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Crack monitoring and failure investigation on inkjet printed sandwich structures under quasi-static indentation test

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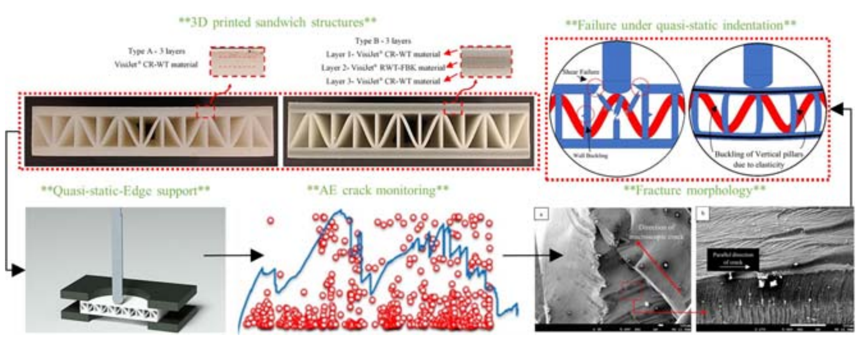
HIGHLIGHTS

- Acoustic emission technique to monitor the invisible crack initiation during quasi-static loading
- Highly scalable design of single and multimaterial inkjet printed sandwich structures
- Failure mechanism and fracture morphology of inkjet printed sandwich structures under three different indenters

GRAPHICAL ABSTRACT



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ABSTRACT

In this research contribution, effort is taken to monitor the crack initiation and crack propagation of three-dimensional (3D) printed corrugated sandwich structures using acoustic emission technique. Vertical pillars were introduced in between the existing sinusoidal wave-like corrugations to improve the load bearing capacity of these structures. The vertical pillared corrugated structures were 3D printed with single and multi-material combinations in the facesheet and tested for their indentation resistance. To monitor the exact invisible crack initiation and crack propagation in the 3D printed corrugated structures, a highly-sensitive acoustic emission (AE) testing method was introduced. The resulting AE data points during testing illustrated a cluster of low amplitude data points from 40 to 65 dB indicating invisible crack initiations. High amplitude points up to 95 dB indicated visible cracks propagating until the end of specimen failure. Prevalent failure mechanism for single material (type A) specimens was found to be shear cracking of facesheets with micro steps and failure mechanism of multimaterial (type B) specimens were found to be delamination and shear cracking of multimaterial layers. Load bearing capacity was maximum at 2.14 ± 0.3 kN for type A specimens under a flat indenter with a displacement of 2.12 ± 0.4 mm.

1. Introduction

Sandwich structures and corrugated panels have very high stiffness and load bearing capacity in the out-of-plane loading directions [1]. These structures are mostly manufactured using corrugation techniques. Corrugated structures are manufactured from various materials like cardboards, aluminum sheets and fiber sheets which include Kevlar,

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Nomex and aramid fibers. By including suitable facings on the top and bottom of these corrugated cores a new classification known as corrugated panels can be obtained. Top and bottom facesheets can be made from materials like aluminum sheets or fiber facesheets with different fiber layup configurations. These corrugated sandwich panels have high load bearing capacity and high stiffness due to the facings at top and bottom [1,2].

These structures are used in marine, aerospace and heavy vehicle industries due to their light weight properties. Even though these structures have high stiffness properties under compressive loading, they are prone to damage when loaded locally. Optimized lightweight sandwich structures can be obtained by proper selection of core design, core material, facesheet layup configuration and facesheet material [3].

Apart from localized bending, the failure mode of corrugated sandwich structures include core crushing, core shear, facesheet delamination, facesheet wrinkling, fiber breaking in facesheet and fiber cracking due to improper stacking [4]. Upon impact of foreign objects on sandwich structures, their load bearing capacity and stiffness reduces until the point of failure. By proper understanding of the failure in sandwich structures, there is a high possibility to prevent the damage foreseen. Therefore, damage initiation maps were developed and tested experimentally, numerically [5] and by theoretical methods [6]. The predicted failure modes matched satisfactorily with experimental results. Reports show that the failure modes of sandwich structures under low-velocity impact tests are found to be similar under quasi-static indentation tests [7,8]. Failure modes in relation to facesheet failure, facesheet wrinkling, and core failure were developed by analytical methods [9]. To overcome the major failure modes, polymeric foam cores were used to control the core crushing. However, these type of foam models showed shear failure [10–12]. Proper selection and layup of facesheet reduce the risk of shear failure by increasing the inertia of the whole sandwich structure [13,14]. Apart from the selection of core and facesheet materials, the impact of foreign objects (indenter geometry in case of quasi-static indentation test) has an effect on the failure mode of sandwich structures. Sandwich structures show different failure modes under various indenter geometries. Tests were conducted apart from standard hemispherical indenter to study the failure modes under other indenter geometries like conical sharp tip and flat faced indenters [12,15–17]. Thus, studying the effect of impacting object on sandwich structures is also considerably important.

Core design plays major role in the load bearing capacity of sandwich structures [18]. Various core design like trusses, cellular cores, corrugated cores, Kirigami [19] and kagome cores [20] are developed to improve the load bearing capacity. However, these structures have their own advantages and limitations. Hence, designing an optimized core that satisfies all the requirements like high load bearing capacity, high energy absorption, stiffness properties is very difficult due to manufacturing process limitations. Despite the manufacturing limitations, efforts were taken to modify the core design to improve the mechanical properties of sandwich structures. Aluminum alloyed trapezoidal corrugated structures with facings on top and bottom were investigated under different indenter geometries. Matrix cracking with delamination was the major failure mode of these structures [21]. Investigations by modifying the kirigami structures based on egg box tessellated patterns resulted in 41% energy absorption improvement compared to conventional corrugated structures [22]. Facesheet lamination using vacuum assisted resin transfer molding (VARTM) showed improvements in compressive strength of the structure [23]. Bi-directional corrugated cores were developed to reduce the anisotropic properties and to improve the bending properties. The results showed that these bi-directional corrugated sandwich structures showed quasi-isotropic bending in three-point bending tests [24]. Other core modifications such as corrugated Y-frames [25], variation in cell configuration [26], variation in core materials were done to improve the mechanical performance of corrugated sandwich structures. However, still there exists a need for an efficient manufacturing process to fabricate cellular cores for achieving the desired optimized configuration that suits the requirements.

3D printing also known as additive manufacturing (AM) has a greater advantage of manufacturing complex geometries at much lower costs than traditional manufacturing processes. A review on AM in unmanned aerial vehicles was done to prove the efficacy of AM components in aerospace industries [27]. Metal additive manufactured components can be produced in net shape or near net shape. These components can be directly used for functional operations without further processing. Optimized sandwich structures having complex core designs that cannot be produced using conventional techniques have started to emerge into aerospace industries. Metrological benchmark studies on the printing capability of inkjet printing machine showed that the structures printed using PolyJet technology can have intricate structures without warpage or distortion [28]. Investigations on PolyJet printed sandwich structures showed shape recovery effects. The results show that these structures have high energy absorption characteristics and can recover their shape after bearing the loading [29]. Quasi-static indentation test of complex core structures like truncated pyramids was performed and verified using finite element analysis [30]. Introducing vertical pillars in trapezoidal sandwich structures improves their mechanical performance. These structures were subjected to quasi-static indentation tests under various indenter geometries. Structures printed using multi material combinations showed excellent load bearing capacity rather than components printed using a single material. Indenter geometry also plays a major influence on the failure mechanism of these structures [17]. Therefore, 3D printed sandwich structures are gaining popularity due to the manufacturing advantages and light weight properties.

Damage to sandwich panels during operation is inevitable. Due to the complexity of core produced using 3D printing, there is a need for a novel technique to determine and monitor the crack initiation and crack propagation in these structures. Without a novel sandwich panel damage monitoring technique, it is very difficult to determine the damage occurred due to morphing actions or impact of foreign objects. In this contribution, efforts are taken to monitor the crack initiation and crack propagation of vertical pillared sinusoidal wave-like corrugated sandwich structures. This technique will help in monitoring even unobservable and hard to predict minor cracks in the structures. Vertical pillared sinusoidal wave-like corrugated sandwich structures were 3D printed using 3D Systems' ProJet® MJP 5500X (3D systems, Rock Hill, CA, USA) using single material and multi-material combinations for the facesheet. The 3D printed structures were then subjected to quasi-static indentation tests under standard hemispherical, conical and flat indenters to determine the failure modes under each impacting object. Furthermore, results were discussed on load bearing capacity, the effect of facesheet material and failure mechanism in relation to acoustic emission monitoring data points.

2. Design, manufacturing and experiment methodology

2.1. Specimen description

To improve the mechanical strength of the corrugated structure, vertical pillars are introduced at regular intervals of 10 mm. Design specification of the new vertical pillared corrugated structure is given in Table 1. These structures are like sandwich panels, the vertical pillared sinusoidal wave-like corrugated structure acts as the core, and top and bottom facings act as facesheets. The new vertical pillared sinusoidal wave-like corrugated structure will be analyzed for its indentation behavior.

2.2. Manufacturing method and materials

In this work, 3D Systems' ProJet® MJP 5500X an inkjet 3D printing machine was used for fabricating the specimens. The advantage of this