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COMPOSITES THEORY AND PRACTICE

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EXPERIMENTAL INVESTIGATION OF DYNAMIC BEHAVIOUR OF THERMOPLASTIC FIBRE REINFORCED LAMINATES

The influence of impact damage on the dynamic behaviour of dry and wet thermoplastic fibre reinforced samples has been investigated. The change of the structural state could be detected in the changes of the modal parameters. In the first part of the investigations, appropriate modes were selected for a reliable structural state detection of the samples. The accuracy of determining these parameters could be identified for the chosen measurement method. Within the second part of the work, the changes in the modal parameters caused by moisture, impact damage and the combination of both have been investigated. This research serves as a foundation for modal analysis based a structural health monitoring (SHM) system for composite structures that include the effects of moisture.

Keywords: CFRP, anisotropic damage, impact, modal analysis, technical diagnostics, SHM, humidity, moisture content

BADANIA DYNAMICZNEGO ZACHOWANIA LAMINATÓW TERMOPLASTYCZNYCH WZMOCNIONYCH WŁÓKNEM CIĄGŁYM

Przeprowadzono badania udarności na zachowanie dynamiczne suchych i wilgotnych próbek kompozytowych o osnowie termoplastycznej, wzmocnionych włóknami węglowymi. W uszkodzonych próbkach wykryto zmiany parametrów modalnych. W pierwszej części badań wybrano odpowiednie mody umożliwiające niezawodne wykrywanie zmian dynamiki próbek oraz określono dokładność parametrów modalnych dla wybranej metody pomiaru. W drugiej części pracy określono zmiany parametrów modalnych we wcześniej wybranych modach spowodowanych wilgocią, przebiciem udarowym oraz ich kombinacją. Badania te mogą służyć jako podstawa dla systemu przeznaczonego do monitorowania stanu konstrukcji (ang. Structural Health Monitoring - SHM) kompozytowych, opartego o analizę modalną i uwzględniającego wpływ wilgoci.

Keywords: CFRP, anizotropowe uszkodzenia, impakt, analiza modalna, diagnostyka techniczna, SHM, wilgotność

INTRODUCTION

Fibre plastic composites provide many benefits through their high degree in freedom of design combined with high specific strength and stiffness properties. Furthermore, they are a promising alternative to conventional materials in the construction of dynamically loaded components. Especially the production of thermoplastic endless fibre-reinforced lightweight structures in large-volume production, presents many benefits regarding the claimed efficiency in costs and energy [1].

For those reasons carbon-fiber-reinforced plastic (CFRP) with a Polyamide 6 (PA6) matrix: Ce-Preg® [2] was examined. It is known that structures made with polyamide (PA) are produced completely dry. If they are exposed to moist air or immersed in water, they absorb humidity at a rate that depends on the conditions of the material compound. Polyamide (Polyamide 6, polyamide 66, copolyamide 66/6) absorb comparatively large amounts of water and must therefore be conditioned, for more information see [3]. Therefore the absorption of water changes the mechanical properties e. g. the impact strength and also the geometrical properties e.g. the dimensions of dry polyamide parts [4]. This can have an adverse effect under service conditions in many applications as shown in [3].

It cannot be ignored that the main disadvantages of fibre reinforced thermoplastics is the low impact tolerance. Unlike ductile materials like steel, where transverse impact loading predominantly occurs as plastic deformation, fibre reinforced thermoplastics react in a brittle manner. Impact damage on composite structures can be in the form of delaminations, fibre fracture or intralaminar cracking. This leads to changes in the dynamic behaviour of the structure, especially in stiffness but also in damping and mass [5].

For many lightweight applications impact tolerance is a sensitive issue. A connection can be observed between the content of humidity and impact damage in polyamide samples [3]. It is important to investigate this relation on CFRP- structures and define a method to specify the humidity content under service conditions. This work contains tests of Ce-Preg® samples, by using the instrumented free-falling dart method and modal test. It shows the direct influence of moisture content on the structure and the resulting modal parameter change.

MATERIALS AND SAMPLE PREPARATION

The thermoplastic pre-impregnated system used in this work, Ce-Preg® manufactured by Cetex, is a modified polyamide 6 (polymeric film, 30 μm, produced by BASF) [6] reinforced with high strength carbon fiber (Tenax® E HTS40 16K F13) [7] in the form of unidirectional tape (0.125 mm thick). The laminates were produced on a high-temperature press at 290°C under a 65 bar maximal pressure during 180 seconds. The total time of the pressure was 20 minutes.

The laminates lay-up studied in this work was based on a $[[0°/90°]_4]_S$ stacking sequence. The average thickness of the cured laminates is 2.4 mm, with a fibre volume content of $V_{fi} \approx 0.58$, based on the material data supplied by the pre-preg manufacturer. More information about Ce-Preg® and the manufacturing process of the investigated plates can be found in [2]. From the manufactured laminates, square samples with a 130 mm side length were cut by using a water jet. The samples had a mass of about 60 g.

EXPERIMENTAL SET-UP

Moisture content

The samples were dried by 50°C hot air for 11 hours. After that, the samples were placed in deionised water at 23 ±2°C. The samples were periodically dried off and weighed immediately to minimize the out-of-water time. Their percent of humidity content M (percent weight gain) was recorded using the gravimetric analysis method where the value is a function of time:

$$M = M(t) = \frac{M_t - M_0}{M_0} \cdot 100\% \qquad (1)$$

M_0 is the weight of the dry material and M_t the weight of the moist material. The rate of absorption and the increase of water uptake in the Ce-Preg® samples can be seen in Figure 1.

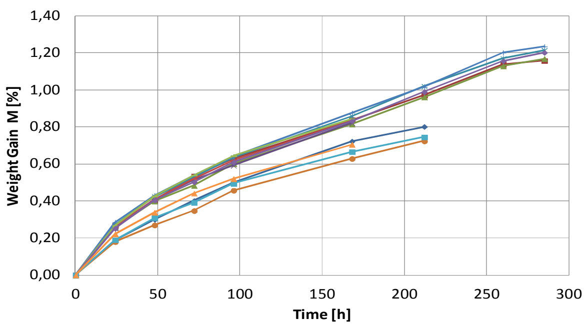

Fig. 1. Percent content of humidity in time of Ce-Preg® samples in deionised water at 23 ±1°C

Rys. 1. Przyrost zawartość wilgoci w próbkach CePreg® w czasie, zanurzonych w dejonizowanej wodzie o temperaturze 23 ±1°C

As can be noticed, the determined values are comparable to the results which were presented by Paplham et al. [8] or [3].

Modal analysis of samples

The modal analysis delivers the modal parameters: resonant frequencies, mode shapes and modal damping. The chosen frequency response function (FRF) is the compliance, therefore the calculated amplitudes of the mode shapes are in units of m/N. In this work, the modal damping is represented by the decay rate with the unit rad/s [9]. Changes in the physical properties, such as reductions in stiffness resulting from cracks or delamination, lead to measurable changes in the modal properties [5]. Therefore, damages in the structure done by absorption and impact change the modal parameters of the samples. The detection of these parameters can be used as damage indicators in a so called vibration-based diagnostic [10].

Measurement instrumentation

For the excitation technique, a modal hammer was used with five hits per excitation point. Therefore a no variable mass loading of the structure is characteristic. This is a particular advantage of light structures, because changing the mass loading from point to point can cause shifts in modal frequencies from one measurement to another [11]. With the used hammer, we were able to cover a frequency range of 0÷5 kHz. The response signal was captured with a uniaxial accelerometer with a mass of 1 g. The clamping device for the samples consists of two steel plates, which allows attaching the composite plate on one side with a specific tightening torque through thirteen M8 screws, with a clamped area of 130x30 mm (see Fig. 2).

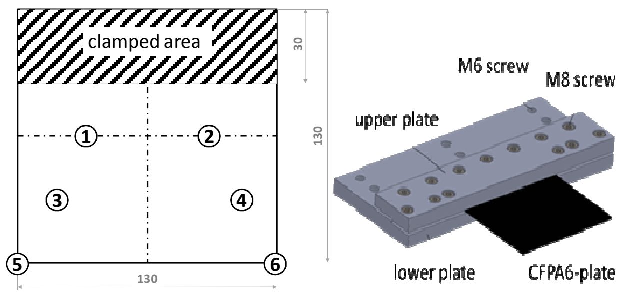

Fig. 2. Defined six degrees of freedom (DOFs) points for modal tests on Ce-Preg® plates (left); clamping tool for Ce-Preg® plates (right)

Rys. 2. Płyta Ce-Preg® z określonymi sześcioma stopniami swobody (DOFs) dla analizy modalnej (po lewej), narzędzie mocujące dla płyty Ce-Preg® (z prawej)

This setting avoids multiple modes with the same natural frequency that will complicate the evaluation.

The lower plate of the clamping device was screwed to an optical table by nine M6 screws with a tightening torque of 20 Nm.

To determine several modes for the Ce-Preg® samples in the frequency range of interest, six DOFs were defined (Fig. 2). Each of the DOFs is an input point for an FRF measurement. The output signal was measured in DOF number 6 with an accelerometer attached with beeswax, on the opposite side of the structure at the excitation point as shown in Figure 3.

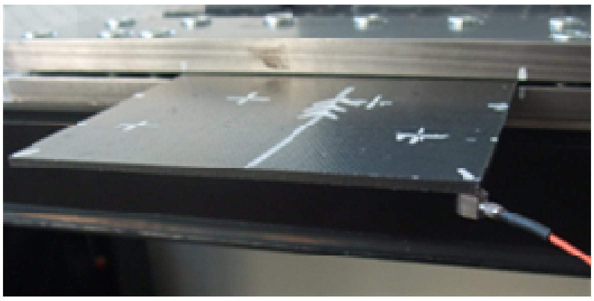

Fig. 3. Position of accelerometer (6th DOF)

Rys. 3. Pozycja akcelerometru (w szóstym stopniu swobody)

Preliminary investigations

Firstly, the reproducibility of the measurement results was examined, to perform a reliable sensitivity analysis of the modal parameters. The measurement accuracy of the chosen method was investigated by clamping the samples with a tightening torque of 20 Nm (M8 screws) and repeating the analysis five times for three samples. The focus was on the modal frequencies which are independent of the chosen FRF as can be seen in [9]. This enables simple determination by observing the maximum magnitudes on the FRF. The best results for the determination of the modal frequency were delivered by the 4th excitation DOF (H_{64}), as shown in Figure 4. The first 10 modes of the plate for the chosen frequency range (0÷5000 Hz), could be determined (e.g. Table 1). Determination of the appropriate modes for damage detection was based on the scattering of the natural frequencies. Above the 6th mode (see Table 1, for example, shown for plate 1_2) the resonance frequencies show significantly (one order of magnitude) higher standard deviations.

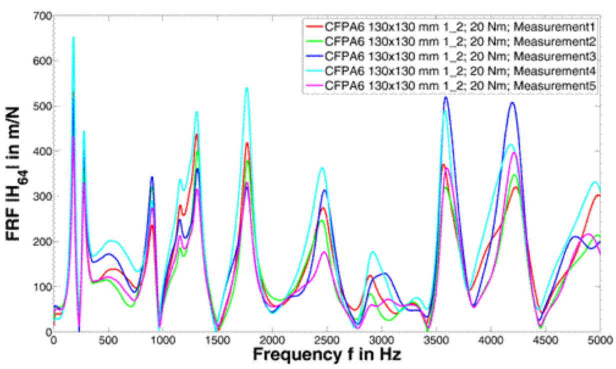

Fig. 4. Examination of measurement accuracy of Ce-Preg® samples

Rys. 4. Badanie dokładności pomiaru próbek z Ce-Preg ®

In this case, only the first five modes are taken into account for a robust and reliable base in respect of technical diagnostics.

TABLE 1. **First 10 modal frequencies of Ce-Preg®-plate 1_2**

TABELA 1. **Pierwsze 10 częstotliwości własnych - płyty Ce-Preg® 1_2**

Mode	Mean frequency [Hz]	Standard deviation [Hz]
1	180.0	0.2
2	276.3	0.3
3	899.8	1.1
4	1311.1	3.5
5	1768.3	2.6
6	2463.9	11.2
7	2958.6	77.6
8	3581.4	11.7
9	4205.4	18.0
10	4913.6	87.7

Sensitivity study

The influence of the clamping device on the modal parameters has also been investigated. Three Ce-Preg® plates were five times reattached (with 20 Nm) in the clamping device. The accelerometer was also reattached each time. The first five chosen modes, from the calculated FRFs can be seen in Figure 5 (for example shown for plate 1_2). The results for the standard deviations of these parameters (see Table 2) can be interpreted as noise in the data that certainly limit reliable damage detection.

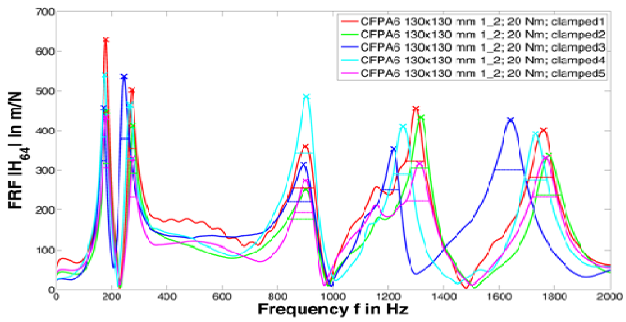

Fig. 5. Influence of clamping device on FRF (H_{64}) of Ce-Preg® samples

Rys. 5. Wpływ mocowania na funkcję przejścia (H64) próbek Ce-Preg®

Additionally, the influence of different clamping torques (5, 10, 15, 20 Nm) was analyzed (Table 3).

TABLE 2. **Scattering of modal parameters by using constant tightening torque of 20 Nm**

TABELA 2. **Rozrzut wartości parametrów modalnych przy zastosowaniu stałego momentu dokręcania 20 Nm**

Mode	Standard deviation		
	Frequency [Hz]	Amplitude [m/N]	Damping [rad/s]
1	4.4	12.7	3.2
2	13.4	15.2	1.1
3	8.7	82.7	41.8
4	42.5	77.3	30.9
5	54.7	112.0	30.2

The higher scattering in this case makes it clear that a defined thrust moment is important to avoid additional variation in the modal parameters.

TABLE 3. **Modal parameters by using different tightening torques (5, 10, 15, 20 Nm)**

TABELA 3. **Rozrzut parametrów modalnych przy zastosowaniu różnych momentów dokręcania (5, 10, 15, 20 Nm)**

Mode	Standard deviation		
	Frequency [Hz]	Amplitude [m/N]	Damping [rad/s]
1	6.0	141.2	5.3
2	18.8	29.8	8.3
3	5.0	58.2	14.9
4	85.8	149.8	25.1

Instrumented free-falling dart method

For better characteristics of the moister influence on the CFRP-Structure, the impact resistance of the samples was examined. This was done with different moisture contents by the instrumented free-falling dart method by considering DIN EN ISO 6603-2:2000. The dynamic failures of the materials are different than those found when testing at slower, steadier speeds. Testing in accordance to DIN 6603-2 allows testing materials for desired properties such as strength, ductility, toughness and energy absorption. The output parameters have been shown in Figure 6 (left). The method is qualified for a detailed specification of the foraminous behaviour a force deformation diagram and force time diagram recorded on an approximate constant speed of impactor.

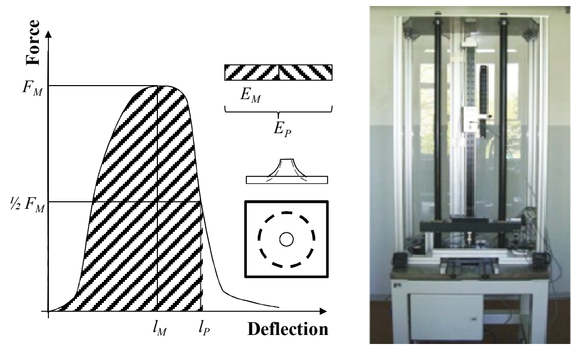

Fig. 6. Impact force and absorbed energy of specimen by instrumented free-falling dart method by considering DIN EN ISO 6603-2:2000 (left); SLK-Falling Dart FD-20 System (right)

Rys. 6. Badanie udarowości sztywnych tworzyw sztucznych instrumentowaną metodą swobodnie spadającego grotu wg DIN EN ISO 6603-2:2000. Pomiar siły udarowej oraz energii przebicia (po lewej); Stanowisko badawcze (po prawej)

For this test, we used our self-made Drop Weight System (Fig. 6, right), instrumented with a maximum standard drop height of 1 m, 200 kN tup, 20 kg dart with 20 mm hemispherical bold insert, data acquisition system (DAS) and Visual Impact software were used to perform this testing.

The first test was done immediately after drying the sample by 50°C hot air for 11 hours (see Figure 8, Table 4). The next test was done after 190 hours, with a moisture content of about 0.8% and the last one after 344 hours with a moisture content of 1.2% (Table 4). A part of the samples with the moisture content of 0.8% became dry after the modal test and finally were been tested with a 0.1% moisture content. With the impact mass and the drop height, the outcome of this is a velocity of 4.4 m/s. For that, the time range for data acquisition was set to 15 milliseconds. The specimens were clamped and the tests were conducted under the standard laboratory atmosphere of 21 ±2°C, and 30% relative humidity. The specimens after the drop-weight impact tests have characteristic damage with a 35 mm diameter (see Figure 7). Figures 8 and 9 presented the characteristic force-deflection diagrams of dry and wet samples. Figure 10 shows the average values of the instrumented free-falling dart test output parameters.

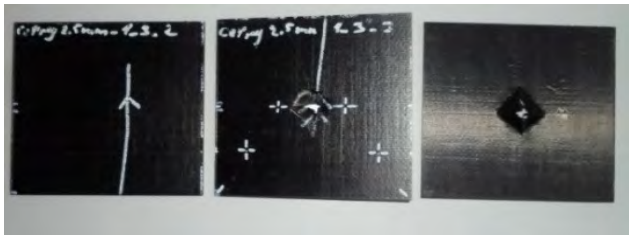

Fig. 7. Speciments before (left) after drop-weight impact tests (center and right)

Rys. 7. Zdjęcie próbki: przed próbą (po lewej), po próbie metodą swobodnie spadającego grotu (środek, po prawej)

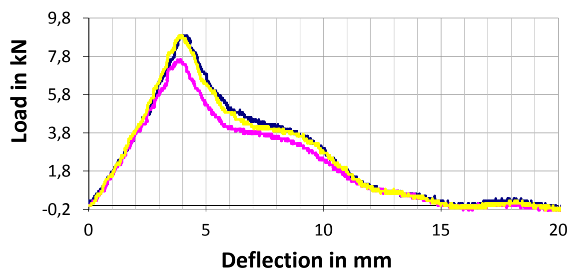

Fig. 8. Force-deflection diagram of dry Ce-Preg samples

Rys. 8. Wykres siła-ugięcie, instrumentalnego badanie udarności suchej próbki z materiału Ce-Preg

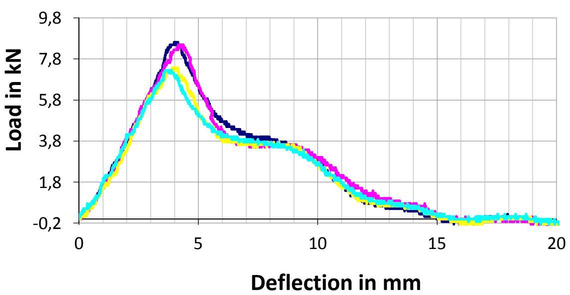

Fig. 9. Force-deflection diagram of Ce-Preg samples with 1.2% moisture content

Rys. 9. Wykres siła-ugięcie, instrumentalne badanie udarności próbki z materiału Ce-Preg z zawartością 1,2% wody w odniesieniu do masy całkowitej

TABLE 4. **Output parameters of drop-weight impact test of Ce-Preg® Samples with different percentage content of moisture M**

TABELA 4. **Wartości parametrów wyjściowych instrumentalnego badania udarności próbek Ce-Preg® z różnym udziałem procentowym wody w odniesieniu do masy całkowitej**

	SAMPLE	l_M [mm]	F_M [kN]	E_M [J]	l_P [mm]	E_P [J]
Moisture content 0%	1_1_1	3.73	7.75	12.92	7.64	33.48
	1_1	3.63	7.38	11.90	8.63	37.56
	1_1_3	3.85	7.75	12.70	7.41	31.84
	Average Value	3.74	7.63	12.51	7.89	34.29
	Standard deviation	0.11	0.21	0.53	0.65	2.94
Moisture content 0.1%	1_2	3.82	8.88	14.51	6.9	34.08
	1_3_1	3.72	7.63	12.83	6.57	28.17
	1_4_2	3.79	8.88	14.72	6.46	31.87
	Average Value	3.78	8.46	14.02	6.64	31.37
	Standard deviation	0.05	0.72	1.04	0.23	2.99
Moisture content 0.8%	1_2_3	3.15	6.88	10.4	6.3	24.93
	1_4_3	3.26	7.81	11.93	7.2	32.63
	1_4	3.19	7.5	10.89	5.51	23.37
	Average Value	3.20	7.40	11.07	6.34	26.98
	Standard deviation	0.06	0.47	0.78	0.85	4.96
Moisture content 1.2%	1_2_1	3.92	8.63	15.13	6.64	34.08
	1_2_2	4.13	8.5	16.53	6.08	28.17
	1_3	3.83	7.38	13.17	6.67	27.94
	1_4_1	3.54	7.25	11.84	8.06	31.87
	Average Value	3.85	7.94	14.17	6.86	30.52
	Standard deviation	0.24	0.73	2.08	0.84	2.98

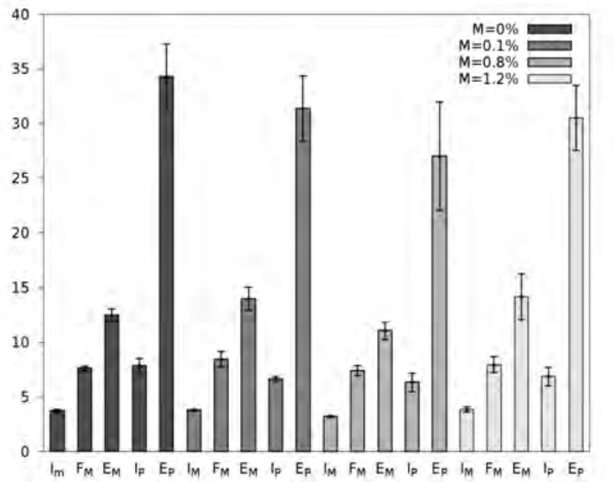

Fig. 10. Average value of drop-weight impact test output parameters: l_M - deflection occurs at maximum force F_M of test; E_M - energy expended up to l_M; l_P - puncture deflection, when force dropped to half of F_M; E_P - energy expended up to l_P

Rys. 10. Zestawienie średnich wartość parametrów wyjściowych: l_M - ugięcie przy maksymalnej sile F_M; E_M - pomiar energi do wartości l_M; l_P - ugięcie przy przebicie (spadku siły do połowy wartości F_M); E_P - energia zmierzona po przebiciu próbki

RESULTS AND DISCUSSION

There were four different states of Ce-Preg® samples analysed: dry, dry with impact damage, moisture and moisture with impact damage. In the first experiment, only the influence of impact-damage on the dynamic behaviour of the dry samples was examined. In the second experiment, the differences in the dynamic behaviour between dry and wet as well as the influence of impact damage on the wet samples was investigated.

Influence of impact damage on modal parameters

There are measurable changes in the modal frequencies, in the amplitudes of the modal shapes and in the modal damping (see Fig. 11).

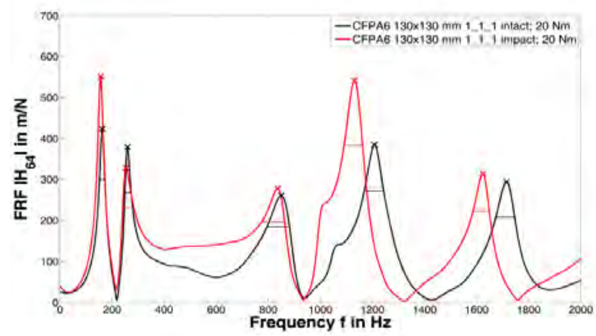

Fig. 11. Influence of impact damage on FRF (H_{64}) of dry samples (for example shown for plate 1_1_1)

Rys. 11. Wpływ impaktu na funkcję przejścia (H_{64}) w suchych próbkach (przykładowo pokazane dla płyty 1_1_1)

Tables 5-7 show the differences in the modal parameters ΔMP between those of intact MP1 and damaged MP2 plates, calculated by the following equation

$$\Delta MP = MP2 - MP1 \qquad (2)$$

The bold marked values in the tables are significantly higher than the scattering in the data caused by the measuring method (compare with Table 2). The grey filled rows in Tables 8-10 show changes in the modal parameters that occur for all the damaged plates (1_1, 1_1_1 and 1_1_3) in the same modes and with the same sign. These common changes in the dynamic behaviour of the three plates can be interpreted as a data pattern.

TABLE 5. **Impact damage influence on modal frequencies**

TABELA 5. **Wpływ uszkodzenia na częstotliwości własne**

Mode	Shifts in modal frequency [Hz]		
	plate 1_1	plate 1_1_1	plate 1_1_3
1	-1.2	-6.3	-6.4
2	1.2	-5.7	-3.5
3	2.0	-13.7	-
4	-9.6	-77.0	-13.1
5	-64.5	-91.2	-76.0

TABLE 6. **Impact damage influence on amplitudes in modal shapes**
TABELA 6. **Wpływ uszkodzenia na amplitudy postaci drgań własnych**

Mode	Changes in amplitudes [m/N]		
	plate 1_1	plate 1_1_1	plate 1_1_3
1	–21.5	127.7	–11.9
2	–258.8	–50.5	–236.4
3	39.4	17.4	-
4	–25.2	157.1	78.8
5	–153.6	20.3	–255.1

TABLE 7. **Impact damage influence on modal damping**
TABELA 7. **Wpływ uszkodzenia na tłumienie modalne**

Mode	Changes in modal damping [rad/s]		
	plate 1_1	plate 1_1_1	plate 1_1_3
1	–1.2	0.0	1.8
2	41.7	56.4	39.9
3	–123.9	4.3	-
4	–4.3	–11.0	5.5
5	22.1	–30.1	29.5

Influence of moisture and impact damage on modal parameters

For this purpose, each of the three samples (plate 1_3_1, 1_4_2 and 1_2) was accordingly conditioned for the states with the designation "dry" (intact), "moisture" and "moisture + impact". Firstly, a modal test for the "dry" state (the plates were dried over 10 hours at 50°C) was performed. The second measurement was done for the samples after six days in a water bath, with a moisture content of 0.7 to 0.8%. Afterwards, the third modal test was performed for the same plates additionally damaged by impact ("moisture+impact"). The results for the FRFs of the three states are for example shown in Figure 12.

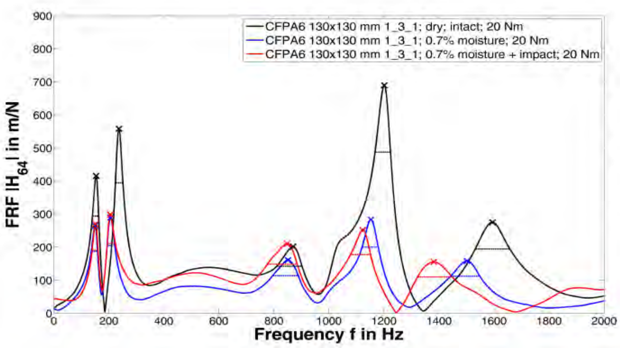

Fig. 12. Influence of moisture and impact damage on FRF (H_{64}) of Ce-Preg® samples (exemplary shown for plate 1_3_1)

Rys. 12. Wpływ działania wilgoci i impaktu na funkcję przejścia (H_{64}) próbek Ce-Preg® (przykładowo pokazane dla płyty 1_3_1)

The differences in the modal parameters between the "dry"/"moisture" and "moisture"/"moisture+impact" states have been calculated in the same manner as as in the previous section using equation (2). The results are shown in Tables 8-10. Similar to recent studies, the differences of the modal frequencies show a kind of pattern in the data (see Table 7). We have got measurable changes in the 2nd till 5th modes caused by moisture and changes in the 5th mode caused afterwards by impact. The differences in the other modal parameters show no regularities. This is probably due to the inaccuracy of the selected measurement method.

TABLE 8. **Moisture and impact influence on modal frequencies**
TABELA 8. **Wpływ wilgoci i impaktu na częstotliwości własne**

Mode	Shifts in modal frequency [Hz]					
	plate 1_3_1		plate 1_4_2		plate 1_2	
	0.7% Moisture	0.7% Moisture +impact	0.7% Moisture	0.7% Moisture +impact	0.8% Moisture	0.8% Moisture +impact
1	–3.7	1.6	–7.2	–2.1	–16.8	1.0
2	–30.7	–1.0	–29.5	–1.8	–49.0	3.9
3	–18.4	–3.5	–34.4	–23.0	–44.1	–22.5
4	–48.8	–29.1	–69.9	–29.7	–92.6	–31.3
5	–92.8	–120.1	–135.5	–91.2	–214.1	–101.6

TABLE 9. **Moisture and impact influence on amplitudes in modal shapes**
TABELA 9. **Wpływ wilgoci i impaktu na amplitudy postaci drgań własnych**

Mode	Changes in amplitudes [m/N]					
	plate 1_3_1		plate 1_4_2		plate 1_2	
	0.7% Moisture	0.7% Moisture +impact	0.7% Moisture	0.7% Moisture +impact	0.8% Moisture	0.8% Moisture +impact
1	–151.0	5.3	181.8	–63.4	–248.3	25.9
2	–268.6	9.0	40.8	–16.5	–151.8	–24.0
3	–40.5	49.1	14.1	–34.0	–159.1	–138.2
4	–406.1	–32.3	26.8	43.6	–186.0	–15.1
5	–117.0	–2.6	–28.4	–64.3	–124.0	–80.9

TABLE 10. **Moisture and impact influence on modal damping**
TABELA 10. **Wpływ wilgoci i impaktu na na tłumienie modalne**

Mode	Changes in modal damping [rad/s]					
	plate 1_3_1		plate 1_4_2		plate 1_2	
	0.7% Moisture	0.7% Moisture +impact	0.7% Moisture	0.7% Moisture +impact	0.8% Moisture	0.8% Moisture +impact
1	1.2	–4.9	–7.4	0.6	1.2	4.3
2	0.6	8.0	24.5	6.1	8.0	17.8
3	2.5	48.5	182.8	–94.5	15.3	51.5
4	7.4	45.4	–16.6	–4.9	–14.1	105.5
5	–60.1	62.6	24.5	8.6	67.5	–25.8

Output parameters of drop-weight impact test of Ce-Preg®

The samples show typical brittle behaviour for fibre reinforced composites due to impact damage. The force-deflection diagrams of dry and wet samples are almost similar and characteristic for failure by yielding (zero slope at F_M) followed by deep drawing, and typical appearance of CFRP specimens after testing. The samples with the 0.8% weight gain (M) have the biggest damage caused by moisture, because the average value of energy expended (E_P) up to puncture deflection and maximum force F_M occurring during the drop-weight impact test shows the smallest value. The test of the dried samples from 0.8 to 0.1% moisture content showed very interesting results. These samples have the highest values of maximum force F_M note in the instrumented free-falling dart tests.

CONCLUSIONS

In the first investigation, appropriate modes were determined for a reliable diagnosis of the structural state. These are, for the examined samples the first five modes which can be found in the frequency range of about 180÷1800 Hz. These modes were selected for their high information content in terms of technical diagnostics. The scattering in the modal parameters for the selected measurement method could be determined. Thereby, minimal differences (greater than data noise) in the modal parameters for safe detection of changes in the structural state were established. There are measurable changes in the dynamic behaviour caused by moisture and impact damage on dry and "wet" Ce-Preg® plates (CFPA6).

Three dry plates showed similar trends for differences in the natural frequencies, amplitudes and modal damping caused by impact. The differences even have the same sign and can be therefore interpreted as a data pattern.

The influence of moisture (0.7÷0.8%) is already well detectable, especially in the differences of resonant frequencies (modes: 2-5) where a data pattern can also be found. These measurable shifts towards low natural frequencies can be explained by reduced stiffness and weight gain caused by moisture. Other modal parameters show differences without regularity. This can be traced back to the accuracy of the measuring method and geometric deviations of the plates.

An additional influence of impact on wet Ce-Preg® samples shows repetitive changes only in the frequencies of the 5th mode.

The investigated high energy impact causes total penetration of the structure. It is well visible damage on the structure. Interest in further research will be the detection of barely visible impact damage caused by a low/medium energy impact.

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