort has been concerned with the use of these structures in energy absorbing systems of vehicles. This significance is mainly due to the complex progressive plastic collapse behavior and interaction between the foam-filler and the column [1–3]. Numerous efforts have been made in the past decades to improve the crashworthiness performance of the tubes such as foam filler [4–8], introducing patterns [9], grooves [10,11], multi-cells [12,13] and functionally graded structures [14–16]. Relative merits of conical tubes with graded thickness subjected to oblique impact loads has been investigated by Zhang [17]. The outcomes of this study could be employed for the crashworthiness design of variable thickness distribution structures subjected to oblique loads. During axial crushing, a circular tube can deform in an axisymmetric (concertina) mode, non-symmetric (diamond) mode, mixed mode or global Euler buckling mode. This depends primarily on the geometrical dimensions of the tube, namely length, diameter and thickness [5].

In real-world, vehicle collapse rarely encounters completely axial or transverse loads, but rather vehicles experience oblique impact collision in more occasions. An oblique load is a basis that tube start to deform with bending collapse mode which is generally unstable and reduces the energy absorption capacity of the tube [17]. Reyes et al. [18–20] studied square aluminum extrusion response, square tubes with and without foam, and circular tubes subjected to oblique loading. Han and Park [21] analyzed the crush behavior of square column subjected to oblique loads. They found that loading angle plays an important role in the axial progressive collapse mode compared with the global bending mode. Qi et al. [22] performed multi-objective optimization for the multi-cell tapered square tubes under oblique impact loading, and they showed that crashworthiness performance of multi-cell tubes is much more than single-cell tapered tube. More recently, Ahmad et al. [23] demonstrated the advantages of using foam-filled conical tubes as energy absorbers under oblique loads.

An inversion tube is able to absorb high energy under certain conditions. Inversion is a mode of plastic deformation which develops, when a thin walled tube is compressed between a flat plate at one end and fileted die at other [24,25]. Recently, many applications of inversion tubes have been made. Such as, force actuating collapsible steering wheels, cushioning air drop cargo, helicopter seats and soft landing of spacecraft [26]. Experimental studies and theoretical analysis on tube inversion have been conducted by many researchers in the recent decades. Al-Hassani et al [27], Reid [28] and Reddy [29] made experimental investigations and theoretical analysis for the deformation behavior and forming load of external inversion. Miscow et. al. [30] studied the theoretical and experimental studies of the static and dynamic inversion process in circular tubes. This theoretical analysis is valuable as the first formula that predicts the axial force versus the axial displacement during the inversion process. But,

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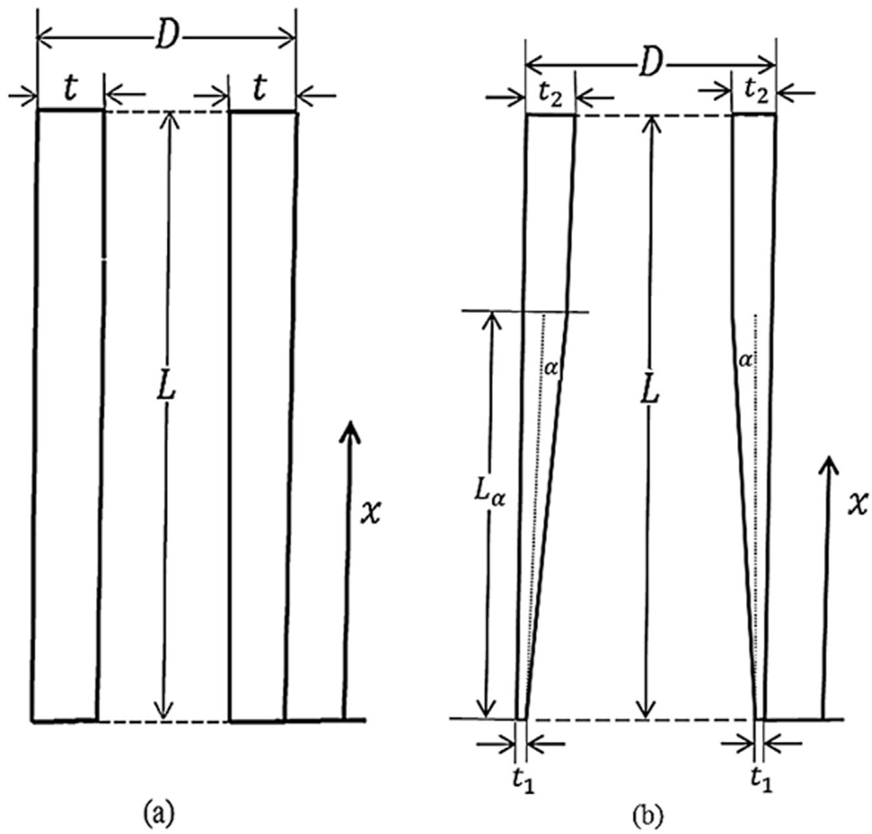


**Fig. 1.** Schematic view of the test specimens, (a) uniform tube UT,(b) variable thickness distribution VTD tube.

theoretical curve that sketched based on the Miscow's theory shows an intensive increment at the onset of loading with a large difference, comparing the experimental curve. The effects of strain rate and inertia during dynamic free inversion process were further investigated by Colokoglu and Reddy [31]. However, the prediction process is very complicated and generally, theory and experiments have not acceptable agreements with each other. Accordingly, the predicted quasi-static inversion load is significantly lower than experimental value while the predicted dynamic mean load is overestimated. Chirwa [32] investigated the plastic collapse of a tapered thin-walled metal energy absorbing tube, subjected to axial impact. The predicted specific energies and loads of collapse modes are found to be in good agreement when compared with the experimental results. Recently, Masmoudi et al. [33] carried out numerical and experimental analyses of external curling of thin-walled round tubes. The experimental results confirmed the results of the finite element simulations, their model provides an accurate prediction on the forming kinematics and the deformed shape. Until now authors research indicates that there is not a study for inversion process of thin-walled tubes with distributed variable thickness subjected to oblique loading.

In this paper, the crush performance of the various VTD inversion tubes under various load angles will be investigated and then will compared with UT tubes through the several experimental tests. Then, numerical simulations of the crush tests were performed and validated to obtain detail information about the crush performance of the VTD tubes by LS-DYNA. To fully understand and quantify the energy absorption behavior of VTD tubes, a parametric study has been undertaken with reference to the geometry parameters through validated finite element FE model on VTD inversion tube with die and uniform circular without die. The FE model is also used to determine dynamic amplification factor to quantify the effect of various parameters on the dynamic response compared to the quasi-static response. The innovation of this study is the generation of new knowledge that can be used to develop guidelines for the efficient design of VTD inversion tubes and shows that under specific inversion conditions, energy absorption performance of VTD inversion tubes are better than


**Fig. 2.** Specimens of f VTD tubes for three different angles $\alpha$=1°, 2° and 3°.