Influence of Element Formulation on the Axial Crushing of Thin-walled Dual-phase Steel Square Sections

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Abstract

This paper presents a systematic numerical investigation of the influence of element formulation on the force-deformation characteristics and crush behaviour of thin-walled dual-phase steel square tubes subjected to axial loading. Influence of shell and volume elements were verified on the crush behaviour. Finite element models square sections were created and analysed using the non-linear explicit finite element code LS-DYNA®. Parameters of interest were the energy absorption, peak crush load capacity, and the crush behaviour. The strain-rate effect has been considered for the dynamic simulations. Even though the initial peak load from numerical analyses differs significantly from the tests, the mean force does not deviate greatly whatever may be the element formulation. Both shell and brick elements predicted the experimental responses reasonably well. However, the element aspect ratio in volume element simulations seems to play a role in accurately capturing the local bending response when subjected to axial compressive load.

Keywords: Thin-walled square tubes, Dual-phase steel, Axial crushing, Nonlinear finite element analysis, LS-DYNA

Introduction

The non-linear finite element method is an efficient and reliable tool for the design of new components in many areas. At the same time the computing methods have been refined to such an extent that today simulations are more and more referred to as basis for important design decisions. Especially crash simulations have greatly reduced the request for expensive physical prototypes. Recently, weight savings are of main concern in the automotive industry and the introduction of high-strength steels in the load bearing components raised the few issues related to folding process, energy absorption and general material modelling in these new materials. For automotive applications, shell-based finite element simulations aid the practical development of such components. Several investigations [1, 2] have pointed out that shell-based axial crush models tend to show softened behaviour compared to experimental investigations. Thus, it is of interest to examine the influence of various element formulations on the crash behaviour and energy absorption in thin-walled sections.

In this numerical study, three different element formulations were tested for the crushing behaviour of thin-walled square tubes using a non-linear explicit finite element code LS-DYNA®. Both shell and volume elements were considered for modelling the tubes. The primary objective was to compare the responses between shell-based and brick-based models. In the analyses, the focus was placed on the force-deformation histories, initial peak force, collapse modes and energy absorption.

Experiments

Fig. 1 shows the details of the thin-walled square tube used in this study. The square tubes were made of dual-phase, high-strength steel DP800. The outer dimensions of the tube were 60 mm × 60 mm, the sheet thickness was 1.2 mm and the length was 410 mm. The lower 100 mm of the specimen was clamped in all tests using a clamping device, while the upper end was free (before applying the load). These tubes were tested under both quasi-static and dynamic loading conditions. Quasi-static axial compression tests were performed in an Instron 250 kN testing machine, while the dynamic crushing tests were conducted in a kicking machine with an impacting mass of 600 kg and the loading velocity was 5, 10 or 15 m/s. The force-time history for the tests was recorded during the impact event. Energy absorption and mean crushing load were calculated by measuring the area under the load-displacement curve.

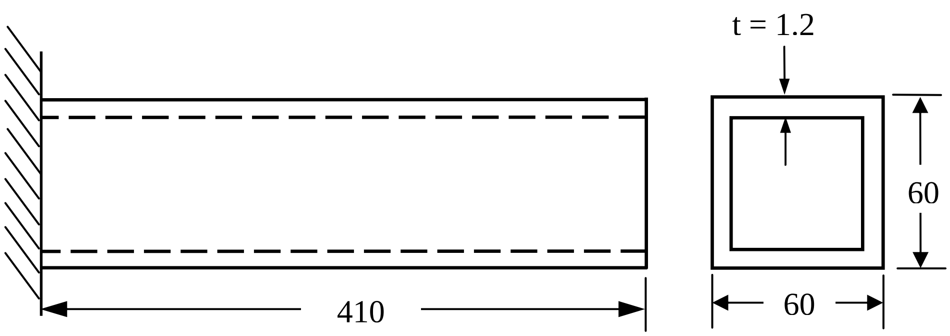

Fig. 1. Schematic representation of the thin-walled square tube

Force - deformation and mean force – deformation histories of the dual-phase steel square tubes are shown in Fig. 2. It can be seen that the filtered initial peak load and the mean force level of the tubes were increased with impact velocity, which means that the inertia and strain-rate play an important role in the dual-phase steel sections. Further details of the experimental results on the crushing behavior of the thin-walled square tubes can be found in Tarigopula et al. [3].

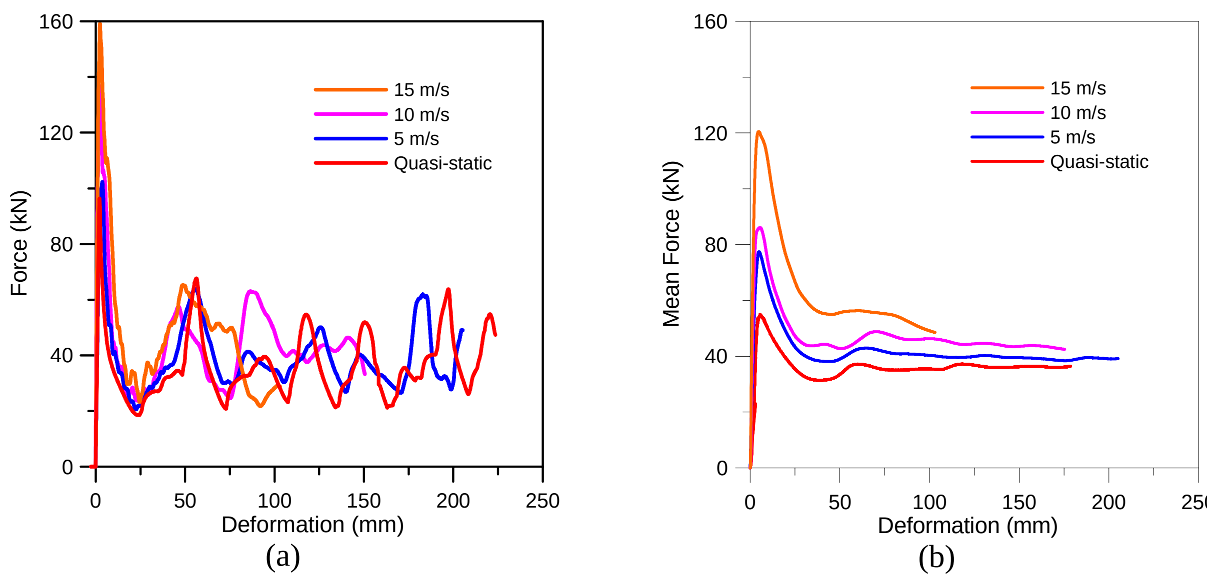

Fig. 2. Test results, (a) force - deformation curves and (b) mean force - deformation curves.

Numerical Modeling

The explicit non-linear finite element code LS-DYNA was used to predict the response of the thin-walled square tube subjected to axial crushing. Four numerical models were created for the square tube with different element formulations, namely Belytschko-Tsay shell element (shell element type 2) with 5 integration points through the thickness and one integration point in the plane of the shell, Belytschko-Tsay shell element with thickness stretching (shell element type 25), fully integrated S/R solid element (brick element type 2) with one or two elements in the thickness direction. These models are listed in Table 1. The load was applied at the upper end of the tube using a rigid block modeled with brick elements. The contact between the rigid block and the specimen was modeled using a "nodes impacting surface". To account for contact between the lobes during deformation, a single surface contact algorithm without friction was used. No crash initiators were employed in the specimen. Geometrical imperfections were introduced by a number of half sine waves in the longitudinal direction [4] in order to account for out-of-flatness of the specimens' side walls.

Table 1. Details of the numerical models

Model No.	**Element type**	**Element size (in terms of mm)**	**Elements in thickness direction**
Model 1	Belytschko-Tsay shell element	2.9×2.7	-
Model 2	Belytschko-Tsay shell element with thickness stretching	2.9×2.7	-
Model 3	Fully integrated S/R solid element	2×1.8	1
Model 4	Fully integrated S/R solid element	1.5×1.3	2

The quasi-static simulations were performed using an isotropic multi-component hardening model (*MAT_103) as defined by

$$\bar{\sigma} = \sigma_0 + \sum_{i=1}^{2} Q_i (1 - \exp(-C_i \bar{\varepsilon})), \tag{1}$$

where $\bar{\sigma}$ is the equivalent stress, σ_0 is initial flow stress, $\bar{\varepsilon}$ is the equivalent plastic strain, and Q_i and C_i are strain hardening constants. Strain-rate hardening was considered for the case of dynamic simulations (*MAT_107), which is defined by using a modified Johnson-Cook expression:

$$\bar{\sigma} = (\sigma_0 + \sum_{i=1}^{2} Q_i (1 - \exp(-C_i \bar{\varepsilon})))(1 + \frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0})^q, \tag{2}$$

here $\dot{\varepsilon}_0$ is a user-defined reference strain rate. The tensile properties at different strain rates were used to obtain the material parameters in the Eqs. (1) and (2), and these parameters are summarized in Tarigopula et al. [3].

Results and Discussion

The results obtained by the numerical analyses of the axial crushing of the thin-walled square tubes are presented in Fig. 3 and Fig. 4. Here, the crush behavior and the force-deformation histories of all models are described and compared with the test results. For the sake of brevity, the collapse modes of Models 1-4 are described for one representative impact velocity, i.e. 10 m/s, in Fig. 5. In this case, all the numerical models underwent progressive buckling (regular inward-outward folding) with varied folding lengths. The folding behavior at the rounded corners is predicted reasonably well with the models (Model 3 and Model 4) based on the volume elements than the models (Model 1 and Model 2) based on the shell element formulations. It is also understood from the force-deformation characteristics that the formation of lobes in all numerical models is more or less correspondent with the tests. In general, the numerical models regardless of the element formulation reproduced successfully the overall collapse behavior of the thin-walled tubes under axial crushing. However, initial peak load is somewhat over-predicted in the numerical models when compared to the test results. This is expected because of the presence of various initial imperfections in the physical tests.

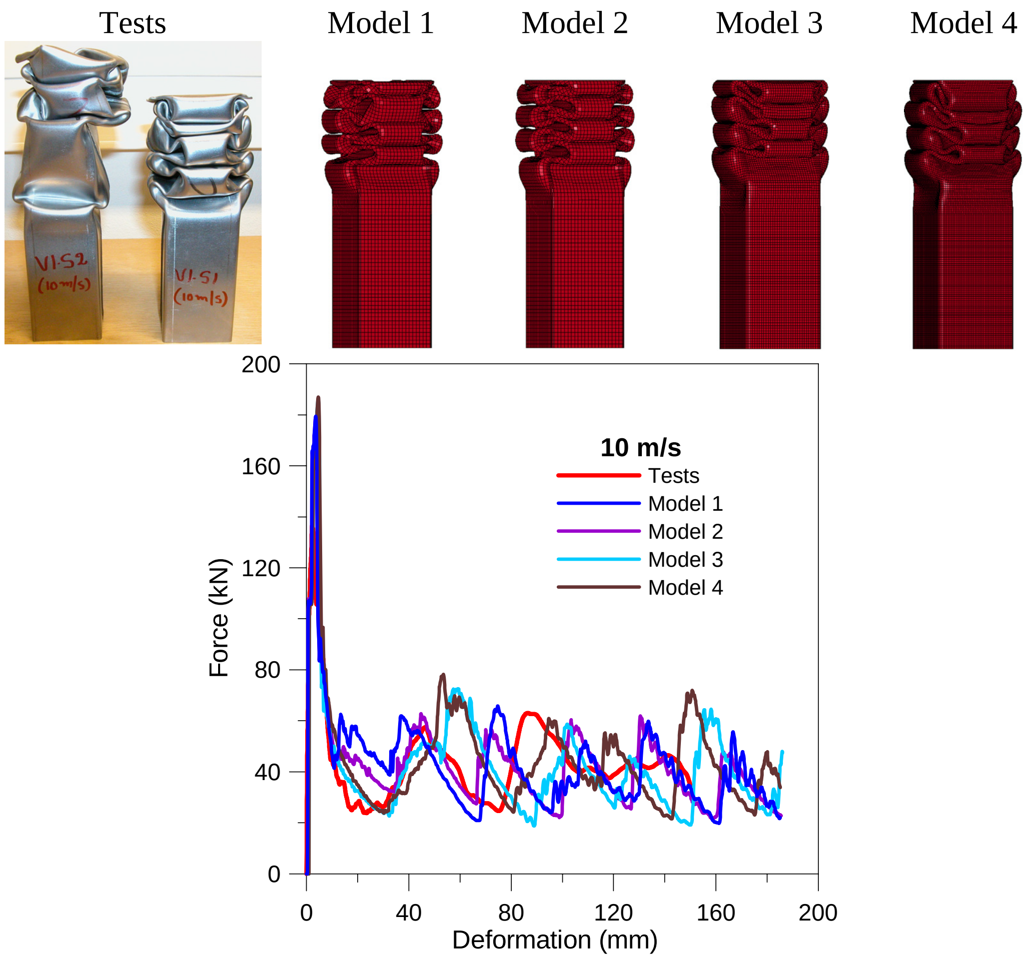

Fig. 6. Comparison of the crush behavior and force-deformation histories between the tests and the numerical simulations with different element types for one representative impact velocity at 10 m/s

Fig. 7 compare the mean force-deformation characteristics (or energy absorption) between different models and the physical tests. On a whole, all the models provided satisfactory results when compared to the test mean force-deformation characteristics. Model 4 slightly over-predicted the experimental response at all velocities. The bad aspect ratio of the element in Model 4 might provide some explanation. Table **2** summarizes the results such as initial peak load and mean force from the numerical simulations and the tests. It can be clearly see that all numerical models provided satisfactory results with respect to the test results. There are not great differences between the models, i.e. the different element formulations do not influence the results significantly in thin-walled sections.

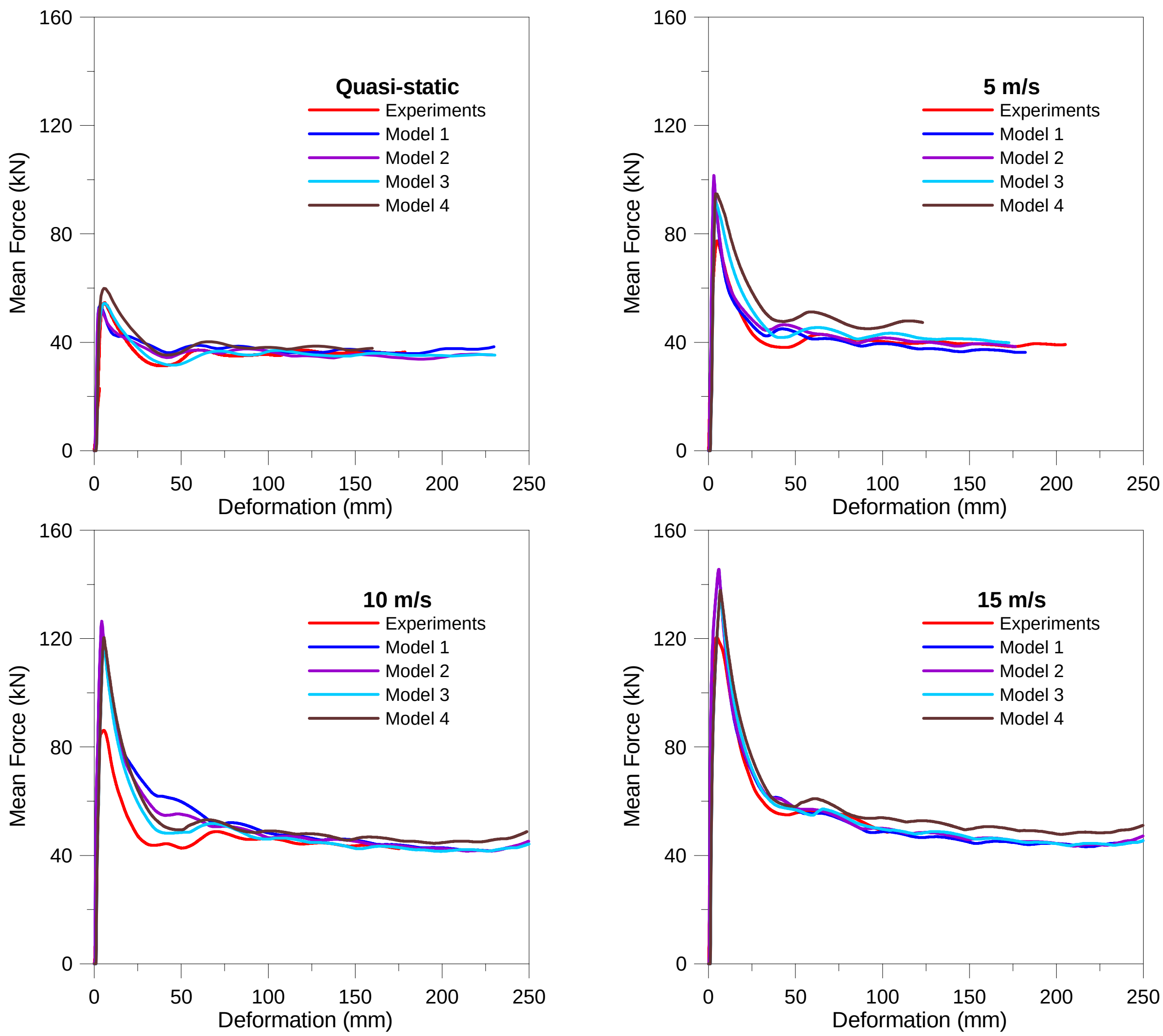

Fig. 8. Comparison of the mean force-deformation histories between the tests and the numerical simulations with different element types at all velocities

On the other hand, the model (Model 2) based on Belytschko-Tsay shell element with thickness stretching provided rather stiffer response than the corresponding Belytschko-Tsay shell element (Model 1) alone. There is also some difference found between using one (Model 3) or two (model 4) fully integrated brick element over the thickness on the energy absorption. In this study, the sections are relatively thin that they have not shown significant differences with various element formulations. It would be interesting to investigate the same for thick-walled sections.

Table 2. Results from the tests and the simulations

Impact velocity	Particulars	Initial peak load (kN)	Mean force (kN)
Quasi-static	Tests	88	35.6
	Model 1	95	36.9
	Model 2	95	35.4
	Model 3	122	35.3
	Model 4	123	37.7
5 m/s	Tests	99	40.7
	Model 1	159	37.8
	Model 2	160	38.4
	Model 3	169	39.8
	Model 4	171	44.6
10 m/s	Tests	127	43.4
	Model 1	179	44.9
	Model 2	179	45.3
	Model 3	186	44.4
	Model 4	187	48.8
15 m/s	Tests	136	48.7
	Model 1	178	49.8
	Model 2	178	52.1
	Model 3	194	49.9
	Model 4	195	55.8

Conclusions

Non-linear finite element analysis by using LS-DYNA is able to reproduce the collapse modes and force-deformation characteristics that were observed in the series of experiments on thin-walled dual-phase square sections under axial crushing. A comparison of the load-displacement responses of models with different element formulations showed that the general behavior of the load-displacement response in thin-walled sections did not change appreciably.

Acknowledgement

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