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Abstract

This paper presents a novel approach in the field of experimental and numerical investigation of mechanical properties of composite structures. It takes into account test data variability resulting from structural dynamic properties measurement. The main goal of the conducted research is to investigate the dynamic and static properties of fiber reinforced composite structure towards assessment of accuracy of the damage detection. Non-destructive experimental and numerical simulation methods are used hereto. In the experimental part static and dynamic test were performed. The dynamic excitation was performed by means of random single point stimuli while the response measurement was done through contact acceleration sensing. In the static test four point bending configuration was implemented. Applied force and strain response was measured. The test results are applied in two ways: for the structural identification of the object and for non-deterministic updating of the numerical model according to a range of experimental models obtained from test. The sources of the test data variabilities were related to the specimen-to-specimen and test-to-test of the investigated object. Non–deterministic model updating and validation included uncertainties of its parameters by means of probabilistic methods. A number of variable test modal models were statistically assessed to investigate impact of variability source onto clarity of damage identification. Then, for each of investigated specimens an individual damage scenario was introduced. Two different vibration based methods were applied for the damage detection. The results are presented and compared. The research was conducted in the context of the FP7 project PROND.

KEYWORDS: probabilistic model updating, uncertainty, inverse problems,

1. Introduction

One of the major trends in wind turbine technology is the increase in size of wind turbines and thereby also increase of composite blade sizes, especially for off-shore sites. Design of future generation's blades requires adequate numerical models based on reliable test data to limit blade weight without compromising the needed dynamic behavior of the blades. Structural health of the large future blades will be monitored for reduction of failure risk. This requires robust identification of the anisotropic material properties and structural dynamic's of the blades.

Experimental modal analysis, structural dynamic and static testing are core methods providing characteristics of mechanical system. Several limiting factors are limiting their application for the wind turbine blades. Static and dynamic tests preformed on the full scale blade are expensive and difficult to perform due to size of the investigated object [1, 2, 3, 4]. Therefore subcomponent are more often investigated to develop measurement, modeling and analysis methods. The usefulness of structural dynamics test and analysis results for solving noise and vibration problems or for performing a damage assessment, depends largely on the confidence that one can have in these results. In other words, the results must be characteristic for the actual problem and the models must be representative for the actual behavior of the investigated structure (s). Essentially, two types of problems are distinguished: (1) the test and modeling data are subject to particular experiment technique related systematic errors and analysis errors and (2) the tested (or modeled) structure is not representative for the actual structure.

The first problem is this of experimentation and analysis uncertainty [5, 6, 7, 8, 9]. The "true" test result can in principle never be achieved. The level of the uncertainty associated with the test result is however not easy to quantify. Also in building numerical simulation models (e.g. based on the Finite Element approach), uncertainty is introduced by discretization effects, through imperfectly known material, geometry or loading parameters, or through uncertainty in the applicable boundary conditions [10, 11].

The second problem is this of product variability [12], introducing changes in the structural dynamics characteristics because of differences in material, geometric, manufacturing or even operational use (loading, temperature…)

parameters when compared to the "nominal" case. It is important to have at least an idea on the magnitude of these changes and their impact on the final product behavior when assessing damage presence based on reference method [13]. Different reference based methods of damage detection can be proposed for Structural Health Monitoring [14, 15, 16]. In the destructive testing stage the comparison of two vibration-based methods applied for the damage detection was made. These two methods are based on the model identification of the undamaged structure and afterwards, models from a measurement of damaged structure are confronted with the model of the intact structure. The presence of test data variability is accounted to prevent "false alarm" due to the non-identical nature of three nominally equal composite panel specimens under investigation. For each of these specimens identical damage scenario was introduced but to a different level (severe, intermediate and low).

Problem of test data variability and uncertainties in model parameters is inherent of composite materials. The review of relevant scientific literature in the field points out that in most practical engineering application there is a serious lack of experimental data that would enable a correct quantification and characterization of stochastic system properties for damage detection [1-16]. The overall objective is introduction of a novel approach in the field of experimental and numerical investigation of mechanical properties of composite structures. The discussion is conducted to assess and evaluate the clearly identifiable damage of wind turbine blade component without false alarms.

2. Experimental campaign

Measurement activity on the plates covered the modal analysis of the intact plates, static four point bending tests and damage detection vibration based measurements.

2.1. Object of the investigations

The objects of the investigation were three E-glass composite material samples. The material is similar to the one typically used in load carrying panel of a wind turbine blade (Figure 1). The individual samples were cut from plates produced by hand lay-up and cured with manufacturers recommended cure cycle. The nominal thickness

of the samples was 20 mm, the length and width had the same dimensions of 320 mm. Table 1 presents the values of the E-glass composite material properties [17].

Property	Value
E_{11}	46.0 [GPa]
E_{22}	13.0 [GPa]
E_{33}	13.0 [GPa]
v_{23}	0.42 [-]
v_{31}	0.3 [-]
v_{12}	0.3 [-]
G_{23}	4.6 [GPa]
G_{31}	5.0 [GPa]
G_{12}	5.0 [GPa]

Table 1 E-glass composite material properties.

Important is the presence of plates geometrical dimensions variability (especially local value of thickness) at level of ± 0,7 %. The reason for this variability is non-fully repeatability of the composite manufacturing process [6]. The samples were named A, B and C.

2.2. Experimental Modal Analysis

Experimental modal analysis was carried out to estimate modal model of the structure. During the measurement campaign the LMS SCADAS Mobile and Test Lab software was used. Each of the three individual composite plates was tested repeatedly for a number of times to acquire variable test data collection. Random signal was used to drive the electro-dynamic shaker exciting the plates. Acquisition of the response signal from all measurement points was done in sets to decrease the sensor mass influence effect. The acceleration was measured in 14 points in one set. Then responses from the four sets were analyzed individually and later on merged in the multi-run modal analysis. Total number of measurement points was 49 measurement points gives the FRF's of the whole sample. The same procedure was repeated for the rest of the samples and with both types of excitation signal. Modal test results for the intact samples yielded first important conclusion that even if the samples were cut from the same construction the behavior of each sample under the investigation was different.
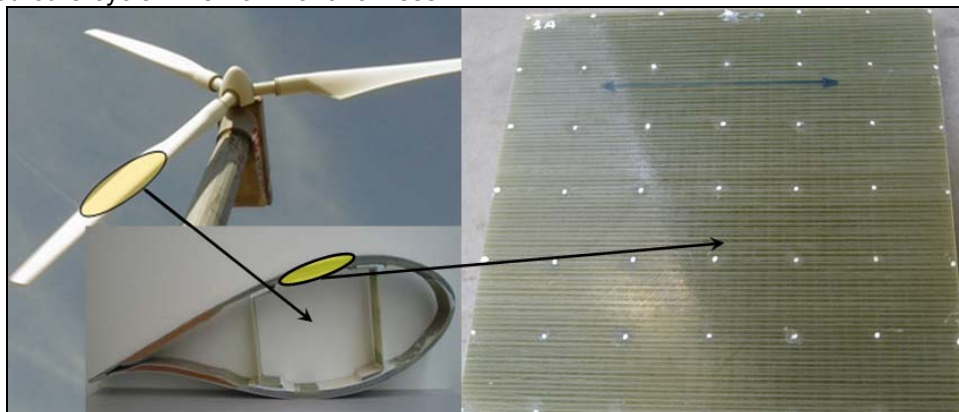

Figure 1 The wind turbine E-glass composite blade.

This is the result of variability of the composite materials production process. It is very important to notice that if differences in behavior occurs in the intact sample, then further research in and development of a structure health monitoring system, based on reference modal model, must take into account not one value of the frequency, but a range of frequencies values (Figure 2).

1st mode frequency test variability
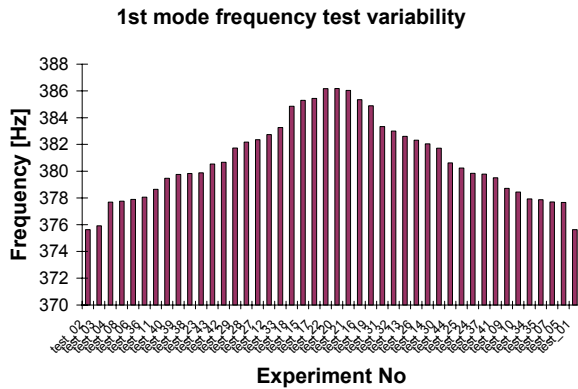
Figure 2 Measured values of the first natural frequency values for the intact samples A, B and C in first measurement point.

Figure 3 presents the examples of the experimental and initial numerical mode shape.


| 566 Hz | 523 Hz |
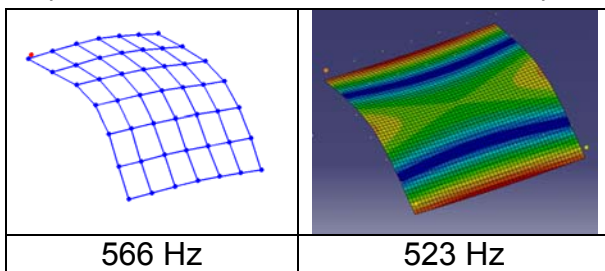
Figure 3 Comparison of the second mode shape from test (left) and simulation (right) before FE model updating

Consistency of modal vectors estimated and calculated was compared by means of the Modal Assurance Criterion. Values of MAC for five first mode pairs was above 65%. Despite the good accordance in the mode shape there is a difference in frequency value of the investigated plates.

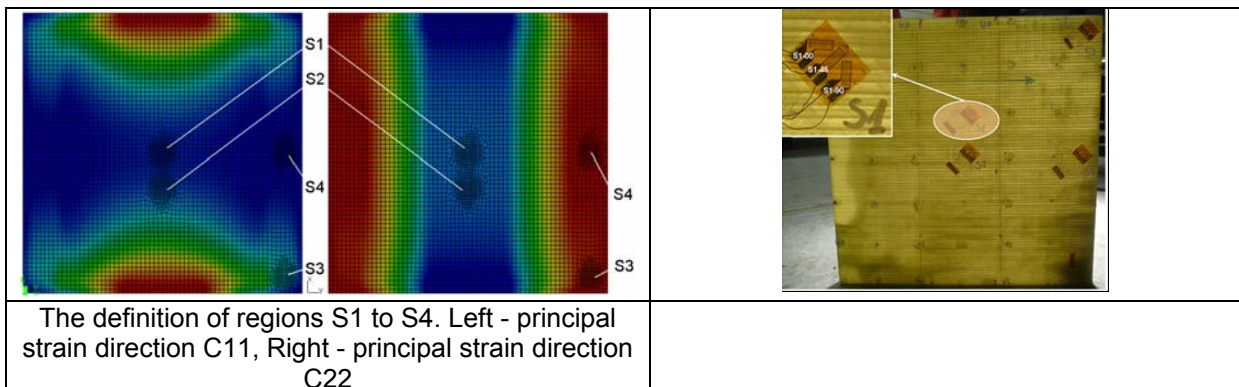## 2.3. Static Four point bending test

Static four point bending test was performed on the plates to measure strains resulting from a given load and support configuration and furthermore to introduce the damage (Figure 4).
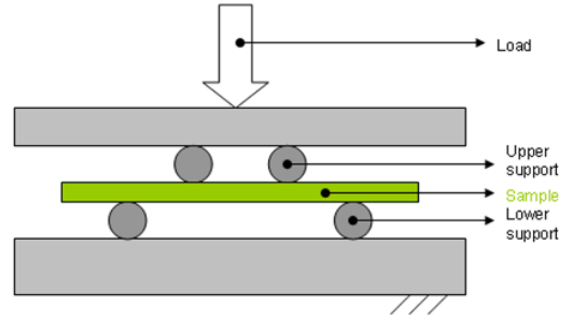
Figure 4 Schema (left) and the setup (right) for the four point bending experimental damage implementation.

All specimens were tested up to damage.

Also the numerical pre-test was made. Differences between basic theory of the four point bending stress and strain distribution of the considered sample and the pre-test results are caused by the orthotropic properties of the multilayer composite material used for making the samples. Figure 5 presents the results of the pre-test made with Virtual.Lab 8B software and the strain gauge rosettes locations. To observe adequate strain levels it is important to fix the strain gauges in the areas of tension or compress only. On that base, four areas were chosen to deploy the strain gauges, denoted as S1, S2, S3 and S4, onto the surface of the specimen.

| The definition of regions S1 to S4. Left - principal strain direction C11, Right - principal strain direction C22 | |

Figure 5 The numerical pre-test result (left) and location of the strain gauges rosettes (right) at the sample A surface.

3. Parametric study of FE modeling for static and dynamic analysis

The numerical modeling study aimed into three goals:

- in the case of an unknown inner composite structure, it is investigated how reliable an orthotropic shell model with averaged values (as presented in Table.1) is both for the static and dynamic simulations,

- how the model's mesh density influencing strain result, and how to average these results which should be furthermore used in the updating process; and lastly,

- how to model an interaction between the composite plate and steel shafts during four point bending test simulation.

During the study three numerical models of supports have been analyzed: shell-to-solid contact; linear-gap contact; and supporting on basis of DOF restrain. In each of these cases plate has been modeled with the same linear shell elements of the same size and orthotropic material properties, cylinders in contact simulations has been modeled with use of 3D linear elements of the isotropic material properties (steel).

The shell-to-solid contact is based on the standard unilateral contact model; that is, normal pressure equals zero on the contacting interface if separation occurs. In this type of contact friction with static friction coefficient 0.4 has been applied (classical Coulomb friction). In the linear gap contact there is assumption of constant node-to-node distance that is defined on basis of the nodes initial position. The DOF restrain type of support, holds all the six possible movement on two outer plate-shafts contact lines, and restrains five movements on two inner plate-shafts contact lines allowing for lateral displacement (y-direction). The plate deformations in z-direction for different types of support obtained under 1mm enforced displacement of upper (inner) shafts is presented in (Figure 7).
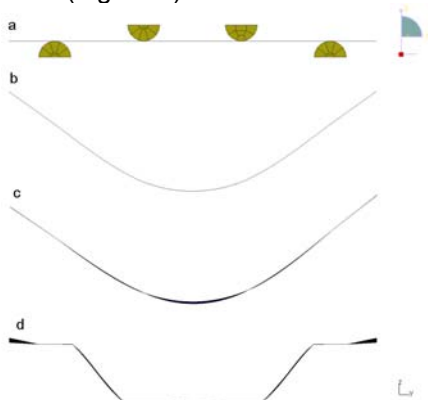
Figure 7 Plate deformation (z-direction) under enforced displacement of 1mm along negative z axis of two middle half-cylinders, a – unreformed model, b – shell-to-solid contact type support; b – support basing on the DOF restrain, b – linear-gap contact type support.

The deflection in case of "b" and "c" (shell-to-solid contact, and DOF restrain support respectively) shows mutually the same results. The maximum deflection is respectively 1.17mm, and 1.2mm. In the case "d" which represents linear-gap contact support it could be seen that continuity of the second derivative of deflection is not held which is unrealistic. In this case maximum displacement is 1.03mm. This situation is caused by the fact that equidistant node assumption introduces additional stiffness realized by rigid bar elements.

Description	region	average C11	average C22
Quad mapped mesh, size 7mm (2278 nodes, 2184 elements)	S1	2.20E-04	-3.51E-04
	S2	1.34E-04	-3.54E-04
	S3	4.35E-04	-3.36E-04
	S4	-2.79E-06	-5.17E-06
Triangular, mapped mesh, size 5mm (4432 nodes, 8606 elements)	S1	2.20E-04	-3.51E-04
	S2	1.35E-04	-3.53E-04
	S3	4.29E-04	-3.04E-04
	S4	-2.65E-05	-5.16E-06
Quad mapped mesh, size 10mm (1122 nodes, 1056 elements)	S1	2.37E-04	-3.52E-04
	S2	2.75E-04	-3.48E-04
	S3	4.90E-04	-3.97E-04
	S4	4.37E-06	-6.46E-05
Triangular, free mesh, size 10mm (1215 nodes, 2289 elements)	S1	2.70E-04	-3.54E-04
	S2	1.41E-04	-3.51E-04
	S3	4.80E-04	-2.81E-04
	S4	3.47E-05	-5.81E-05
Triangle, free mesh, size 15mm (555 nodes, 1022 elements)	S1	2.21E-04	-2.13E-04
	S2	3.21E-04	-1.95E-04
	S3	7.30E-06	-1.12E-03
	S4	4.60E-04	-7.91E-04
Triangle, free mesh, size 15mm with local refinement 2mm (1153 nodes, 2218 elements)	S1	2.20E-04	-8.09E-05
	S2	3.11E-04	-3.91E-04
	S3	5.54E-04	-3.48E-04
	S4	-2.25E-06	-3.46E-04

Table 2 Comparison of strain values in direction C11 and C22 for numerical simulation at load of 3827N

Comparing deformation (b) and (c) it could be stated that the DOF restrained model is slightly stiffer than the model with shell-to-solid contact.

Deformation in case of surface-to-surface support and DOF restrained support is little different, whereas linear contact gap support produce an over-stiff model with unrealistic deformation. In the case of surface-to-surface support more computational costly nonlinear analysis with potential convergence problems must be performed. Keeping in mind that the FE model should be used for optimization purposes (very large number of simulation runs), and almost identical results of simulation with use of surface-to-surface and DOF restrained support the latter one has been selected for furthest numerical analyses.

In order to determine the best mesh topology for the FE model optimization, additional simulations featuring different mesh densities and element types have been performed. The definition of regions is given in Figure 5. These regions correspond to the placement of strain gauges in the static test. Some selected results of the strains in longitudinal (C11), and lateral (C22) directions for different meshes topology are presented in Table 2. As it could be seen meshes of size 10 and less generates almost the same results in the principal strains regardless of the elements topology and the local refinement. On the contrary, over-all rough mesh with fine local refinement does not give good principal strains results.

As the final topology for the static simulation, quad mapped mesh of size 5mm (4225 nodes and 4096 elements) without refinement has been chosen. The dynamic simulation has been performed on the quad mapped mesh of size 10mm, with the free-free supporting condition

4. Probabilistic model updating

Computations were performed with Optimus software on a 50Tflop cluster in TASK Academic Computer Centre (Figure 8).


Figure 8 TASK Front view of the 50Tflop computing power cluster in TASK Supercomputing Center (fot. M. Gburski)

Static and dynamic measurements results were used to update the numerical model of the composite material plate. For this purpose the analysis flow was defined as presented on the Figure 9. Material properties parameters were defined as the variables for the updating procedure. Next both static and dynamic finite element models were incorporated. Static stains, natural frequencies and Modal Assurance Criterion were selected as output variables which were compared to the test results. The first step of the analysis was calculation of the Design of Experiment (DOE). The scheme chosen was Three Level Full Factorial to generate sufficient results for the precise Response Surface Model calculation. Fifth order RSM model was computed on the DOE results with the regression coefficients values of 0.96. Based on this model a Self Adaptive Evolution optimization was defined with built-in target values of the variables as obtained from particular measurements (Figure 10).
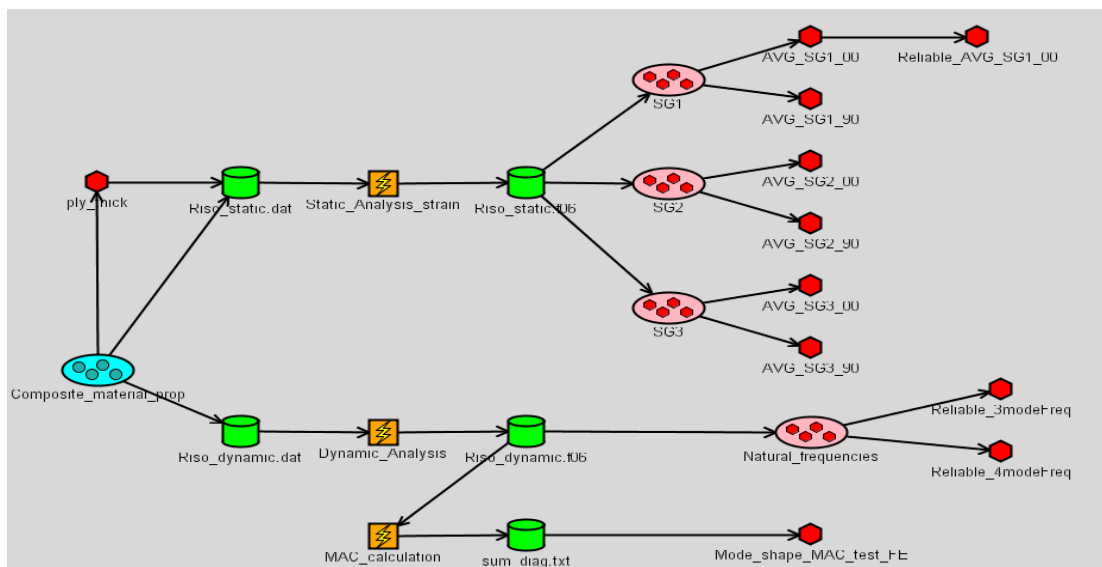

Figure 9 Graph of the model updating process
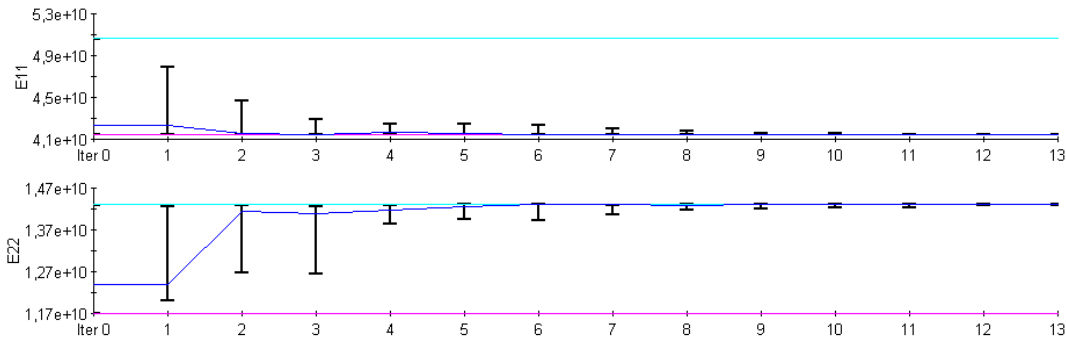
Figure 10 Examples of the evolution of updating parameters with the iteration range indicators

Based on the global optimum found by the SEA the gradient based method was applied to fine tune the values. Next the reliability of the solution was assessed by means of the probabilistic Monte Carlo method. 20 000 experiments (sets of input variable values) were calculated and all of them were feasible meaning that the found optimum is reliable. As the result of presented probabilistic model updating procedure the final set of material properties values within 20% difference from initial ones was found. For these updated model parameter values results of both static and dynamic analysis are better consistent with measurement results (Figure 11).
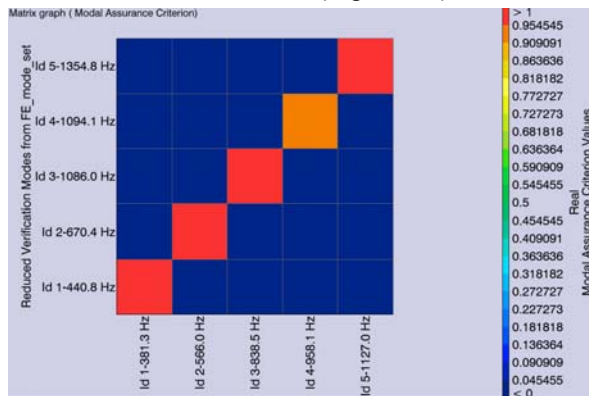
Figure 11 Modal Assurance Criterion for comparison of modal vectors from test and updated model

The FE model of the composite plate has been presented, as far as the results of modal analysis obtained from the model itself. Furthermore a correlation between numerical and experimental modal analysis results has been carried out by means of the Modal Assurance Criterion approach in order to associate the closest numerical and experimental mode shapes. The updating procedure accounted for both natural frequency value and the mode shape consistency. Main diagonal MAC terms present very high values and it was possible to trace the corresponding mode shape pairs. These mode pair table can be considered close to the optimal correlation line; as a consequence it is possible to assert that within the investigated frequency bandwidth the numerical model presents a dynamical behavior adequately close to the real plate.

5 Damage detection

The same measurement equipment and test setup as in the modal test of the intact samples were used for the damaged plates testing. The various numbers of the poles were identified for the different damaged samples. For sample A with the highest load (most severely damaged, however not totally failured) the number of poles increased up to ten, for sample C (medium damaged) up to nine poles and for the lowest load for sample B (lowest damaged) the number of poles was the same as before damage implementation – namely eight poles.

Table 3 compares the values of natural frequencies for test made for the intact and damaged samples A and C.

In order to perform damage detection using piezo–excited elastic waves, piezoelectric transducers were used to excite and register elastic waves in the considered specimens. Propagating waves interact with material inhomogeneities and can be used for Structural Health Monitoring purposes, particularly in this case for damage detection. In this study even the approximate size of introduced damage was unknown, therefore high frequency (short wavelength) waves were used to ensure sensitivity. Piezoelectric transducers were excited and then responses from their electrodes were gathered using integrated generation/acquisition device. It conducts generation and amplification of the signals to drive the piezos. In registration path it collects the signals, refines them and sends to a PC via USB.

Set_1	MIN A	MEAN A	MAX A	Damage A	MIN C	MEAN C	MAX C	DamageC
Mode 1	375,63	375,73	375,92	268,62	378,45	378,60	378,71	378,00
Mode 2	562,08	564,52	565,76	392,42	567,78	568,19	568,40	554,34
Mode 3	837,19	843,34	855,52	546,18	830,86	832,61	834,55	833,49
Mode 4	945,72	946,08	946,63	663,62	959,71	961,84	964,35	929,40
Mode 5	1 099,31	1 103,49	1 111,76	739,26	1 117,69	1 118,29	1 118,61	1 116,31

Table 3 Comparison of the natural frequency for the intact and damaged sample A and C.

The concept of this device was born at the Department of Mechanics of Intelligent Structures (Institute of Fluid–Flow Machinery, Polish Academy of Sciences). Transducer network was designed to obtain as much information about the specimen condition as possible. Twelve transducers were distributed on the whole specimen surface. However they could not be placed uniformly due to the fact that four–point bending quasi–static test was performed on this specimen to introduce damage. Excitation was applied to each transducer from configuration while registration was realised in the rest of transducers. In result 132 signals were obtained for intact plate and the same number of signals was obtained from measurement for damaged specimen. Measured signals were processed with special signal processing algorithm. Obtained results were normalised to the maximum value. Colour scale is from blue – minimum to red – maximum. Conducted mapping procedure indicated that the greatest differences between damaged an intact sample are in its lower half (see Figure 12). This suggests that damage could occur in this area. However it should be underlined that the difference could be also a result of transducer debonding caused by four–point bending test. In order to ensure this is not the reason a transducer self–testing procedure ought to be incorporated in the detection procedure.
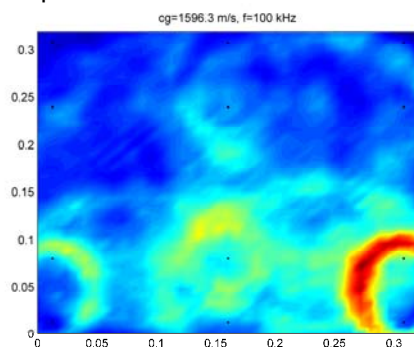
Figure 12 Results of damage detection using Lamb wave propagation for 100 kHz frequency.

6. Conclusions

The multidisciplinary and interdisciplinary research, presented partly in this paper, is oriented towards test data variability and estimation of numerical model parameters uncertainties obtained within the E-glass wind turbine reinforcement composite material structure.

Experimental test data examples were presented and used for modal models estimation. Some general remarks have been formulated. Optimal locations of the strain gauges rosettes were computed in preliminary FE model calculation. Also the numerical prediction of the dynamic behavior of the structure in the frequency range corresponding to global modes was carried out.

Due to the differences of three series of tests for each intact sample a first conclusion was drawn that even if the samples were cut from the same construction the behavior of samples under the investigation was different. This is probably the result of variability of the composite materials production process.

The damage implementation process was carried out by means of the very precise hydraulic press. This approach provided full control over the load value and led to different level of damage in each sample structure. The main conclusion is that the implemented damage caused a significant change in the sample FRF's and in the number of poles of FRF's. It was therefore possible to detect damage in the investigated composite plates by means of experimental modal analysis. It is important to notice that if the differences in behavior occur in the intact sample then further research in and development of the structure health monitoring system, based on reference modal model, must take into account not only one value of the "accurate" frequency, but a range of frequencies values.

Both presented methods successfully identified the presence of damage based on the reference model comparison. Lamb wave based approach provides also the localization of the damage. The drawback of this method is more complex test procedure than in case of experiemtnal modal analysis.

Further research activity should account for the numerical modeling of the fracture mechanism which was not included in the present investigation. This will allow the prediction of the defect before it occurs.

7. Acknowledgements

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