Thin-Walled Structures 131 (2018) 417–427

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Snap-through buckling of fly ash cenosphere/epoxy syntactic foams under thermal environment

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ARTICLE INFO

Keywords:
Fly ash cenospheres
Syntactic foam
Snap-through buckling
Non-uniform heating

ABSTRACT

Experimental investigation on deflection behaviour of fly ash cenosphere/epoxy syntactic foam at room temperature and under thermal environment (three different heating conditions) is investigated. Influence of fly ash cenosphere volume fraction and nature of temperature variation on deflection behaviour of syntactic foam beam is discussed elaborately. Results reveal that the syntactic foam beam experience snap-through buckling under thermal environment and is reflected by two bifurcation points in temperature-deflection plot. It is observed that the time duration for which the foam beam stays in the first buckled position increases with increase in cenosphere content. Thermal environment induces compressive stresses in the samples causing such snap-through buckling. However, such phenomenon is not observed when mechanical compressive loads are applied under room temperature conditions. Temperature variation across the beam strongly influences snap-through buckling in syntactic foams in addition to volume fraction of filler content.

1. Introduction

In the design process of automobile, aircraft and marine structural components, it is important to investigate their behaviour under thermal loading condition, as weight requirements initiate designers to develop thinner and lighter structures. The development of newer materials necessitates to explore the suitability of thinner structures from stability perspective, as they are prone to undergo static instability [1]. One of the light weight material system which is gaining more popularity due its closed cell structure, built in porosity and higher specific compressive properties is known as syntactic foams. Syntactic foams are prepared by dispersing hollow microballoons in matrix resin resulting in light weight material system having potential weight saving applications. Owing to their higher specific properties, syntactic foam composites are widely used in automotive, marine and aviation sectors [2–5]. Operating conditions of such syntactic foam components in service vary due to mechanical and thermal loads necessitating their investigations under varying temperature conditions.

Existing literature on the temperature dependent properties of the syntactic foams represent coefficient of thermal expansion (CTE), thermal conductivity (TC) and dynamic mechanical analysis (DMA) [6]. Parameters such as volume fraction and wall thickness can be used to tailor these properties effectively. Labella et al. [7] examined CTE of vinyl ester matrix/fly ash and observed 48% decrease in CTE by with increasing filler content from 30 to 60 vol%. In comparison with neat resin, foams exhibited lower CTE values. Li et al. [8] presented numerical investigation of TC in syntactic foams. Their results revealed that TC of foam decrease with increase in microballoons vol%. Numerical investigation by Park et al. [9] revealed that thermal conductivity ratio (ratio of thermal conductivities of microballoon shell to matrix) increases significantly with relative wall thickness of the microballoons at all volume fractions. Effect of volume fraction and wall thickness of hollow glass microballoon (GMB) on thermo mechanical properties of epoxy matrix syntactic foams are studied by Lin et al. [10]. They observed that the CTE of syntactic foams is lower than the neat epoxy due to presence of ceramic particles. The filler volume fraction has a strong effect on the glass transition temperature as compared to wall thickness variations.

Temperature dependent elastic properties of syntactic foam composites have been addressed in Ref's. [11,12]. Gu et al. [13] investigated DMA of fly ash /epoxy syntactic foams and reported that the addition of fly ash enhanced the damping capacity. Studies also revealed that the damping mechanism is governed by matrix viscoelasticity, grain boundary sliding with the cenosphere particles and interfacial sliding friction between the constituents. Similar trend is also observed for modified epoxy and fly ash cenosphere syntactic foams [14]. Hu and Yu [15] investigated thermal, DMA and tensile properties of hollow polymer particle filled in epoxy resin. As compared to neat

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https://doi.org/10.1016/j.tws.2018.07.013
Received 10 March 2018; Received in revised form 3 July 2018; Accepted 10 July 2018

resin these foams showed higher damping with peaks shifting to higher temperature. Thin-walled structural members with in-plane restrained deflections subjected to thermal environment results in buckling mode failure. Several researchers investigated effect of thermal load on buckling behaviour of structural components having simple geometrical shapes. However, most of the studies are based on analytical [16] and numerical [17–19] approaches with a very less focus on experimental investigations. The influence of nonuniform temperature field on nonlinear buckling behaviour of isotropic beam is investigated through experimental and numerical methods by George et al. [20]. They observed that the critical buckling temperature is strongly influenced by temperature variation conditions. Bhagat and Jeyaraj [21] investigated buckling strength of the aluminium cylindrical panel subjected to nonuniform temperature profiles through experimental approach. Results revealed that the buckling strength significantly varied with location of heating source. These studies bring forth the role of nonuniform temperature profile on the thermal buckling behaviour of the structures and needs to be looked into.

The snap-through buckling of curved beams, shallow arches, cylindrical panels and shells under thermal and mechanical loads has been studied analytically and numerically by several researchers [22–25]. However, experimental investigation on snap-through buckling is scarce. The fundamental mechanisms of snap-through buckling subjected to mechanical load is investigated using shallow arch and a pair of linkages by Wiebe et al. [26]. Dehrouyeh-Semnani et al. [27] examined snap-through buckling behaviour of microbeam made of functionally graded material when subjected to uniform thermal load using numerical method. Wang and Fancey [28] studied bistable morphing of polymeric composite caused due to viscoelastic force induced owing to temperature changes [29]. The snap-through buckling of beam structures subjected to quasi-static loading is analyzed by using elastic theory of prismatic bars by Haung and Vahidi [30]. Chandra et al. [31] combined experimental-computational framework to analyse the snap-through buckling behaviour of clamped-clamped shallow arches subjected to harmonic distributed loadings. Keleshteri et al. [32] investigated snap-through instability of functionally graded carbon nanotube reinforced composite plate with piezoelectric layers. Chandra et al. [33] examined the performance of beam using continuum nonlinear finite element formulations in conjunction with several popular implicit time stepping algorithms to assess the accuracy and stability associated with numerical simulations of snap-through events. Plaut et al. [34] investigated snap-through behaviour of shallow elastic arches under dynamic, unilateral displacement control, with the in dentor moving at constant velocity. Plaut et al. [35] investigated numerically snap-through buckling characteristics of beams and circular arches with the help of unilateral displacement control technique. Liu et al. [36] investigated the stochastic nonlinear snap-through response of a clamped composite panel subjected to the combined severe acoustic excitation and a steady thermal effect using single mode fokker plank distribution function. Studies indicated that the stationary statistical solution of the single-mode analysis captures the features of the displacement density distribution and showed the evolution from no snap-through to a persistent stochastic response. Chen et al. [37] studied the snap-through buckling of a hinged elastica subjected to a midpoint force theoretically and compared the results with experimental observations.

Literature review indicates that the nature of thermal loading influences critical buckling temperature of the structures exposed to elevated temperatures. Similarly, thermal buckling studies on structures made of materials having viscoelastic effect indicate that they are subjected to snap-through buckling. Syntactic foams find applications in marine, automobile and aerospace industries which may be subjected to elevated temperatures during their service resulting from aerodynamic and solar radiation heating. Though wide literature is available fly ash reinforced thermosetting and thermoplastic syntactic foams [38–43], snap-through buckling under thermal environment of these foams are not yet reported to the best of authors knowledge with a focus on interior panels of aircrafts and marine vessels. Cenospheres are varied by 20, 40 and 60 vol% in epoxy matrix and prepared foam samples are subjected to temperature variations in the range of 27–45 °C with three different heating conditions namely, increase-decrease, decrease and decrease-increase along the length of the samples. Effect of filler content and heating conditions on snap-through buckling is presented in this work. Critical buckling temperature is estimated through temperature-deflection plots which are recorded using in-house developed LabVIEW program. Deflection plots of thermal and mechanical loading conditions are compared to discuss the snap-through phenomena. DMA tests are also conducted to understand viscoelastic behaviour of the developed syntactic foams in thermal environment and further to critically analyse snap-through event.

2. Materials and methods

2.1. Constituents materials

LAPOX L-12 epoxy with K-6 room temperature curing hardener (Atul Ltd., Gujarat, India) is used as matrix resin. Cenosphere of CIL 150 grade procured from Cenosphere India Pvt Ltd, Kolkata, West Bengal, India is used as filler. These fly ash cenospheres are spherical in shape and physical, chemical and sieve analysis details in as received condition are available in Ref. [39]. Alumina, silica, calcium and iron oxides are the major constituents of these abundantly available environmental pollutants.

2.2. Syntactic foam preparation

Cenospheres (20, 40 and 60 vol%) and epoxy resin are weighed in a predetermined quantity and stirred slowly until homogenous slurry is formed. Polymerization process is initiated by adding 10 wt% of K6 hardener into the slurry before pouring it into the mold. Subsequently this mixture is decanted into aluminium mold. Silicone releasing agent is applied to the mold for easy confiscation of cast slabs. The castings are allowed to cure for 24 h at room temperature and trimmed using diamond saw to the dimensions of 370 × 12.5 × 4 mm (Fig. 1c). All samples are coded as per nomenclature EXX, where letter 'E' denote neat epoxy resin, 'XX' represents cenosphere volume fraction. Neat resin samples are also prepared under similar processing conditions for comparison.

Experimental densities of all the samples are estimated as per ASTM D792-13. For each composition five samples are tested and the average values with standard deviation are presented in Table 1. Theoretical densities of syntactic foams are calculated using rule of mixtures and is given by,

$$\rho^{th} = \rho_m v_m + \rho_f v_f \tag{1}$$

where ρ and v represent density and volume fraction respectively and suffixes m and f represent matrix and filler respectively. Air entrapped during manual mixing of cenospheres in epoxy resin is represented as void content. Void content (ϕ_v) is calculated by the comparative difference between the theoretical (ρ^{th}) and experimentally measured (ρ^{exp}) density [44] and is given by,

$$\phi_v = \frac{\rho^{th} - \rho^{exp}}{\rho^{th}} \tag{2}$$

Void content estimation is crucial as it compromises the mechanical properties.

2.3. Buckling at room temperature under mechanical loading

Buckling behaviour under mechanical load is carried out with the help of Universal Testing Machine (H75KS, Tinius Olsen make, UK,