Mechanical and fatigue behaviour of Sandwich elements with 
ABS core cells and GFRP plies, as function of cellular 
geometry and process parameters

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Abstract. The present work aim is to fully apply the potential of FDM (Fused Deposition Modelling) technology with economic printing machine, in order to create performant ABS cores, to be subsequently used as shaped moulds for sandwich plate assembly with GFRP skins, representing simple prototypes to validate production concept and its structural behaviour. The further task of this study is to empirically optimize the geometry of the core as function of required thickness and technological building parameters, in order to achieve light and mechanically performing structures with extremely reduced costs. After compression experimental tests on core cell geometries, fatigue tests under bending are also executed on reinforced GFRP plates in order to validate best compromise between ABS core design and GFRP laminated skin properties and stiffness requirement, highlighting influence of ABS wire performances as deposited in the form of beam-based lattice geometry. In addition, the authors employ the digital image correlation technique to perform the strain and displacement field of lattice structures and sandwich interfaces.

Keywords: DIC analysis; fatigue bending test; FDM 3D printing; lattice ABS structure; sandwich panel.

1. Introduction

Engineering advances often must combine the light-weight requirement of mechanical structures with a suitable preservation in terms of stiffness and resistance, highlighting the common solution of a proper employment a different material with superior properties (i.e., composite materials) [1]. However, the problem seems to be not often resolved due to advanced material cost and mainly due to the possibility to combine the structural performance and lower density.

A promising strategy consist of adopting the new approach of topology optimization that provides the design tool to gain new unit cells for lattice material [2]. Recently, the research development gained an important focus on lattice structures obtained with the Additive Manufacturing (AM) process due to their distinctive specific properties such as high specific stiffness and strength, proper thermal and acoustic properties resulting a suitable heat exchanger and energy absorber [3]. Lattice structures consist of a spatial array arranged periodically to form specific unit cells with edges and faces, often related to cellular solids [4]. Cellular solids consist of stochastic (such as open-cell and closed-cell foams) and non-stochastic structures (2D and 3D lattice structures) with different
mechanics and physical properties depending directly by structure and shape of unit cell itself [3, 4]. Traditional manufacturing process such as melt foaming or powder metallurgy using blowing agents could provide only the stochastic structures, whilst the additive manufacturing allows the introduction of the ordered non-stochastic components [5]. As described by different authors [2, 4, 6], the structural optimization seems to highlight the interdependencies between the application of AM and lightweight strategies such as topology optimization or latticing for structural optimisation.

The Sandwich-type structures seem to combine the well-known lightweight and high mechanical properties for the employment of stochastic or non-stochastic structures as material constituent of core [7]. Therefore, sandwich structures with different core material and geometries require simple but optimised manufacturing phases for reliable construction and proper structural design, especially in initial the prototyping stage. At same time, the realization of sandwich structures reinforced with GFRP skin may result to be rather convenient from the point of view of manufacturing times and costs. In fact, the main idea is to achieve complex geometry of the component by laminating external shell fabrics directly on the previously shaped core geometries, without using die and other equipment, with only exception for use of simple vacuum bag method.

In the present work, the authors propose a different GFRP (Glass fibre reinforced polymer) / ABS (Acrylonitrile butadiene styrene) lattice sandwich structures for aeronautical and biomedical field, manufacturing with the consolidated technologies of 3D printing and the vacuum bag techniques, as alternative to very low-weight core material as expanded polyurethane.

The employed core is an ABS lattice structures manufactured with FDM (fused deposition modelling) technology, employed as a ‘base’ for lamination of GFRP skins the external surfaces in ABS. Preliminary compressive tests are carried out on five selected lattice structures to evaluate different mechanical specific properties for a suitable selection of lattice configuration for sandwich panels. In the second phase of study, four-points bending static tests are executed firstly in static conditions to compare the effects of core lattice geometries, aided by digital image correlation (DIC) analysis to select the proper sandwich lattice structures for a fatigue campaign [8]. In addition, a simple numerical model is employed to simulate bending behaviour of the selected GFRP/lattice core geometry, verifying structural performance before static test.

In fact, numerous studies are present in literature, regarding mechanical behaviour and damage modes under static loads of lattice-based structures, but the recent interest is focused also on fatigue assessment and stiffness behaviour under cyclic loading [8, 9]. Therefore, fatigue assessment under bending loads is also performed after static tests to validate the selected compromise between core design and GFRP skin reinforcement, highlighting influence of ABS performances as deposited in the flat sandwich specimens. Experimental results and damage modes are described in the following work.

2. Materials and Methods

2.1. Lattice elements

For this research work, two sample series are employed for mechanical evaluation of 3D cell topologies analysis. Effect of extrusion width in terms of stress-strain curves are investigated, i.e. extrusion width of 0.4 mm or 0.2 mm. As shown in Figure 1a, smaller values of extrusion width seem to give better morphological accuracy, but longer printing time.

Then, the final configuration of lattice panels is optimized based on effect of extrusion width, as shown in Figure 1b. Core manufacturing parameters and cell geometries are studied and optimized to achieve a cellular structure with sufficient geometric accuracy as function minimum cell size. The influence of ABS 3D building direction and printing flow parameter on strength was also studied, as shown in example diagram of Figure 2a.

Therefore, each samples set is manufactured in the same 3D printer CREALITY ender 3 pro with the same process parameters (i.e. printing speed, nozzle temperature and heated bed temperature). Process parameters are selected following best practices recommended on printer manual. The first batch of samples consists of five lattice structures manufactured with a filament SUNLU type in ABS with a diameter of 1.75 mm. The selected lattice unit are the BCC (basic centred cubic), FCC (face centred cubic), SFCC, SFBCC and OCTET [9].
Each sample batch consists of 3 cubic specimens with 27 cell units (3 × 3 × 3) subjected to the compression test; these samples are manufactured with the upper and bottom flat surfaces to improve load conditions and the contact with test machine.

Cubic lattice samples present thickness and dimensions of the cell unit reduced in such a way as to create specimens ensuring enough units in thickness, such as to create functional components with a complex geometry. An overall summary of specific geometrical and physical properties is reported in Table 1.

Figure 1. (a) Macroscopic effects of extrusion width on morphological accuracy and (b) final configuration of lattice panel.

| ID LATTICE STRUCTURE | BCC | FCC 50_45 | SFCC | SFBCC | OCTET |
|----------------------|-----|-----------|------|-------|-------|
| Beam thickness [mm]  | 1.2 | 1.2       | 1.2  | 1.2   | 0.4   |
| Cell size [mm]       | 7   | 7         | 7    | 7     | 10    |
| ρ [g/cm³]            | 0.29| 0.45      | 0.35 | 0.42  | 0.53  |

The second case of study includes hybrid sandwich elements realized by ABS lattice panels laminated with GFRP skins. Operational steps for the manufacturing of GFRP / ABS lattice sandwich panels consist of surface preparation of lattice panels, the lamination process of GFRP skins, vacuum bag polymerization and cutting of sandwich panels; the final sandwich samples is reported in Figure 2b.

The manual lay-up process in steel or carbon molds represents the mainly common manufacturing method of sandwich structures with complex geometry with additional plastic deformation and machining processes to achieve the final shape of designed element. After lamination process, the resulting structures of external skins and core is assembled during cure cycle in autoclave for uniform transfer of resin and additives used for bonding. In this sample batch, the ABS lattice panels are the sandwich core constituent employing their wider external surfaces as ‘base’ for lamination process of GFRP skins. A single ply of twill e-glass 0/90 fabric (160 g/mm²) is employed for each GFRP skin.

Table 2. Geometric properties of GFRP/ABS lattice sandwich elements for 4p static bending tests.

| ID GFRP/ LATTICE ELEMENT | Lattice structure | Glass fabric of skin | N. of samples | Thickness [mm] | Width [mm] | Length [mm] |
|--------------------------|------------------|----------------------|---------------|---------------|------------|-------------|
| SFCC 1.2 × 7 P4n         | SFCC             | twill e-glass 0/90   | 6             | 22            | 23         | 129         |
| SFBC 1.2 × 7 P4n         | SFBC             | twill e-glass 0/90   | 5             | 22.5          | 28         | 129         |
| FCC 50_45 1.2 × 7 P4n    | FCC              | twill e-glass 0/90   | 5             | 20            | 30         | 152         |
Data results of compression test provide specific mechanical properties of employed lattice structures, resulting more performing for the FCC 50.45, SFCC and SFBCC geometry, utilized as lattice core for sandwich panels, avoiding the employment of octet structure as core due to higher density and complex geometry. Geometrical properties of sandwich elements are summarized in Table 2.

Static bending tests are performed to evaluate specific mechanical behaviour of employed sandwich structures, showing that the SFCC lattice panels provide the best pattern between mechanical properties and simplified manufacturing geometry. In addition, three fatigue tests are performed on lattice-GFRP sandwich structures (344.5 × 26 × 22.5 mm$^3$).

![Stress-strain curve](image1.png)  
![Final sandwich elements](image2.png)  

**Figure 2.** (a) Influence evaluation of ABS 3D building direction and (b) final sandwich elements.

### 2.2. Experimental and monitoring procedures

The compressive and bending static tests are carried out are performed in displacement control mode using an MTS 810 servo-hydraulic axial testing machine. The test system is equipped with a load capacity of ±100 kN and governed by a computer equipped with Station Manager 3.A 900 software in the Experimental Mechanic Laboratory at University of Salento (Lecce, Italy). All experimental parameters (time, strain, load and displacement) are recorded during whole test.

![Experimental setups](image3.png)  

**Figure 3.** (a) Experimental setups for compressive tests and (b) for four-points bending tests.

Strain data of specimens are detected by an MTS S / N 1067668 extensometer and the authors select the load speeds of 0.2 mm/min and 1 mm/min are employed during compressive and bending
static tests respectively to maximize the high resolution of acquired images for a proper evaluation of damage and for a suitable DIC analysis. As shown in Figures 3a and 3b, two specific experimental setups are performed employing specific steel supports for compressive and both static and fatigue bending tests respectively. As shown in Figure 3a, two steel plates are gripped in the machine clamps for the correct transmission of axial compressive loads on lattice cubic specimens during whole test.

The four-points bending test is performed with appropriate steel supports applied to simulate a four-point bending, following the ASTM C393-00 "Standard test method for Flexural Properties of Sandwich Constructions" to ensure correct constraint and load conditions determining determination of final flexural properties. As shown in Figure 3b, sandwich elements are positioned on two fixed steel rollers with elastomeric blue slices and loaded with two compression rollers fixed at a determined distance from specimen centre.

In addition, during bending static test, a Digital Sony Alpha 77 camera with macro lens is employed to acquire the high-resolution images of 4000 × 6000 pixels during whole low-speed test. The Ncorr and Ncorr_post open source 2D codes [9, 10] implemented in MATLAB are employed for a full-field post-processing DIC analysis of acquired images of experimental tests, previously used in other works [11, 12]. The lattice structural configuration seems to highlight a high random white-black contrast on the inspected samples. Therefore, the authors decide to avoid the surface preparation with the speckle pattern for DIC analysis on the Region of Interest (ROI). In fact, as shown in Figure 3b, the non-stochastic structure could be directly used as random speckle pattern for strain and displacement mapping of lattice elements, as observed also for stochastic foams [13, 14].

2.3. Numerical model

In this work, a numerical model is performed on the bending test of GFRP/ABS sandwich element with more performing lattice FCC 50_45 to optimize sandwich panel design, skin thickness and critical zones. FEM model is built using ANSYS software, simulating only a quarter of sandwich specimen. Table 3 report the mechanical and physical properties of GFRP / ABS sandwich constituents with FCC 50_45 1.2 × 7 core geometry, implemented in the FEM model. In the analysis, core isotropy is adopted, related to a bilinear behaviour with a tangent modulus ET equal to about 44% of elastic modulus is adopted, whilst for GFRP fabric 0/90°, experimental data were obtained from static test.

![Figure 4](image_url) (a) FEM boundary conditions for bending test of GFRP/lattice core sandwiches elements and (b) deformed configuration of sandwich specimen under bending loads.

| Table 3. Element constituent properties for FEM model of GFRP/ABS FCC 50_45 sandwich panel. |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| **Material properties** | **Element constituent** | **Young's modulus** | **Shear modulus** | **Tangent Modulus** | **Yield strength** | **Poisson's ratio** |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| [MPa] | [MPa] | [MPa] | [MPa] | [MPa] | [g/m³] | [mm] |
| ABS_FCC P4n | 201.59 | 74.55 | 161.27 | 7.58 | 0.35 | 550000 | 21.7 |
| GFRP | 10000 | 5500 | / | / | 0.22 | / | 0.5 |
Constraint conditions are applied for the supports, with load conditions on the contact lines of
internal supports, imposing progressive displacement along the Z axis, as reported in Figure 4a. A
non-linear analysis is defined since core elements result heavily distorted. The equilibrium equations
in non-linear field are solved using the modified Newton-Rapson method, capable of improving the
solution convergence. Figure 4b shows the deformed condition of the sandwich panel subjected to a
door-point bending load condition.

3. Results and discussion
The mechanical properties of cell solids are influenced by base material, relative density, topology,
and shape of unit cell. In particular, the relative density represents the ratio between the density of
cellular unit and the base material density, calculated as

\[ \rho_r = \frac{\rho_{cu}}{\rho_{bm}} \]  

(1)

Where \( \rho_{cu} \) is the density of specific cellular unit (empirically evaluated) and \( \rho_{bm} \) represents
density of base material (available in datasheet) of stochastic elements. In the present study, the same
3D-Printer Filament ABS is employed for manufacturing process of lattice materials. The authors
evaluate specific mechanical properties normalized respect to \( \rho_r \) in both test cases.

3.1. Compression test results
In this case, an evident stiffness variation and damage evolution is observed for cubic lattice tested
elements under compressive loading for each experimental test. Comparative analysis of mechanical
behaviour in terms of specific stress-strain is presented in Figure 5a, where the example of static
compression behaviour could be observed for different lattice configurations.

After elastic phase, all \( \sigma / \varepsilon \) curves seem to exhibit an increasing trend due to continuous
densification process of cellular units that obviously arises after the first collapse of specific lattice
unit.

In Figure 5a, the FCC, SFCC and SFBCB structures seems to provide an almost similar behavior in
the initial linear phase, whilst different behaviors could be observed for OCTET and BCC structures.
In fact, the octet configurations result the most rigid structures due to the consistent increase in
density. The BCC structure also exhibits an approximating constant stress state with a slightly increase
of stresses during the static test. After the first collapse of specific lattice unit, the SFCC core shows a
severe decrease in the stress state with a successive slightly augmentation before final failure, whilst
both SFCC and FCC structures provide an almost constant behavior.

![Specific stress-strain Diagram](image)

**Figure 5.** (a) Comparison of specific Stress-strain and (b) specific stiffness behaviours for different
cellular structures under compressive loads.

Example comparative analysis of compressive properties is also reported in the histogram of Figure
5b. The stiffness results of the five structures are normalized to relative density of specific lattice unit
and show evident similar values for FCC_50_45 and SFBCC elements, whilst higher and lower data are observed for OCTED and BCC cellular geometries, respectively. By visual monitoring, damage evolution could be observed during compression test, as reported in example Figures 6a – 6d. The acquired images show damage initiation and progression of a cubic element with BCC_1.2×7 lattice configuration where the structure collapse seems to begin at the nodes of central units and subsequently the structure is affected by a continuous and gradual densification during compression test.

![Figure 6](image)

**Figure 6.** (a) – (d) Example of damage evolution during compression test of BCC element.

### 3.2. Results and discussion of static bending tests

A monitoring strategy for these tests consists of compliance and digital image correlation analysis, employed in this work to evaluate damage progression during bending loading of sandwich samples, shown in Figure 2b.

The specimens are positioned on steel supports of test machine clamps, following the specific ASTM regulation, and monitored in real time with digital high-resolution Nikon camera for damage evaluation, as shown in Figure 7a.

![Figure 7](image)

**Figure 7.** (a) Example of failure mode for SFCC F5 n after static load; (b) example of specific load-displacement curves of SFCC, FCC 50_45 and SFBCC sandwich series.

For each test case, specific load-displacement diagrams are analysed showing better results in terms of specific mechanical parameters for FCC 50_45 lattice sandwich elements, as reported in the example curves of Figure 7b. The SFCC F2n specimen is affected by a first detachment of the laminate subject to compression, at the first peak, followed by a break in the tensile laminate, therefore in agreement with theoretical previsions.

In SFBCC case, not considering the intensity of the load per unit width, all specimens exhibit a similar behaviour characterized by a first detachment of laminate on compressed side arisen at the first peak of specific curve (as shown in Figure 7b), followed by a total separation of laminate on the opposite tensile side and by a final core shear failure.
In the FCC 50_45 elements, an almost flat stabilization is observed in the final test phase, where a slightly reduction of 2% between the residual and initial stiffness. The flexural properties are calculated according to ASTM C393-00 "Standard Test Method for Flexural properties of Sandwich Constructions" and consists of Core Shear Stress $\tau$ [MPa], Facing Bending Stress $\sigma$ [MPa] and Sandwich Beam Deflection $\Delta$ [mm]. For each lattice core configuration, Table 4 reports the average flexural properties, where $P_{w}$ represents the maximum axial force normalized to specimen width.

Samples damages seem to be affected highlight two modes of failure, the detachment of laminate subject to compression load with shear break of core and detachment of laminate subjected to compression load followed by a break in laminate subject to traction with final break of core. The last failure mode results perfectly aligned with the theoretical foundations, demonstrating the proper design of sandwich panels, as reported in Figures 8a - 8c.

In Figure 9, a comparison of the expected (real) stress values and those obtained from numerical simulations is reported. Given the geometric approximations used, the limits that characterize a non-linear analysis, the low number of experimental tests and the approximations introduced relating to the behaviour of the material, the numerical models created cannot be considered acceptable due to the high discrepancy between the values obtained experimentally, as shown in Figure 9.

| ID GFRP/ LATTICE SANDWICH SAMPLE | Lattice structure | $P_{w}$ [N / mm] | $\bar{\tau}$ [MPa] | $\bar{\sigma}$ [MPa] | $\Delta$ [mm] |
|----------------------------------|-------------------|------------------|------------------|--------------------|----------------|
| SFCC 1.2 × 7 P4n                | SFCC              | 54.45            | 1.31             | 115.40             | 2.84           |
| SFBCC 1.2 × 7 P4n               | SFBCC             | 92.41            | 2.09             | 104.13             | 2.74           |
| FCC 50_45 1.2 × 7 P4n           | FCC               | 110.43           | 2.76             | 137.30             | 4.94           |

Table 4. Average flexural properties of each GFRP/ABS lattice sandwich elements.

![F1n](image1)
![F2n](image2)
![F5n](image3)

Figure 8. (a) – (b) Failure modes of GFRP / ABS panels with an SFCC 1.2x7 geometry core.
In the cellular solids, the strain field should provide the most important aspect of bending damage prediction and propagation prior to final failure; thus, the authors employ the digital image processing to analyze strains and displacements for selected ROIs of specimens, performed with Ncorr software implemented in MATLAB environment. Specific ROIs are selected for different test cases for a proper evaluation in critical areas where maximum stress, displacements and strain concentration should be observed. The DIC data are analyzed at the various regular intervals evaluating during entire test to estimate displacement and strain variation. The Figures 10 to 11 report an example comparative analysis the angular deformation $\gamma_{xy}$ and displacement V along Y axis maps respectively for four points bending test of SFCC F5n lattice sandwich sample at two different instants (50% and 95%). In Figures 10a and 10b, high angular deformations are observed near the bending supports on the compressed lattice unit.

**Figure 9.** Numerical-experimental comparison for GFRP/ FCC_50-45 sandwich.

![Numerical vs experimental results](image)

**Figure 10.** (a) Angular deformation $\gamma_{xy}$ maps at 50% and (b) 95% bending test for SFCC F5n lattice sandwich sample.

**Figure 11.** (a) Axial displacement V maps at 50% and (b) 95% bending test for SFCC F5n lattice sandwich sample.
### 3.3. Preliminary fatigue results

Table 5 reports the experimental overview of fatigue results on SFCC lattice sandwich panels, where the maximum fatigue load $F_{\text{MAX}}$ to specific sandwich width [N/mm] and the amplitude load to specific sandwich width AMP [N/mm] are normalized according to the average maximum axial force over sandwich width $P_{\text{avg}}$ [N/mm].

| ID GFRP/ LATTICE ELEMENT | Weight [g] | Density [g/cm$^3$] | Stress ratio R | $F_{\text{MAX}} / P_{\text{avg}}$ [%] | AMP / $P_{\text{avg}}$ [%] | Cycles to failure |
|--------------------------|------------|--------------------|----------------|----------------------------------|----------------------------|------------------|
| SFCC 1.2 × 7 P4n F7     | 30         | 0.353              | 0.2            | 37.19                            | 14.87                      | 41430            |
| SFCC 1.2 × 7 P4n F8     | 30         | 0.353              | 0.1            | 33.05                            | 14.87                      | 19162            |
| SFCC 1.2 × 7 P4n F9     | 31         | 0.365              | 0.1            | 28.92                            | 13.01                      | 53113            |

Figure 12a shows normalized stiffness results against fatigue life of three tests. By the general trend of the curves, an almost flat behaviour of stiffness is observed from 0% to approximately 50% ÷ 60% of fatigue life. Subsequently, a rapid decrease appears before the final failure of lattice element. As shown in Figure 12b, fatigue damage seems highlight two failure modes, the detachment of laminate subject to compression load with shear break of core and break of core at bending support followed by laminate detachment.

### 4. Conclusions

In the present study, a comparative analysis is carried out to evaluate mechanical behavior of different sandwich structures with lattice unit core and GFRP skins.

Preliminary compressive tests are conducted on cubic lattice elements manufactured in ABS with five different reticulated geometries for a suitable selection of final cellular solid configuration.

The FCC 50.45, SFCC and SFBCC lattice unit are employed for the manufacturing of sandwich panel cores due to their proper mechanical properties combined to lower density. The octet structure provides better results but present the high density and difficult complex geometry.

From bending tests results, GFRP/ABS sandwich elements seem to provide good mechanical behavior as stress absorber due to large deformations, despite loss integrity. These interesting results seem to be perfectly aligned to initial assumption of a possible employment of ABS lattice core sandwich structures due to higher specific mechanical properties combined to lower costs.

### Reference

[1] Rajak D K, Pagar D, Kumar R and Pruncu C 2019 Recent progress of reinforcement materials: a comprehensive overview of composite materials. *J of Mater Rese and Tech* 8 (6), 10.1016/j.jmrt.2019.09.068
[2] Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams C B, Wange C C L, Shina Y C, Zhang S and Zavattierif P 2015 The status, challenges, and future of additive manufacturing in engineering, *Computer-Aided Design* 69, pp 65 – 89

[3] Tao W and Leu M C 2016 Design of lattice structure for additive manufacturing, *International Symposium on Flexible Automation (ISFA)*, 16544329, 325-332, 10.1109/ISFA.2016.7790182

[4] Seharing A, Azman A H and Abdullah S 2020 A review on integration of lightweight gradient lattice structures in additive manufacturing parts, *Advan in Mechan Engin* 12 (6): 168781402091695, 10.1177/1687814020916951

[5] Lehmhus D, Vesenjak M, De Schampheleire S and Fiedler T 2017 From Stochastic Foam to Designed Structure: Balancing Cost and Performance of Cellular Metals, *Mater* 10 (8): 922, 10.3390/ma10080922

[6] Nagesha B K, Dhinakaran V, Shree V M, Kumar K P M, Chalawadi D and Sathishc T 2020 Review on characterization and impacts of the lattice structure in additive manufacturing *Mater Today: Proc* 21, Part 1, 916-919, 10.1016/j.matpr.2019.08.158

[7] Austermann J, Redmann A J, Dahmen V, Quintanilla A L, Mecham S J and Osswald T A 2019 Fiber-Reinforced Composite Sandwich Structures by Co-Curing with Additive Manufactured Epoxy Lattices, *J of Comp Sci* 3(2):53, 10.3390/jcs3020053

[8] Sutton M A, Orteu J J and Schreier H 2009 Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications. 1st ed. Springer Publishing Company, Incorporated, 10.1007/978-3-87-78743-3

[9] Ling C, Cernicchi A, Gilchrist M D and Philip Cardiff 2019 Mechanical behaviour of additively-manufactured polymeric octet-truss lattice structures under quasi-static and dynamic compressive loading. *Materials & Design* 162 (15) 106 - 118, 10.1016/j.matdes.2018.11.035

[10] Blaber J, Adair B and Antoniou A 2015 Ncorr: Open-Source 2D Digital Image Correlation Matlab Software. *Exp. Mech*. 55 (6): pp 1105–1122, 10.1007/s11340-015-0009-1

[11] Nežerka V Antoš J, Sajdlová T and Tesarek P 2016 Use of Open Source DIC Tools for Analysis of Multiple Cracking in Fiber-Reinforced Concrete. *Appl Mech and Mater* 827: 336 – 339, 10.4028/www.scientific.net/AMM.827.336

[12] Dattoma V, Panella F, Pirinu A, Castriota A. 2019 Fatigue damage on CFRP plates under bending by thermographic and UT analysis, aided with FEM-DIC prediction. *Pro Stru Inte* 24: pp 978– 987.

[13] Jung A, Al Majthoub K, Jochem Ch, Kirsch S M, Welsch F, Seelecke S and Diebels S 2019 Correlative digital image correlation and infrared thermography measurements for the investigation of the mesoscopic deformation behaviour of foams. *J of the Mech and Phy of Sol* 130, pp 165-180

[14] Huo X, Sun G, Zhang H, Xiaojiang Lv and Qing Li 2019 Experimental study on low-velocity impact responses and residual properties of composite sandwiches with metallic foam core. *Composite Structures* 223, 110835