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Local buckling and energy dissipation in a sandwich square column

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Abstract
Local buckling, post-buckling and energy dissipation of a sandwich box column was investigated computationally. Box steel columns are widely used as crushing tubes to improve automotive crashworthiness and passenger safety. Sandwich panels, with steel face sheets and soft core, may enhance energy dissipation and crashworthiness. Simulations, verified against published experimental results, were employed to assess the energy dissipation of sandwich panel columns. Computational results indicated noticeable gain in energy absorption over conventional solid steel tubes. Sandwich panels were shown to have better crashworthiness than standard steel tubes. Sandwich crushing tubes could enable lighter structures or enhanced resiliency if weight is not a controlling factor.

1. Introduction

Energy dissipation is essential for arresting extreme dynamic events such as progressive collapse, blast and impact (Stefan Szyniszewski and Krauthammer 2012; Stefan Szyniszewski 2009; Zhou and Yu 2004; Deng et al. 2014; Eatherton et al. 2010). Among various approaches that facilitate dissipation of kinetic energy (Lu and Yu 2003), stub steel tubes are commonly employed in automotive applications. The initial buckling response of these members is less significant for energy dissipation than post-buckling. In fact, sequential post-buckling wave collapse, with large strains and deflections, is responsible for the energy dissipation mechanism. Solid tubes have been known for their energy dissipation since early eighties (Abramowicz and Jones 1984; Wierzbicki and Abramowicz 1983; Wierzbicki et al. 1992), and are commonly used to increase impact safety by automotive industry (Sun et al. 2014).

Foam filled tubes have been studies by (Abramowicz and Wierzbicki 1988; Reyes, Hopperstad, and Langseth 2004; Hanssen et al. 2005), and sandwich columns with composite face sheets were tested experimentally by (Mamalis et al. 2003; Mamalis et al. 2009). Sandwich panel plates have been shown to possess higher capacity than solid plates if width to thickness ratio, $b/t > 50$ (S. Szyniszewski, Smith, Hajjar, et al. 2012a; S. Szyniszewski, Smith, Hajjar, et al. 2012b). Stability of square columns made of sandwich plates with metallic face sheets and low-density, compressible core has been researched over recent years (S. Szyniszewski, Smith, Zeinoddini, et al. 2012; Li and Szyniszewski 2013). However, articles on crashworthiness of sandwich tubes

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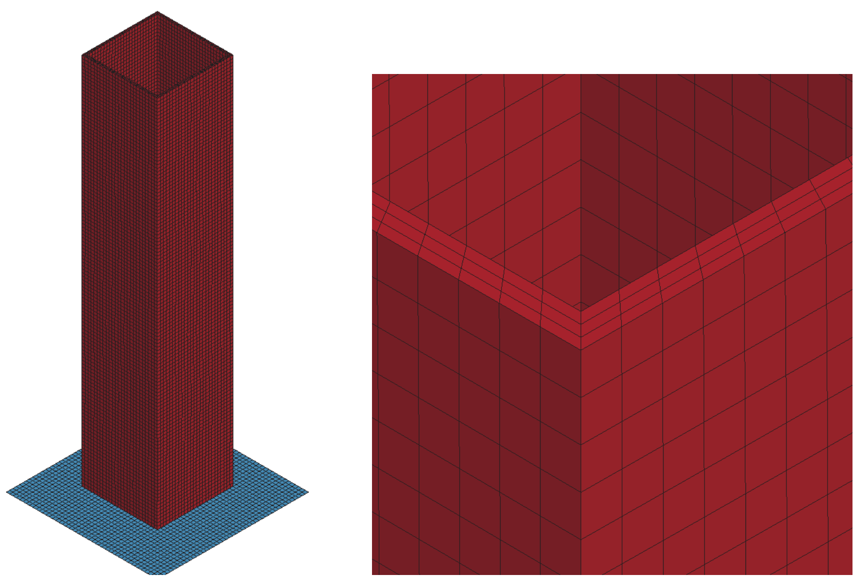
have not been found in the available literature. The objective of this paper is to compare energy dissipation of a metallic sandwich panel stub column with a conventional crushing tube.

2. Calibration and validation of finite element simulations of crushing behavior

Experimental results reported by (Abramowicz and Jones 1984) were employed to validate the computational approach. Abramowicz and Jones tested crushing behavior of steel tubes: 49.30 mm wide, 1.625 mm thick and 244.1 mm high. To provide predictions of the ultimate buckling strength and post-buckling crushing a series of finite element models was constructed. The models were completed in LS-DYNA (Hallquist 2006). Brick elements (100,000 to 900,000 type 164 solids) were used throughout 50 transverse elements, three elements through the thickness of steel tubes, and five elements through the thickness for sandwich columns. Load was applied via prescribed boundary motion such that the tube was pushed into a fixed steel plate (see Figure 1). Sufficiently slow loading rate was selected such that no kinetic energy was observed in the simulations. The steel face sheets were modeled with a standard J-2 plasticity formulation and isotropic hardening. The steel properties: E = 203000 MPa, f_y = 268 MPa, and complete strain hardening regime were obtained from coupon tests of steel sheet shown in Figure 2 after (Abramowicz and Jones 1984). Buckling imperfections were imposed as a sinusoidal wave with a half-wave length approximately equal to the width of the column. Maximum magnitude of imperfection displacement was equal to one tenth of the tube thickness, with peak perturbations at centers of local buckling half-waves.



A) Steel square column B) Brick elements

Figure 1. Numerical models of a square tube tested by (Abramowicz and Jones 1984)

Simulation exhibited three distinctive stages: 1) local buckling along the column, 2) localization of deformations in a single half-wave, 3) propagation of half-wave collapses. Stub columns under axial loads showed multiple half-waves during the initial buckling. However, plastic localization in one of the buckling waves followed quickly and led to moderate unloading of the remaining buckling waves. The localization was a bit random, and the location of the first half-wave collapse was most likely influenced by miniscule numerical round-off errors that are inevitable in all numerical calculations. Consecutive half-wave collapses propagated toward the top of the column with applied prescribed boundary motion. Once the top was reached, half-wave collapse spread toward the bottom, fixed plate, starting from the initial collapsed half-wave as shown in Figure 3.

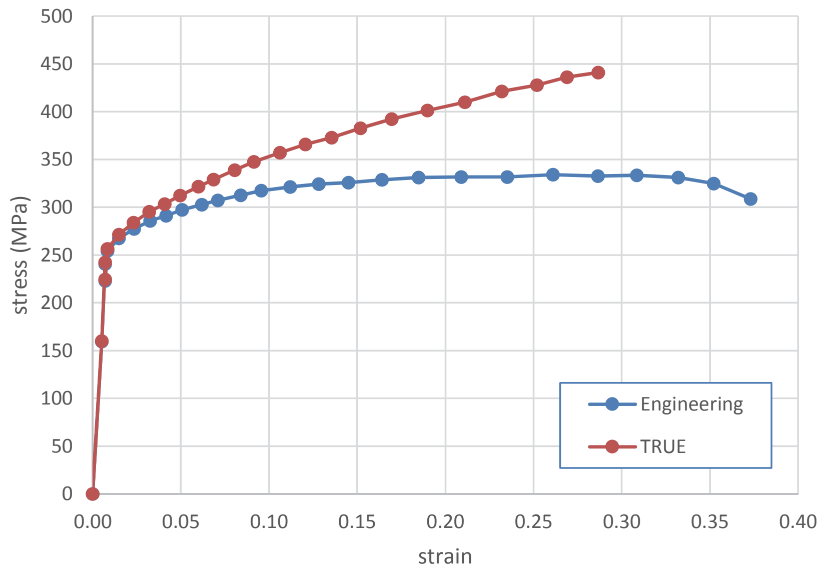


Figure 2. Steel tube material properties (Abramowicz and Jones 1984)

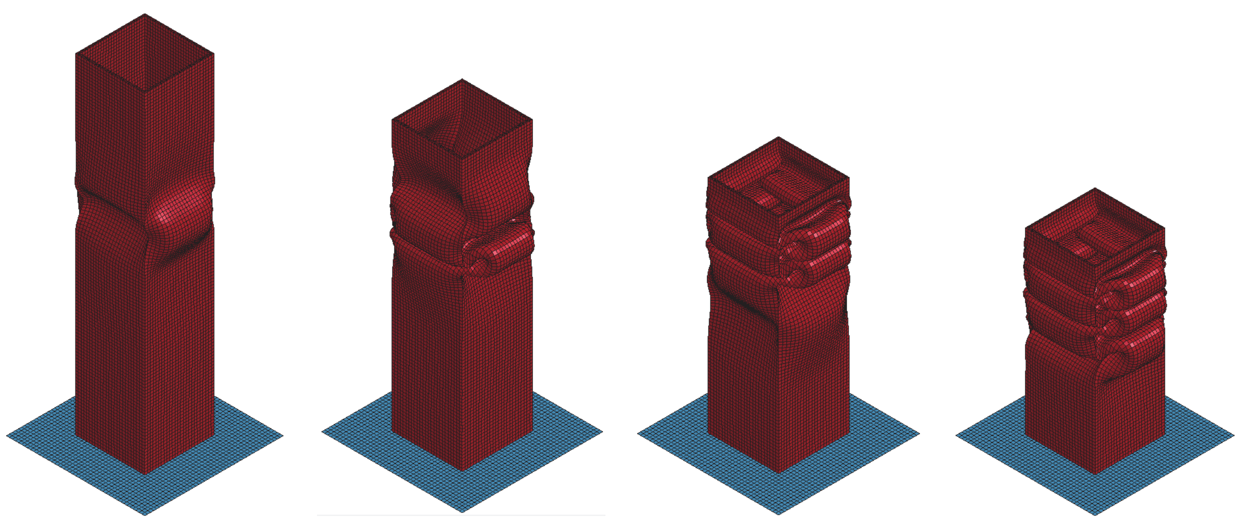


Figure 3. Simulated buckling and post-buckling sequence during crushing of a steel tube

Simulated resistance to crushing was compared with experimental measurements reported by (Abramowicz and Jones 1984). Reasonable agreement was observed between the simulated curve and data points from the test (Figure 4). Simulated average crushing force was within 10% of the experimental value. Considering noticeable material and geometric nonlinearity, as well as likely variation in test results between various test specimens, simulations were judged as satisfactory to investigate the effect of sandwich panel walls on the overall energy dissipation.

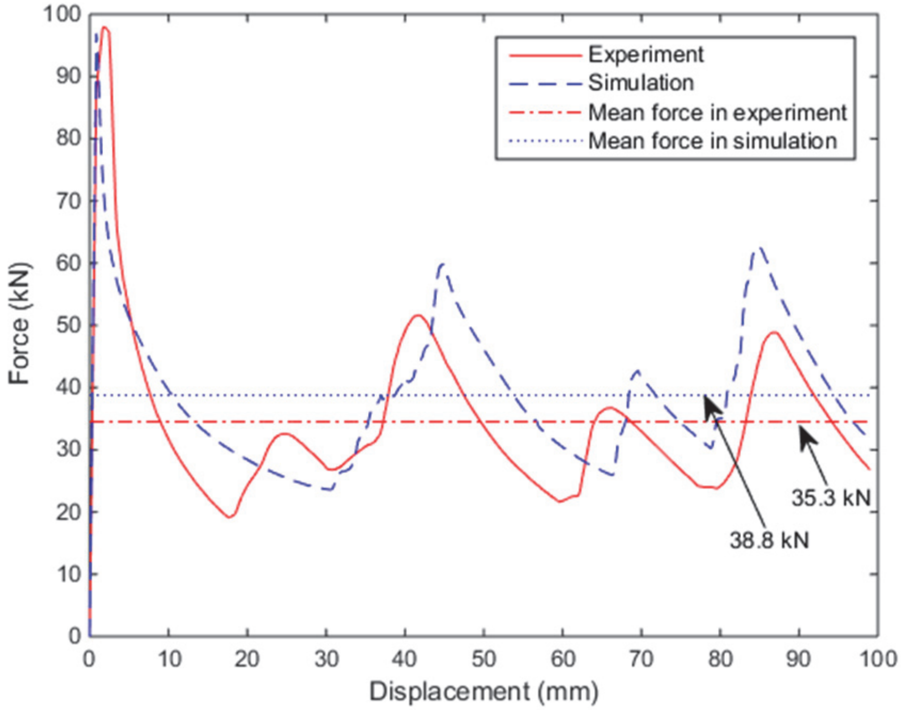
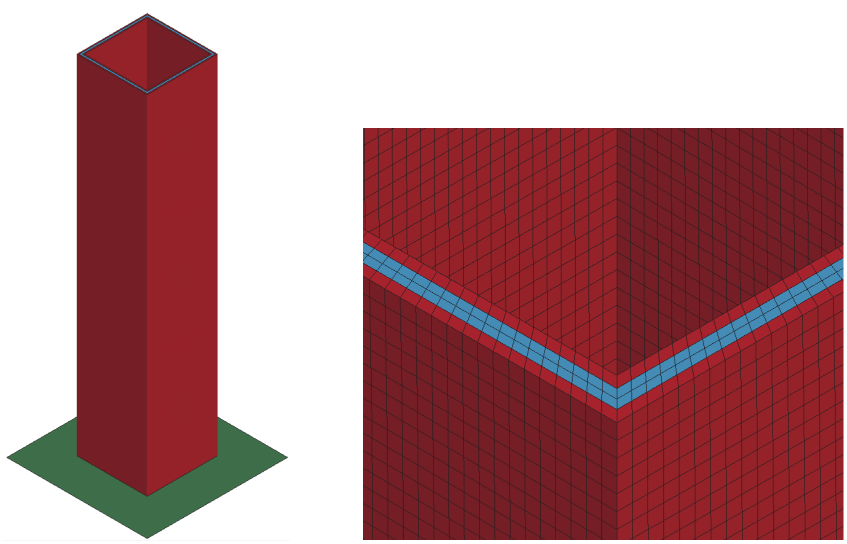


Figure 4. Simulation of steel tube crushing was verified against experiment by (Abramowicz and Jones 1984). Simulated mean force agreed with the experimental value within 10%.

3. Sandwich panel tubes. Computational study of crashworthiness.

Sandwich panels, that combine metallic sheets with a soft core, have become available in recent years (Neugebauer and Hipke 2006; S. T. Szyniszewski et al. 2014; Yuan, Rayess, and Dukhan 2014; Smith et al. 2012; Bhattacharjee et al. 2011). Sandwich panels offer larger bending stiffness than a solid plate and higher buckling capacity in comparison to thin plates.



A) Sandwich square column   B) Brick elements employed in face sheets and core

Figure 5. Numerical models of a sandwich panel tube

The steel crushing tube employed by (Abramowicz and Jones 1984) was modified such that steel plates were replaced with a sandwich panel. Face sheets had thickness, tf = 0.7 (mm) and core thickness was selected as tc = 1.2 (mm). Mild steel material model was employed for face sheets. Steel face sheet properties were the same as for the solid plate above. Soft core had the following properties: Young modulus, E = 686 MPa, yield stress, f_y = 22 MPa, ultimate stress, f_u = 27 MPa (at 0.26 engineering strain).

Simulated crushing mechanism was similar to a conventional steel tube. Firstly, a series of buckling waves formed along the column height, and later deformations localized in a single half-wave. The location of localization varied from a simulation to simulation. It was most likely influenced by miniscule perturbations produced by numeric round-off errors that are inevitable in computer calculations. Similarly to a steel crushing tube simulation, half-wave collapse propagated toward the moving boundary first. Simulations terminated after 120mm displacement was reached (approximately 50% of column height).

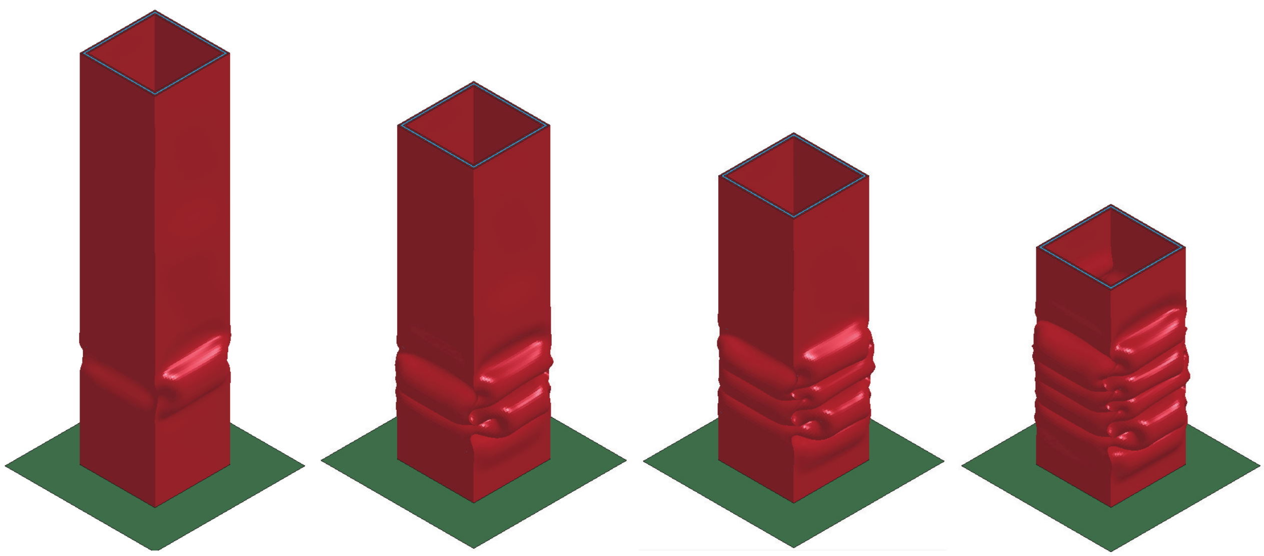


Figure 6. Simulated crashworthiness of sandwich panel tube under axial loading.

Sandwich panel tube dissipated 50% more energy when compared to a conventional steel tube (see Figure 7). Mean crushing force of 58 kN was observed for a sandwich panel and was significantly higher than 39 kN for a conventional steel tube. Although the sandwich member buckled under a 10% lower load than a steel column initially, its post-buckling descent in capacity was slower, and the residual resistance did not reduce below 40 kN. Also, the following sequence of half-wave collapses produced a relatively constant resistance force that oscillated around the mean crushing force of 58 kN. Considering that sandwich column dissipated 50% more energy than steel column, sandwich panels could reduce weight of crushing tubes by 33%.

Steel plate exhibited noticeable variation in resistance between post-buckling peaks (60 kN) and dips in resistance (20 kN). Stable resistance helps maintain relatively constant deceleration, and it is essential for limiting passenger injuries during automotive accidents and collisions.

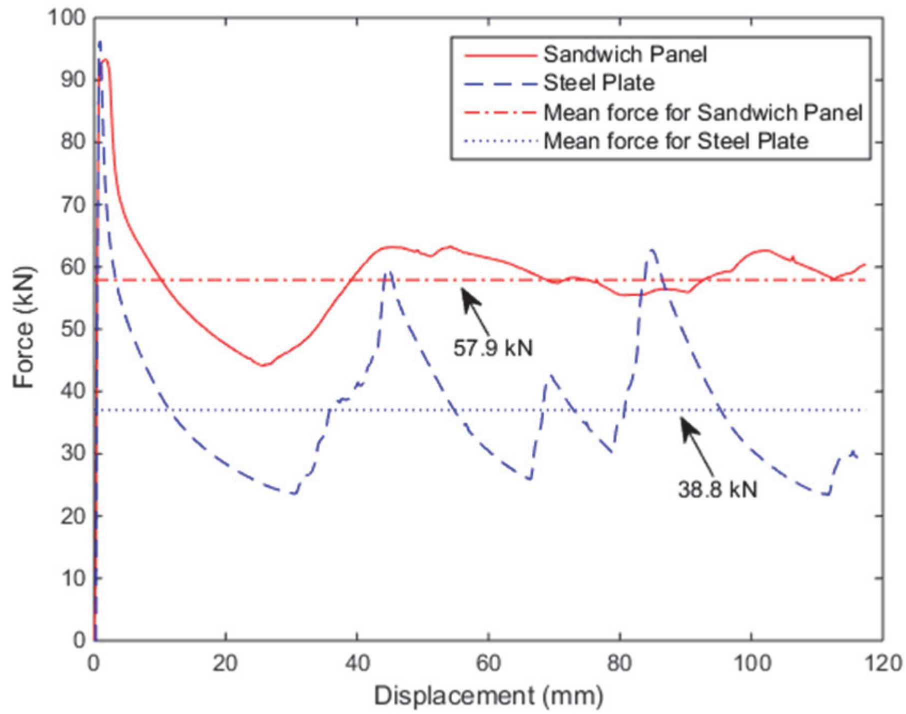


Figure 7. Simulated crushing resistance of sandwich panel tube (red) and conventional steel tube (blue). Sandwich panel tube dissipated 50% more energy than steel tube of equal weight.

6. Conclusions

Dynamic simulations were employed to evaluate energy dissipation of a novel sandwich panel crushing tube. Firstly, numerical model was validated against experimental tests reported in the literature such that computational results were within 10% of the experimental crushing force. Next, validated model was employed to compare two crushing tubes with the same weight: A) conventional steel column, B) sandwich panel column made of three layers, namely: steel – polymer – steel.

Simulation results indicated that a sandwich panel column offers superior energy dissipation and smoother post-buckling resistance than conventional steel crushing tube. This study demonstrated that sandwich panel members may provide enhanced energy dissipation over typical thin-walled steel components. Thus, they have a potential to increase resiliency in applications that are exposed to dynamic and extreme loads such as earthquakes, blast, and impact.

Although sandwich panels with polymer and other soft cores are widely available on the market and employed in a range of industrial applications (civil, shipbuilding, mechanical and automotive to name a few), further work is needed to develop cold-form sandwich members. Specifically, manufacturing of studs and columns made of thin-walled sandwich panels needs further effort such that sandwich panel members become widely available on the market. On the theoretical front, columns with various local slenderness of walls as well as a range of global slenderness warrant future studies. Also, direct strength methods could be adopted to enable design of sandwich members. This work is part of a larger effort to help develop sandwich panels as a structural solution with relevance to civil engineering, infrastructure, and automotive applications.

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