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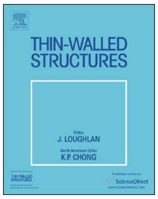

Full length article

Experimental and numerical study on crashworthiness of cold-formed dimpled steel columns

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ABSTRACT

The UltraSTEEL® forming process forms plain steel sheets into dimpled steel sheets and this process increases the sheet material's strengths by generating plastic deformation on the material during the process. This paper presented experimental testing and developed a finite element (FE) model to predict the energy absorption characteristics of dimpled thin-walled structures under axial impact loads, and compared the energy absorption efficiencies (specific energy absorption) of plain and dimpled columns. Dynamic experimental tests were conducted using the drop tower at two different impact velocities. Explicit FE analysis were then carried out to simulate the experiments. The FE method was validated by comparing the numerical and experimental failure modes, crushing force response and specific energy absorptions. The validated FE method was then applied in an optimization study on the parameter of forming depth. The effects of forming depth on both geometry and material properties have been taken into account in the optimization study. It has been found that the specific energy absorption of dimpled columns is up to 16.3% higher than the comparable plain columns.

1. Introduction

Thin-walled structures are widely used as kinetic energy absorbers in sea, land and air vehicles for their light weight, high energy absorbing capacity and low cost [1]. Among various types of loads, axial crushing is one of the most typical loading conditions that thin-walled columns are designed to carry. When subjected to an axial crushing load, thin-walled columns can absorb a large amount of energy through plastic deformation [1]. Wierzbicki and Abramowicz [1] proposed the super folding element (SFE) theory to predict the crush response of thin-walled columns. Many researchers have also studied the crushing mechanisms of thin-walled columns being crushed [1–4].

In recent years, there is a particular interest in improving the crashworthiness of thin-walled structures from different angles. Some studies focused on thin-walled columns with innovative cross-sections [5–15]. By contrast, some studies focused on columns made of high strength materials [16–19], or filled by different materials [20–22]. Tang et al. [5] proposed a new strategy to increase the energy absorption capacity of thin-walled columns by introducing non-convex corners in cross sections. Abbasi et al. [6,7] extended this strategy by carrying out numerical and experimental studies on hexagonal, octagonal and 12-edge section columns' response to both quasi-static and dynamic axial crushing loads. The numerical results were validated by comparing to experimental results in terms of failure mode as well as specific energy absorption (SEA). It was claimed that the SEA of 12-edge section column was the highest among the three sections. According to Abbasi et al. [7], a good agreement between numerical and experimental results in terms of SEA was achieved, where difference was smaller than 8.6%. Jusuf et al. [8] numerically and experimentally studied the response of prismatic multi-cell section columns to dynamic crushing loads. It was suggested that comparing to double wall structure with the same mass, the mid-rib cross-section structure had a 91.2% higher mean crushing force. Qiu et al. [9] used FE method to predict the response of hexagonal multi-cell columns to off-axis quasi-static loads. Tran et al. [10] proposed the triangular multi-cell and employed the SFE method to optimize the geometric parameters. A similar approach was adopted to optimize the geometric parameters of angle element multi-cell structures [11]. Zhang and Zhang [12] conducted a similar study to optimize the geometric parameters of quadruple cell section columns. To validate the FE models, Zhang and Zhang compared the numerical results with both experimental and theoretical results [12]. It was claimed that the simulation errors were smaller than 4.40% and 8.40% in terms of mean

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crushing force and peak force, respectively [12]. White et al. [13] theoretically analysed the effect of top-hat and double-hat section columns' geometric parameters on the crush response. Ly et al. [14] then extended the research by using the finite element method and optimized the geometrical parameters of top-hat structures. Zhang et al. [15] modified the conventional closed square section by introducing graded thickness. It was claimed that the introduction of graded thickness can lead to up to 30–35% increase in SEA without increasing the peak force. The simulation errors in their study [15] were up to 12.97% in terms of SEA. Huh and Kang [16] compared the mild steel and high-strength steel columns under quasi-static and dynamic loading conditions, a similar research was done by Schneider and Jones [17]. It was pointed out that for closed square section columns, using high-strength material significantly increased the SEA. Tarigopula et al. [18] focused on the strain rate sensitivity of dual-phase high-strength steel columns, the Cowper-Symonds material model was adopted to characterise materials' strain rate sensitivity. Lam et al. [19] did a case study to analyse the gauge sensitivity of high-strength steel. Hanssen et al. [20] has suggested empirical equations to theoretically predict the energy absorption performance of foam-filled thin-walled tubes. These empirical equations were then validated by experiments and modified to suit dynamic loading conditions [21]. Zarei et al. [22] pointed out that the foam-filled tube absorbs the same energy while weight was 19% lighter compared with the optimum empty columns through numerical and experimental studies. In the previous studies, two types of triggering mechanisms have been used to initiate the crushing process in simulations. The first type is to create an initial in-extensional geometrical imperfection [8]. The second type is to introduce indentation triggers on the outside plates of the columns [12,15]. Positions of both types of triggers were the same as those observed in experimental tests [8,12,15].

Dimpled steel sheets are cold-roll formed from plain steel sheets by the UltraSTEEL® process developed by Hadley Industries plc [23]. The process uses a pair of rollers with rows of specially shaped teeth that form the dimple shapes from both sides of the plain sheet, as shown in Fig. 1 [24]. The dimpled sheet can then be progressively formed into a desired profile by passing through a series of rolls, arranged in tandem, or by press braking. It has been reported through experimental tests and numerical simulations that the strength of dimpled samples was significantly greater than plain samples originating from the same coil material [24–29]. The greater strength of dimpled samples is caused mainly by the work hardening of the material during the dimpling process. In previous articles, the response of open-section dimpled steel columns under quasi-static compression loads has been studied experimentally as well as numerically [27–29]. However, the study only focused on the response of the open section till the buckling point, and the strain rate effect is not taken into account. Finite element simulations of the dimpled columns subjected to dynamic crushing loads requires validation. The challenge is that the effects of dimpled geometry and non-uniform stress and strain distribution in the dimpled material need to be appropriately represented in the FE models. Additionally, the response of dimpled steel columns to dynamic impact loads has not been investigated yet.

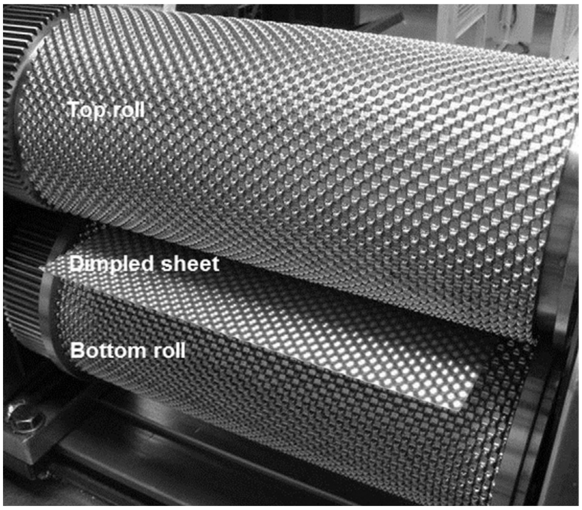

Fig. 1. The UltraSTEEL process and dimpled steel sheet [24].

This paper aims to investigate the finite element modelling method to accurately predict the energy absorption characteristics of dimpled thin-walled columns under dynamic axial crushing loads, as well as analyse the effect of the dimple forming parameters in the UltraSTEEL® process. To achieve this aim, both numerical and experimental studies were carried out on plain and dimpled open-section thin-walled columns under two different impact velocities. Then, finite element simulations were carried out to analyse the effect of the dimpling parameters in the UltraSTEEL® process on the energy absorption characteristics of dimpled thin-walled columns.

2. Method

2.1. Experimental setup

Dynamic crushing tests were carried out at the Warwick Manufacturing Group (WMG) by using INSTRON 9250 drop hammer test machine connected computer control and data acquisition system. Data acquired included instantaneous forces and axial displacements measured at a sampling frequency of 80 kHz, as well as videos taken at 12,500 fps. The schematic plot of the experimental setup is shown in Fig. 2. Two different impact velocities were set as 3.44 m/s and 4.33 m/s, while the impact mass was 168.5 kg. Initiators were introduced when the impact velocity was 4.33 m/s, in order to maintain a consistent failure mode. Tests were repeated for 5 times under each test condition.

The specimens tested in the dynamic crushing tests were made of plain and dimpled galvanised steel. All the specimens originated from the same coil of material. Plain and dimpled specimens are shown in Fig. 3(a). The specimens were fabricated using band saw-cut techniques. 1 mm gauge thickness open section columns were tested. The cross sections of the plain and dimpled specimens are shown in Fig. 3(b), where the gap size d_3 was controlled to be within 1 mm and 3 mm. The specimens were 200 mm long and fixed at one end by clamps with a depth of 40 mm, which means the effective axial length was 160 mm.

The material properties of plain and dimpled steel were determined from quasi-static tensile tests complied with the appropriate British Standard [30]. The quasi-static engineering stress-strain curves of these two materials are shown in Fig. 4. Table 1 shows these two materials' mechanical properties. Details of the tensile test procedure and area measurements are described by Nguyen et al. [26].

2.2. Numerical modelling

The explicit dynamic finite element analysis code integrated in Ansys Workbench 16.0 [31] was employed to simulate the thin-walled columns' response to dynamic axial impact loads in this study. The solver is suitable for dealing with large deformation and complex contact interaction in crash simulations.

In order to reduce computational time, the dimpled plates were modelled using full-integration shell elements with four nodes and five integration points throughout the thickness. In reality, the thickness of dimpled plate slightly varies at different locations around the dimple valley [24]. However, it was assumed that the thickness was uniform across the entire plate. The equivalent uniform thickness for dimpled plate was set as 0.9516 mm, which was determined based on the mass conservation of the 1 mm gauge plain plate. Additionally, the dimpled material was assumed to be homogeneous in terms of mechanical