Dynamic Buckling and Recovery of Thin Cylindrical Shape Memory Shells

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Abstract

Shape-memory alloys can sustain relatively large strains and fully recover without noticeable residual strains. This is referred to as superelasticity. We have been studying quasi-static and dynamic buckling of relatively thin circular cylindrical shells consisting of shape-memory alloys in order to understand the response when used as the core of the sandwich structures. The work consists of experimental characterization of the buckling process, as well as numerical simulation. For comparison, we have also studied both dynamic and quasi-static buckling of aluminum tubes of similar dimensions. This presentation will focus on numerical simulation of dynamic buckling of these tubes and correlation with experimental observations.

Keywords: Shape memory alloy; Numerical simulation; Cylindrical shell; Aluminum 7075; Superelasticity

Introduction

Fundamental to the use of many metal components as energy absorbers is the ductility which permits large plastic strains without failure of the structural system. Plastic deformation and specifically plastic buckling of tubes is an effective mechanism by which energy can be dissipated. Circular tubes have comparatively high energy absorbing capacities. Therefore sandwich structures consisting of two plates separated by metal tubes are good candidates to mitigate impulsive (short duration) loads. Some investigations suggest excellent energy absorbing characteristics of tubes under high velocity impact loading conditions (Reid 1993)

In this paper, we report the results of our numerical simulations to support our experimental investigation of the dynamic and quasi-static response of tubes made of shape-memory alloys, and aluminum 3003 and 7075. Shape-memory alloys can sustain relatively large strains and fully recover without noticeable residual strains. In addition, both the aluminum and shape-memory alloys show good ductility and plasticity at low temperatures and high strain rates, without displaying noticeable damage and micro-cracking.

Numerical simulations

Material nonlinearities, geometrical imperfections, large strains, dynamic effects (including the influence of strain rate on the yield stress) are just some of the complications that can not be easily treated using classical buckling theories. Using the unique features that recent finite element codes provide, one can reliably and reasonably predict the overall behavior of complicated structures under quasi-static and dynamic loading conditions. These analyses can be performed with minimum cost which makes it a powerful design device.

Two shape-memory alloy tube buckling simulations have been conducted, one consists of a thin-walled tube of 4.5mm nominal outer diameter, 0.125mm nominal wall thickness, and 11.3mm nominal length, and the other is a relatively thick-walled tube with 7mm gauge length, 8mm outer diameter, and 0.5mm wall thickness. Both of these simulations have been conducted under dynamic loading conditions with crosshead speed of 32m/s.

Since both of the simulations are dynamic, LS-DYNA 970 explicit solver has been employed. The Belytschko-Tsay shell element, known for its computational efficiency, has been used in these simulations to model the thin-walled tube. Using two Gauss integration points through the thickness has enabled us to capture the bending behavior of the tube without too much computational cost. On the other hand, 8-node, fully integrated S/R solid elements have been used to model the thick-walled shape-memory alloy tube. The contact between the aluminum tubes is modeled using code's automatic single surface contact option with no friction; see LS-DYNA user's manual. The sandwich plates are modeled using rigid walls and the nodes of the tubes are considered as slave nodes. Fixed boundary conditions have been assumed at both ends of all the tubes that will account for the welding to the sandwich plates.

User defined material has been used to model the buckling behavior of the tubes. This material model is based on a linear evolution equation for capturing the austenite to martensite phase transformation plateau. In addition, this material model can capture the irreversible plastic behavior of the martensite. It is used for both solid and shell elements.

To obtain a better understanding of the mechanical behavior of the tubes, additional simulations have been conducted using aluminum tubes with different geometrical and loading conditions. All these simulations have been paralleled by experimental tests and the detailed finite-element model results agree well with the experimental results, both in the buckling modes and buckling loads. Figure 1 and 2 present shape-memory alloy and aluminum thin-walled tubes buckling modes.

Conclusions

A set of numerical simulations are performed to investigate the dynamic and quasi-static response of tube-based sandwich structures under compressive loads. These finite-element models are used to support and validated the results of a parallel set of systematic experiments. The thin-walled shape-memory alloy tube initially buckles into an axisymmetric pattern near one end, and as the buckling proceeds, the tube deforms into a non-axisymmetric chessboard mode. Whereas, the thick-walled tube continues to buckle axisymmetricly.

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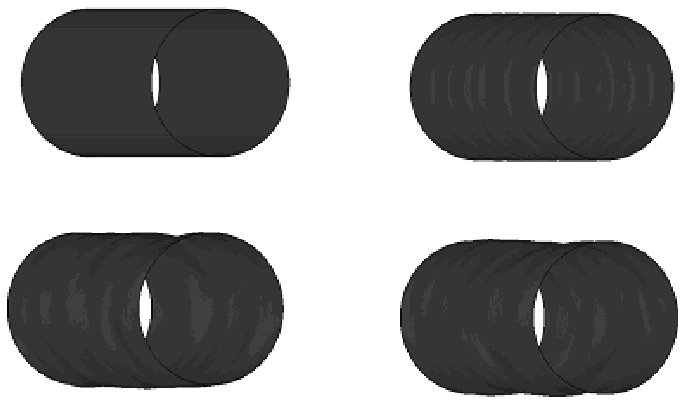

Fig. 1. Finite element simulation of the thin NiTi tube buckling, followed by the recovery and permanent deformations; ratio of L/D is 2.5.

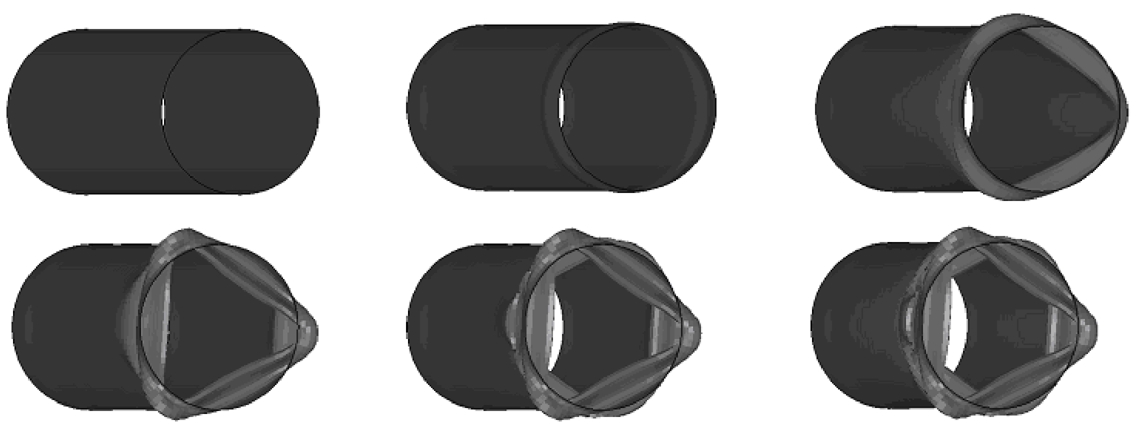

Fig. 2. Simulation steps of aluminum tube buckling in uniaxial compression; displacement-controlled loading with crosshead speed 6.71×10^{-3}mm/s.