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Technical Note

Buckling of tubular superelastic shape memory alloy shafts

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1. Introduction

Owing to stress-induced martensitic transformation (SIMT), superelastic shape memory alloy (SMA) shows the unique capability of shape recovery from a largely deformed state when the mechanical load is withdrawn. The typical hysteresis loop known as pseudo-elasticity or superelasticity (SE) is shown in Fig. 1. The SIMT is actually a solid-solid, diffusion less phase transformation process from the parent austenite phase to product martensite phase. Four transition temperatures typically mark SIMT: martensite finish (M_f), martensite start (M_s), austenite finish (A_f), and austenite start (A_s) (Otsuka and Wayman 1998).

A number of studies, concerning superelastic SMA beams, columns and shafts are reported in the literature; a few are listed in the references (Rejzner *et al.* 2002, Rahman *et al.* 2001, 2005, Tokuda *et al.* 2000, Raniecki *et al.* 1999). Especially, in the previous study (Rahman *et al.* 2006), it was rigorously demonstrated that having highly nonlinear torque-angle of twist relations, the slender solid SMA shafts are found to buckle easily when the critical twisting moment is exceeded (unlike a stainless steel (SUS304) shaft having the same slenderness ratio). Moreover, under increasing torsional load, the resulting stress distribution over the solid superelastic SMA shaft's cross-section can be non-uniform, with its core being austenitic. Beyond this austenitic core, the shaft material will be in the mixed phase or in the SIM phase (Rahman *et al.* 2006). Obviously, there may not be any austenitic core at all, if the shaft is tubular. Therefore, torsional buckling for the tubular shafts is here studied exclusively.

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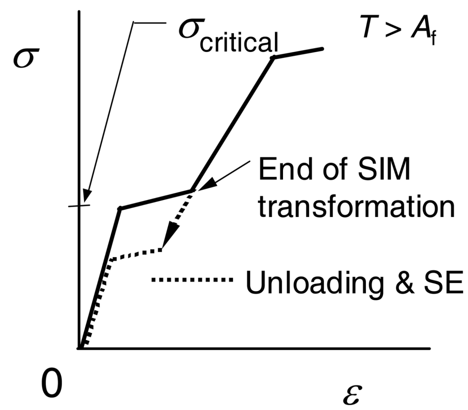

Fig. 1 Idealized stress-strain diagram of the superelastic SMA

2. Experiment

Particulars are as follows for the experiments: specimens made of superelastic SMA tubes (OD = 1 mm, ID = 0.8 mm), the test temperature range was 23ºC-26ºC. An Instron machine was used and the speed during torsional loading-unloading cycle was 1rpm. According to the supplier data, the specimens have chemical composition (Ni54-58%, Ti balance). Though the transformation temperatures and other physical properties are not stated, the specimens distinctly exhibit superelasticity for the test conditions as shown later on.

For shafts fixed at both ends, the critical twisting moment is given by $2.861\pi\, EI/L$, where, EI is the flexural stiffness and L is the unsupported length of the shafts (Rahman *et al.* 2006). Since the slender shafts are likely to buckle in the austenite/mixed phase, the corresponding elastic stiffness governs the buckling load. As those physical properties (elastic stiffness) are not readily available for the tubes (and of course, difficult as well to determine by experiment because of small sized specimens) used in this study, the torsional buckling load is demonstrated by a series of experiments. Following the method in the previous study (Rahman *et al.* 2006) the torque-angle of twist data is continuously obtained from the machine, while snaps were taken from a digital camera at different state of loading in order to identify and demonstrate the postbuckled shapes. It is noteworthy that the same method was successfully used in the previous study (Rahman *et al.* 2006).

Since torsional buckling is concerned, it is quite difficult to continuously trace the load-transverse deflection curve for an element on the shaft and find the buckling load from those curves. It is because an element on the shaft rotates continuously and at the same time may move in any direction as soon as instability starts. Therefore, a digital camera was used following our previous study to demonstrate that the shape of the deformed SMA shafts changes notably in the vicinity of the buckling loads.

Before the tests, the straightness of specimens was checked. Moreover, buckling was observed for at least three different specimens of the same slenderness ratio. The perfect alignment of fixtures was also ensured. The above steps were necessary since buckling phenomenon is imperfection sensitive. Results are presented for two highly slender shafts with an unsupported length (L) of 90 mm.

3. Results and discussion

To identify the buckled shapes and the failure pattern the specimen number 2 was loaded until failure. Fig. 2 presents the snaps taken at different states of loading. Fig. 2(a) shows the straight configuration of the shaft at 0 Nm. For increasing loading, the shaft buckles and at a load of 0.17 Nm its profile appears to be sinusoidal (Fig. 2(b)). Upon further loading another postbuckled

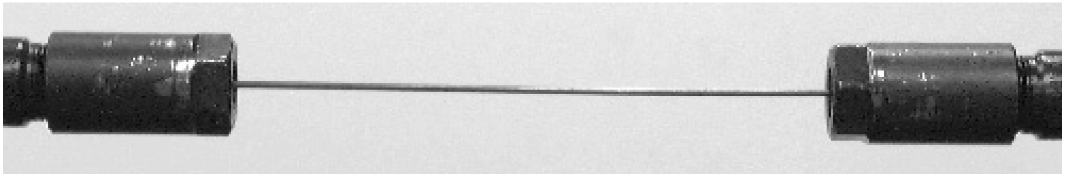

Fig. 2(a) straight hollow shaft before loading

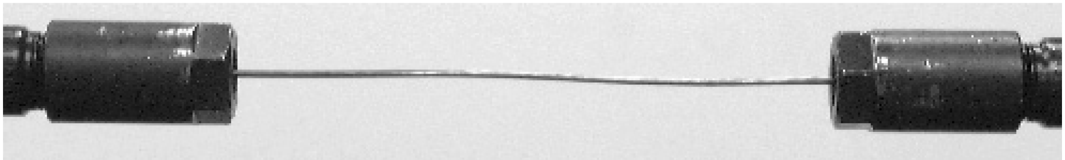

Fig. 2(b) Buckled shape at 0.17 Nm

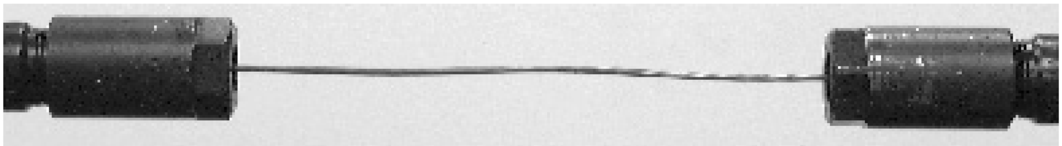

Fig. 2(c) Buckled shape at 0.19 Nm

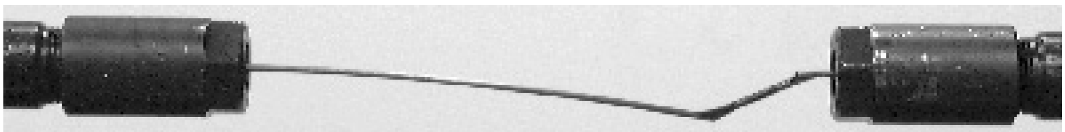

Fig. 2(d) Fractured hollow shaft

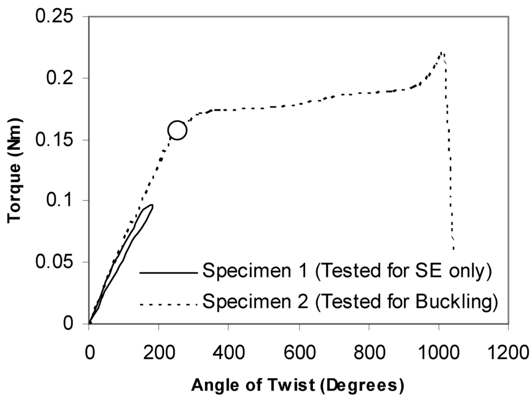

Fig. 3 Load-deformation curve for two different tubular shafts ($L = 90$ mm), critical load indicated by a circle

shape can be seen from Fig. 2(c). Fig. 2(d) shows the fractured tubes due to excessive postbuckling deformation. It appears the tubular superelastic SMA shaft behaves as fibrous material. The shaft fails at 0.22 Nm corresponding to an angle of twist of 1040^o. Fig. 3 shows the corresponding torque-angle of twist curve for the concerned tubular shaft. The SMA's superelasticity at test conditions can also be verified for a different specimen (number 1) from this Fig. 3. Regarding the effect of temperature on the buckling load of specimens, interested readers may refer to Rahman (2001) and Rahman *et al.* (2006), where it was demonstrated through experiments that if the room temperature do not change drastically, the shafts buckling response are not likely to change.

4. Conclusions

Stress distribution over its cross-section is completely different for a tubular shaft from that for a solid shaft particularly if the shaft material is superelastic SMA. This is because of the fact that for this functional material the torsional strength increases nonlinearly for increasing strain. Commercial superelastic SMAs, however, usually have low Young' modulus at room temperature (austenite phase), that results in low torsional buckling load. As a result, under pure torsion the slender tubular SMA shafts are found to buckle when the critical twisting moment is exceeded.

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