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In situ strengthening of thin-wall structures using pressurized foam

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HIGHLIGHTS

- We investigated the effect of pressurized foam on strengthening thin-wall structures.
- The gap-sealing foam results in enhanced load carrying capacity of the original structure.
- We performed experiments on thin-wall beverage cans as well as aluminum honeycombs.
- Peak load and energy absorption are significantly enhanced.
- Potential applications in multiple-use energy absorbing components.

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ABSTRACT

A simple and effective *in situ* method for strengthening or healing thin-wall structures is presented. In this method, a liquid-state gap-sealing foam is injected within the enclosed spaces of a structure. After injection it expands to fill and pressurize the cavities, then solidifies in few hours. The stiff pressurized foam enhances load carrying capacity both by supporting part of the load, and by retarding the buckling of thin-wall structural components. A simple demonstration of the proposed technique is provided by load-testing thin-wall beverage cans, and also both intact and damaged aluminum honeycomb, filled with commercially available gap-sealing polyurethane foam. By adding foam, the structures' peak load and energy absorption were significantly enhanced. The injected foam partially restored the original undeformed shape during unloading, highlighting the potential advantage to apply this method for multiple-use energy absorbing components.

1. Introduction

Recent developments in cost-effective production of thin-walled members and cellular materials have encouraged their exploitation in light-weight structures [1–3]. They are commonly used in energy absorbers and sandwich panels for increasing the crashworthiness of structures in automotive and aerospace structures, including modern military airframes, which would benefit from rapid repairability of local damage [4–8]. Additionally, cellular materials are widely used as threat-resistant sandwich panels for tactical protection [1,9–11], sound/thermal insulation [9,12], and heat transfer and active cooling [13–17]. As the use of thin-wall structures increases, establishing a cost-effective and easy way to reinforce them is increasingly needed.

In the design of energy dissipating systems, thin-walled circular metal tubes under axial loading conditions have been identified as highly efficient impact energy absorbing elements [18–20]. Many experimental and numerical studies have been conducted to determine the crushing behavior of such structures [7,18,21]. In several cases, viscous filler was used to increase the stability and energy absorption of thin-walled structures [9,19,20,22–27]. A summary of the results from the previous literature is presented in Tables 1 and 2, where strength is seen to increase along with (diameter)/(wall thickness), more than doubling for the truly thin-walled tubes. However, the response of the systems to repeated loading was not considered in the past literature. As part of this investigation, we studied multiple loading/unloading cycles of thin-walled tubes as well as thin-walled honeycomb, to provide

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Table 1
Literature results for axial crushing of foam filled circular tubes. Weight ratio denotes the ratio of the foam-filled tube weight to that of the empty tube. Strength ratio denotes the ratio of the peak crush load of the foam-filled tube to that of the empty tube. Energy absorption ratio is defined in a similar fashion.

Structural material	Foam	Thickness/diameter	Weight ratio	Strength ratio	Energy absorption ratio	Refs.
Aluminum	Pressurized compliant polyurethane	0.0015	2.14	2.83	5.77	This paper
Aluminum	Rigid polyurethane	0.0017	N/A	2.65	2.79	Reddy and Wall [19]
Aluminum	Extruded polystyrene foam sheets	0.012	1.10	N/A	1.12	Aktay et al. [20]
			2.21		2.32	
		0.014	1.13		1.10	
			1.17		1.41	
Glass-fiber/ epoxy	Rigid polyurethane	0.023	1.95	N/A	N/A	Harte et al. [22]
Aluminum	Alporas aluminum foam sheets	0.036	1.09	N/A	1.17	Zarei and Kroger [23]
			1.30		1.40	
			1.38		1.51	
			1.45		1.64	
			1.51		1.65	
			1.72		1.77	
			1.93		1.91	
Glass/polyester	Rigid polyurethane	0.045	N/A	1.56	1.07	Palanivelu et al. [24]
Aluminum	Foamable aluminum alloy	0.049	N/A	1.61	2.5	Hall and Ebil [25]

Table 2
Available literature for crushing response of foam filled cellular structures.

Structural material	Foam	Wall thickness (mm)	Weight ratio	Peak crush load ratio	Energy absorption ratio	Refs.
Aluminum	Pressurized compliant polyurethane	0.25	1.33	1.86	1.42	This paper
Aramide	TEEK-L polyimide-foam	0.25	N/A	1.5	N/A	Kuwabara et al. [26]
304 stainless	Closed-cell PVC foam	N/A	1	1.6–2.2	3–9	Vaziri et al. [9]
Aluminum	Pressurized polyurethane	1.56	N/A	1.5	N/A	Niknejad et al. [27]

insight into the typical mechanical behavior of thin-walled materials after reinforcement. In many such materials, the compressive response in quasi-static loading condition is characterized by three regimes: An initial elastic response, followed by a relatively flat extended stress plateau, and eventually a significant crushing regime which results in greatly increased stiffness [1,28,29]. Regular aluminum honeycombs with visible damage, exhibit significantly lower structural stiffness and strength, but injected foam improved their crushing behavior [30,31]. This method was followed for different types of structural damage, which permitted exploring the effects of local and global foam-infusion repair.

Here, we describe a simple method to strengthen and repair lightweight structures by injecting a liquid-state foam into the enclosed spaces or damaged areas of the structure. Upon injection, the foam expands to fill and pressurize spaces inside the structure. It hardens in few hours and contributes to the mechanical performance of the structural system by directly supporting part of the loading, and by reducing the lateral deformation and instability of structural components. This method can potentially be used for *in situ* strengthening of intact structural components and systems, or for reinforcing damaged parts of a structure. Simple demonstrations of the proposed technique are provided by load-testing thin-wall beverage cans, and also both intact and damaged aluminum honeycombs, that have been filled with commercially available gap-filling polyurethane foam. In Section 2, we present the single- and multi-cycle axial compressive behavior of aluminum beverage cans (a simple example of thin-walled circular tubes, which are identified as efficient impact energy absorbers in the literature [23–25]), along with the changes that result from being filled with pressurized foam. The fractional improvements to strength and energy absorption somewhat exceeded the fractional weight increase. We also examined foam's potential to repair or strengthen cellular structures, by in-plane experiments on aluminum honeycomb (which is often used to provide insight into cellular materials behavior and mechanics). Sections 3–5 describe the use of foam injection to reinforce hexagonal honeycombs with two different kinds of damage. Injection of foam in both sample types demonstrated a fractional increase in the peak strength and the energy absorption, consistent with the fractional increase in weight.

2. Crushing behavior of empty and filled thin-walled circular cylinder structures

Aluminum drink cans of 355 ml capacity, with dished bottoms and thicker sheet metal tops, were utilized for testing. The cylindrical portions were 66 mm diameter with 0.1 mm wall thickness, and 122 mm overall length. With the opening handle removed, the average weight of an empty can was 13.1 g. Some of these cans were partially filled (about 75% of volume) with 15 g of commercially available polyurethane foam sealant in the liquid state (GREAT STUFF™ Big Gap Filler, Dow Chemical Company, Midland, MI), and the opening was covered with adhesive tape. Thus, the weight of the can plus foam is approximately 2.15 times the can weight. (10 ml of water was also added during filling to facilitate foam curing in its virtually sealed container. The water is mostly not consumed, but simply runs off if the can is later opened, so we do not count it as part of the foam weight). The foam-filled cans were kept at room temperature for at least 24 h prior to testing to allow the foam sealant to expand and solidify. During the expansion and hardening phase small amounts escaped the adhesive tape while simultaneously curing, thereby blocking the opening and preventing the rest of the foam from escaping.

Some of the filled cans were reserved for testing, while others were opened with axial wall cuts to remove the cured foam specimens, which did not adhere to the can walls. These were observed to be somewhat imperfect, with occasional large voids and folds. After removal the cylinder diameters expanded approximately 4 mm (6%), which in combination with a modulus of order