Vibration-Based Non-Destructive Evaluation of Internal Damage in Foam Cored Sandwich Structures Using Wavelet Analysis

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Modern mechanical and civil structures are increasingly designed using polymeric composites that ensure great strength-to-mass ratio and are resistant to various environmental interactions, like corrosion. The application of sandwich structures in the design of mechanical and civil constructions is determined by their good stiffness properties and very low mass, which is a very attractive combination. Due to their wide applicability, these structures should be properly maintained and diagnosed, and thus, appropriate non-destructive testing (NDT) methods should be developed in order to detect and identify various types of damage. Special attention should be paid to internal damage (damage to the core of a sandwich structure), which cannot be detected during a visual inspection. In the paper, an NDT method based on modal analysis and further processing of modal shapes using a wavelet transform is proposed. Three sandwich structures with damage to the core of various types were experimentally tested using modal analysis, the damage positions were detected and identified using wavelet analysis, and verified by comparing the results of previously performed thermographic tests. The obtained results show a high effectiveness of the proposed approach, which could find an application in the industrial inspection of sandwich structures in a non-destructive and non-contact manner.

1. INTRODUCTION

Sandwich composite structures are manufactured from various materials and in different configurations depending on the area of their application. One of the types of such sandwich composites which has found wide application both in mechanical and civil constructions is a foam cored sandwich that consists of a thick core and thin face sheets usually made of an aluminium or glass fibre-reinforced polymeric (GFRP) composite. Considering the wide applicability of these structures' appropriate inspection procedures, they are necessary both at the stage of quality control (manufacturing-damage assessment) and at the stage of maintenance (damage caused by fatigue, overloading, sudden accidents, etc.). The inspection and diagnosis of sandwich structures, due to the modern demands of industry, should be non- destructive and sensitive enough to detect and localize damage positions at possibly an early stage of their development.

Numerous NDT methods dedicated to the inspection of thick polymeric sandwich structures have been developed or adapted to date. The most often applied methods for such structures include acoustic emission (AE) testing, ultrasonic testing (UT), infrared thermography (IRT) and X-ray computed tomography (CT). A comprehensive overview on these methods applied for thick composite structures was presented by Ibrahim.[10] Several recent studies describe AE-based methods of damage evaluation; however, they are based[4] mostly on comparison with reference measurements, e.g. Burlayenko and Sadowski[4] who have analysed a delamination in foam and honeycomb cored sandwich plates using a numerical model based 1on shifts of natural frequencies. Arora et al.[1] compared the frequency response functions (FRFs) and modal shapes of healthy and damaged structures in order to detect damage. An original approach was presented by Dickinson and Fletcher,[6] where they tested aircraft composite panels with impact damage in honeycomb cored sandwich structures by using a reference-free AE-based method, and they detected and localized the damage with high confidence. Several other approaches of damage detection are described in Ben et al.[3] and Masmoudi et al.[17] However, the tests were based on fatigue tests, counting the number of hints, and the observation of evolution of mechanical properties of tested structures until the failure.

Various UT-based techniques have been applied for damage identification in sandwich structures. The results presented by Holmes et al.[9] and Smith et al.[22] confirm the effectiveness of these techniques in damage detection and identification. In the experimental study presented by Chakraborty et al.[5], the authors used Lamb waves for damage detection in honeycomb cored sandwiches with wavelet-based post- processing, and based on the obtained results, they could detect and distinguish the damage. This group of methods is efficient in damage evaluation in sandwich structures. However, such methods are often limited to the laboratory conditions. Successful damage identification is also possible using transient IRT[11] and vibrothermography,[2,19] the method which uses ultrasonic-vibration excitation of a tested structure with a simultaneous measurement of thermal response using IRT. Both external and internal damage in sandwich structures can be effectively detected and identified using this method. Finally, X-ray CT methods provide a possibility of obtaining a 3D scan with the best resolution as compared to other NDT methods. The application of this technique to damage detection and identification of thick sandwich structures gives very precise results.[7] However, the high cost of inspection and limitation to the possibility of performing tests in laboratory conditions often limits its application to manufacturing or in-service inspections.

One of the oldest groups of NDT methods covers the vibration-structural analysis which is usually based on modal analysis and further evaluation of natural frequencies and modal shapes of tested structures. This group of methods is relatively inexpensive in comparison to the above-mentioned ones, simultaneously not limited to the laboratory conditions, and effective enough in damage evaluation of sandwich structures. Initially, vibration methods were based on a comparison of FRFs and/or modal shapes to a reference structure. Several experimental studies using this approach were described by Gagneja et al.[8] and Ratcliffe et al.[20] The comparative analysis of modal parameters is often inefficient, especially when damage size is relatively small. Another difficulty is that the reference (healthy) structure is not always available for comparison. In order to make vibration-based damage-identification approaches local, i.e. to enrich them by a possibility of damage localization, an analysis of modal shapes should be supported by advanced signal processing techniques. Several approaches were used to date: Nichols et al.[18] used entropy measures based on correlation functions obtained by means of multiple sensors measurements which allowed them to detect impact damage in sandwich structures; another approach was proposed by Zhu et al.[24] where the authors detected debonding in honeycomb cored sandwich structures using FRFs; meanwhile, Lestari and Qiao[16] successfully identified damage in thick sandwich composite structures using a damage-index approach determined for modal shapes of tested beams. Several attempts in damage detection and identification were made in the previous studies conducted by the author,[14] where both internal and external damage of thin sandwich honeycomb-cored structures were identified using wavelet analysis.

The main goal of this paper is to investigate the possibility of detection and identification of various types of internal damage of foam cored thick sandwich structures based on analysis of modal shapes with their further post-processing using wavelet analysis. The main difficulty of such an analysis is that the foam used for a sandwich core is a highly damping material which has an influence on decreasing the natural frequencies of vibration as well as lowering the vibration magnitudes. Taking into account a relatively large thickness of tested sandwich structures and the fact that all of the investigated cases contained internal damage only makes the problem more challenging.

2. MATERIAL AND TESTING PROCEDURE

2.1. Specimens Preparation

The tested specimens with spatial dimensions of 300×300 mm consist of a polyurethane core (manufactured by Ruukki Construction Polska Sp. z o.o.) and glass-epoxy composite face sheets (manufactured by Izo-Erg S.A.) bonded by a two-component polyurethane adhesive Macroplast U.K. 8309 and Macropur U.R. 521 (hardener) mixed in a ratio of 5:1. The foam has a closed-cell structure, approximately 40 kg/m^3 density and a thickness of 57 mm manufactured during polymerization reaction from ingredients such as polyol, isocyanates, catalysts and blowing gases. A total thickness of the tested specimens is 58 mm.

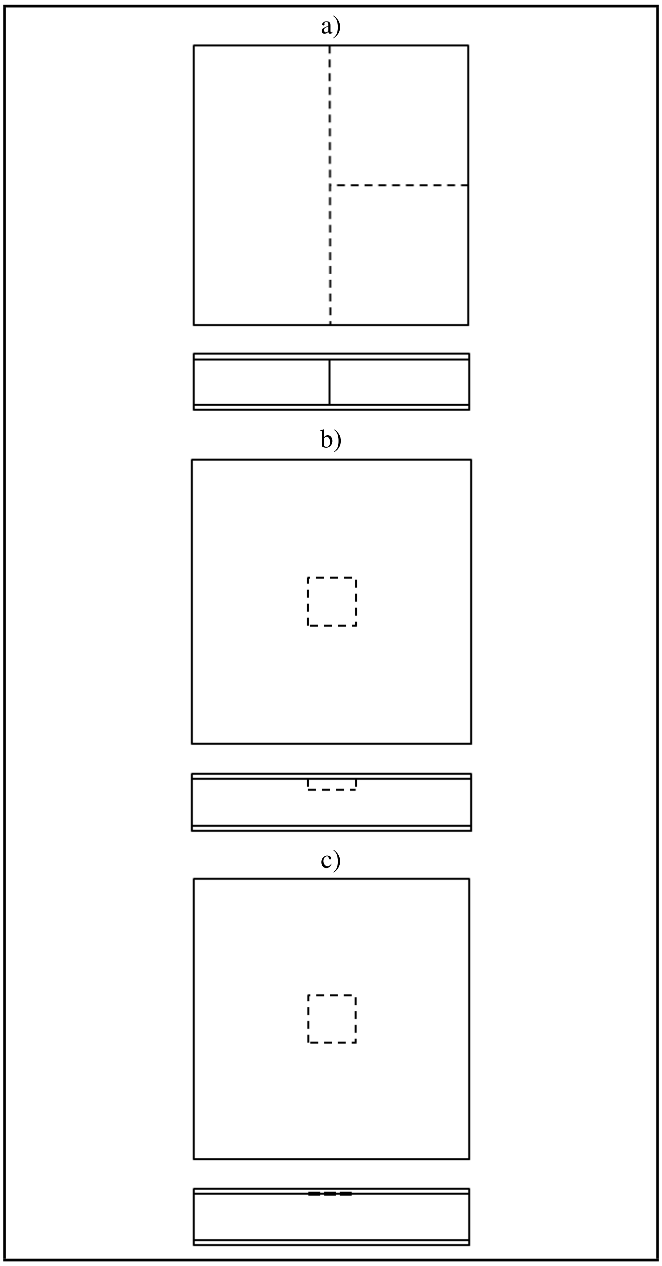

Figure 1. Considered sandwich structures with simulated damage: a) through-the-width crack, b) local lack of a core, c) debonding.

Three types of damage of a core were considered in this study: through-the-thickness crack in two orthogonal directions, as shown in Fig. 1a; local partial lack of a core with spatial dimensions of 50×50 mm located in the geometric centre with a depth of 1/4 of total thickness of a core, as seen in Fig. 1b; and local lack of an adhesive between a core and a face sheet on the same area as in a previous case which simulated debonding, which is shown in Fig. 1c.

The damage types were selected according to their often occurrence during manufacturing and in-service maintenance in foam cored sandwich structures used in various engineering applications.[15,21,23]

2.2. Modal Analysis

In order to acquire modal shapes of vibration for tested structures, a modal analysis was performed following the setup

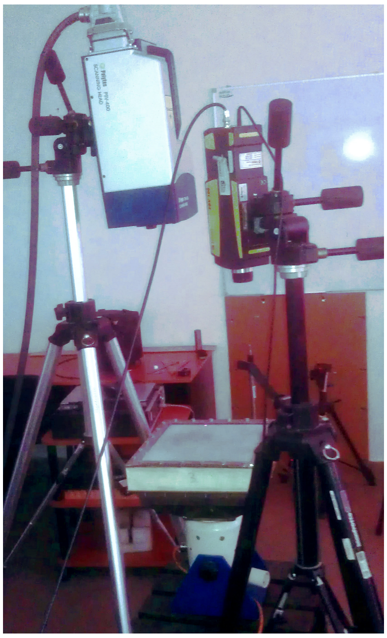

Figure 2. Experimental setup.

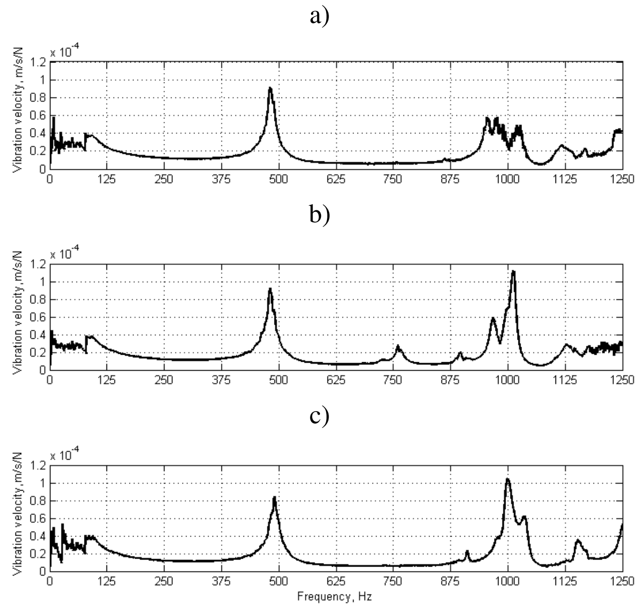

Figure 3. FRFs of tested structures: a) through-the-width crack, b) local lack of a core, c) debonding.

presented in Fig. 2. Two laser Doppler vibrometers (LDVs) were used during the tests: the scanning LDV Polytec® PSV-400 was used for the measurement of velocity of displacements on the surfaces of structures in the defined net of 64×64 measurement points while the point LDV Polytec® PDV-100 was used as a reference. The measurement of the reference signal (velocity of displacements of the clamping frame) allows eliminating the influence of natural frequencies and modal shapes of this clamping frame onto the measured response of the tested specimen. The analysed plate was clamped in a steel frame by 24 bolts around its perimeter which resulted in a reduction of the analysed area of the plate to 250×250 mm. The frame with the tested specimen was mounted on the point LDV that was focused on the surface of the clamping frame. The scanning LDV was connected with a vibrometer controller Polytec® OFV-5000 with built-in velocity decoder and a PC. In order to ensure good quality of measurement signal the tested plates were covered by Helling® anti-glare spray designed for the laser scanning. The frame was mounted on the electrodynamic shaker TIRA® TV-51120 by 4 bolts (in order to transfer an excitation directly to the tested specimen), which excited the specimen with a pseudo-random signal generated directly from the software intended for scanning LDV and amplified by the power amplifier TIRA® BAA 500.

The frequency bandwidth during the modal analysis was set in the range of 0–1.25 kHz with a resolution of 0.78125 Hz. The FRF for each measured point was averaged five times. The resulting FRFs of the whole sandwich structures are presented in Fig. 3.

Considering that the detectability of damage positions depends on the magnitudes of considered modal shapes it is necessary to select more than one modal shape in order to overcome a problem when the magnitudes of vibration velocity in the damaged region are small (corresponding with the nodal lines of a given modal shape or the regions near the clamped edges). Following this fact, particular modal shapes were selected for every considered structure; their frequency values are stored in Table 1. The corresponding modal shapes for the considered cases are presented in Fig. 4.

3. ANALYSIS OF RESULTS AND VERIFICATION

Collected modal shapes corresponding to the natural frequencies determined for each tested structure (see Table 1) were then subjected to wavelet analysis. Considering the previous studies[12], the Stationary Wavelet Transform (SWT) algorithm was selected for the analysis because using SWT during decomposition led to the resulting set of coefficients not reducing its size, e.g. in the case of a decomposition using discrete wavelet transform. This allows for the obtainment of more accurate damage localization. The damage identification procedure was performed using the developed WavStructDamAs tool in a Matlab® environment.[13] Based on comparative studies presented in Katunin[12] and preliminary testing, the biorthogonal B-spline wavelet of order 1.3 was selected for the analysis. The damage identification consisted of the following steps: firstly, a single-level SWT-based decomposition was applied to each acquired modal shape; from the obtained sets of approximation and detail coefficients, the latter were selected as they contain diagnostic information about damage (tiny inconsistencies in modal curvatures resulted from local decrease of stiffness in damaged regions can be observed in sets of detail coefficients); and finally, the absolute values of sets of detail coefficients were added up for every tested structure. The resulting sets of coefficients after the above-described operations are presented in Fig. 5. For the clarity of presentation, the boundary effect was removed using an asymmetric-padding method.

One can observe that the damage positions in the case of local lack of a core and debonding were properly detected and identified. In the first analysed case of a damaged sandwich structure, the cracks are detectable, but not on their whole length (cf. Fig. 1a and Fig. 5a). This is caused by the low influence of a presence of these cracks on local stiffness of a

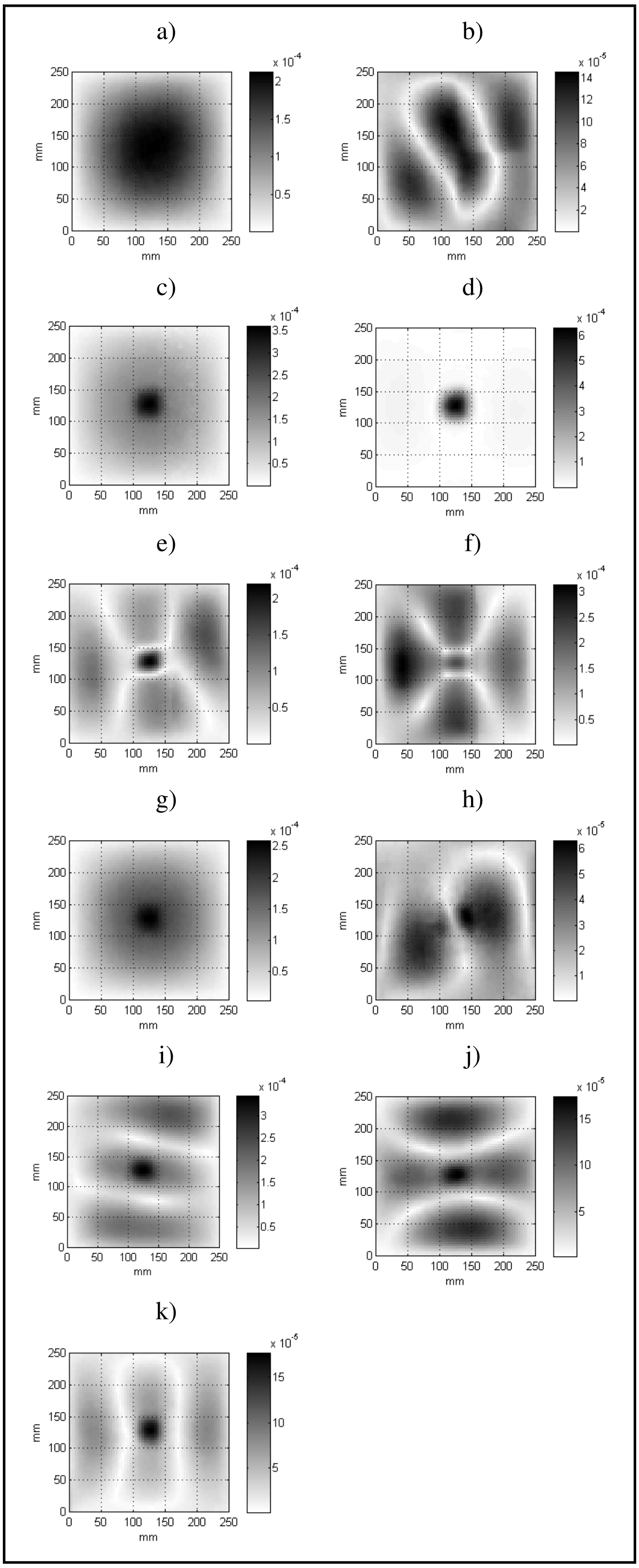

Figure 4. Considered modal shapes of the tested specimens with damage: a), b) through-the-width crack, c)-f) local lack of a core, g)-k) debonding.

Table 1. Considered natural frequencies for the tested structures, Hz.

Through-the-width crack	482.03	953.91	...		
Local lack of a core	481.25	760.94	967.19	1011.72	...
Debonding	490.62	910.94	999.22	1036.72	1152.34

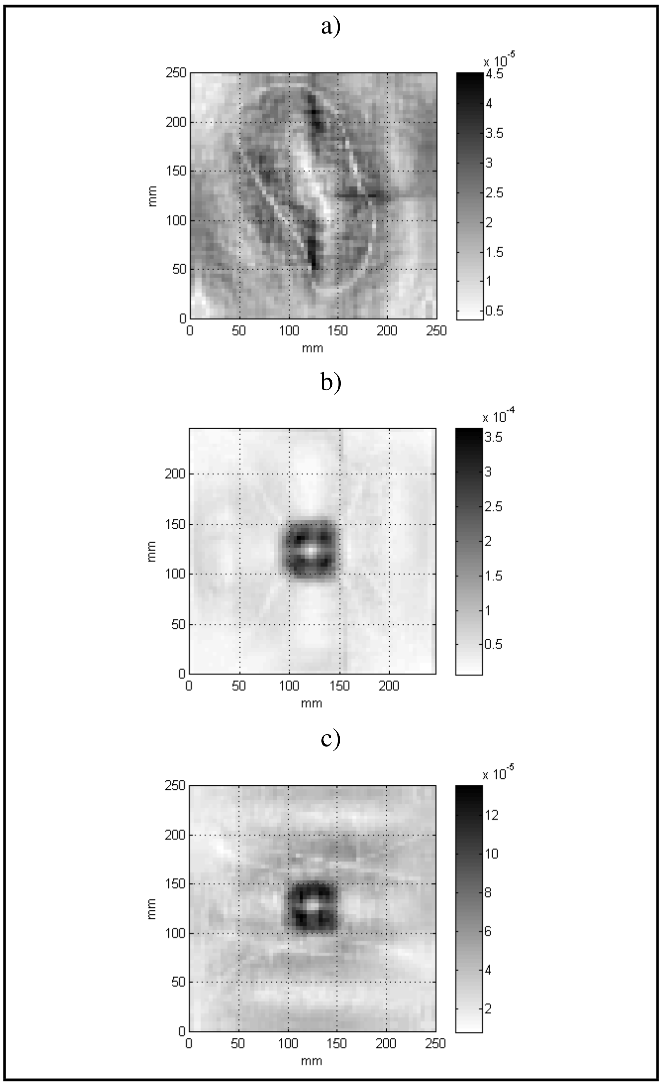

Figure 5. Results of damage identification in considered sandwich structures: a) through-the-width crack, b) local lack of a core, c) debonding.

tested structure (see Fig. 4a,b) which is confirmed by the lowest maximal value of resulting coefficients in comparison with other investigated cases as seen in Fig. 5. The face sheets integrate the structure in such a way that they do not allow for large displacements between the parts of the cracked core of the sandwich structure. The strongest influence of a damage is observed for the case of a local lack of a core where the damage was perfectly detected and localized. Such a good result was obtained due to the rapid and significant decrease of a structural stiffness in the location of the damage. This is confirmed by the highest maximal value of resulting coefficients (ca. 10 times higher than for the previously discussed case as seen in Fig. 5b). A similar result was obtained from the sandwich structure with simulated debonding between a core and a face sheet (see Fig. 5c). The reduction of stiffness in the debonded region allows detection and identification of the damage.

For additional verification of identified types of damage, the resulting sets of coefficients were compared to the results obtained for these structures using transient IRT.[11] The thermograms for the considered cases are shown in Fig.6. Additional artefacts visible in the thermograms are caused by local surpluses of glue from the manual gluing of face sheets to the core.

As it can be observed, the results of damage identification obtained using the vibration-based method are quite similar to those obtained using transient IRT as well as the schemes of a true damage (cf. Fig. 1, Fig. 5 and Fig. 6). This implies that the proposed vibration-based NDT method is effective enough to detect, localize, and identify internal damage in sandwich structures. One should mention two major drawbacks of the vibration-based approach: poor resolution with respect to other NDT methods (e.g. UT, IRT) and a long duration for tests. However, the advantage of applying this approach is that the measurements can be performed during in-field conditions and in a non-contact manner at far distances from the tested object which is suitable in such cases when an other NDT method cannot be applied.

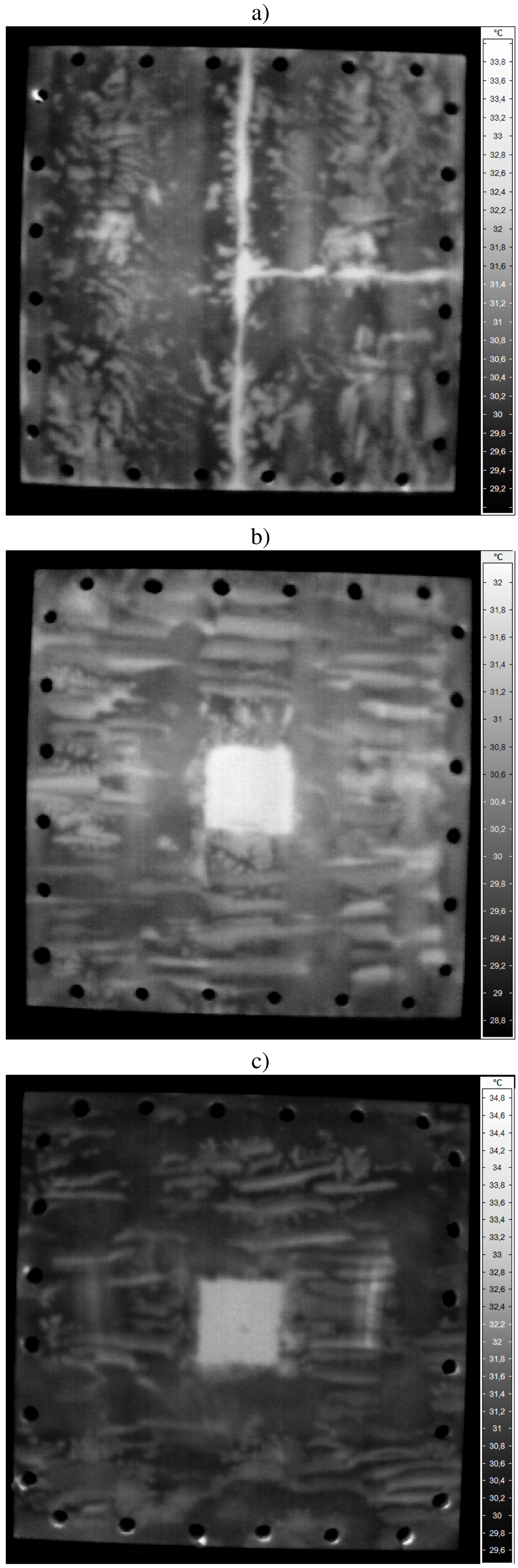

Figure 6. Thermograms obtained using transient IRT for considered sandwich structures.

4. CONCLUSIONS

In the presented study, the sandwich foam cored composite structures with various types of simulated, internal damage were tested for damage identification based on analysis of modal shapes of vibration using wavelet transform. Three types of the most common damage were considered during the tests. The parameters of wavelet analysis were selected in such a way that the damage was detected and identified in all considered cases. The obtained results allow a conclusion about the effectiveness of the proposed approach in NDT applications even if the tested structures are considered as thick. The effectiveness of this approach was additionally confirmed based on a comparative study of vibration-based and IRT-based tests. The proposed method may find an application during manufacturing (quality control) and routine testing of aircraft-thick sandwich structures as well as civil structures being in operation. The main advantage of the proposed approach with respect to other NDT techniques is a possibility of non-contact measurements using the LDVs of structural elements with no direct access when most of the other NDT techniques cannot be applied (e.g. UT, radiography) or their application is limited (e.g. IRT).

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REFERENCES

[1] Arora V., Wijnant Y. H., and de Boer A. Acoustic-based damage detection method, *Applied Acoust.*, **80**, 23–27, (2014). https://dx.doi.org/10.1016/j.apacoust.2014.01.003

[2] Ayorinde E., Gibson R., Kulkarni S., Deng F., Mahfuz H., Islam S., and Jeelani S. Reliable low-cost NDE of composite marine sandwich structures, *Compos. Part B:Eng.*, **39** (1), 226–241, (2008). https://dx.doi.org/10.1016/j.compositesb.2007.02.028

[3] Ben Ammar, I., Karra, C., El Mahi A., El Guerjouma, R., and Haddar, M. Mechanical behavior and acoustic emission technique for detecting damage in sandwich structures, *Appl. Acoust.*, **86**, 106–117, (2014). https://dx.doi.org/10.1016/j.apacoust.2014.04.016

[4] Burlayenko V. N. and Sadowski T. Influence of skin/core debonding on free vibration behavior of foam and honeycomb cored sandwich plates, *Int. J.Non-Lin. Mech.*, **45** (10), 959–968, (2010). https://dx.doi.org/10.1016/j.ijnonlinmec.2009.07.002

[5] Chakraborty, N., Rathod V. T., Roy Mahapatra D., and Gopalakrishnan S. Guided wave-based detection of damage in honeycomb core sandwich structures, *NDT&E Int.*, **49**, 27–33, (2012). https://dx.doi.org/10.1016/j.ndteint.2012.03.008

[6] Dickinson L. P. and Fletcher N. H. Acoustic detection of invisible damage in aircraft composite panels, *Appl. Acoust.*, **70** (1), 110–119, (2009). https://dx.doi.org/10.1016/j.apacoust.2007.12.012

[7] Dietrich S., Weidenmann K., and Elsner P. 3D tomographic characterization of sandwich structures, *NDT&E Int.*, **62**, 77–84, (2014). https://dx.doi.org/10.1016/j.ndteint.2013.12.001

[8] Gagneja S., Gibson R. F., and Ayorinde E. O. Design of test specimens for the determination of elastic through-thickness shear properties of thick composites from measured modal vibration frequencies, *Compos. Sci. Technol.*, **61** (5), 679–687, (2001). https://dx.doi.org/10.1016/S0266-3538(01)00006-9

[9] Holmes C., Drinkwater B. W., and Wilcox P. D. Post-processing of the full matrix of ultrasonic transmit-receive array data for non-destructive evaluation, *NDT&E Int.*, **38** (8), 701–711, (2005). https://dx.doi.org/10.1016/j.ndteint.2005.04.002

[10] Ibrahim M. E. Non-destructive evaluation of thick-section composites and sandwich structures: A review, *Compos. Part A: Appl. Sci. and Man.*, **64**, 36–48, (2014). https://dx.doi.org/10.1016/j.compositesa.2014.04.010

[11] Katunin A. and Chuda-Kowalska M. Assessment of internal damages in sandwich panels via active thermography, *Eng. Trans.*, **63** (2), 171–180, (2015). Retrieved from http://et.ippt.gov.pl/index.php/et/article/view/237

[12] Katunin A. Damage identification based on stationary wavelet transform of modal data, *Model. Eng*, **20**, 35–41, (2014). Retrieved from https://www.researchgate.net/profile/Andrzej_Katunin

[13] Katunin A. Nondestructive damage assessment of composite structures based on wavelet analysis of modal curvatures: state-of-the-art review and description of wavelet-based damage assessment benchmark, *Shock Vib.*, 2015, ID 735219, (2015). https://dx.doi.org/10.1155/2015/735219

[14] Katunin A. Vibration-based spatial damage identification in honeycomb-core sandwich composite structures using wavelet analysis, *Composite Structures*, **118**, 385–391, (2014). https://dx.doi.org/10.1016/j.compstruct.2014.08.010

[15] Koissin V., Shipsha A., and Skvortsov V. Compression strength of sandwich panels with subinterface damage in the foam core, *Compos. Sci. Tech.*, **69** (13), 2231–2240, (2009). https://dx.doi.org/10.1016/j.compscitech.2009.06.014

[16] Lestari W. and Qiao P. Damage detection of fiber-reinforced polymer honeycomb sandwich beams, *Compos. Struct.*, **67** (3), 365–373, (2005). https://dx.doi.org/10.1016/j.compstruct.2004.01.023

[17] Masmoudi S., El Mahi A., and El Guerjouma R. Mechanical behaviour and health monitoring by acoustic emission of sandwich composite integrated by piezoelectric implant, *Compos. Part B: Eng.*, **67**, 76–83, (2014). https://dx.doi.org/10.1016/j.compositesb.2014.05.032

[18] Nichols J. M., Seaver M., Trickey S. T., Salvino L. W., and Pecora D. L. Detecting impact damage in experimental composite structures: an information-theoretic approach, *Smart Mater. Struct.*, **15** (2), 424–434, (2006). https://dx.doi.org/10.1088/0964-1726/15/2/023

[19] Pieczonka L., Aymerich F., and Staszewski W. J. Impact damage detection in light composite sandwich panels, *Proc. Eng.*, **88**, 216–221, (2014). https://dx.doi.org/10.1016/j.proeng.2014.11.147

[20] Ratcliffe C. P., Crane R. M., and Gillespie J. W. Damage detection in large composite structures using a broadband vibration method, *Insight*, **46** (1), 10–16, (2004). https://dx.doi.org/10.1784/insi.46.1.10.52653

[21] Shafiq B. and Quispitupa A. Fatigue characteristics of foam core sandwich composites, *Int. J. Fatigue*, **28** (2), 96–102, (2006). https://dx.doi.org/10.1016/j.ijfatigue.2005.05.002

[22] Smith R. A., Nelson L. J., Mienczakowski M. J., and Challis R. E. Automated analysis and advanced defect characterisation from ultrasonic scans of composites, *Insight*, **51** (2), 82–87, (2009). https://dx.doi.org/10.1784/insi.2009.51.2.82

[23] Zenkert D. *Damage tolerance of naval sandwich panels, in: Major Accomplishments in Composite Materials and Sandwich Structures: An Anthology of ONR Sponsored Research*, Daniel I. M., Gdoutos E. E., Rajapakse Y. D. S. (Eds.), Springer Science and Business Media, Dordrecht, (2009). https://dx.doi.org/10.1007/978-90-481-3141-9_11

[24] Zhu K., Chen M., Lu Q., Wang B., and Fang D. Debonding detection of honeycomb sandwich structures using frequency response functions, *J. Sound Vib.*, **333** (21), 5299–5311, (2014). https://dx.doi.org/10.1016/j.jsv.2014.05.023