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Behaviour of cold-formed dimpled columns under lateral impact

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ABSTRACT

The UltraSTEEL® forming process forms plain steel sheets into dimpled steel sheets. During the forming process both geometry and mechanical properties are considerably altered. This study aims to understand the response of the dimpled steel columns to low velocity lateral impact loads. Explicit finite element (FE) models were created and validated, including boundary conditions, element types and element sizes. Plain, dimpled columns and columns with dimpled geometry and plain material (DGPM) were analysed under lateral impact, to find out the difference between plain and dimpled columns, and the influence of the introduced dimpled geometry. Comparisons were made based mainly on the mean impact force, crush efficiency, and ability to maintain stability. A series of numerical analysis was carried out under different axial compressive loads. The dimpled columns have shown an up to 32.5% greater mean force and an up to 24.4% greater crush efficiency over the plain ones. The dimpled columns have also shown a better stability under axial compressive loads. A further investigation on the support conditions indicated that the dimpled geometry contributes to the reduction of the maximum impact force and therefore increasing the crush efficiency, where at least one end of the column is fully fixed.

1. Introduction

Hollow tubular members are widely used in many infrastructures. It has been identified in some previous researches that hollow tubular members are prone to transverse impact loading [1]. Past research and statistic data have revealed that accidental collision is one of the main causes of structural failure [2,3]. During the collision, the structural components are exposed to the operating axial compressive load as well as the lateral impact loads [4]. The collision energy is absorbed by the tubular members subjected to bending conditions. Kecman [5] has studied the bending collapse behaviour of rectangular section columns when subjected to quasi-static lateral loads. Kecman's [5] study has established the foundation for the analytical prediction of the response of rectangular section columns to lateral quasi-static loads, and can be further extended to analytically predict the columns' behaviour under lateral impact load. Liu and Jones [6] experimentally studied the behaviour of steel and aluminium clamped beams under transverse impacts. Their study was further extended by Yu and Jones [7], who have taken the materials' strain rate sensitivity into account. Wierzbicki et al. [8] extended the super folding element (SFE) method to theoretically predict columns' behaviour in the case of bending and combined bending/compression loading [8]. In all these previous proposed analytical methods [5–8], the columns were assumed to be plain and have constant thickness, and no theoretical prediction method for concave-convex surface columns have been developed. Zeinoddini et al. [9,10] introduced an axial compressive load under lateral impacts through an experimental study. This experimental study was then repeated by running FE simulations. Their experimental and numerical results were adopted to validate the FE models in the present study. Based on the research of Zeinoddini et al. [9,10], Al-Thairy and Wang [4] carried out a study by developing FE models to simulate the transverse impact behaviour and failure modes of axially compressed tubes subjected to transverse impact. Those studies [4,9,10] have all pointed out the significant influence of axial compressive loads on the failure modes, and similar boundary and loading conditions were investigated in the present study.

In recent years, there is a particular interest in improving the resistance of tubular members to lateral impact loads. Some research focused on strengthening tubular members with various types of fillers [11–16], such as concrete, foam or metal honeycomb core. By contrast, some research focused on tubular members strengthened by applying carbon fibre reinforcement [17–19]. It has been reported that the mean impact forces and/or crush efficiencies can be effectively increased by using those design strategies [11–19]. Although different strategies

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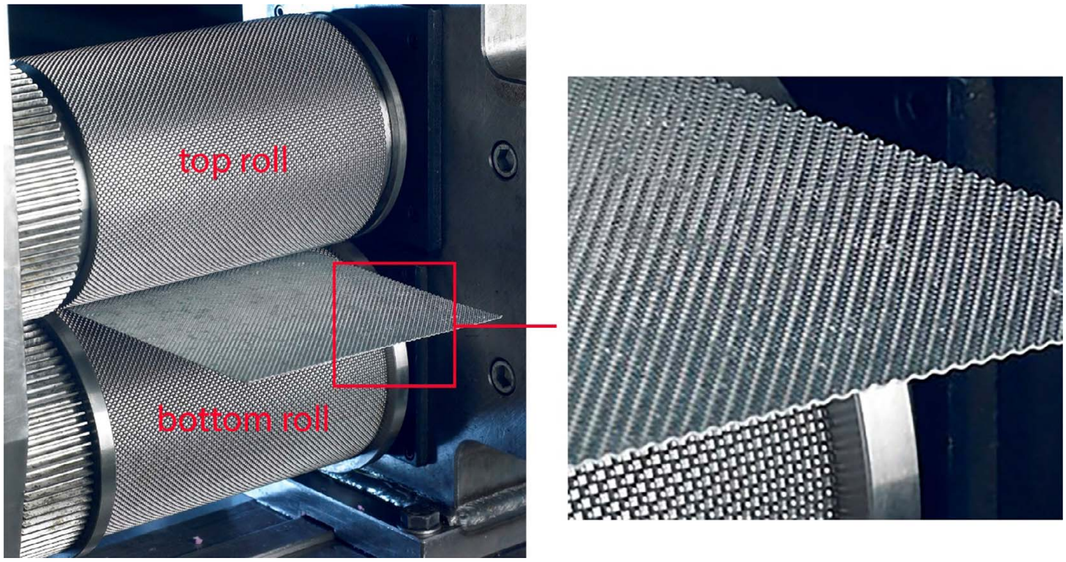

Fig. 1. The UltraSTEEL® forming rollers and dimpled steel sheet.

have been studied to improve the energy absorption performance of structural members subjected to lateral impact loads [11–19], all those studies were limited to columns with plain surfaces, and the effects of introducing concave-convex geometry on the surfaces have not been previously investigated.

Dimpled steel columns are formed from plain mild steel sheets by the UltraSTEEL® cold-roll forming process developed by Hadley Industries plc [20]. In this forming process, plain mild steel coil is progressively fed into a pair of rollers with rows of specifically shaped teeth and formed into dimpled steel sheets, as shown in Fig. 1. [21]. Dimpled sheets are then formed into desired profiles by passing through a series of rolls or press braking. Several previous numerical and experimental research has revealed that the strengths of dimpled steel sheets are significantly greater than those of the original plain steel sheets [21–27]. The increase in strength is mainly due to work hardening developed throughout the forming process. The increase in strength was accurately predicted by Nguyen et al. [22] through FE simulations. Previous research mainly focused on the UltraSEEL® forming process and dimpled structures' behaviour under quasi-static loads. Liang et al. [23] extended previous research and investigated the dimpled structures' response to dynamic axial impact loads numerically and experimentally. The FE models were developed and validated to predict dimpled structures' behaviour under impact loading conditions. An optimization study on the UltraSTEEL® forming process was also carried out for achieving higher crashworthiness [23]. However, the behaviour and energy absorption performance of dimpled tubular members subjected to lateral impact loads have not been studied.

This paper aims to investigate the behaviour of thin-walled dimpled steel columns under lateral impact loads. To achieve this aim, numerical simulations based on the validated FE models were conducted. In this study, the dimpled column was analysed under various loading and support conditions. Comparisons between dimpled and plain steel columns subjected to lateral impacts were conducted.

2. Finite element modelling

In this study, the explicit dynamics finite element code integrated in Ansys Workbench 17.1 [28] was employed to simulate the plain and dimpled steel columns' response to lateral impact loads. This explicit dynamics FE code is commonly used to deal with non-linear simulations involving complex contact interactions. The specific employment of this code to simulate the behaviour of dimpled steel structures with medium strain rate (between 0.1 and 100 s^{-1}) was validated by Liang et al. [23]. Main challenges about numerical analysis for dimpled structures under dynamic loads are constructing the geometrical model, selecting element types and sizes, and assigning appropriate material properties. In [23], the FE method was developed to resolve these issues. Experimental tests were conducted to validate the FE method. Good agreement was found in terms of failure mechanisms and impact forces. Therefore, only additional features of the numerical models will be introduced in this paper.

2.1. Material properties

The materials' mechanical properties were obtained from quasi-static tests, following the appropriate British Standard [29]. The quasi-static tensile testing procedures are presented by Nguyen et al. [24]. The plain and dimpled samples used in the tensile test were originated from the same coil of steel. The tensile test results are shown in Fig. 2, where the engineering yield and ultimate strengths of the dimpled steel are around 17% and 9% higher than the plain steel, respectively. True stress and strain were input into the programme.

It has been pointed out in a number of research papers that materials' strain rate effect plays an important role in energy absorption when structural components are subjected to dynamic loads. In this study, the Cowper-Symonds material model was adopted to characterise the strain rate sensitivity of plain and dimpled steel, as shown

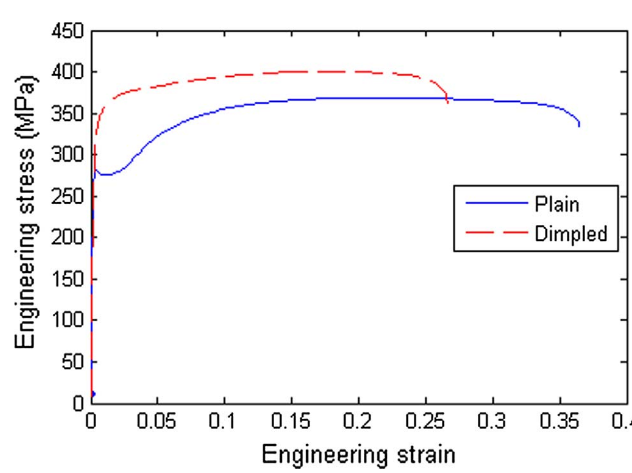

Fig. 2. Quasi-static engineering stress-strain curves for plain and dimpled materials.