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Optimization of the UltraSTEEL Dimpling Forming Process for Energy Absorption

Ce Liang[a,*], Chang Jiang Wang[a], Martin English[b], Diane Mynors[a]

[a]*Departmnet of Engineering and Design, University of Sussex, Brighton, BN1 9RH, United Kingdom*
[b]*Hadley Group Technology, Hadley Industries PLC, Downing Street, Smethwick, West Midlands, B66 2PA, United Kingdom*

Abstract

The UltraSTEEL dimpling forming process forms plain steel sheets into dimpled steel sheets, which have higher energy absorption performance. The energy absorption performance of dimpled products can be further improved through optimizing the forming depth in the UltraSTEEL process. In this paper, forming depths have been optimized through numerical simulations. Explicit dynamics finite element simulations were carried out to analyze the effect of forming depth on material properties as well as the effect of geometry on energy absorption separately. It has been found that yield strengths are maximized when the forming depth is approximately 1mm, and the energy absorption performance is optimized when the forming depth is approximately 0.9 times of the gauge thickness.

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Keywords: UltraSTEEL forming process; Explicit dynamics analysis; Optimization; Crashworthiness;

1. Introduction

The UltraSTEEL dimpling process, developed by the Hadley Industries plc, is an industrial manufacturing process that cold-rolled forms a plain steel strip into a dimpled strip [1]. The process uses a pair of rollers with rows

* Corresponding author. Tel.: +44 1273 877995
cl305@sussex.ac.uk

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of specially shaped teeth that form dimpled shapes from both sides of the plain sheets [2].Previous numerical and experimental studies have shown that the strengths of the UltraSTEEL dimpled samples are significantly greater than the original plain samples under quasi-static tensile, bending and compression tests [2-7]. From previous studies, it has been revealed that comparing with the plain plates, the yield and ultimate strengths of the UltraSTEEL dimpled ones are up to 51% and 34% higher, respectively [6].The increase in yield and ultimate strengths are mainly due to the non-uniform work hardening developed during the forming process.

Metal sheets are often formed to thin-walled structures, which are widely used as energy absorbers on transportation vehicles. The energy absorption characteristics of the UltrasTEEL dimpled products has been studied by Liang et al. [8]. Liang et al. has developed a finite element (FE) model to predict the response of dimpled columns to impact loads. The FE model was then validated by comparing with experimental results.It has been reported that the specific energy absorption (SEA) of dimpled columns is up to 16.3% higher than the SEA of plain columns [8]. Additionally, Liang et al. has pointed out that the energy absorption performance is affected by the dimpled geometry and materials' mechanical properties, which are both essentially affected by the forming depth [8].

This paper aims to investigate the effect of forming depth on energy absorption of dimpled columns. In order to achieve this aim, numerical simulations have been carried out, using validated FE models. In this study, the influence of forming depth on mechanical properties and the influence of dimpled geometry on crashworthiness have been studied independently as well as combined.Optimization guidelines of the UltraSTEEL dimpling forming process have been provided based on the results.

2. Method

Forming depth is a parameter that can be easily controlled in the forming process. It refers to the relative vertical movement between the upper and lower forming teeth. The forming depth is reflected on the dimpled sheet, as illustrated in Fig. 1(a).Fig. 1(b) explains how the energy absorption performance is indirectly affected byforming depth.

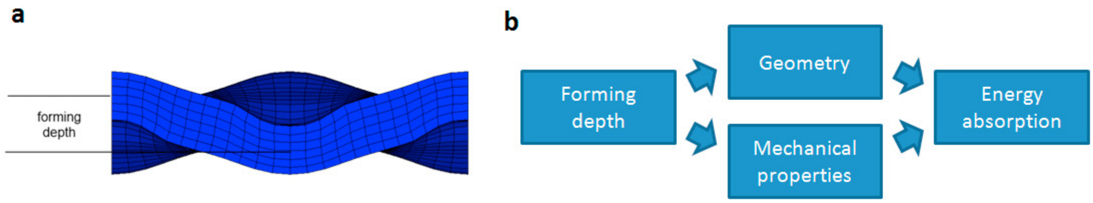

Fig. 1. (a) Dimpled plate and its forming depth; (b) Relationship forming depth and energy absorption performance

Explicit dynamics finite element method is suitable for analyzing large deformation and complex contact interaction in crash simulations. Explicit dynamics code integrated in Ansys Workbench 17.1 [9] was employed in this study. Models were constructed using 4-node full-integration shell elements with five integration points throughout the thickness. The thickness for dimpled plates was assumed to be uniform. A convergence study on element size suggested that an element size of 1mm can provide sufficiently accurate results. However, due to the dimpled geometry, an element size greater than 0.55mm could result in noticeable geometrical distortion. Therefore, a uniform element size 0.55mm was selected for the dimpled finite element models.

Fig. 2(a) shows the experimental quasi-static engineering stress-strain curves of the UltraSTEEL dimpled plate and its original plain plate. The mechanical properties of the dimpled material were assumed to be homogeneous in simulations. Fig. 2(b) shows the quasi-static engineering stress-strain curve of the dimpled model with homogeneous mechanical properties and the corresponding experimental result. The slight difference can be neglected. Symmetric boundary conditions were applied to simplify the FE model when simulating the quasi-static tensile tests. As shown in Fig. 2(c), symmetric boundary conditions in x-direction were applied on face B and its opposite face. Displacement along z-axis was restrained for all nodes on the opposite face of face A. Displacement along y-axis was restrained for node 1, to prevent the plate from moving wildly along y-axis. Displacement along x-axis was restrained for all nodes on the mid-plane between face B and its opposite face, to prevent the plate from moving wildly along x-axis. And a uniform displacement in z-direction was applied to all nodes on face A, representing the tensile loading.

True stress and strain were used, as large plastic deformation was involved. The Cowper-Symonds material model was employed to describe the materials' strain rate sensitivity. The self-interaction during the crushing process was taken into account.

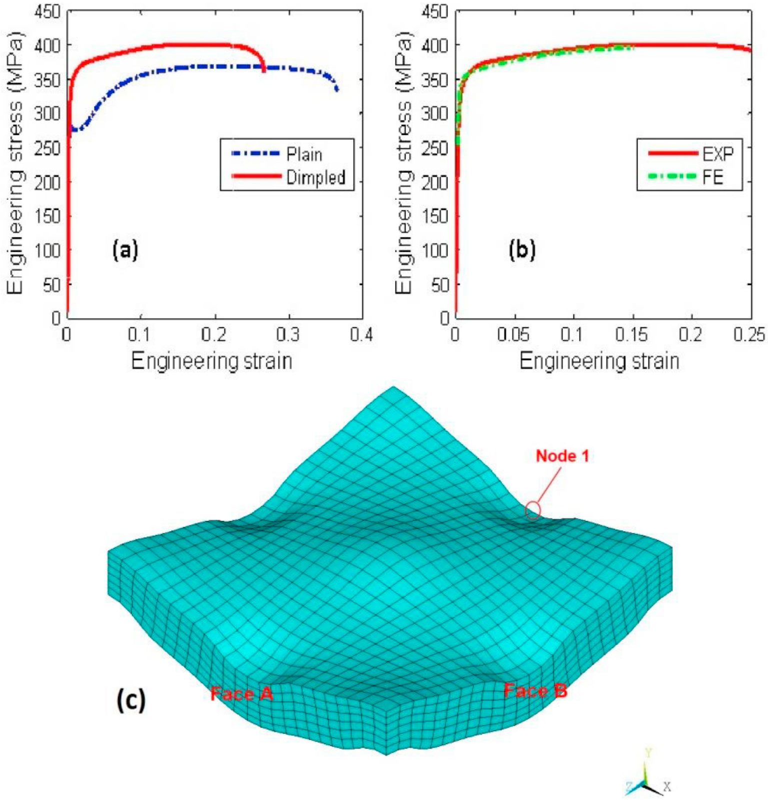

Fig. 2. (a) Experimental quasi-static engineering stress-strain curves of plain and dimpled plates; (b) Experimental and numerical engineering stress-strain curves of dimpled plates; (c) Dimpled FE model of the tensile tests

3. Results

3.1. Effect of the forming depth on materials' mechanical properties

In this study, the UltraSTEEL forming process on a single dimple was simulated first. Tensile tests were then carried out with geometry, residual stress and strain kept from the last step. As the forming depth increases, the work hardening developed during the forming process causes the materials' yield strengths to be greater. However, the equivalent yield strength of the dimpled plate does not always increase. The variation of the dimpled plates' equivalent yield strengths against forming depth is shown in Fig. 3(a). The results shown in Fig. 3(a)were obtained from FE simulations. As shown in Fig. 3(a), the optimal forming depths are approximately 1mm. While the dimpled plate is being pulled in tensile tests, the dimpled geometry results in stress concentration around peak and valley local regions. Therefore, in tensile tests, yielding has already initiated while other areas are still at a low stress level. The stress concentration effect outweighs the work hardening effect when the forming depth is beyond the optimal point. Fig. 3(b) shows the FE numerical result of the normalized local stress against the forming depths. It is observed that greater forming depth results in higher normalized maximum stress and lower minimum stress, where the normalized stress is defined in Eq. (1). The increasing difference between normalized maximum and minimum stresses has indicated a more significant stress concentration effect. Figs.4and 5show the von-mises stress distributions under axial tensile loading for 1mm gauge dimpled plates with global equivalent strains of 1% and 2%, respectively. It is noticed in both cases, stress concentration becomes more severe as the forming depth increases.

$$Normalized\ stress = \frac{Local\ stress \times Sectional\ area}{Axial\ tensile\ force} \tag{1}$$

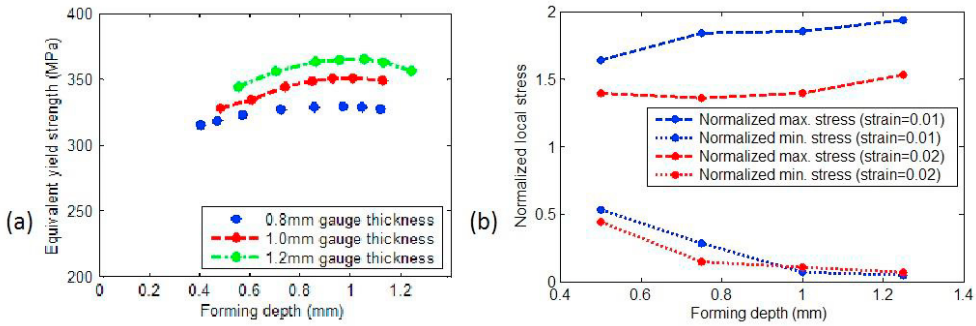

Fig. 3. (a) Equivalent yield strengths vs forming depths; (b) Normalized local stress vs forming depths

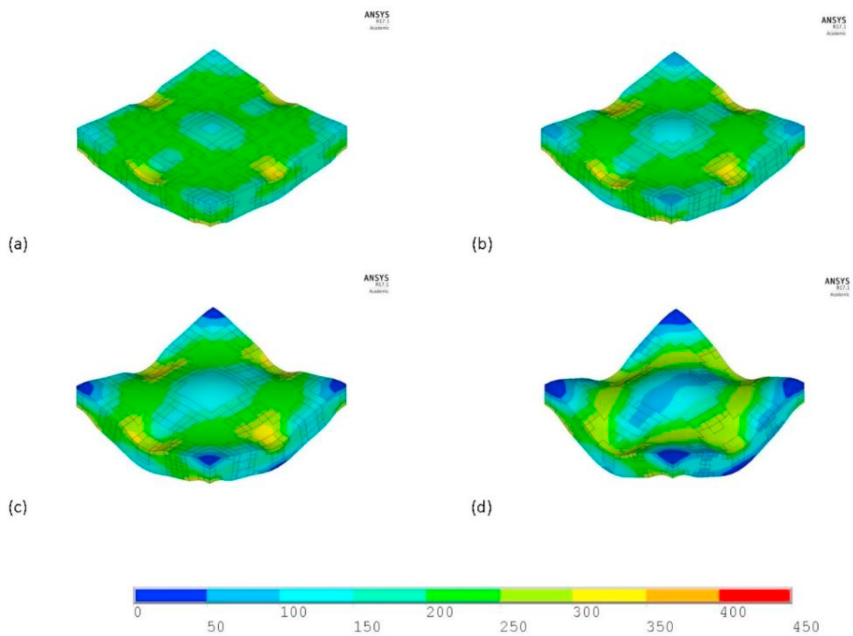

Fig. 4. Von-mises stress in 1mm gauge dimpled plate under tensile loading with 0.01 equivalent strain and forming depths of (a) 0.5mm; (b) 0.75mm; (c) 1mm; (d) 1.25mm

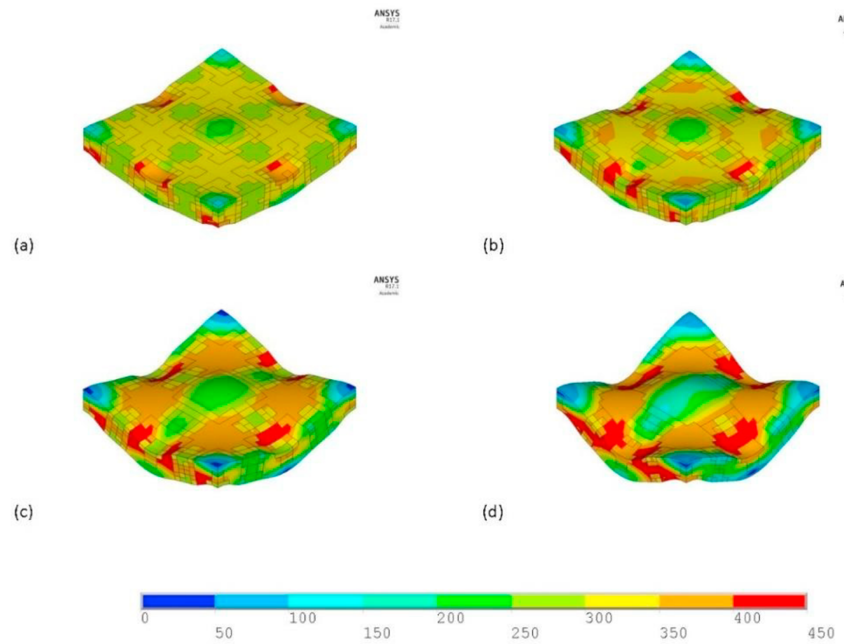

Fig. 5. Von-mises stress in 1mm gauge dimpled plate under tensile loading with 0.02 equivalent strain and forming depths of (a) 0.5mm; (b) 0.75mm; (c) 1mm; (d) 1.25mm

3.2. Effect of the forming depth on energy absorption

Square shape thin-walled hollow columns subjected to axial crushing loads are adopted to analyze the energy absorption performance of dimpled columns. The columns analyzed in this study were 46 mm wide, 250 mm long, fully fixed at one end and free at the other end. The striker had a mass of 251 kg and an initial velocity of 8 m/s. Specific energy absorption (SEA) and the normalized SEA are employed to evaluate the energy absorption performance. SEA is defined in Eq. (2), where P refers to the instantaneous crushing force, and m refers to the mass of the deformed column. SEA of a dimpled column is then normalized by dividing the SEA value of its original plain column. The normalized SEA reflects the increase in energy absorption performance of dimpled columns over plain columns.

$$SEA = \frac{\int_0^{\delta_{total}} P d\delta}{m} \tag{2}$$

$$Normalized\ SEA = \frac{SEA}{SEA\ of\ the\ original\ plian\ column} \tag{3}$$

Fig. 6(a) shows the variation of the normalized SEA against the forming depth when identical material properties were used (i.e. the effect of forming depth on yield strength was neglected). The result shows that the dimpled geometry generally improves the energy absorption performance, although the increase is not significant. As the forming depth increases, the normalized SEA tends to drop, due to the reduced actual thickness and more severe stress concentration. For 1mm gauge thickness dimpled columns, the normalized SEA has even dropped below 1 when the forming depth is greater than 0.93mm.Additionally, it has been found that the crushing modes are consistent, regardless of the forming depth. Fig. 6(b)shows the result when the effect of the forming depth on yield strength is taken into account.It is observed that for all four gauge thickness dimpled columns, the normalized SEA peaks when the forming depth is approximately 0.9 times of the gauge thickness.The decreased yield strength also contributes to the drop after the optimal points. For 0.7, 0.8, 0.9 and 1.0mm gauge dimpled columns, the maximum SEA are 10.4%, 13.7%, 14.9% and 16.3% higher than their original plain columns, respectively.

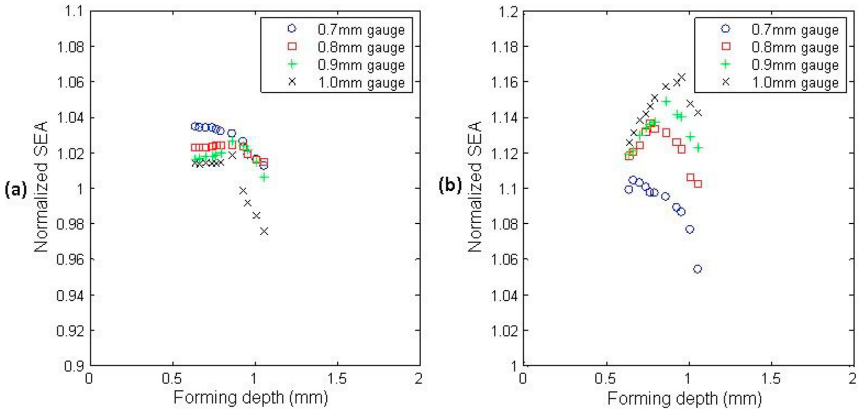

Fig. 6. (a) Normalized SEA vs forming depth without the material properties taken into account; (b)Normalized SEA vs forming depth with the material properties taken into account

4. Conclusion

In this study, finite element analysis was carried out to analyze the effect of the forming depth on the energy absorption performance of dimpled steel columns. The overall effect has been broken down in order to analyze the effects of material properties and the dimpled geometry separately. The equivalent yield strengths of dimpled plates reach optimal point when the forming depth is around 1mm. Generally, the dimpled geometry will slightly increase the energy absorption performance. When taking the both factors into account, energy absorption performance is optimized when the forming depth is about 0.9 times of the gauge thickness. The drop afterthe optimal points is due to reduced yield strengths, reduced actual thickness and enhanced stress concentration.

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