Chapter 13
Enhanced Structural Imperfection Resistance in Thin-Walled Tubes Filled with Liquid Nanofoam

Mingzhe Li, Fuming Yang, and Weiyi Lu

Abstract Thin-walled structures have been widely used in automotive and aerospace industries to improve the system crashworthiness and impact protection. However, during manufacturing, transporting and handling processes, initial geometric imperfections are inevitably introduced to the thin-walled structures, which imposes negative impacts to the mechanical performance and service life of the thin-walled structures. In this study, we have introduced structural imperfection with controlled geometry and dimension to thin-walled steel tubes and characterized the mechanical response of these empty tubes and LN-filled tubes by quasi-static compression tests. Results show, the structural imperfection reduces the energy absorption capacity of empty tubes by about 20%. As the tube is filled with LN, the structural imperfection does not affect the energy absorption capacity of LN filled tube. The enhanced imperfection resistance is attributed to the suppression of imperfection growth caused by the strong liquid-solid interaction between the LN and tube wall. These findings suggest that the LN filling material can effectively reduce the adverse impact of structural imperfection and shed light on future design of thin-walled energy absorption devices.

13.1 Introduction

Thin-walled structures have been widely used in automotive and aerospace industries to improve the system crashworthiness and impact protection due to its light weight and good energy absorption performance [1]. For instance, thin-walled alloy structures have been fabricated to function as rocket engine thrusters at higher temperature [2]. However, during the processes of manufacturing, transporting and handling of thin-walled structures, initial structural imperfections are inevitably introduced, which imposes adverse impacts to the mechanical performance and service life of the thin-walled structures. For example, dent imperfections have led to 33% reduction of the load carrying capacity of thin-walled tubes [3]. While the buckling behavior of dented thin-walled structures have been thoroughly studied [4–6], approaches to mitigate the negative effect of these structural imperfections on thin-walled structures are still lacking.

Recently, a novel hybrid thin-walled structure, namely liquid nanofoam-filled tube (LNFT), is designed with considerably enhanced energy absorption density compared to solid foam-filled tubes [7, 8]. The significantly improved energy absorption capacity of the LNFT is due to much-enhanced liquid-solid interaction at the LN-tube wall interface as well as the mechanical response of the liquid nanofoam (LN) filler. The intrinsic fluidity of the LN filler creates a nearly perfect liquid-solid "bonding" at the interface and results in a much higher strengthening effect of the LNFT. Thus, the LN, endowed with the unique liquid-solid interaction, is a promising filler to reduce or even eliminate the adverse effect of structural imperfections on the mechanical performance of thin-walled structures.

The LN is composed of hydrophobic nanoporous material and a non-wettable liquid [9–11]. Due to the surface hydrophobicity of nanoporous particles, the liquid molecules cannot go into the nanopores spontaneously at ambient condition. As an external pressure is exerted and reaches a critical value, the energy barrier is overcome and the liquid molecules are continually driven into the nanopores. The mechanical energy is then converted to the liquid-solid interfacial energy at the liquid-nanopore wall interface. Since the nanoporous materials possess ultra-high nanopore surface area (~100–1000 m^2/g [12]), massive amount of energy is mitigated.

In this study, we examine the suppression effect of LN on thin-walled tubes with structural imperfection. Dents with controlled depths have been introduced to the thin-walled tubes and quasi-static compression tests have been performed on the

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hybrid thin-walled tubes to evaluate their energy absorption performance. Results show the negative impact of dent on thin-walled tubes is well suppressed by the LN filler.

13.2 Method

Thin-Walled Tube The stainless steel thin-walled tube used in current study was purchased from Microgroup (No. 304F10500X006SL). The radius, wall thickness and height of the tube samples are 6.35, 0.15 and 25.4 mm, respectively. Dent with depth *d* of 1.5 mm was created on the thin-walled tube by a V-shaped wedge (Fig. 13.1).

LN Filler The LN contained a hydrophobic silica gel and water. The silica gel was purchased from Sigma Aldrich (No. 60759). The particle size and average nanopore size were 40–63 μm and 7.8 nm. The LN filler was consisted of 0.5 g silica gel and 1 g water. The air inside the LN filler was minimized by pre-compression. The mechanical behavior of LN was characterized by pressure-induced infiltration test (Fig. 13.2). The details was reported in ref. [13].

LNFT Sample Preparation The LN filler was added into the thin-walled tube and sealed by attaching both ends with two metallic caps by a J-B Weld 50,112 epoxy adhesive (Fig. 13.3). The effective height of the tubes was about 20 mm. Uniaxial quasi-static compression tests were conducted on LNFTs by a 5982 Instron universal tester. The loading speed was 2 mm/min. No liquid leakage from either end was observed during all compression tests.

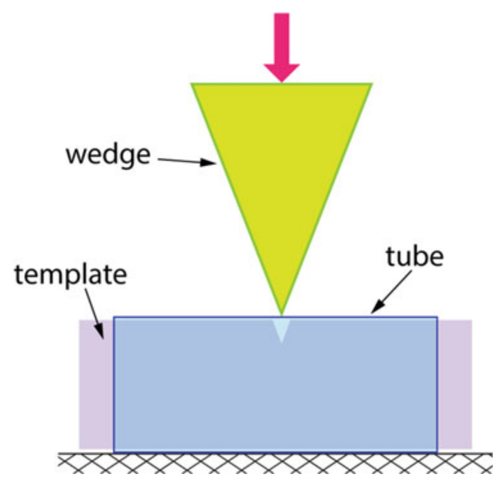

Fig. 13.1 Schematic of the dent creation on thin-walled tube

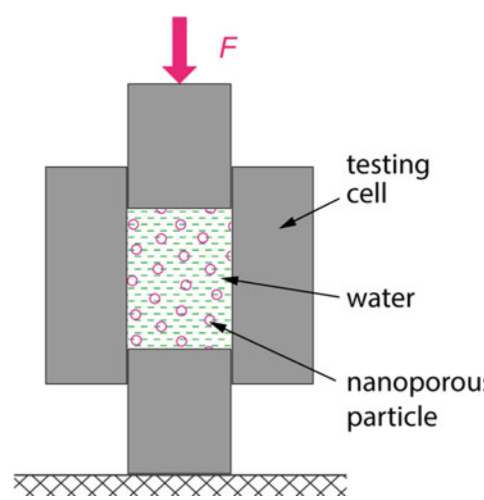

Fig. 13.2 Schematic of the pressure-induced infiltration test

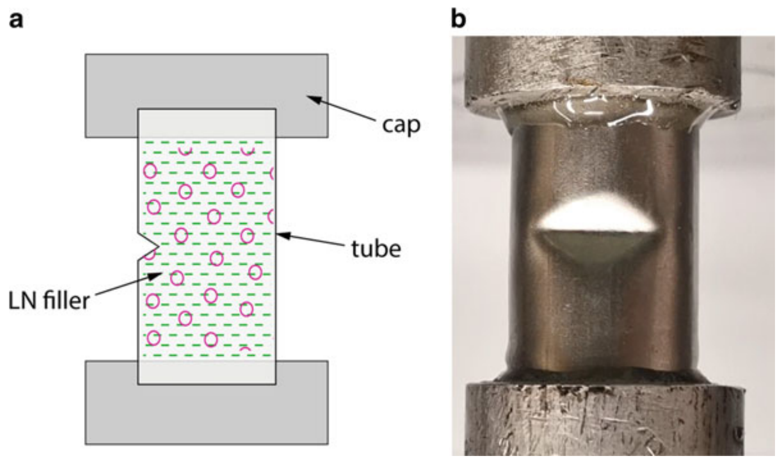

Fig. 13.3 (**a**) Schematic of dented LNFT sample (**b**) as-prepared dented LNFT sample

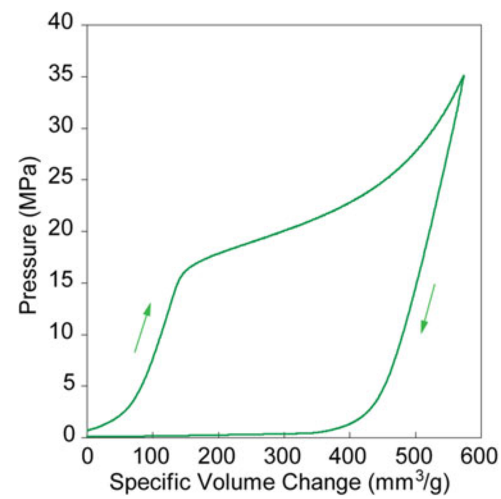

Fig. 13.4 Mechanical behavior of LN

13.3 Results

Mechanical Behavior of LN Figure 13.4 shows typical mechanical response of LN. When an external pressure is applied, the LN behaves elastically at the beginning. As the pressure rises to 18 MPa, the slope of the curve shows large reduction. This is due to the water molecules being driven into the nanopores. The system compressibility increases dramatically and a stress plateau is observed. The plateau ends as all the nanopores are filled with water molecules. The average pressure of the plateau is defined as the infiltration pressure of the LN, P_{in}. Here, $P_{in} = 22$ MPa. The width of the stress plateau is determined by the nanopore volume of LN, $V_n = 430$ mm^3/g. As the pressure is removed, the pressure drops quickly. The highly hysteric behavior of LN indicates massive mechanical energy is mitigated.

Reinforcement Effect of LN on Thin-Walled Tube Figure 13.5 shows typical mechanical response of empty tube and LNFT without dent under quasi-static compression test. The empty tube shows an elastic behavior initially. As the force reaches 1600 N, the tube wall buckling is triggered. The force quickly drops after buckling initiation and forms a low post-buckling force plateau. The average force of the plateau, F_0, is around 600 N. As the tube is filled with LN, the initial response is quite close to that of empty tube due to the air trapped inside. As the displacement reaches 2 mm, the internal pressure is sufficient and the LN starts to take effect. The force quickly rises to 1300 N and a broad force plateau is observed. The width of the plateau is related to the nanopore pore volume of the LN as well as the deformability of the tube material. As the displacement reaches 12 mm, the tube wall cracks and the force suddenly decreases to about 400 N. The average force of the LNFT is approximately 2300 N, much higher than that of empty tube.

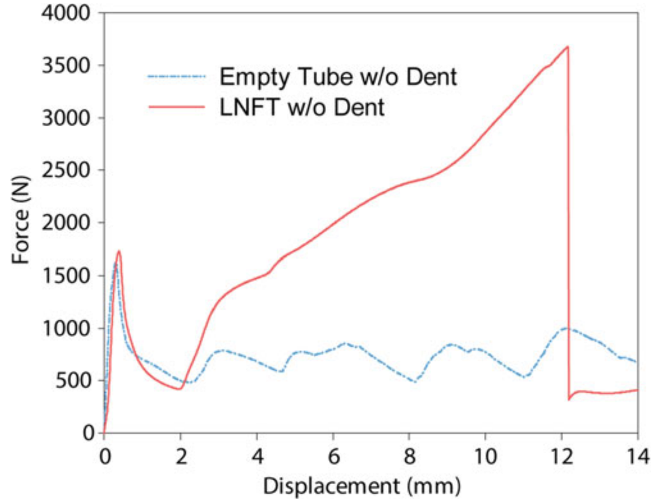

Fig. 13.5 Mechanical behavior of empty tube and LNFT without dent

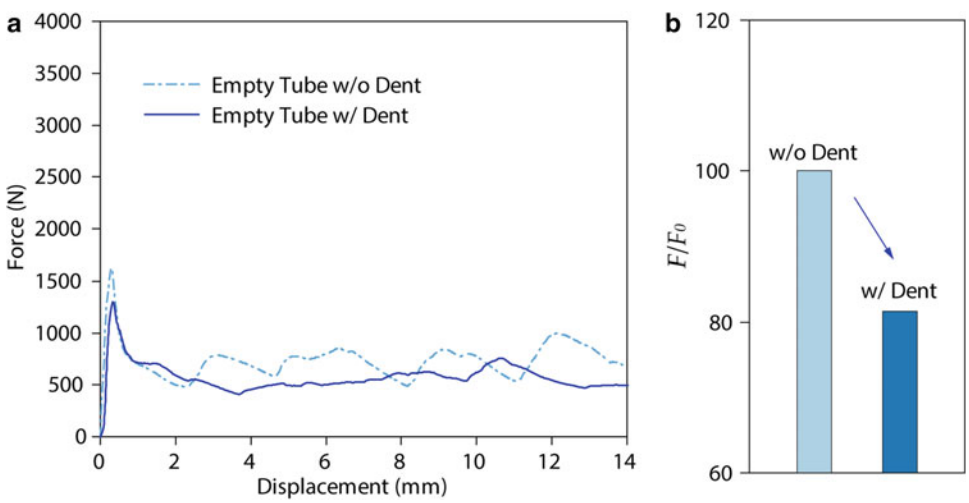

Fig. 13.6 (**a**) Mechanical behavior of empty tubes (**b**) negative effect of dent on empty tube

Negative Effect of Dent on Empty Tube Figure 13.6 shows typical mechanical response of empty tubes. As dent is introduced into the empty tube, the buckling initiation force is reduced from 1600 N to about 1250 N (Fig. 13.6a). The post-buckling force plateau becomes flatter and exhibits a much lower average force around 500 N. The reduced buckling initiation force as well as the lower post-buckling force plateau lead to the reduction of the energy absorption performance. As shown in Fig. 13.6b, the mechanical performance is reduced by about 20%.

Suppression Effect of LN filler on Structural Imperfection Figure 13.7 shows typical mechanical response of LNFTs. When dent is introduced into the LNFT, the buckling initiation force is also slightly reduced (Fig. 13.7a). As the buckling further progresses from 1to 2 mm, the force level is higher than that of intact LNFT. This is due to the plastic hinge inhibition effect in the buckling pattern. The beginning and ending points of the broad force plateau of dented LNFT are exactly the same as that of intact LNFT. While the first half of the force plateau is similar to that of intact LNFT, the force level of the second half of the force plateau shows slight increase, which further promotes the energy absorption performance of the hybrid thin-walled structure. As shown in Fig. 13.7b, compared to intact LNFT, the mechanical performance of dented LNFT is slightly increased. The enhanced imperfection resistance is attributed to the suppression of imperfection growth caused by the strong liquid-solid interaction between the LN and tube wall.

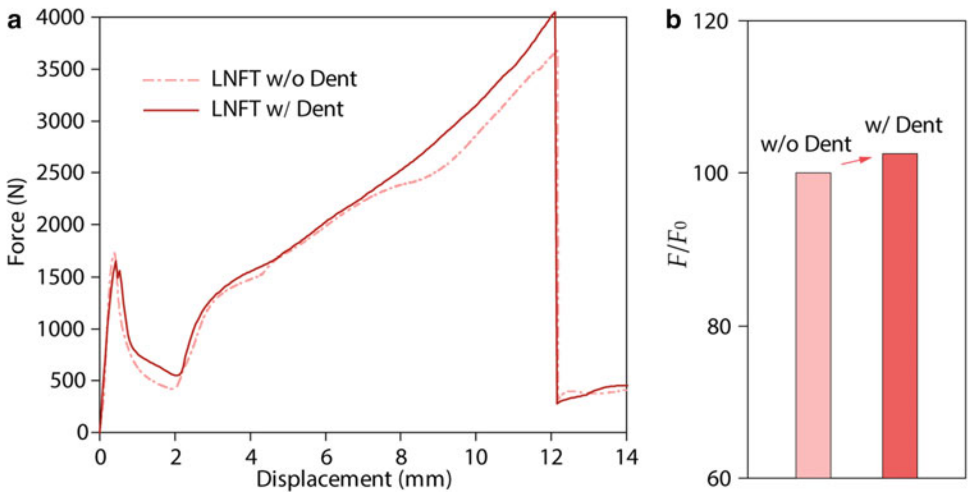

Fig. 13.7 (**a**) Mechanical behavior of LNFTs (**b**) suppression of the negative effect of dent on thin-walled tubes by LN filler

13.4 Conclusion

In this study, we have presented a promising solution to suppress the negative effect of structural imperfection on the mechanical performance of thin-walled tubes. The proposed solution employs a liquid filler, LN, in the thin-walled tube. Based on the quasi-static compression testing results of empty tube and LNFTs, we have demonstrated:

1. The thin-walled tube is reinforced by adding LN as a filler;
2. The mechanical performance of empty tube is significantly reduced as dent exists;
3. The negative impact of structural imperfection on thin-walled tube is mitigated by the LN filler.

In short, LN is a promising filling material in thin-walled tube, leading to a hybrid structure with enhanced structural imperfection resistance. The findings provide guidance on the design of composite structures for vehicle crashworthiness.

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References

1. Baroutaji, A., Sajjia, M., Olabi, A.G.: On the crashworthiness performance of thin-walled energy absorbers: recent advances and future developments. Thin-Walled Struct. **118**, 137–163 (2017)
2. Martin, J.H., Ashby, D.S., Schaedler, T.A.: Thin-walled high temperature alloy structures fabricated from additively manufactured polymer templates. Mater. Des. **120**, 291–297 (2017)
3. Ghanbari Ghazijahani, T., Jiao, H., Holloway, D.: Plastic buckling of dented steel circular tubes under axial compression: an experimental study. Thin-Walled Struct. **92**, 48–54 (2015)
4. Ferdynus, M., Kotełko, M., Urbaniak, M.: Crashworthiness performance of thin-walled prismatic tubes with corner dents under axial impact - Numerical and experimental study. Thin-Walled Struct. **144**, 106239 (2019)
5. Ghanbari Ghazijahani, T., Jiao, H., Holloway, D.: Experiments on dented cylindrical shells under peripheral pressure. Thin-Walled Struct. **84**, 50–58 (2014)
6. Prabu, B., Raviprakash, A.V., Venkatraman, A.: Parametric study on buckling behaviour of dented short carbon steel cylindrical shell subjected to uniform axial compression. Thin-Walled Struct. **48**, 639–649 (2010)
7. Li, M., Li, J., Barbat, S., Baccouche, R., Lu, W.: Enhanced filler-tube wall interaction in liquid nanofoam-filled thin-walled tubes. Compos. Struct. **200**, 120–126 (2018)
8. Li, M., Barbat, S., Baccouche, R., Belwafa, J., Weiyi, W.: Enhanced energy absorption performance of liquid nanofoam-filled thin-walled tubes under dynamic impact. In: Lamberson, L. (ed.) Dynamic Behavior of Materials, Volume 1. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham (2020)

9. Li, M., Lu, W.: Liquid marble: a novel liquid nanofoam structure for energy absorption. AIP Adv. **7**, 055312 (2017)
10. Li, M., Lu, W.: Adaptive liquid flow behavior in 3D nanopores. Phys. Chem. Chem. Phys. **19**, 17167–17172 (2017)
11. Li, M., Xu, L., Lu, W.: Nanopore size effect on critical infiltration depth of liquid nanofoam as a reusable energy absorber. J. Appl. Phys. **125**, 044303 (2019)
12. Zhang, Y., Li, M., Gao, Y., Xu, B., Lu, W.: Compressing liquid nanofoam systems: liquid infiltration or nanopore deformation? Nanoscale. **10**, 18444–18450 (2018)
13. Xu, L., Li, M., Lu, W.: Effect of electrolytes on gas oversolubility and liquid outflow from hydrophobic nanochannels. Langmuir. **35**, 14505–14510 (2019)