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Enhanced filler-tube wall interaction in liquid nanofoam-filled thin-walled tubes

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ABSTRACT

Interfacial bonding is essential to the mechanical properties of foam-filled tubes, but the imperfection in the solid–solid interfacial bonding limits the filler-tube wall interaction, leading to reduced performance. Here, we have employed liquid nanofoam (LN) as a novel filling material in thin-walled tubes, creating a liquid–solid "interfacial bonding". The crushing behavior of LN-filled tube (LNFT) has been characterized by quasi-static compression and dynamic impact tests. Results show that the strengthening coefficient of the LNFTs was 3.8, much higher than that of best solid foam-filled tubes. The improved reinforcement effect indicates that the filler-tube wall interaction is much enhanced at the liquid–solid interface, which demonstrates the "perfect bonding" between LN and the tube wall. These findings provide new concepts in designing novel composite materials and structures.

1. Introduction

Interfacial bonding is of fundamental importance to the performance of composite materials and structures, such as fiber reinforced polymeric composites [1], laminated composite structures [2,3], honeycomb sandwich structures [4], hydrogel-elastomer hybrid materials [5], among others. Tailoring the interfacial bonding between different components in the composites provides exquisite control of their mechanical [6], thermal [7], electrical [8] properties and environmental stability [9]. In particular, interfacial bonding between the tube wall and the filler material in foam-filled thin-walled tube plays an important role in its crushing performance. Thin-walled tubes have been widely used as energy absorbing devices in crashworthiness applications due to their light weight, low cost and high energy absorption capacity [10,11]. To improve the mechanical properties and energy absorption capacity of thin-walled tubes, researches have been focused on reinforcing the empty tube by metallic foam fillers [12–17]. Santosa et al. [18] investigated the reinforcement effect of interfacial bonding by numerical simulations and found that the presence of adhesive bonding can increase the average post-buckling strength of foam-filled tubes by enhancing filler-tube wall interaction. Furthermore, they experimentally demonstrated that the foam strengthening coefficient increased from 1.8 to 2.8 as the adhesive was applied [19], which was further confirmed by Toksoy et al. [20] and Bonaccorsi et al. [21].

The interfacial bonding between the foam and the tube wall can be achieved by two different methodologies, either by applying an adhesive or by direct foaming inside the hollow tube. Although adhesive can create bonding at the interface, the curing process is either time-consuming [19,20] or require additional heat treatment [22]. Direct *in situ* foaming can facilitate the formation of interfacial bonding during the foaming process. However, the performance of the filled tube has large variation due to poor quality control and process-induced structural defects [21]. Importantly, the interfacial bonding created by both methods inevitably contains imperfections, leading to a lower post-buckling strength of foam-filled tubes than theoretical value [18].

Another promising method to produce interfacial "bonding" between the filler and the tube wall is to employ liquid fillers. Due to their intrinsic high fluidity, liquids fit well with the tube wall shape, resulting in "perfect bonding" at the liquid–solid interface. Consequently, the filler-tube wall interaction can be stabilized, and the tube wall is reinforced during the complete deformation process. However, as most liquids are nearly incompressible, the reinforcement effect will be at the cost of total deformability of the system.

In the last decade, a highly compressible liquid-based system, liquid nanofoam (LN), was developed for high-performance of protection [23–28]. In the LN, hydrophobic nanoporous particles are dispersed in a non-wettable liquid phase. Due to the capillary effect, the hydrophobic nanopores remain empty at ambient condition. As sufficient load is applied, the capillary resistance is overcome and the liquid molecules are forced into the nanopores. Due to the ultra-large surface

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area of nanoporous materials, tremendous amount of energy can be absorbed [29]. Given these advantages, LN is a promising filler for thin-walled tubes. Recently, a few investigations have been conducted with regard to the quasi-static [30,31] and dynamic [32] behaviors of LN-filled tube (LNFT). However, the dominant reinforcing mechanism, e.g. the liquid–solid interaction between LN and the tube wall, remains unclear. In this study, we systematically examine the underlying mechanism of the strengthening effect of the LN on thin-walled steel tubes. We experimentally demonstrate that "perfect bonding" between the LN and the tube wall leads to much enhanced liquid–solid interaction. We also validate that the liquid–solid interaction increases the strain rate sensitivity of LNFTs under dynamic impacts.

2. Material and methods

2.1. Materials and sample preparation

The thin-walled stainless steel tube (304F10500X006SL, MicroGroup) used in this study had outer diameter (*D*), wall thickness (*t*) and height (h_0) of 12.7 mm, 0.15 mm and 25.4 mm, respectively. The thin-walled stainless steel tube was filled with different fillers, i.e. water or LN. The water-filled tube was prepared by completely filling the tube with deionized water, while the LNFT was filled with a pre-compressed LN to minimize the amount of air bubbles trapped in the LN. After filling, the steel tubes were sealed by two metal endcaps using epoxy adhesive (50112, J-B Weld). Fig. 1 shows a representative LNFT sample. The effective height of the tube between the two endcaps (*h*) was 20.3 mm. During all experiments, no liquid leakage was observed before tube wall burst. Empty steel tube sealed by the same endcaps was used as reference.

The LN used in current study contains a nanoporous silica and DI water. The nanoporous silica (60759, Sigma-Aldrich) was denoted as SG90. The particle size and average nanopore size of it were 40–63 µm and 7.8 nm [33], respectively. The as-received SG90 had modified surface, which was non-wettable to water.

2.2. Test procedures

The mechanical behavior of empty, water-filled, and LN-filled steel tubes were characterized by a series of quasi-static compression and drop weight impact tests. At least three specimens were tested for each type of tubes. The quasi-static compression tests were conducted by an Instron 5982 universal tester at a constant speed of 2 mm/min (Fig. 2a). The nominal stress is calculated as

$$\sigma = F/A \tag{1}$$

where *F* is the external force applied by the Instron machine and *A*, is the cross-sectional area of steel tubes. The nominal strain is calculated as

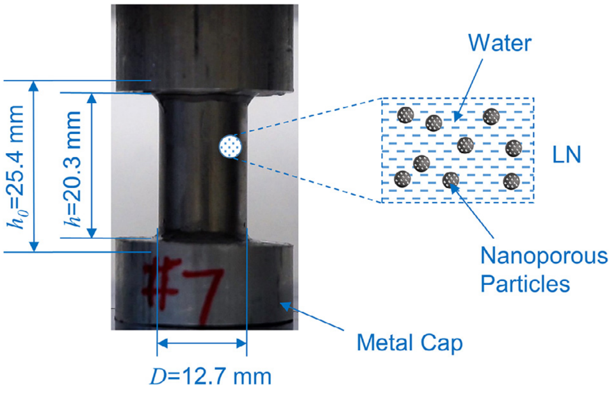

Fig. 1. A Typical LNFT sample.

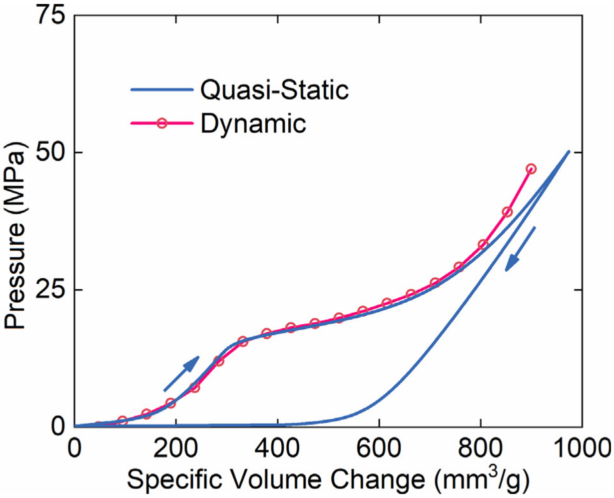

Fig. 2. Schematic of the experimental set-up of (a) quasi-static compression tests (b) dynamic impact tests.

$$\varepsilon = \delta/h \tag{2}$$

where δ is the crosshead displacement.

The dynamic behavior of the steel tubes was characterized by a lab-customized drop tower apparatus (Fig. 2b). The impact speed of all dynamic tests, *v*, was maintained at 3.0 m/s by fixing the free drop height at 0.45 m. An accelerometer (353B03, PCB Group, Inc.) was attached to the 10 kg drop weight to measure the deceleration time-history which was recorded by a high-speed digitizer (PXIe-5105, NI Corp.) at the sampling rate of 10^6 samples/s. The nominal stress is calculated as

$$\sigma = m_w \times a(\tau)/A \tag{3}$$

where m_w is the drop weight and $a(\tau)$, is the measured deceleration of the drop weight at time τ. The displacement is calculated as

$$\delta = \int\int a(\tau)d^2\tau \tag{4}$$

The incident speed is confirmed by calculating

$$v = \int a(\tau)d\tau \tag{5}$$

3. Results

3.1. Liquid infiltration behavior of the LN

The solid curve in Fig. 3 shows a typical quasi-static mechanical behavior of the LN. As the LN was compressed at low pressure, the initial system volume change was slow. When the applied external pressure was in the range of 15 MPa and 30 MPa, a sudden volume change was observed, which indicated that liquid molecules were compressed into nanopores as the capillary effect of the hydrophobic nanopore surface was overcome. The total 0.55 cm^3/g specific volume

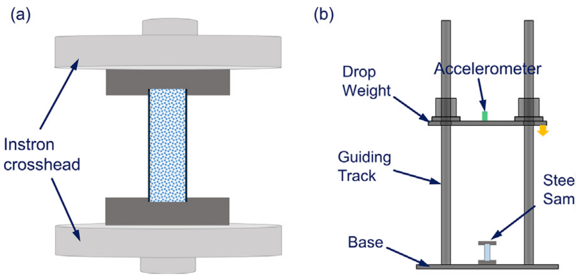

Fig. 3. Typical sorption isothermal curves of LN.