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Relative merits of conical tubes with graded thickness subjected to oblique impact loads

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ABSTRACT

The energy absorption characteristics of a type of conical tubes with graded thickness (CTGT) under oblique impact loads were investigated in this paper. The influences of load angle, structure layout, strain rate effect, inertia effect and forming effects on the responses of CTGT were analyzed numerically by using finite element model validated by experiments. The reverse layout of CTGTs showed very much better performance against oblique loads than the original straight circular tubes employed to fabricate it. The thickness variation and material hardening during fabrication delayed the switch from progressive to global buckling for reverse layout of CTGT and enabled it to preserve most of the axial crush resistance when subjected to oblique loads with load angle up to 20°. The increase in the extent of forming effects was not always found to be beneficial and moderate extent of forming was suggested in applications against oblique loads. The outcomes of this study will facilitate the crashworthiness design of CTGT structures with better performance when subjected to oblique loads.

1. Introduction

Thin-walled metallic tubes are highly efficient energy absorbers under axial loading [1]. However, energy absorbers are seldom subjected to pure axial loading in the real impact applications and therefore the study of structural crashworthiness of them under oblique loading is even more important. To maintain the good energy absorption efficiency of thin-walled metal tubes under oblique loads, tapered sheet metal tubes were firstly proposed and experimentally validated by Reid and Reddy [2] to be effective structures that can withstand oblique loads as effectively as axial loads. Nevertheless, after that, it is surprising to find that quite limited studies have been conducted on the response of thin-walled tubes under oblique loading.

Until recently, increased focus has been given to this subject. The static and dynamic responses of square tubes under oblique loads were firstly investigated by Han and Park [3] and then Kim and Wierzbicki [4] and Reyes et al. [5–6]. The structural responses of empty and foam-filled square or circular tubes under axial and oblique quasi-static loading were then studied by Reyes et al. [7], Børvik et al. [8] and more recently by Li et al. [9]. A critical load angle was reported for these straight tubes to indicate the transition from axial progressive to global bending collapse and dramatic decrease in energy absorption capability was observed when the load angle, even small, is larger than the critical value.

Relatively more studies were concentrated on the axial loading of tapered tubes [10–13]. Although limited, the oblique loading of tapered thin-walled structures also received some concerns in recent years. Nagel and Thambiratnam [14] compared the response of straight and tapered rectangular tubes under oblique loading and conducted parametric studies in the influence of load angle, impact velocity and tube dimensions on energy absorption. The crush response of foam-filled conical tubes subjected to oblique impact loads was investigated by Ahmad et al. [15] and the foam filler was reported to help maintain the energy absorption capacity of tube under oblique loading. The responses of empty and foam-filled conical tubes under oblique loads were also investigated by Qi and Yang [16] and the empty tubes was reported to outperform foam-filled tubes in terms of specific energy absorption (SEA). Recently, multi-cells were found to be a type of highly efficient energy absorbers [17–25] and Qi et al. [26] conducted numerical analysis and multi-objective optimization of tapered multi-cell square tubes under oblique loading. The tapered multi-cells were reported to show the best crashworthiness performance when compared to tapered single-cell, straight single-cell or multi-cell tubes.

Up to now, there is no relevant study on the oblique loading of tapered tubes with graded thickness. Introducing graded thickness on thin-walled structures will extend the design domain of the structures and can definitely improve their crashworthiness performance.

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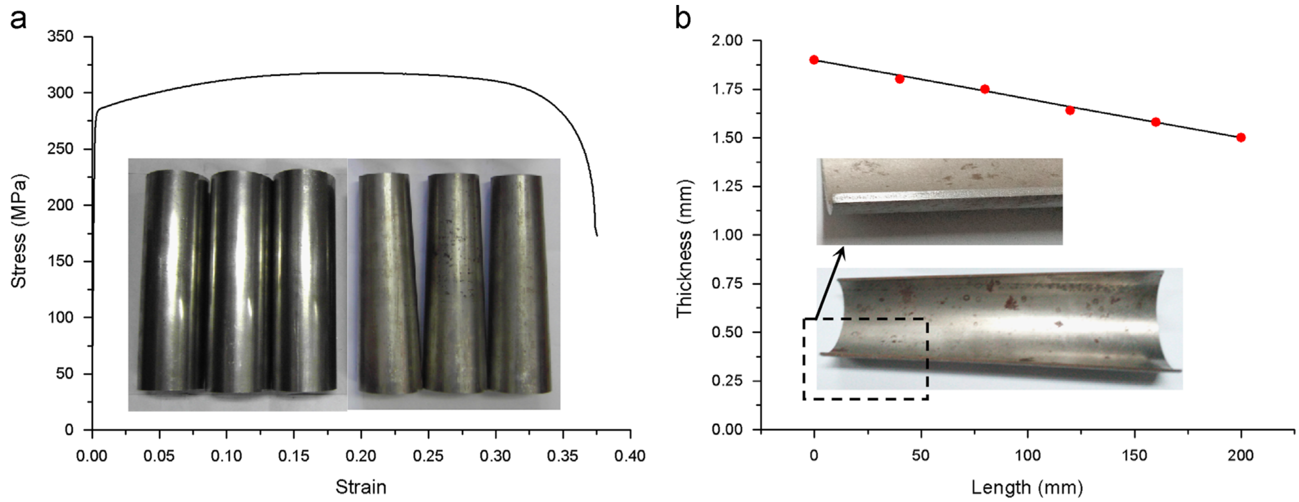

Fig. 1. (a) Engineering stress–strain curve of steel ST12 and specimens for experiment. (b) Thickness distribution in the longitudinal direction of conical tube.

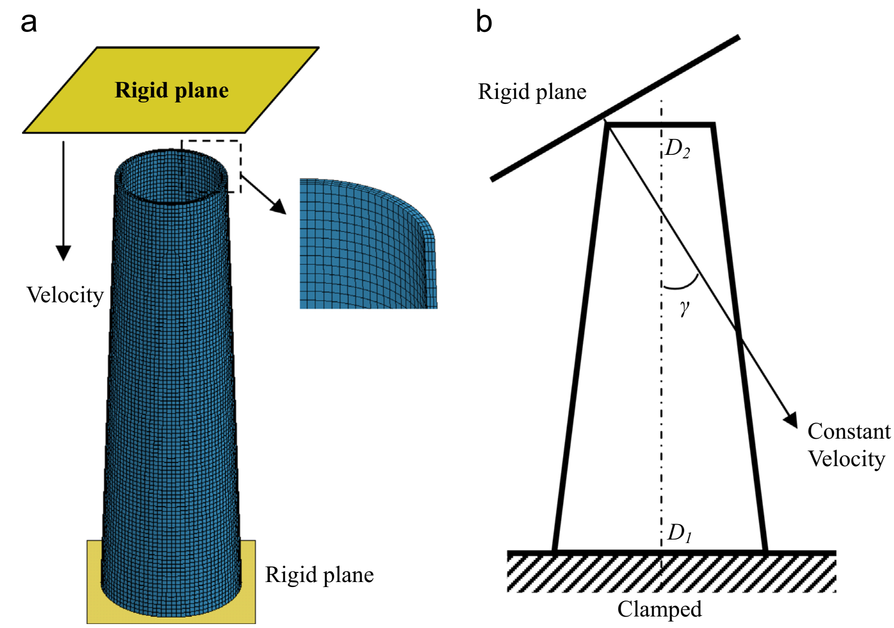

Fig. 2. (a) Representative finite element model for tubes under axial loading. (b) Scheme for oblique loading.

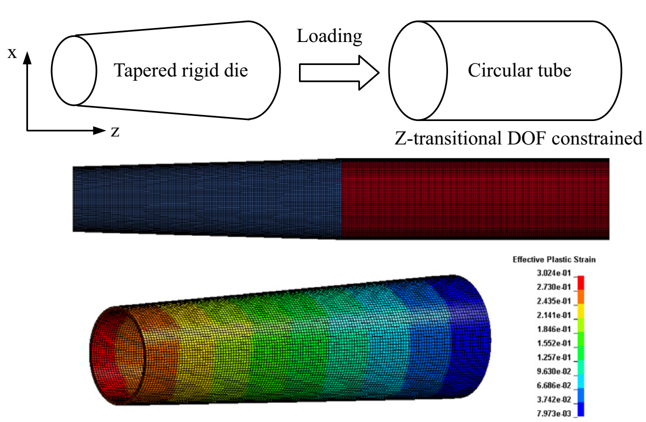

Fig. 3. Numerical model and results for forming process of CTGT specimen.

The inversion buckling of taped circular tubes with variable thickness along the longitudinal direction was firstly studied by Chirwa [27] and significant efficiency increase (up to 50%) was observed when compared to tubes with uniform thickness. Gupta [28] also investigated the inversion behavior of metallic frusta with varying wall thickness under axial loading. The crushing behavior of square tubes with graded thickness in the transverse direction was recently investigated by Zhang et al. [29]. Multi-objective optimization for square tube with graded thickness in the longitudinal direction was studied by Sun et al. [30]. All these studies validated that introduction of graded thickness was an effective way to increase the energy absorption efficiency of thin-walled structures. Since tapered tubes outperform straight tubes under oblique loads, tapered tubes with graded thickness are expected to show better performance in the same load condition.

As the advance in material processing technology, the manufacture of metal plates with continuous thickness changes [31] is not difficult any more. Tapered tubes with graded thickness can also be produced by different metal forming processes. However, the material hardening and residual stresses during the forming process could have important influence on the crashworthiness performance of the fabricated components. Dutton et al. [32] quantified the influence of different forming effects including