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Real-time Crack Monitoring in Lattice Sandwich Structures Using High-Resolution Imaging

Costanzo Bellini[a]*, Rosario Borrelli[b], Vittorio Di Cocco[a], Stefania Franchitti[b], Francesco Iacoviello[a] and Luca Sorrentino[a]

[a]*Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, Italy*
[b]*Additive Manufacturing LAB, CIRA, Capua, Italy*

Abstract

Sandwich structures with composite skins and 3D-printed titanium lattice cores are gaining prominence in aerospace and other industries due to their exceptional strength-to-weight ratio and mechanical performance. However, they are prone to crack propagation, posing a significant risk of catastrophic failure. This study focuses on employing high-resolution camera monitoring to track crack initiation and growth in these structures.

Short beam bending tests were conducted on sandwich specimens, applying loads within the laminate plane. A high-resolution camera was positioned to capture real-time images during the tests. The captured data were correlated with the load-displacement curve to analyse crack propagation patterns.

The findings demonstrate the effectiveness of high-resolution camera monitoring in detecting and tracking crack propagation in composite-skinned sandwich structures, even amidst background noise. This methodology offers a valuable tool for developing advanced inspection and maintenance strategies to ensure the structural integrity of these critical components.

Keywords: Lattice structures; Additive manufacturing; Crack path monitoring; In-plane bending.

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1. Introduction

Sandwich structures, comprising a low-density core sandwiched between two face sheets, have gained significant attraction in aerospace, automotive, and civil engineering applications owing to their superior strength-to-weight

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* Corresponding author. Tel.: +39 0776 299 3617
E-mail address: costanzo.bellini@unicas.it

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ratio. Polymer matrix composites, commonly employed as face sheets, offer exceptional specific stiffness and strength, while foam or honeycomb cores provide excellent energy absorption capabilities. Recent advancements in additive manufacturing have enabled the fabrication of intricate lattice core geometries, such as titanium lattice structures, further enhancing the design flexibility and performance of these sandwich panels.

As stated by Bellini et al. (2022), sandwich structures with metallic lattice cores exhibit a unique combination of mechanical properties, including high stiffness, low density, and good impact resistance. However, the presence of geometric discontinuities within the lattice can facilitate the initiation and propagation of cracks, thereby compromising the durability and safety of the structure (Di Caprio et al. (2022)). Consequently, investigating crack propagation in these structures is paramount to ensure their reliable service performance.

The damage mechanisms in sandwich structures are intricate and influenced by various factors, including material type, core geometry, loading conditions, and environmental exposure (Bellini et al. (2023)). Common damage modes include: delamination, that is the separation between the face sheets and the core, induced by interlaminar stresses or impacts; core crushing, which is the plastic deformation or fracture of the core under compressive loading; and face sheet cracking, that is the initiation and propagation of cracks in the face sheets due to excessive loads or initial defects (Bellini et al. (2021)).

Early damage detection is crucial to prevent structural failure, and different studies about damage monitoring are in the literature. Thasler et al. (2019) proposed a method based on strain analysis through Digital Image Correlation (DIC) to determine the crack length in lap shear joints subjected to fatigue loading. Ramezani et al. (2024) used the DIC to determine the strain in composite specimens subjected to longitudinal and out-of-plane tensile test, as well as to shear test. The data were processed by using Moire open-source software. Comer et al. (2013) used both 2D and 3D DIC to evaluate the strain in single lap joints of composite laminates, and validated their method by using strain gages appropriately positioned in strategic points. Kumar et al. (2013) presented a methodology to measure shear and peel strains through DIC in single lap joints and evaluate their corresponding stresses. Huang et al. (2013) analysed the strain field around the fatigue crack tip in double cantilever beam specimens, using a camera to detect the initiation of the fatigue crack. Chandra and Chakraborty (2024) evaluated the error in DIC strain measurement in fatigue testing, and found a correlation with the type of skipped frames. Schmuck et al. (2024) developed an algorithm to measure the crack tip opening displacement and the crack length from images acquired on the specimen, in order to determine the fracture mode of the same. Grefe et al. (2020) used DIC to investigate the damage mechanisms of lap shear specimens subjected to high strain rates.

More complex equipment can be implemented to monitor the crack growth and damages in different materials. For instance, Borstnar et al. (2015) used synchrotron radiation computed tomography and laminography to detect the damage in such material. Diez et al. (2024) applied DIC to SEM images taken on micro-textured specimens under load to study the mechanical behaviour of joints at the nanoscale. Makarenko et al. (2022) adopted the DIC to analyse the strain distribution in sandwich structures made through laser metal deposition, in order to detect the strain concentrators. Lima et al. (2021) compared the results of optical backscatter reflectometry to DIC in double cantilever beam specimens, demonstrating the effectiveness of the former for detecting the onset of plastic deformation. Saleh et al. (2020) correlated the DIC results to acoustic emission ones to detect damage initiation in metal-composite double lap joints. Zamani et al. (2019) combined backface strain measurement and optical microscopy to evaluate the effect of different loads on crack initiation.

This study aims to evaluate the effectiveness of high-resolution vision systems in monitoring crack propagation in sandwich structures with composite face sheets and 3D-printed titanium lattice cores. In particular, the analysis was carried out on short beam specimens subjected to 3-point bending, with the load parallel to the planes of the skins. This load configuration has been scarcely analysed in the past since the load is usually applied along a direction orthogonal to the skin plane (Bellini et al. 2024).

2. Materials and methods

In the present study, the failure mode and the crack propagation in short-beam sandwich specimens were monitored during the three-point bending test. In particular, the core presented a lattice geometry and was made of titanium, while the skins were made of composite material: AFRP (Aramid Fibre Reinforced Polymer) and CFRP (Carbon Fibre Reinforced Polymer).

The core of the beam was constructed using octet-truss cells, renowned for their exceptional mechanical characteristics and widespread use. These cells comprised two lattice structures: an inner octahedron and an outer cube with centred faces. Each cell, with a side length of 6 mm, incorporated 36 trusses, each measuring 1 mm in diameter. The core of the sample had a cross-section of 10x9 mm² and a length of 30 mm. The skin thickness remained consistent at 1 mm across all types, ensuring meaningful comparisons between different skin materials. Fig. 1 illustrates the sample's geometry. The lattice was fabricated using Ti6Al4V alloy powder, a material specifically designed for the EB-PBF (Electron Beam- Powder Bed Fusion) process and produced through atomisation. The skins were composed of various materials depending on the specimen type: carbon or aramid prepreg was utilised for CFRP and AFRP specimens, respectively. The aramid-based prepreg featured a satin weave reinforcement fabric, while the carbon prepregs had a twill weave pattern. To establish a strong bond between the titanium lattice and the composite material skin, a structural adhesive was used, namely the Hexcel Hexbond ST 1035 epoxy adhesive in film form.

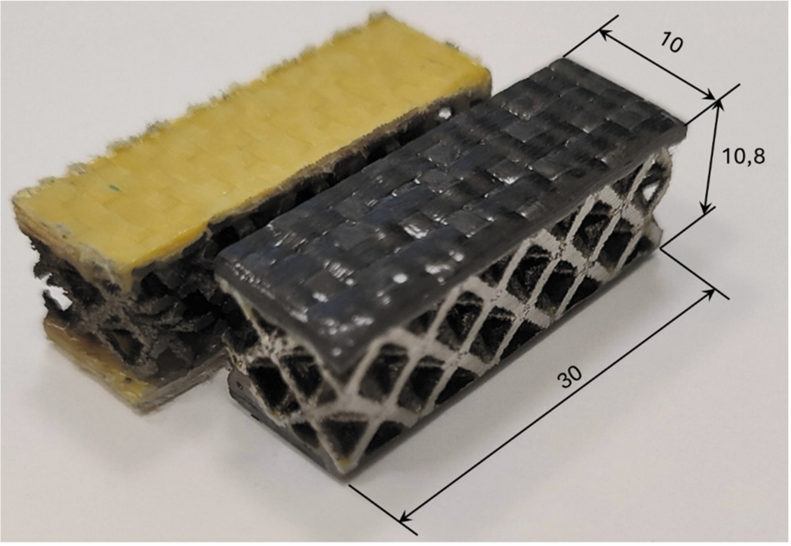

Fig. 1. Specimen geometry (dimensions in mm).

All samples featured a lattice core fabricated using EB-PBF technology, a method widely used in the aerospace sector. This technology was chosen due to the peculiar geometry of the part to be produced; in fact, additive manufacturing processing is advantageous for complex shape parts (Cantaboni et al. (2022)). The composite skins were incorporated through a co-curing process, wherein the prepreg and adhesive were simultaneously cured, utilising the core as a mould. This technological solution has been implemented by other authors too, as De Pasquale et al. (2023). The core production process began with the creation of a digital geometric model using Materialise Magics software, specialised in designing lattice structures within confined spaces. After optimising the CAD model, the slicing and process parameters were configured using ARCAM Build Processor and EBM control 3.2. The ARCAM A2X EBM system was then prepared, and titanium powder was loaded into the hoppers. To establish optimal conditions, the production chamber was evacuated before calibrating the electron beam and preheating the building plate. Upon reaching the preheating temperature (approximately 700 °C), the specimen cores were produced using a powder bed additive manufacturing process. Following production, the chamber was gradually cooled, and the samples were carefully removed from the unmelted powder. A thorough cleaning process then commenced, employing sandblasting equipment, a pressurised air chamber, and an ultrasonic bath. To create the composite skins, the prepreg-vacuum bag method was selected. The FRP prepreg layers and the fabricated lattice core were assembled onto the metal mould. To maintain consistency, five prepreg layers were used for carbon skins and four for aramid skins, resulting in a uniform thickness of approximately 1 mm for all face sheets. This uniformity was essential for conducting meaningful comparisons between different specimen types. Before sealing the mould with the vacuum bag, all layered specimens were covered with a release film and a breather fabric, a standard practice in the vacuum bag process. After sealing, the mould was placed in the autoclave for curing. Upon completion of the thermal cycle, the bag was removed from the autoclave, and the specimens were extracted. Subsequently, any excess resin was removed, and the specimens were set for testing.

The manufactured specimens were subjected to three-point bending tests: supported on both ends, each specimen was centrally loaded. While this method is commonly used for sandwich structures to evaluate out-of-plane properties, this study specifically focused on in-plane characteristics. The span length, the distance between the supports, was fixed at 20 mm, and the loading rate was kept at 2 mm/min. Loading continued until each specimen was fractured. Five samples of each type were tested, resulting in a total of 10 experimental trials. The damage progress of the skin laminates was evaluated by using a high-resolution camera, equipped with a suitable lens, placed in front of the specimen, as visible in Fig. 2. In this manner, it was possible to record the crack growth and then relate the damage features to the load/displacement curve recorded for each specimen.

Fig. 2. Experimental equipment for damage monitoring during three-point bending test.

3. Results

The load/displacement curve for an aramid specimen is reported in Fig. 3. The curve is formed by a first linear elastic load increase followed by a nonlinear one part. The switch from linear to nonlinear happened for a load of 2750 N, and was characterised by a slight load drop due to the buckling of the skin under the loading nose. However, no crackling was heard from the composite, and neither crack appeared from the lower edge, as visible in Fig. 3. Incrementing the displacement, the load increased with a nonlinear trend till a maximum value of about 4100 N. After this point, the curve presented a sudden load drop, while a crack appeared on the lower part of the skin, opposite to the loading nose, halfway between the supports. The load did not reach a null value, but a load of more than 2000 N was maintained for quite a long period. During this lapse of time, the damage grew relatively slowly, and the skin fraying was observed. This particular damage behaviour, typical of aramid fibres, allowed the specimens to maintain a certain residual strength after the attainment of the maximum load. Finally, a second significant load drop was observed, accompanied by a sudden crack advancement and the complete failure of the specimen.

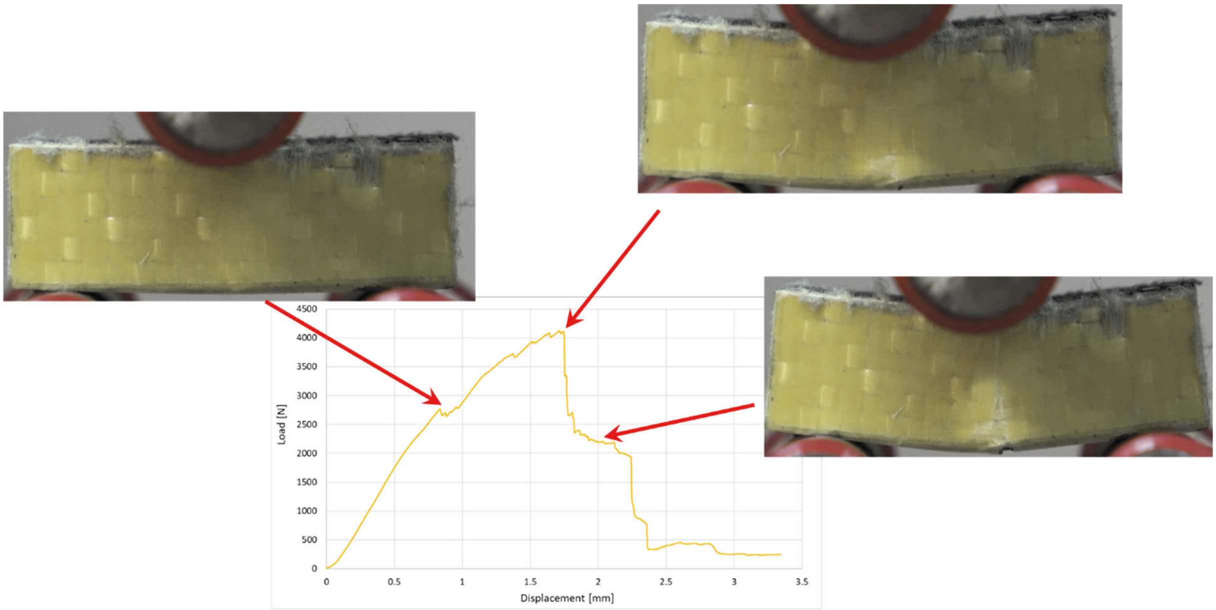

Fig. 3. Damage behaviour of AFRP specimens.

Concerning the CFRP skinned specimens, the relevant curve is reported in Fig. 4, together with the main features of the damage development. As for the previous case, also in this one a first linear load increase with the displacement was observed, followed by a nonlinear part. However, an unclear shift was observed in the graph, which was different from what happened for AFRP. In the nonlinear increase zone, the bucking under the loading nose was noted, together with the separation of vertical bundles in the same zone. Increasing the loading, the crack started under the loading nose grew, and bundle separation was noted in the centre of the specimen, too. Right after, a sudden load drop happened in the curve, accompanied by the growth of a crack from the lower edge of the specimen, which led to the failure of the sample itself. In fact, the residual strength was lower compared to the aramid one.

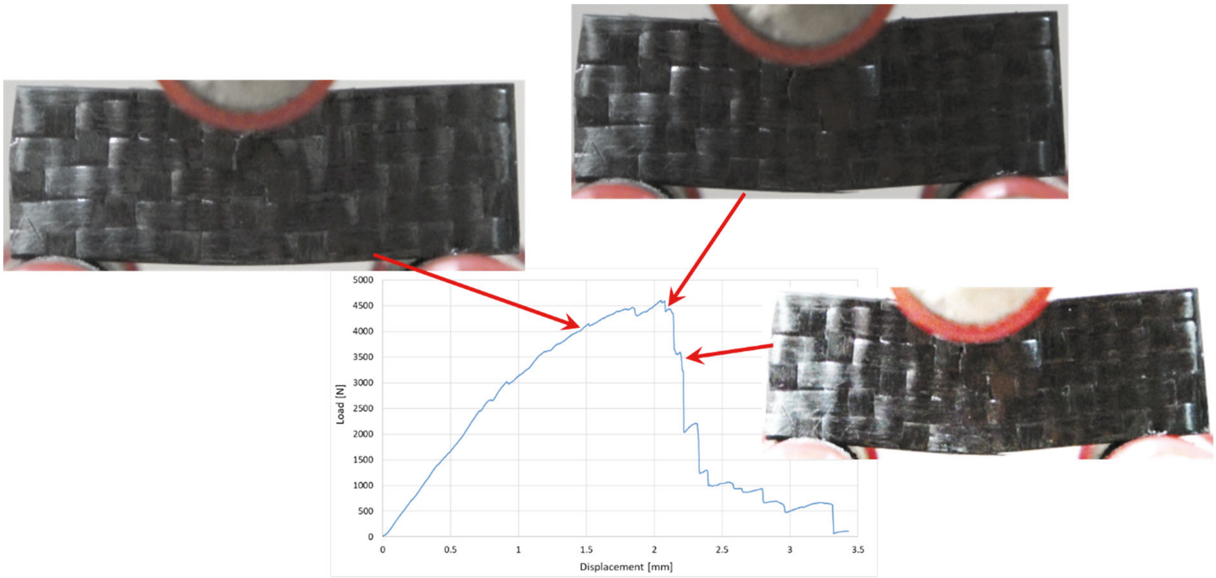

Fig. 4. Damage behaviour of CFRP specimens.

4. Conclusions

This study aimed to evaluate the effectiveness of high-resolution vision systems in monitoring crack propagation in sandwich structures with composite face sheets and 3D-printed titanium lattice cores. The focus was on short beam specimens subjected to three-point bending with a load parallel to the skin planes, a less explored loading configuration. The study found distinct failure modes and crack propagation behaviours for AFRP (Aramid Fibre Reinforced Polymer) and CFRP (Carbon Fibre Reinforced Polymer) specimens.

The load/displacement curve for AFRP specimens showed an initial linear elastic load increase followed by a nonlinear phase. The transition was characterised by a slight load drop due to skin buckling. Despite the buckling, no audible cracking or visible cracks were observed. The load increased nonlinearly to a maximum, then dropped suddenly as a crack appeared on the lower part of the skin. However, residual strength persisted. Damage progression was slow, with skin fraying being observed. In the end, a second major load drop led to complete failure. For CFRP skinned specimens, an initial load increase was noted, followed by a nonlinear phase. However, the transition was less clear than that of AFRP. Buckling and vertical bundle separation were observed in the nonlinear increase zone. A sudden load drop then occurred, followed by a crack from the lower edge, leading to failure. The residual strength of CFRP specimens was lower than that of AFRP specimens.

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