3D CONFINED PROGRAMMING AND FREE SHAPE RECOVERY OF A SMP BASED SYNTACTIC FOAM

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Abstract:

A recent development in shape memory polymers (SMPs) is the use of the shape memory functionality for self-healing structural-length scale damage such as impact damage. It is found that compressive programming and confined shape recovery can seal (close) macroscopic damage such as macrocrack repeatedly, efficiently, and almost autonomously (the only human intervention is by heating) [1,2]. One-dimensional (1D) compressive stress-controlled programming and strain-controlled recovery, free-recovery, and stress-controlled recovery were investigated by Li and Nettles [3]. Again, it is found that, even partially confined shape recovery can close macroscopic cracks. In another study, a thermodynamic based constitutive model has been developed, which provides predictive capability for this type of SMP based syntactic foam [4].

As discussed previously [2-4], it is realized that confinement during programming is the key for the SMP based syntactic foam to possess self-sealing capability. From an application point of view, inherent confinement can be found in some lightweight structures such as sandwich structure (syntactic foam core partially confined by the skins) [1], syntactic foam core confined by a grid skeleton in the in-plane direction and by the skin in the transverse direction [5,6], and 3D woven fabric reinforced syntactic foam panels [2]. Therefore, it is desired to understand the effect of various confinements on the thermomechanical behavior and shape recovery of this SMP based syntactic foam so that it can be properly designed and used in these lightweight composite structures.

The purpose of this study is to investigate the effect of lateral confinement on the thermomechanical behavior as well as on the shape recovery ratio of this syntactic foam. To this end, 3D confined and strain-controlled compression programming with varying lateral confinement (from zero lateral confinement to almost rigid lateral confinement) and free shape recovery were conducted on a SMP based syntactic foam consisting of multiwalled carbon nanotubes. Uniaxial compression test was also conducted to determine the stress-strain behavior. In addition, volume change after programming was determined for specimens without lateral confinement. The effect of the lateral confinements on the thermomechanical behavior and shape recovery ratio was evaluated based on the test results.

The raw materials used in this study were similar to the ones used in [1]. The shape memory polymer (*Veriflex* polystyrene, CRG industries) has a T_g of 62°C, tensile strength of 23MPa and modulus of elasticity of 1.24GPa at room temperature. Glass microballoons (Potters Industries Q-cel 6014) have a bulk density of 0.08g/cm^3, effective density of 0.14g/cm^3, particle diameter range of 5 - 200μm, average outer diameter of 85μm, average wall thickness of 0.8μm, and crushing strength of 1.72MPa. Multi-walled carbon nanotubes (Cheap Tubes Inc.) have a density of 2.1g/cm^3, diameter of 20-30nm, and length of 20-30μm. The foam was prepared by dispersing 40% by volume of microballoons and 0.15% by volume of carbon nanotubes into the SMP matrix.

Two types of specimens, cylindrical specimens for 3D confined compression and block specimens for tests without lateral confinement, were prepared. Double-walled cylindrical tubes were prepared for providing varying lateral confinement to the cylindrical specimens. Due to the lateral confinement, uniaxial compression created 3D compressive stress condition within the specimens, similar to fiber reinforced polymer (FRP) tube confined concrete cylinders [7,8].

Uniaxial, isothermal compressive stress-strain test was conducted at both room temperature and 79°C. It is found that the stress-strain behavior at room temperature is similar to conventional polymer based syntactic foams [9-11]. Strain-controlled programming with three prestrain levels (5%, 30%, and 60%) was conducted and the programming temperature was 79°C. A typical axial stress - axial strain - temperature representation during programming is shown in Fig. 1.

After programming, a free shape recovery test was conducted for all the programmed specimens. The shape recovery ratio is summarized in Table 1. In addition, volume change at the end of programming for the specimens without lateral confinement was also conducted.

Based on the testing results, the following conclusions are obtained:

- Under 3-D compressive confinement, the strain-controlled programming can be represented by two typical steps, instead of three steps. The cooling and unloading are integrated into one step.
- With higher lateral confinement such as steel liner and nylon liner, the cooling step during programming can be further divided into three distinct regions dominated by different deformation mechanisms.
- At the same programming temperature (79^{o}C), the strain recovery ratio depends on the type of liners and the prestrain levels. For the parameters investigated in this study, specimens without lateral confinement leads to the highest shape recovery ratio. Also, higher prestrain leads to lower recovery ratio.
- While the volume reduction for the pure SMP during programming is pretty much independent of the prestrain level, the volume reduction of the foam reduces as the prestrain level increases, due to the crushing and densification of the microballoons.
- Because the self-sealing capability of this foam depends on the shape recovery ratio, it is suggested that the lateral confinement during programming should be within a certain limit; otherwise, the shape recovery ratio and the self-healing capability will be reduced.

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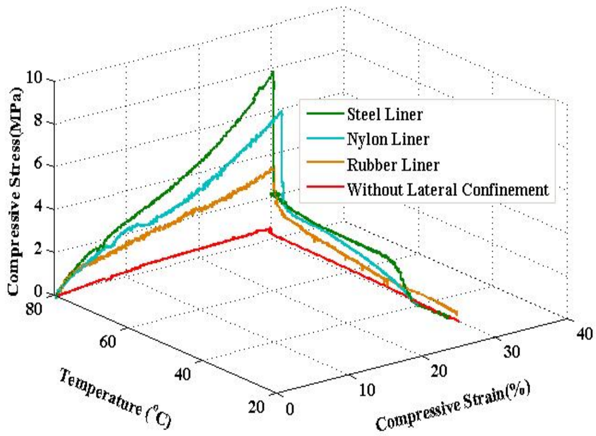

Fig.1 Programming of the foam with various confinements

Table 1. Free recovery ratio of the SMP foam

Liner type in the double-walled confining tubes	Prestrain level (%)	Free shape recovery ratio (%)
Steel liner	5	81.7±4.51
	30	68.76±4.62
	60	62±12.02
Nylon liner	5	93.35±1.2
	30	79.9±0.64
	60	71.97±3.04
Rubber liner	5	82.22±3.84
	30	79.13±5.42
	60	68±1.73
Without confinement	5	100±0.01
	30	86.6±1.37
	60	84.3±0.17