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Tension, compression, and bending of superelastic shape memory alloy tubes

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ABSTRACT

While many uniaxial tension experiments of shape memory alloys (SMAs) have been published in the literature, relatively few experimental studies address their behavior in compression or bending, despite the prevalence of this latter deformation mode in applications. In this study, superelastic NiTi tubes from a single lot of material were characterized in tension, compression, and pure bending, which allowed us to make direct comparisons between the deformation modes for the first time. Custom built fixtures were used to overcome some long-standing experimental difficulties with performing well-controlled loading and accurate measurements during uniaxial compression (avoiding buckling) and large-rotation bending. In all experiments, the isothermal, global, mechanical responses were measured, and stereo digital image correlation (DIC) was used to measure the evolution of the strain fields on the tube's outer surface.

As is characteristic of textured NiTi, our tubes exhibited significant tension–compression asymmetry in their uniaxial responses. Stress-induced transformations in tension exhibited flat force plateaus accompanied by strain localization and propagation. No such localization, however, was observed in compression, and the stress "plateaus" during compression always maintained a positive tangent modulus. While our uniaxial results are similar to the observations of previous researchers, the DIC strain measurements provided details of localized strain behavior with more clarity and allowed more quantitative measurements to be made. Consistent with the tension–compression asymmetry, our bending experiments showed a significant shift of the neutral axis towards the compression side. Furthermore, the tube exhibited strain localization on the tension side, but no localization on the compression side during bending. This is a new observation that has not been explored before. Detailed analysis of the strain distribution across the tube diameter revealed that the traditional assumption of elementary beam theory, that plane sections remain plane, does not hold. Yet when the strain was averaged over a few diameters of axial length, the tensile and compressive responses input into elementary beam theory predicted the global bending response with reasonable accuracy. While it is encouraging that a simple model could predict the moment–curvature response, we recommend that beam theory be used with caution. The averaged strain field can under/over predict local strains by as much as two-fold due to the localized deformation morphology.

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1. Introduction

Shape memory alloys (SMAs), such as NiTi-based alloys (Nitinol), exhibit two remarkable properties, the *shape memory effect* and *superelasticity*. The shape memory effect is the material's ability to recover large mechanically induced strains upon heating above a transition temperature. Superelasticity (or pseudoelasticity) refers to the material's ability, above a transition temperature, to recover large strains isothermally during a mechanical load/unload cycle, usually via a hysteresis loop. The mechanism for superelasticity is a stress induced transformation from austenite (Aust) to martensite (M) during loading and a reverse transformation from M to Aust during unloading. The magnitude of the tensile strain recovery in a Nitinol polycrystal is between 5% and 8% in the low-cycle limit and near 2.5% in the high cycle fatigue limit.

The bending flexibility of SMAs has led to numerous applications in the consumer, civil, transportation, and biomedical engineering sectors. In the consumer sector, superelastic SMAs are used for their bending compliance in eyeglass frames, clothing, headphone headbands, and rugged cell phone antennas (Humbeeck, 1999). SMAs are being explored for vibration damping of civil engineering structures, using the superelastic hysteresis in bending (Dolce and Cardone, 2005; Choi et al., 2009). In recent years, SMAs have been extensively used in biomedical devices, where the strong trend towards minimally invasive surgery in medicine is often enabled by superelastic SMAs (Duerig et al., 1999). Self-expanding stents and stent grafts comprise the largest fraction of existing SMA biomedical applications. These devices are often laser cut from NiTi tubes into a series of crowns and struts, which are locally bent to fit the stent inside a catheter. The catheter delivers the stent to the desired location in the body, where it expands and scaffolds the circumference of a tubular lumen. Other SMA bending examples include catheter guidewires, inferior vena cava filters, tissue ablation devices, retrieval baskets, birth control devices, endoscopes, intra-aortic balloon pumps, and biopsy forceps. In dentistry, superelastic SMAs are used as pretensioned orthodontic wires and root canal files that must bend to accommodate tortuous crevices (Duerig et al., 1999; Morgan, 2004).

Despite the myriad of applications that employ superelastic SMA in bending, and despite the number of SMA bending models (we found 13) (Atanacković and Achenbach, 1989; Thier et al., 1991; Pelton et al., 1994; Plietsch et al., 1994; Berg, 1995b; Auricchio and Sacco, 1997; Raniecki et al., 2001; Rejzner et al., 2002; Purohit and Bhattacharya, 2002; Liew et al., 2004; Rajagopal and Srinivasa, 2005; Buratti, 2005; De la Flor et al., 2010), few careful pure-bending experiments exist in the literature. Traditional 4-point bending fixtures operate under the assumptions of small beam displacements and rotations, which are easily violated when used with slender SMA specimens. Under large displacements, undesirable axial loads tend to develop due to the support constraints. Also, curvature measurements are usually inferred from grip displacements or rotations. Measuring deformation from the grips is problematic with superelastic SMAs, since they frequently transform to martensite prematurely inside grips where stress concentrations exist. This causes grip slippage that makes the deformation measurement inaccurate, and it tends to mask any stress peaks associated with the onset of transformation. In effect, the very bending compliance that makes SMAs attractive for applications also creates experimental difficulties.

A number of researchers have built custom devices to apply pure bending moments to SMA wires with negligible shear and axial loads, but each study has certain limitations. Berg (1995a) performed one of the first pure bending studies on SMA wires in the published literature. Berg's work is notable because he bent his specimens roughly twice as far as other researchers, and he used an optical microscope to measure the curvature (κ) rather than relying on the grip rotation. In Berg's fixture the bending moment (M) was applied by hanging weights, resulting in a moment-controlled experiment. Unfortunately, this control mode was unstable when $\mathrm{d}M/\mathrm{d}\kappa$ was close to zero, so gaps exist in Berg's data when this occurred. Furthermore, it is well known that the strain rate (especially in uniaxial tension) has a significant impact on the stress–strain response during the A→M and M→A transformation (e.g. Chang et al., 2006). Consequently, the bending response depends on the curvature rate, but as Berg acknowledged, his fixture had little control over this quantity. In other work, Bundara et al. (2000) also constructed a custom pure bending fixture, where the moment was applied to SMA wires by hanging weights. The moment curvature relation they measured was not as flat as Berg's, so they were able to capture more data points, but the strain rate still was not controlled. Rejzner et al. (2002) avoided this problem by building a displacement-controlled custom pure bending fixture that integrated directly into a load frame, but this design suffered from friction and imparted a small axial load on the specimen. The axial load was considered negligible by the authors and a friction correction was made, but the method was somewhat unclear to us. Furthermore both Bundara et al. (2000) and Rejzner et al. (2002) measured the curvature from the rotation of the grips, and bent their specimens roughly half as far as Berg, such that the outer fibers did not fully transform to martensite.

In this study, we sought to combine some of the best features of the previous studies and add new measurement capabilities.

1. Instead of wires, NiTi tubes with a larger outer diameter were used to accommodate large bending deformations without requiring an extremely small radius of curvature. Although not used in the experiments shown here, this also allowed us to flow fluid within the tube to perform experiments at various temperatures while leaving the outer specimen surface unobscured for infrared or optical imaging (see Churchill, 2010).
2. A custom pure bending fixture was built and integrated into a tensile testing machine, facilitating rotation-controlled experiments under large displacements and rotations.