Thin-Walled Structures 95 (2015) 208–220

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Design of progressively folding thin-walled tubular components using compliant mechanism synthesis

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ARTICLE INFO

Article history:
Received 21 March 2014
Received in revised form
19 January 2015
Accepted 19 June 2015
Available online 18 July 2015

Keywords:
Thin-walled square tubes
Progressive buckling
Compliant mechanisms
Topometry design
Structural optimization
Hybrid cellular automata

ABSTRACT

This work introduces a design method for the progressive collapse of thin-walled tubular components under axial and oblique impacts. The proposed design method follows the principles of topometry optimization for compliant mechanism design in which the output port location and direction determine the folding (collapse) mode. In this work, the output ports are located near the impact end with a direction that is perpendicular to the component's longitudinal axis. The topometry optimization is achieved with the use of hybrid cellular automata for thin-wall structures. The result is a complex enforced buckle zone design that acts as a triggering mechanism to (a) initiate a specific collapse mode from the impact end, (b) stabilize the collapse process, and (c) reduce the peak force. The enforced buckle zone in the end portion of the tube also helps to avoid or delay the onset of global bending during an oblique impact with load angles higher than a critical value, which otherwise adversely affects the structure's capacity for load-carrying and energy absorption. The proposed design method has the potential to dramatically improve thin-walled component crashworthiness.

1. Introduction

Thin-walled tubular components are extensively used as structural members in the majority of transportation vehicles because of their low cost, good energy absorption capability, and relatively low density. They have the ability to absorb the kinetic energy of the impacting body in the form of plastic deformation, hence protecting the structure and passengers involved. These structures can be used in various loading conditions such as axial crushing, bending, oblique impact, and transverse loading. Tubular structures show significant energy absorption for long strokes in an axial crushing mode and, therefore, present an attractive option in crashworthiness designs.

A great deal of research has been done to study the axial crushing of thin-walled tubes since the pioneering work of Pugsley [1] and Alexander [2] during the 1960s. In the 1980s, work on both the static and dynamic responses of tubes focused more on theoretical and experimental studies [3,4]. The concept of a superfolding element was introduced by Wierzbicki and Abramowicz [5] to better understand the crushing mechanics of thin-walled structures. With the advancement in computing power and the numerical implementation of finite element methods in the last two decades, considerable work has been done to create equivalent numerical models for tube crushing and their validation with experimental tests [6–9]. With the help of advanced nonlinear software like LS-DYNA and ABAQUS, results from numerical models of axial and oblique loadings of thin-walled structures sufficiently match experimental results.

Various experimental and numerical studies revealed three dominant modes of deformation during the axial crushing of thin-walled structures: progressive buckling, global or Euler-type buckling, and dynamic plastic buckling [10]. Of these three, the progressive buckling mode is desired for crashworthy designs because of its efficient energy absorption and better force–displacement behavior. In progressive buckling, crushing starting at one end (often the end close to the impact) and progressing systematically toward the other end of the structure is preferred since it utilizes the maximum possible material for plastic deformation without jamming. Also, the progressive buckling from the front end to the back end helps to protect important components close to or behind these energy absorbing structures. For example, the damage for low intensity (~7–10 mph) frontal impacts in automobiles can be restricted to the bumper-beam and crash-box (hence saving the front frame-rail behind them) if the crash-box

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http://dx.doi.org/10.1016/j.tws.2015.06.010
0263-8231/

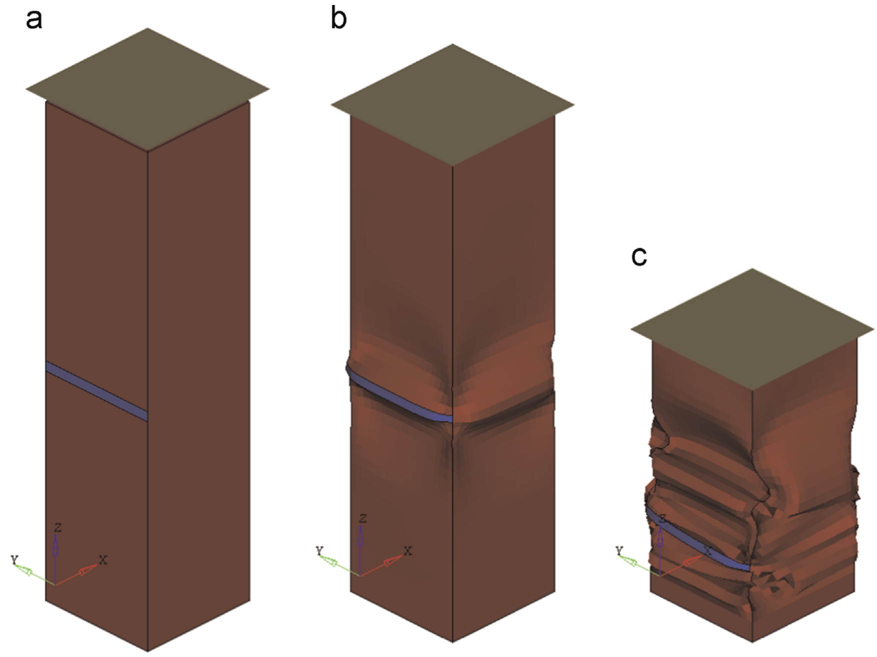

Fig. 1. Progressive collapse of a thin-walled tubular component with a geometric imperfection (blue stripe) under axial crushing load by a rigid plate. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

collapses progressively without jamming. Thin-walled square tubes, however, do not buckle progressively from the front end to the back end in all cases. The buckling behavior is dependent on many factors such as loading conditions, geometry, imperfections, and asymmetries in the structure. For example, Fig. 1 shows the deformation under axial compression of a tube of uniform thickness (1 mm) except for a small imperfection in the form of a patch (blue stripe) of thickness 0.8 mm. It can be seen that buckling starts at the location of the imperfection and then progresses in both directions. Interestingly, for this model, even though the imperfection is located in one single face, the initial progressive buckling mode is extensional; in other words, the four collapse elements (one per face) “extend” outwards (see Section 2).

Collapse initiators, also known as triggers, stress concentrators, or imperfections, can be used to initiate a specific axial collapse mode, stabilize the collapse process, and reduce the peak force during the axial crush [11–13]. Researchers have proposed ways of introducing buckle initiators or surface patterns to enhance energy absorption and buckling behavior by introducing various crush zones in the structure in the form of chamfering [14], dents [15], multi-corners [16], multi-cells [17,18], diamond notches and holes [19], triggering dents, circumferential grooves and stiffeners [20]. The use of collapse initiators has been demonstrated to reduce sensitivity to geometric and material imperfections, reduce peak crushing force, and increase energy absorption density; however, its effectiveness largely depends on the direction of the load and the general shape of the component. An overview of techniques using geometric and material modifications to improve the buckling behavior and energy absorption characteristics of thin-walled tubes under axial crushing can be found in a review article by Yuen and Nurick [21].

During an actual crash event, the tubular structure will seldom be subjected to pure axial loads. Thin-walled structures are subjected to both axial forces and bending moments in an oblique crash. During the study of thin-walled tubes under oblique impacts, Han and Park [22] and Reyes et al. [23] observed a phenomenon of the onset of global bending or Euler-type buckling if the load angle was higher than a critical value. This onset of global bending severely reduces the energy absorption capability of tubular component.

In the methodology presented here, thickness-based (topometry) design [24] is extended to thin-walled square tubes under axial compression using compliant mechanism synthesis [25]. The ability of compliant mechanisms to transfer motion and forces from an input load location to the desired points in the structure is utilized to achieve the desired buckle zones in the axial member. By suitably defining the output port locations and desired displacement directions, progressive buckling can be initiated at the desired locations. Moreover, using this method, thin-walled structures can be designed to show progressive buckling even in cases of oblique impact at angles higher than the critical value at which bending collapse dominates the axial collapse and leads to poor energy absorption. To perform thickness-based topometry design of mechanisms, the structural synthesis method for compliant mechanism of Bandi et al. [25] is modified by using thickness as the design variable. In the following sections, a detailed description of the proposed method and two illustrative examples are presented.

2. Progressive buckling in square tubes

During pure axial crushing of a thin-walled tubular component, the maximum peak force (F_{max}) appears when the structure starts buckling for the first time, and after that, the force oscillates between local peaks and minima as shown in Fig. 2. Each pair of peaks is associated with the development of a wrinkle or buckle. Usually, these wrinkles or buckles develop sequentially from one end of a tube so that the phenomenon is known as progressive buckling. Designers often ignore the oscillations in the force–displacement behavior and use a mean value (F_{mean}) as an indicator of the energy absorption capability.

Two basic forms of collapse elements have been identified by Wierzbicki and Abramowicz [5]: Type I and Type II (Fig. 3). These basic elements have been used to study the progressive buckling of square tubes with mean width w and mean wall thickness t. Based on the geometric compatibility requirements at the vertical interfaces of the basic elements, there are four different collapse