EXPLICIT DYNAMICS FINITE ELEMENT ANALYSIS OF ENERGY ABSORPTION CHARACTERISTICS OF THIN-WALLED ULTRASTEEL COLUMNS

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ABSTRACT

UltraSTEEL material has been reported to have higher yield and ultimate strengths than plain mild steel under quasi-static loads. This project aims to study the energy absorption characteristics of UltraSTEEL thin-walled structures when subjected to axial impact loads. The numerical modelling starts from duplicating the UltraSTEEL dimpling process and defining the resultant material properties by taking strain hardening and strain rate sensitivity into consideration. Features including element type, mesh density, symmetric boundary conditions and imperfections are then studied. The responses of 1mm gauge plain and UltraSTEEL columns to the same impact load are compared by conducting explicit dynamics finite element simulations. Comparing to the plain columns, the effect of gauge on the UltraSTEEL columns' failure mode and specific energy absorption (SEA) are analysed through a parametric study.

Keywords: *Explicit dynamics analysis; UltraSTEEL; Axial crushing; Thin-walled Structure*

1. Introduction

The UltraSTEEL process, developed by Hadley Industries plc, is to cold-roll form plain sheet mild steel into dimpled sheet steel. During the process, a pair of rolls with specially shaped teeth that stretch the surface forming the dimpled shape is used, and the plain sheet steel is progressively fed into this pair of rolls [3]. Quasi-static tensile test results showed that the UltraSTEEL dimpling process can increase the yield and ultimate strengths of the plain steel material by up to 51% and 34%, respectively [3]. The UltraSTEEL process and subsequent quasi-static tensile tests were duplicated on a generic finite element model [3].

Thin-walled structures are widely used as kinetic energy absorbers because of their low cost, light weight and high energy absorbing capacity. Within various dynamic loading conditions, representative axial impact load is of particular interest. In order to analytically predict the response of thin-walled square tubes to axial crushing loads, the super fold element (SFE) method was proposed [1]. This method was then modified by taking effective crushing distance and strain rate effect into account, and verified experimentally [1]. Light weight and high mean crushing force are desired in general applications, therefore, specific energy absorption (SEA) is employed to describe a certain structure's energy absorbing performance. In recent years, SEA has been improved mainly by introducing alternative cross-section profiles, fillers and high strength materials [2, 4, 5].

To understand the energy absorption characteristics of UltraSTEEL structures when subjected to dynamic axial crushing loads, explicit finite element simulations were conducted. Failure modes and SEA of plain and UltraSTEEL columns were compared. Effect of the gauge was also analysed through parametric studies.

2. Numerical modelling

Explicit dynamics method was selected to complete the numerical simulations. The closed square hollow cross section with 60×60mm outer dimensions was adopted in this study, with a slenderness ratio of 5 (i.e. length is 300mm), to avoid global bending. The hollow columns were fully fixed at one end. Both plain and UltraSTEEL models were meshed with shell elements (Element Type 181). According to the convergence study, for the plain columns used in this research, an element size of 1.25mm is capable of providing converged results, and 1mm element size was used in plain models.

However, due to the nature of UltraSTEEL dimpled geometry, the element size was specified to be 0.55mm in UltraSTEEL models. Since the element size is uniform throughout the whole column model, time scaling method is not applicable.

In non-linear dynamic analysis, material properties are critical. According to existing researches, the dynamic mean crushing force is greater than the quasi-static crushing force by up to 30%, when a mild steel column is subjected to low velocity axial loads. In this study, the impactor was treated as a rigid body, while the Cowper-Symonds material model was assigned to plain and UltraSTEEL columns. By applying the Cowper-Symonds material model as shown in Equation 1, the materials were assumed to be strain rate sensitive and purely plastic. The parameters in the strain hardening term were determined based on experimental tensile tests, while the parameters in the strain rate term were obtained based on theoretical models.

$$\sigma^d = [\sigma_y + B\varepsilon_{pl}{}^n]\left[1 + \left({}^{\dot{\varepsilon}_{pl}}/_{D}\right)^{1/q}\right] \qquad (1)$$

where σ^d represents equivalent dynamic stress flow, B represents hardening constant, ε_{pl} represents equivalent plastic strain, n represents hardening exponent, $\dot{\varepsilon}_{pl}$ represents equivalent plastic strain rate, D and q represent strain rate constants.

In the modelling process, the columns were simplified by modelling a quarter of the original closed square hollow cross section with the longitudinal dimension unchanged, since the stress wave is dominantly propagating along the longitudinal direction. The rationality of this simplification was justified by comparing the responses (failure modes and force-displacement curves) of the original and simplified models. The force-displacement curves presented in Figure 1 indicate that phase lag appears as the axial displacement increasing. However the SEA curves of two models agree very well. The numerical results showed that after simplifying the model, failure modes are the same, the difference in SEA and peak crushing force are 0.65% and 0.02%, respectively.

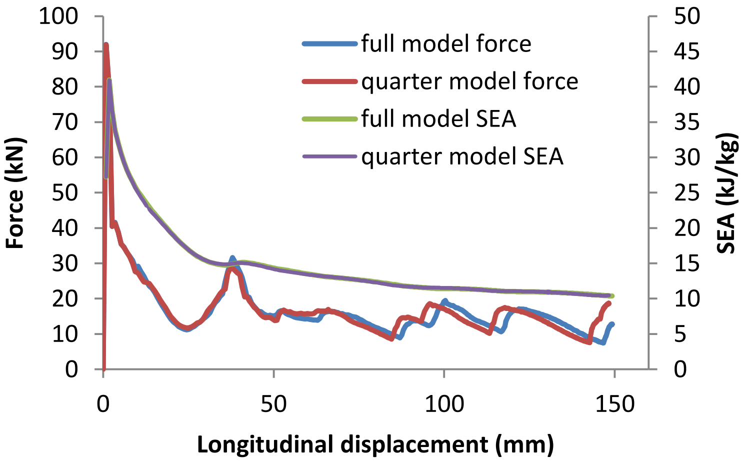

Figure 1 Crushing force and SEA vs longitudinal displacement of full and simplified quarter models

Another important feature of the numerical models is the artificially introduced imperfection. Since the column is initially regarded by the programme to be perfectly perpendicular to the impactor plane, two rigid triggers were introduced to initiate the deformation at the top of the column. A sensitivity study reveals that the effect of triggering on the initial peak crushing force can be neglected.

3. Results and discussion

Figure 2 shows failure modes of 1mm gauge plain and UltraSTEEL columns. It can be observed that failure modes of 1mm gauge plain and UltraSTEEL columns are similar. Following the

Abramowicz's theoretical model [1], each layer of folds has been initiated after the last layer of folds has been fully developed.

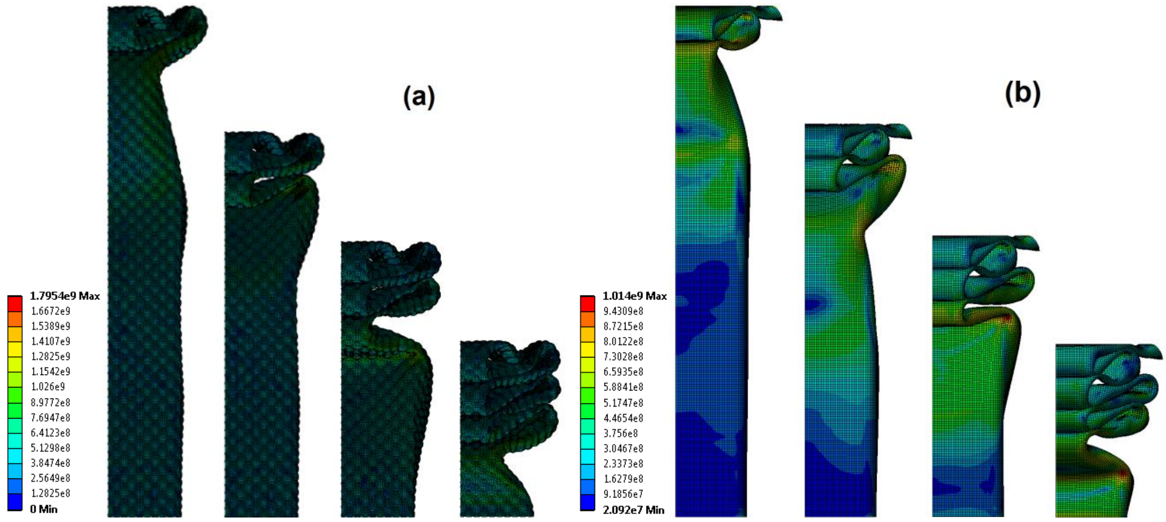

Figure 2 Failure modes of 1mm gauge (a) UltraSTEEL column and (b) plain column

In lightweight design, specific energy absorption (SEA) is the primary variable used to describe a column's energy absorption characteristics. Equation 2 is the definition of SEA.

$$SEA = \frac{\int P d\delta}{\rho A \delta_{total}} \tag{2}$$

where P represents the instantaneous crushing force, δ represents the reduction of the column's length in axial direction, ρ represents density of the material, and A represents the cross-sectional area of the column. Results presented in Figure 3 reveals that SEA converges at the beginning of the second fold. It is also revealed that SEA of the 1mm gauge UltraSTEEL column is 12.4% higher than the same gauge plain column. The increase in SEA is not as high as static yield strength due to the following reasons:

1. Impactors have not been stopped, which results in a higher average strain rate in the UltraSTEEL. Therefore, the strain rate sensitivity effect on the UltraSTEEL column is less significant;
2. The average plastic strain in the UltraSTEEL column is lower due to a greater longitudinal distance between two adjacent layers of folds.

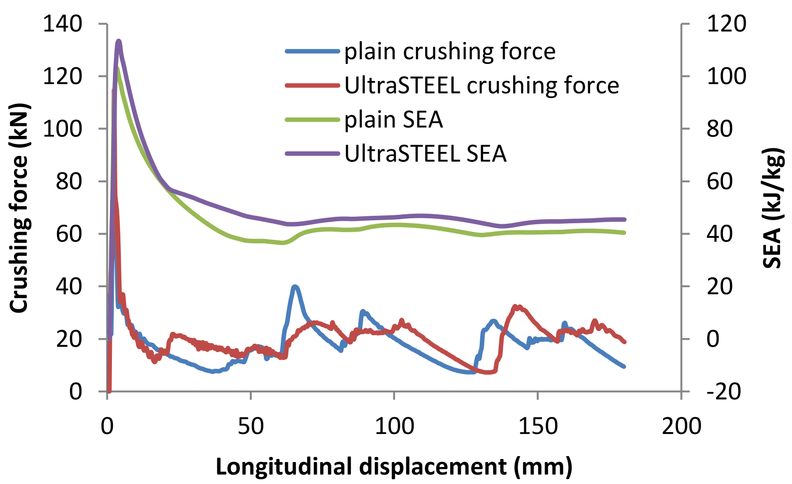

Figure 3 Crushing force and SEA vs longitudinal displacement of 1mm gauge plain and UltraSTEEL columns

The parametric study on gauge reveals that, in terms of failure mode, UltraSTEEL columns are more sensitive than plain columns. Failure modes do not vary significantly in plain columns of 0.7mm to 1.3mm gauge. However, as the gauge increasing, failure modes of UltraSTEEL columns are different. Taking 0.8mm, 1.0mm and 1.2mm gauge UltraSTEEL columns as an example (failure modes shown in figure 4), it is noticed that position of the first fold is different on the 1.2mm gauge column. This is due to a greater cross-sectional modulus. Moreover, a certain layer of folds is initiated to different extend by its previous layer of folds, as highlighted in Figure 4. Since the pre-initiation will reduce the energy absorption capacity, the advantage of UltraSTEEL columns compared to plain columns is predicted to gradually diminished as the gauge increasing. This prediction is then justified by the data shown in Figure 4(d).

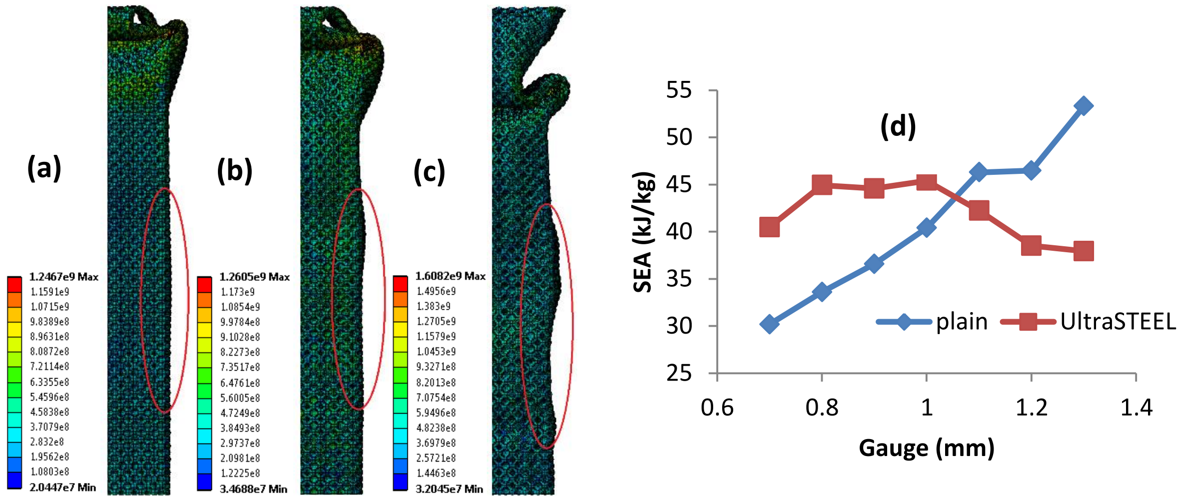

Figure 4 Failure modes of (a) 0.8mm (b) 1.0mm (c) 1.2mm gauge UltraSTEEL columns after the first fold and (d) SEA vs gauge of plain and UltraSTEEL columns

4. Conclusion

In this paper, explicit dynamics finite element simlations were conducted to analyse responses of UltraSTEEL columns to axial impact loads. Cowper-Symonds material models was used to reflect the effect of strain rate sensitivity. It is found that SEA is increased by 12.4% in UltraSTEEL material than plain mild steel closed square section columns, while both types of columns have similar failure modes. The dimpled geometry has made UltraSTEEL column more sensitive than plain columns to its gauge. As a result, the advantage of UltraSTEEL columns in SEA is more significant at small gauges. sensitive than plain columns to its gauge. As a result, the advantage of UltraSTEEL columns in SEA is more significant at small gauges.

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