On the use of optical methods in the validation of non-linear dynamic simulations of sandwich structures

LAMPEAS, George and PASIALIS, Vasileios <http://orcid.org/0000-0002-2346-3505>

Published version

LAMPEAS, George and PASIALIS, Vasileios (2012). On the use of optical methods in the validation of non-linear dynamic simulations of sandwich structures. In: 14th International Congress on Mesomechanics28, 2012, Budapest, Hungary, 25-28 September 2012.

On the use of optical methods in the validation of non-linear dynamic simulations of sandwich structures

G. Labeas [a,*], V. Pasialis

[a] University of Patras, Department of Mechanical Engineering and Aeronautics, 26500, Rion,Patras, Greece

Abstract

Innovative designs of transport vehicles need to be validated in order to demonstrate reliability and provide confidence. The most common design approach of such structures involves simulations based on Finite Element (FE) analysis, which require reliable validation techniques, especially if anisotropic materials, or complex designs, such as sandwich panels are to be applied. The present paper aims to integrate sophisticated numerical analysis with full-field optical measurement system data in order to improve the quality of both methods and increase reliability of the design.

Keywords: full-field optical measurement , low-velocity impact tests; sandwich structures; honeycomb, digital image correlation, zernike moments

1. Introduction

During the design and analysis of structural components, it is normal practice to assess the accuracy of numerical results by comparing the numerically predicted values to corresponding experimental data. However, current practice tends to focus on identifying hot-spots in the data and checking that the experimental and modeling results agree in these critical zones, while often the comparison is restricted to a single point where the maximum stress occurs. This highly localized approach neglects the majority of the data generated by full-field optical techniques and carries with it the risk that critical regions may be missed all together. To overcome this drawback, the use of full field optical techniques, e.g. [1, 2], provides a number of significant advances which are emerging from the innovation process. In optical deformation measurement, these advances include digital image correlation and fringe projection techniques. Deformation, strain, or vibration modes due to defined loads are often measured by digital image correlation methods (DIC), e.g. [3] or fringe techniques, such as moiré, holographic and digital speckle pattern interferometry (DSPI) or shearography, e.g. [4]. The strength of full-field optical techniques is that the entire displacement field can be visualized and analyzed. By using High Speed cameras, the DIC method can be applied to highly non-linear dynamic events and deliver quantitative information on three-dimensional (3D) displacement and strain fields.

There exists special need for validation of simulations in the high energy, dynamic regime of impact loading or crash, when composite materials are involved. In this frame, the objective of the present paper is to integrate full-field optical measurement methodologies to state-of-the-art computational simulation techniques for the case of non-linear transient dynamic events, in order to improve both methods. Whilst the impact simulation of homogeneous isotropic panels is a relatively straightforward task, the simulation of impact and subsequent development of damage in a composite panel is probably at the leading edge of current knowledge.

For the needs of the present work, sandwich panels have been selected, as they are widely used in energy absorbing applications involving low or high-velocity impact conditions. The investigated sandwich panels comprise two types of core (truss and honeycomb) and two types of skin (aluminum and carbon/epoxy, respectively), as presented in Fig.1. The truss core sandwich panels consist of 'Wadley'-type metallic open cell core placed between two aluminum skins and have dimensions of 150x150x50 mm^3. The 'Wadley'-type core is fabricated by ATECA-France [5] in the frame of EC funded project CELPACT (Cellular Structures for Impact Performance), using 304L stainless-steel sheets (density of 8000 kg/m3 and

*Corresponding author.
E-mail address: labeas@mech.upatras.gr

elasticity modulus of 193 GPa); the production process involves the punching and folding technique for fabrication of layers, which are then stacked and brazed to form the cellular core. The representative unit-cell for this core type is an irregular Body Centered Cubic (BCC) of dimensions 8,7x6,55x10,7 mm^3 in x, y and z directions, respectively. The strut rectangular cross-section has width of 1,6 mm and thickness 0,55mm. The thickness of skin is 2mm. The dimensions of honeycomb core sandwich panels, manufactured by HPS company [5], are 150x150x40 mm^3. The honeycomb core material is Al 5056 of density 2640 kgr/m^3 and elasticity modulus of 70 GPa. The cell shape is regular hexagon with 0.0254 mm thickness and 4,7625 mm cell's size. The skins covering the cellular core are produced of carbon/epoxy $[0/90]_4$ fabric composite material. The thickness of skin is 2 mm.

Aiming to assess the panel energy absorbing capability, the panels have been tested in hard-body low velocity, low energy, mass-drop impact loading, in the drop-tower shown in Fig.1, with impact velocities ranging from 4.86 m/s to 7,4 m/s and impact energies ranging from 148,26.J to 493,39.J. The boundary conditions comprise the panel sustain on four spherical supports of 20 mm diameter.

In parallel, simulation models of the sandwich panels have been developed, as presented in detail in the next section 2. In addition, the sandwich panels were properly instrumented during the tests by Dantec Dynamics full-field optical measurement systems [6], such that the transient history of deformation and displacement fields are recorded, to achieve the maximum amount of quantitative data for understanding the panel behavior, as well as to enable the applicability of test results in the validation of respective impact simulation models. The High Speed Image Correlation system was used to deliver full field optical measurement data, which were used to correlate experimentally recorded and numerically calculated strain histories at the top skin of the sandwich structure.

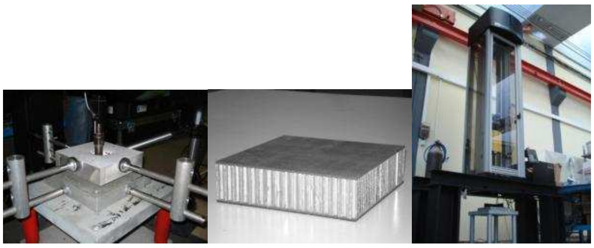

Fig.1. Sandwich panels with truss core (left) Honeycomb sandwich panel (middle) Drop-tower used for the sandwich panels impact testing (right)

The experimental validation of the simulations of the dynamic event using full-field optical methods are based on a quantitative correlation of calculated and measured shape features and their changes occurring as a consequence of high energy dynamic events.

2 Development of FE models

2.1 FE mesh and boundary conditions

Finite Element simulations of the low-velocity impact tests of truss type sandwich panels have been performed using the explicit dynamic FE code PAM-Crash. The spherical supports are modeled as infinite mass rigid walls, while the impactor is modeled as a rigid body with one degree of freedom in the direction of impact. The skin is modeled using quad-shell elements. The core structure is modeled by both beam and shell elements.

For all impact simulations, quarter symmetric models of the test specimens were developed and proper symmetry boundary and loading conditions were applied, in order to reduce the calculation cost, which is especially high for sandwich structures. The FE model, as well as the boundary and loading conditions applied, are schematically presented in Fig.2, while more details can be found in [7].

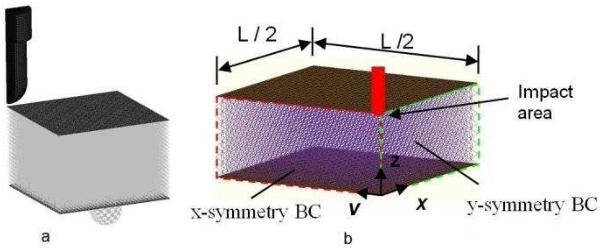

Fig.2. Quarter sandwich panel FE model: impactor and support system of the quarter model (left) and symmetry boundary conditions (right)

The FE mesh of the impactor is presented in Fig.3. It consists of a narrow part (radius 12.7mm and length 42mm) that corresponds to the impactor tup and a wider part (radius of 15,9mm, modeled length 20mm) that corresponds to the tup extender. Due to the described impactor geometry and the high panel thickness (50mm), if the impactor energy is not completely absorbed by the upper skin and the core deformation, a second impact occurs. The second impact takes place when the wider part of the impactor reaches the upper skin and causes its further deformation.

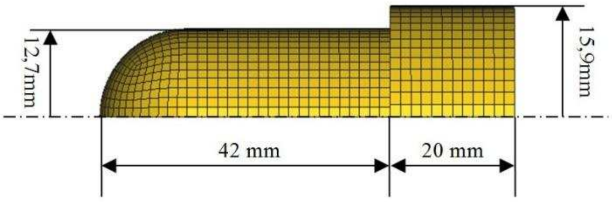

Fig.3. Geometry and FE model of the impactor

2.2 Material models

The skin is modeled with elastic-plastic shell elements, which are assigned the material data of aluminum alloy 2024. For the metallic core two modeling approaches are applied, both involving a bi-linear elastic-plastic material model for the stainless-steel 304L core material, i.e. a shell element model and a beam element model (Fig.4).

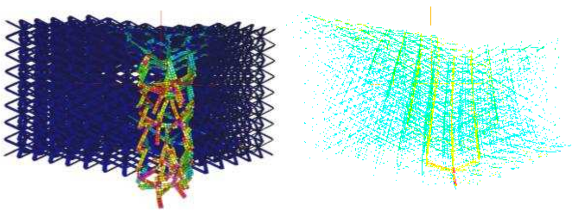

Fig.4. Damage as calculated from the two different truss-type core models: a) Shell element model; b) Beam element model

In the shell element model twenty quad-shell elements per strut were used for the truss-type core. The shell element model can represent more accurately the geometry of the region where struts are joined together, providing a stiffer connection. In the beam element model ten higher order beam elements are applied for each strut. When the struts are modeled with beam elements, the complex surface of the strut junction is degraded to a single point; as the real connection is not perfect, the more flexible beam element model gives a better simulation of core response under impact loading.

The calculated behaviour of both core models under the same impact conditions is presented in Fig.5a (shell element model) and 5b (beam element model). The observed experimental behaviour of the truss-type core is better approximated with the beam element core model.

2.3 Material interfaces and contact definitions

Two sets of contact definitions were applied, i.e. the self-impacting type for core and skins and node-to-surface type for the contact of the impactor to the skin-core system. The core and the skin in this truss sandwich structure are bonded by brazing technique. The brazed bonds fail at low loading and the skin de-bonds from the core during impact. The addition of a tie-break interface is necessary in order to model the failure of brazed bonds between the core and the skins. The rupture model associated to this interface type requires special attention. For this purpose in the present simulations and due to lack of experimental interfacial strength values, the rupture model parameters were roughly estimated by performing a parametric study. For successful modeling of this type of structure, it is of major importance to experimentally determine the type and the parameters of the brazed bonds rupture.

2.4 Impact simulation results

The simulated impact test on the truss-type sandwich structure was performed with impact energy of 493,39J and impact velocity of 7,4 m/s. In Fig.5a, core compaction due to impact and the upper skin-core de-bonding are presented at the moment when the impactor is trapped in the core. The plastic deformation of the upper skin can be observed in Fig.5b.

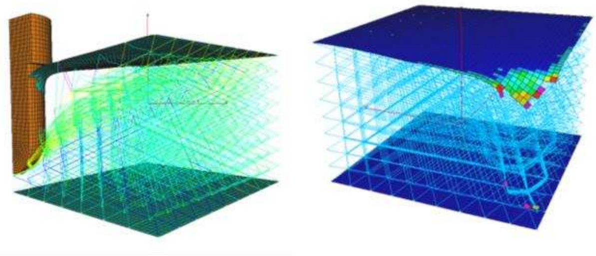

Fig.5. a) Impactor penetration and core deformation (left side); b) Plastic deformation of upper skin (right side)

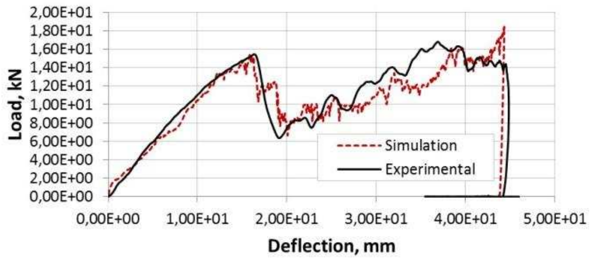

Fig.6. Experimental and calculated load-deflection diagrams for the 493,39J impact on truss-type structure

The experimental and calculated load-deflection curves are compared in Fig.6. It can be observed that the upper skin failure, which corresponds to the first peak in the diagram of Fig.6 followed by a sudden load drop, is well predicted with the adopted material model for the aluminum skin. The process of simultaneous core de-bonding from the upper skin and its compaction under the impactor loading is also well predicted, as can be observed in the same diagram in the region between two load peaks. The calculated final peak loading and the final depth at which the impactor gets trapped in the core are slightly larger than the measured ones, but still within satisfactory accuracy. A comparison of the numerically calculated strains to those experimentally measured by the optical system is performed in the following section 3.

3 Optical measurement data and comparison to model results

During the impact experiment of the sandwich honeycomb panel, the upper panel surface displacement was recorded by optical measurement methods. Before the test, a speckle pattern was applied on the surface using matt paint from a paint can. For the image acquisition, highspeed cameras (Phantom V310) with 1200 x 800 pixels resolution were used. The maximum frame rate at full resolution of these cameras is 3500 fps (frames per second). For this measurement the number of pixels was adapted to the field of measurement. Due to this reduced number of pixels the frame rate was increased to 5000 fps. In Fig.7, the setup including the highspeed cameras and illumination in front of the test machine is shown.

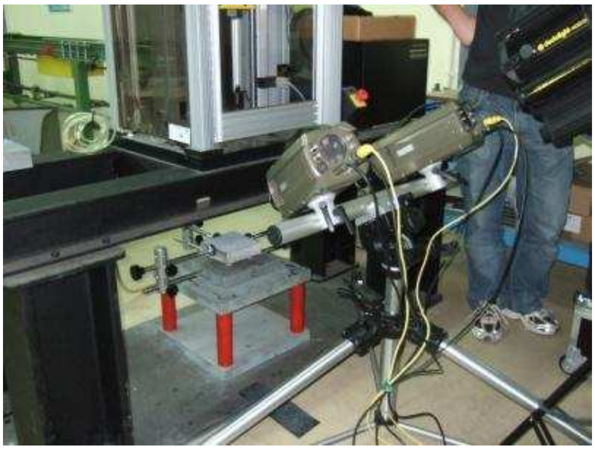

Fig.7. Experimental setup of the High Speed Digital Image Correlation System Q-450 for the measurement of the impact on a sandwich honeycomb panel

The position and projection parameters of the cameras are determined using a calibration process [8]. With this information and the knowledge of the position of an object point in the images of both cameras the position of this object point in 3D space can be calculated. Using multiple points, the full field information is obtained. From a series of images the displacement and strain of the object surface can be derived.

In Fig.8, the full field deformation at 1 msec after the contact of the impactor on the honeycomb specimen is presented. In the same figure, the out-of plane displacement of a point near the impact is plotted as a function of time.

In Fig.9, a detailed comparison between vertical displacement fields for the case of truss-type core sandwich panel as derived by the optical measurement system and calculated by the FE model is presented. A relatively good correlation may be observed (Fig.9a,b), although locally in the vicinity of the impacted area some differences between the damaged patterns may be observed (Fig.9c).

The conventional practice of identifying hot-spots in the data and checking that the experiments are in a satisfactory agreement to the simulation model results in these critical zones, as demonstrated in the previous chapter, neglects the majority of the data generated by optical techniques and carries with it the risk that critical regions will be missed all together.

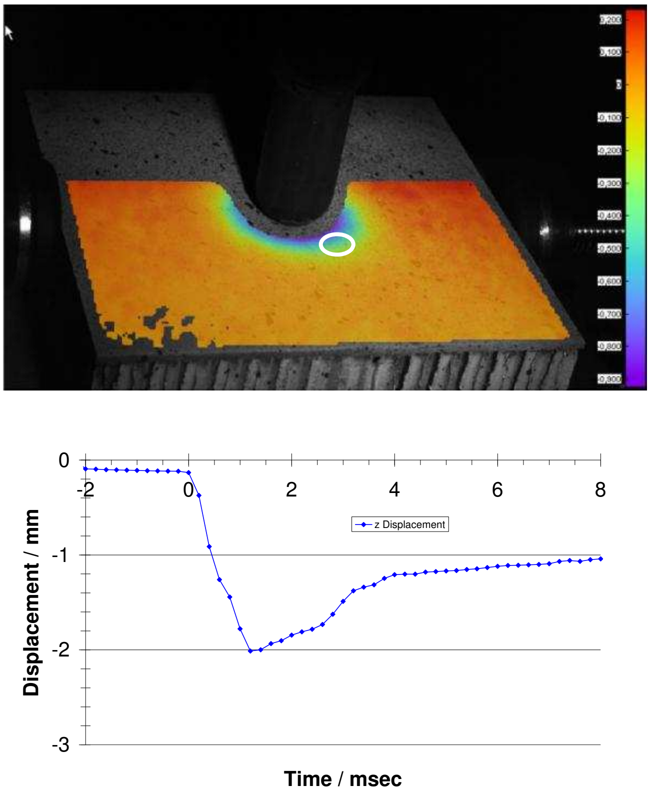

Fig.8. Honeycomb panel: a) displacement in the field of view as seen from one camera 1 msec after the contact of the impactor (upper side); displacement over time of the marked point (lower side)

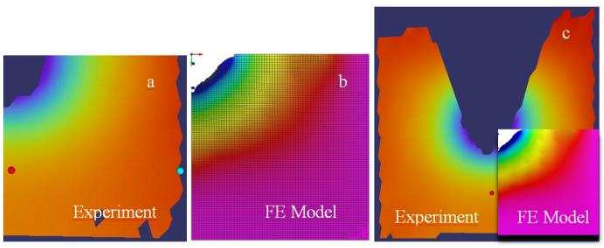

Fig.9. Comparison between displacement fields obtained by the optical system and FE model of structure with Wadley'-type metallic open cell core

In Fig.10 it is clearly seen that numerical and experimental results from the honeycomb core panel case portray a very successful correlation in the critical area around the impact. This fact may easily lead to erroneous conclusions about data agreement as other areas do not depict the same convergence in out-of-plane displacement values.

Progress has been made in the frame of project ADVISE [4] in developing an integrated methodology for comparing FE simulations to experimental data, including the use of reduced or decomposed data. Different shape descriptors (Zernike moment, Discrete Fourier transform (DFT), Tchebichef features, etc) can be used to reduce the amount of the data in order to simplify the data comparison.

Presently, the Zernike polynomials, shown in the following equations (Eqs (1-3)), are used to perform decomposition of a strain or displacement image plots taken from the DIC measurements and the simulation results at a specific time interval.

$$Z_{n,m} = \frac{n+1}{\pi}\int_0^{2\pi}\int_0^1 I(\rho,\theta)V^*_{n,m}(\rho,\theta)\rho\, d\rho\, d\theta \qquad \text{Eq. (1)}$$

$$R_{n,m}(\rho) = \sum_{s=0}^{(n-|m|)/2} (-1)^s \frac{(n-s)!}{s!\left(\frac{n+|m|}{2}-s\right)!\left(\frac{n-|m|}{2}-s\right)!}\rho^{n-2s} \qquad \text{Eq. (2)}$$

$$V^*_{n,m}(\rho,\theta) = R_{n,m}(\rho)e^{-j\theta} \qquad \text{Eq. (3)}$$

A suitable area of the upper skin of the honeycomb was selected for comparison purposes, as shown in Fig.10. Before the application of the Zernike polynomials to decompose the images, a mapping of the rectangular shaped area into a circular shape is performed, as shown in Fig.11. The following decomposition of images is performed using only the most important Zernike moments such that upon image reconstruction using Eq. (4), the reconstruction error computed by Eq. (5) remains negligible. Further details can be found in the relative reference [9].

$$\hat{I}(\rho,\theta) = \sum_{n=0}^{N}\sum_{m} Z_{n,m}V_{n,m}(\rho,\theta) \qquad \text{Eq. (4)}$$

$$\overline{e^2} = \frac{\iint_D \left|I(x,y)-\hat{I}(x,y)\right|^2 dxdy}{\iint_D I(x,y)^2\, dxdy} \qquad \text{Eq. (5)}$$

Consequently, the reconstructed images can be compared quantitatively, as shown in Fig.12; from Fig.12 a fair qualitative comparison for the case of the honeycomb upper skin can be observed. Furthermore, the Zernike moment descriptors calculated from the decomposition of the simulation plot image are quantitatively compared to the terms calculated from the decomposition of the optical system image, indicating a roughly fair agreement (Fig.13).

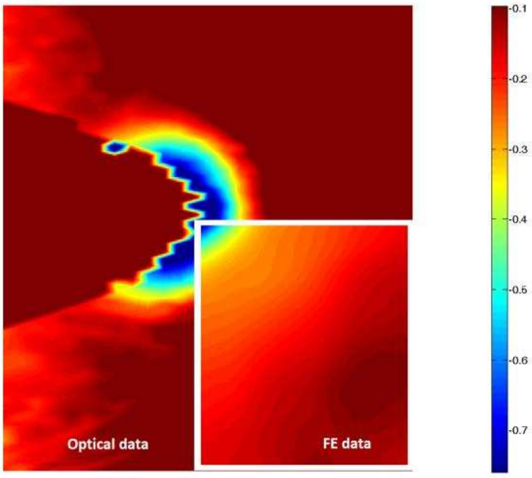

Fig.10: Area of the upper skin of the honeycomb selected for comparison: optical system image and FE image.

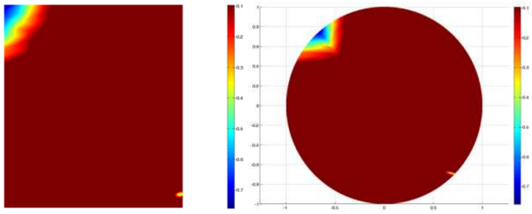

Fig.11: Mapping of the rectangular shaped area (left) into a circular shaped geometry (right)

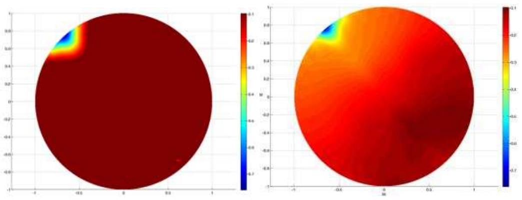

Fig.12: Reconstruction of the unit disc with the most important Zernike moment terms: optical system reconstructed image (left) and simulation plot reconstructed image (right)

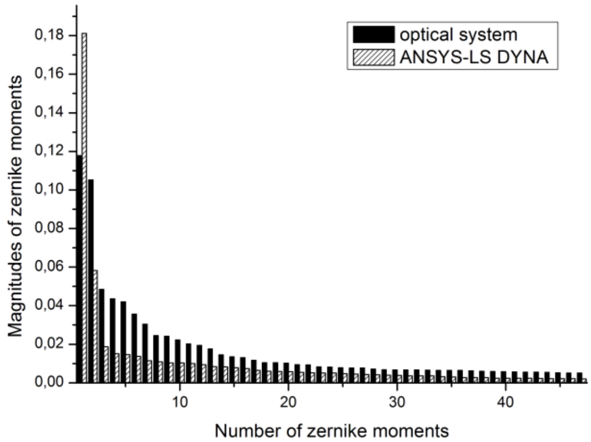

Fig.13: Quantitative comparison of Zernike terms between the simulation plot image and the optical system image

4 Conclusions

The honeycomb core sandwich panels have demonstrated an integral sandwich structure without severe core-skin debonding and very good energy absorbing performance of the core structure. The truss-type metallic open cell core has also demonstrated very good energy absorbing performance. At low velocity impact energy, the upper skin is penetrated but the impactor can be stopped by the core. The upper skin is additionally loaded by the impactor extension, resulting to separation of the upper skin from the core and appearance of strain waves on the skin.

Qualitative comparison between out-of–plane displacement fields, as derived by the optical measurement system and calculated by the FE models are in a relatively good agreement for the case of the 'wadley'-type metallic core sandwich structure. Experimental and numerical impactor load-deflection diagrams are also in good correlation. Investigation on the deviations can potentially lead to advances for both analytical and experimental approaches.

Quantitative full-field data comparison between experimental and simulation displacement results for the case of the honeycomb-type core sandwich structure has also been worked out. Numerical results are obtained using commercial FE codes, while experimental data are acquired using a drop tower facility and a full field optical measurement system.

The 'shape descriptor' approach was successfully applied in comparisons between simulation and experimental results for the case of the honeycomb structure under highly non-linear dynamic loading. It may be observed that a relatively low number of terms is required for image reconstruction of the selected area of the upper skin.

Current engineering practice focuses on data agreement of hot-spots on a critical area and ignores full-field comparison between numerical and experimental results. In this work the 'shape descriptor approach' was implemented for the case of the honeycomb-type core sandwich panel to expose the weakness of this practice.

However, optical systems take measurements only on the external surfaces of the structures. Despite the fact that the displacement field produced on the upper skin of the honeycomb is dictated by the mechanical behavior of the whole sandwich structure, validation procedures must include the use of more generic results such as the impactor force-displacement diagram, in the absence of optical comparison techniques for the core of the panel. A useful idea to overcome this problem could be the use of appropriate homogenized numerical models and specimens of minimum thickness in place of sandwich models and structures.

Nevertheless, the 'shape descriptor' comparison approach seems to be a powerful tool with the main advantage of a radical data reduction, therefore by its further development it is expected to become a reliable tool for integrated comparisons between experimental and simulation results of large scale complex structures, subjected to highly non-linear dynamic events.

5 Acknowledgement

This work has been partly funded by the European Community's Seventh Framework Programme under Grant Agreement no. SCP7-GA-2008-218595 (ADVISE project).

6 References

1. P. Rastogi, D. Inaudi (Eds.), Trends in optical non-destructive testing and inspection, Elsevier, Amsterdam, 2000
2. V.P. Shchepinov, V.S. Pisarev, S.A. Novikov et al., Strain and Stress Analysis by Holographic and Speckle Interferometry, John Wiley, Chichester, 1996
3. Th. Siebert, R. Wood, K. Splitthof, "High Speed Image Correlation for Vibration Analysis", 7th International Conference on Modern Practice in Stress and Vibration Analysis, Cambridge, 2009
4. R. Kästle, E. Hack, and U. Sennhauser, "Shearography for determination of 2D strain distributions", Proc. SPIE 3824, 38-44, 1999
5. www.hps-gmbh.com, www.ateca-fr.com
6. http://www.dantecdynamics.com/Default.aspx?ID=1521
7. CELPACT (Cellular Structures for Impact Performance), Deliverable D.4.2.1
8. Th. Siebert, Th. Becker, K. Splitthof, I. Neumann, R. Krupka, "High-speed digital image correlation: error estimations and applications", Opt. Eng. 46(5), 051004 (2007).
9. W. Wang, J. Mottershead, C. Mares. Mode-shape recognition and finite element model updating using the Zernike moment descriptor, Mechanical systems and signal processing, 2009.