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The Influence of Conditioning on Dynamic Behaviour of Polymer Composites

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ABSTRACT

The aim of this study is to determine the effect of environmental factors in the form of UV radiation and temperature on the amplitude-frequency behaviour of polymer composites (prepregs) based on a framework of thermosetting epoxy resin reinforced with high-strength R-glass fibres. Two series of composites with different fibre arrangements were prepared. The series had fibres arranged at angles of 30°, 45°, and 60°, at symmetric and asymmetric orientations in relation to the central layer. The composites were subjected to conditioning which simulated a six-month period of use in the spring and summer in the temperate warm transitional climate of Central and Eastern Europe. An UV QUV/SPRAY/RP accelerated aging chamber manufactured by Q-Lab Corporation was used for this purpose, and UV-A 340 lamps were used to simulate daylight. In addition, varying loads caused by sudden temperature changes were simulated using the Thermal Shock Chamber T/60/V2 Weisstechnik. Conditioned samples were tested using a TIRAvib 50101 electromagnetic exciter in combination with an LMS Scadias III controller and Test. Lab software. The results of the tests, in the form of amplitude-frequency diagrams in resonance regions, indicated that certain changes occurred as a result of the conditioning, which is a new development in the area of material tests. The results shed light on the effects of environmental conditions on the stiffness characteristics of composites, causing dynamic nonlinearities when operating at resonant frequencies.

Keywords: vibrations; conditioning; composites

INTRODUCTION

Depending on their field of application, manufactured construction materials should undergo tests to determine the influence of their composition or manufacturing technology on the reliability of the final components [1]. However, in addition to design assumptions and specific material properties [2, 3], the environment in which the components operate must also be taken into account, as it may cause physical or chemical changes in the components, deformation of their structure or even a gradual change in their parameters as they age [4], including beyond permissible limits [5]. The ageing processes themselves are an inherent aspect of the existence of technical objects, and knowledge of the basics of their ageing and wear processes [6-8] facilitates study pro-cesses in support of diagnostic measures. This renders possible the conscious tracking of changes in the condition of an object, which can be used to predict its damage [9, 10]. When considering components used in outdoor applications [11], outdoor conditions related to local climate should be accounted for when determining their reliability. This makes it possible to adopt an informed approach to potential degradation processes in the objects. Figure 1 shows the types of degradation processes present in polymer-based materials.

Influence of environmental conditions on the properties of polymer composites

Environmental factors which may facilitate the degradation of composite materials include UV radiation and temperature. Polymer composites are used in many applications where they are exposed to UV radiation (e.g. in sporting goods, aircraft or vehicle parts [11, 12]). The Authors of paper [13] provided the evaluation of the blast response of composite plates after prolonged exposure to ultraviolet radiation. There are analysed carbon fiber/epoxy and glass fiber/vinyl composite materials. UV radiation in the 290-400 nm wavelength range (see Figure 2) is considered to be one of the most destructive factors that negatively affect the reliability of composites.

Failure to provide protection by using adequate modifiers results in the inevitable destruction of the structure of materials and loss of the designed functional qualities [15]. Although the energy of UV radiation reaching the Earth's surface depends greatly on the latitude, season, altitude and atmospheric pollution (for example by dust, smoke, clouds and SO_2), the energy absorbed by the polymer is sufficiently high to break the chemical bond. Although sometimes the excitation of chromophore groups may end in harmless energy dissipation (in the form of heat or fluorescence), some of the undissipated energy contributes to the start of the degradation processes. When considering UV radiation, it is important to note that the ratio of the number of degradable particles to the number of excited particles is referred to as the degradation efficiency factor. The value of this factor for most polymers is 10.3 to 10.5. This means that between one in one thousand and one in one hundred thousand photon-absorbing molecules will degrade. However, as the value of radiant flux is about 1021 photons/cm^2 per year, this still carries the risk of causing extensive damage to polymers. The progressive degradation of the composite results in yellowing, loss of mechanical properties, makes the composite brittle, causes its surface to lose its gloss, become rough, and crack extensively. This increases the susceptibility of such material to other degrading factors, such as environmental or biological factors. It should be noted that continuous exposure of the polymer to UV radiation further contributes to the deterioration of polymer chains [16]. There is extensive research available on the effect of UV radiation on selected mechanical properties of composites. For example, paper [12] analyses the effect of UV radiation on the mechanical properties of glass-polyester composites. Samples were exposed to radiation at three different time intervals (3, 6 and 12 months) in an aging chamber. Samples were subjected to tensile testing, which indicated a decrease of up to 15% in mean failure strain value, a decrease of up to

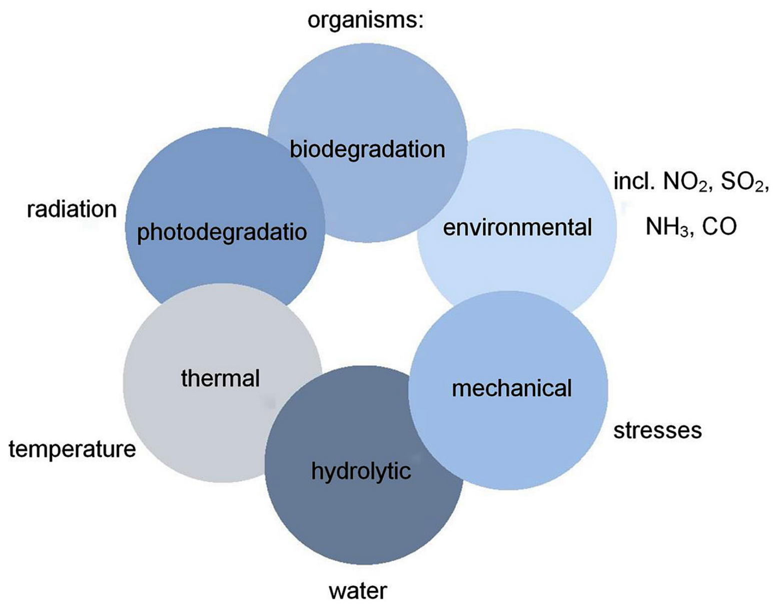

Figure 1. Factors affecting the degradation of polymeric materials (based on: [12])

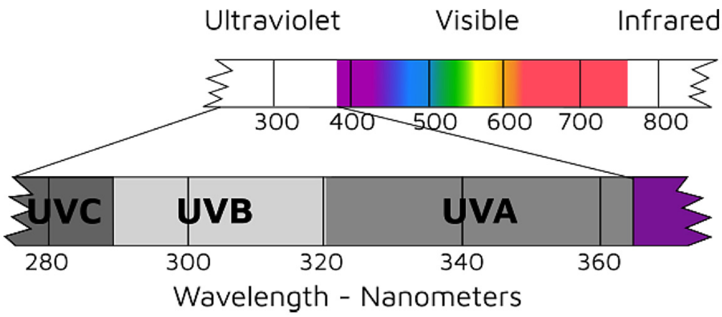

Figure 2. Ultraviolet spectrum (based on: [14])

30% in ultimate strength and an 18% decrease in tensile modulus after 100 hours of UV exposure. The authors of article [17] repeatedly stress that exposure of polymeric materials to ultraviolet radiation (UV) and high temperature causes deterioration of mechanical properties, leading to irreversible damage preventing further use of such materials. This is because these agents can cause short-term physical changes or long-term chemical changes in polymeric materials. Prolonged exposure to UV radiation will lead to discolouration and loss of mechanical properties of the polymers. The risk of the occurrence of irreversible changes leading to damage to components made from composites is so high that some researchers have attempted to model such processes. One example of such work is the paper published by Lu et al. [18], where UV damage was numerically simulated as a function of UV intensity, surface topography and exposure time. Predictions of local material degradation rates on sinusoidal epoxy surfaces exposed to UV radiation were applied to experimentally determined degradation rates for a unidirectional glass/epoxy composite. The authors of the paper were able to demonstrate that damage caused by UV radiation to uneven polymer surfaces reduces their roughness and smooth them out. Furthermore, they were able to find that the rate of degradation is highest at the peaks of local surface elevations. Research on determining the effect of UV radiation on polymer composites was also carried out by Komorek et al. [19]. Composites were made from Epidian 52 epoxy resin with Z1 hardener and reinforced with glass fabric and carbon fabric. The study concluded that UV radiation has a negative effect on the appearance of the composite and the flexural strength of the materials. The reduction in strength of specimens subjected to impact loading and the effect of UV radiation is just over 50%. As already mentioned, in addition to UV radiation, temperature is among the factors resulting in the destruction of polymer structure [20, 21]. This has not escaped the attention of researchers seeking to determine the relationship arising between exposure to a change in conditioning temperature and progression in degradation [22-26]. Deter-mining the impact of conditioning of polymer composites on dynamic properties is important for analysing the properties of new materials, especially for specialised applications such as aerospace components [27]. The authors of this paper therefore set out to determine the changes in dynamic properties of polymer composites following their exposure to UV radiation and changes in temperature values. The influence of environ-mental conditioning is especially important in the composite tubular parts which are frequently used to manufacture complex parts applied in aeronautical, automotive or industrial [28, 29].

Experimental investigation

In the main tests carried out on the composites sample based on the equipment for conditioning, there were two independent investigations of conditioning provided. The first was climatic shocks, where the samples were exposed to a wide range of temperature changes and the second was exposure to UV radiation. The temperature shocks operated in the range -50°C to +50°C which was ensured in the thermal shock chamber T/60/V2 Weisstechnik (Weiss Umwetltechnik GmbH, Heuchelheim, Germany) in Figure 3a. The chamber consist of two zones, hot and cold. In order to stabilize the temperature in the entire volume of the samples, they were exposed to both the hot and cold chambers for 30 minutes and then shift between hot and cold chambers are changing smoothly within time of 6 seconds. The separate samples were aging by UV radiation, and it took place in the QUV/SPRAY/RP accelerated chamber shown in Figure 3b. UV-A 340 lamps simulating daylight were used as the light source as the light source in the aging chamber. The temperature during lighting was 60°C, and the radiation intensity was 0.83 W/m^2. Experiments simulated the time period of a half year exposures for both the climatic and UV environmental sources. Conditioning effects were divided into three steps of two-month periods. Simultaneously, the influence of temperature range and UV radiation were tested on the beam samples during the dynamic tests by means of a TIRAvib electrodynamics exciter as shown in the Figure 4. The cantilever beams were excited at a constant gravity force equal to 1g in an excitation frequency range from 10 Hz up to 320 Hz. This frequency range assured observation of three based transversal resonance modes which were crucial in dynamic behaviour analysis. The measurements were performed by applied two piezoelectric accelerometers where the gravity force acting on the sensors are converted into electrical voltage due to the piezoelectric effect. First sensor as a reference one controls an assumed excitation force, but the second one records the output signal, corresponding to the beam behaviour.

The samples used in the experiment are the polymer composites (prepregs) based on a matrix of thermosetting epoxy resin reinforced with high-strength R-glass fibres. Glass Fibre Reinforced Plastics (GFRP) are one of the most common types of reinforcement used in

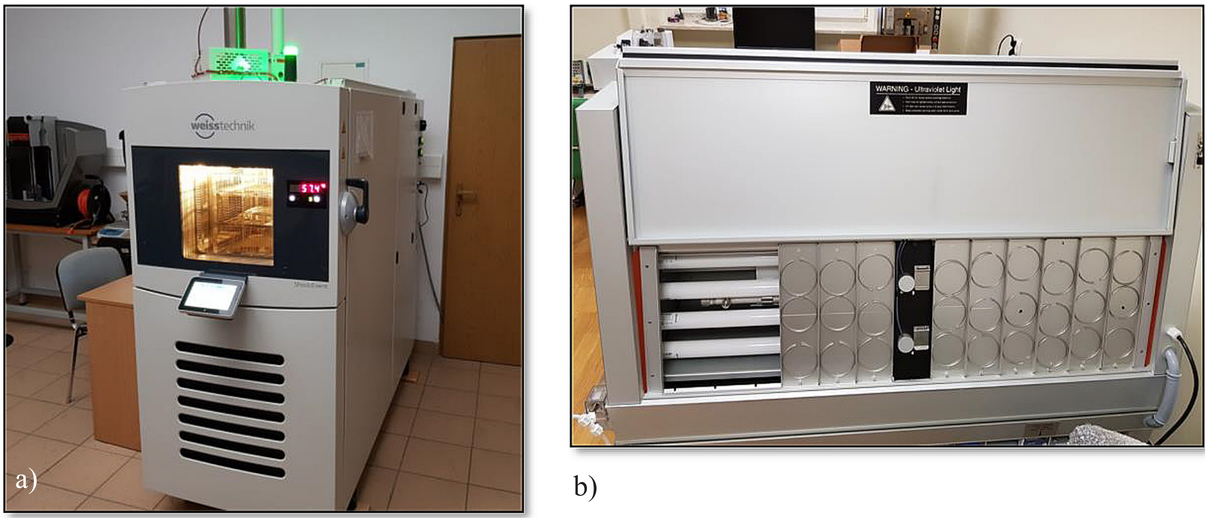

Figure 3. (a) Stand of the thermal shock chamber Weisstechnik used in laboratory; temperature range, hot chamber: +50°C to +220°C, cold chamber: -80°C to +70°C (b) stand of the accelerated atmospheric aging chamber QUV/SPRAY/RP

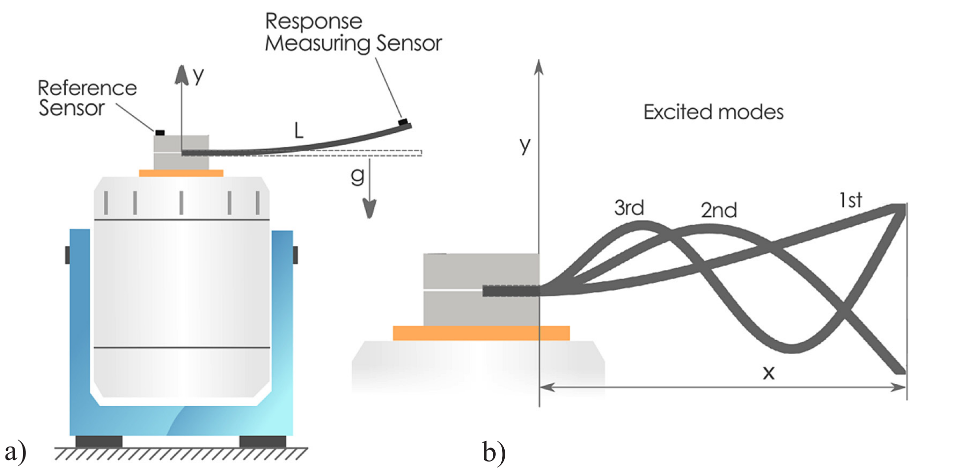

Figure 4. Schematic of the experimental stand of the electro dynamical shaker TIRAvib with positions of mounted accelerometers (a), the mode shapes excited during the dynamical tests (b)

polymer composites because of their mechanical properties and are applying in structures which require high stiffness and resistance to high temperatures. For the experiment the samples are prepared in laboratory with the nominal volume content of glass fibres in the composite (after hardened) 60% and the nominal thickness of the composite layer after harden process at 0.25 mm. The beams were manufactured by autoclave technique with applied 11 layers in assumed stacking sequence. The six geometrical sets of composite beams are manufactured. This staking sequence sets are fixed in angular positions of 30°, 45°and 60° in both symmetric and asymmetric configurations in relation to the middle layer which is at 0° position as shown in schematic (Figure 5a). The composites were produced as larger panels from which the samples were cut out in mechanical processing by milling for assumed dimensions. In the laminate production process, a peel-ply fabric was used to obtain the appropriate surface roughness of the laminate. In accordance with the defined sample size, conditioning tests were carried out on 10 samples for each series in dimensions as detailed in Table 1. Note in case of asymmetric beams the pre-twisting effect appeared, which introduced a twist angle (see Figure 5b). However the pre-twisting influence is negligible on the amplitude-frequency response. It is because of the sensor position mounted at the twist angle correction, it secure the output amplitude in the vertical axis.

RESULTS

Temperature conditioning

The first results regard the cantilever beams exposed to the temperature shocks. Figure 6 presents the overall responses in the frequency ranges, including three resonance zones of the analysed cases of stacking sequence layer sets of the beam before conditioning.

The excitation frequencies in the first base resonance zone turned out to be insensitive to thermal shocks for each configuration of the composite layers, but the second and the third zones displayed some changes in the dynamic behaviours of the materials. Moreover, differences in the output amplitude are clearly noticeable between symmetric and anti-symmetric set configurations around the second resonance zone. In each case, there is a visible dominant pick in the second resonance area of the beams with symmetric

Table 1. Stacking sequences and dimensions of the composite beams

Stacking sequences	Dimensions of the composite beams
+30°(5)/0/-30°(5)	The length *L* = 300 mm
+45°(5)/0/-45°(5)	The width *b* = 20 mm
+60°(5)/0/-60°(5)	The thickness *t* = 2.75 mm
+30°(5)/0/+30°(5)	
+45°(5)/0/+45°(5)	
+60°(5)/0/+60°(5)	

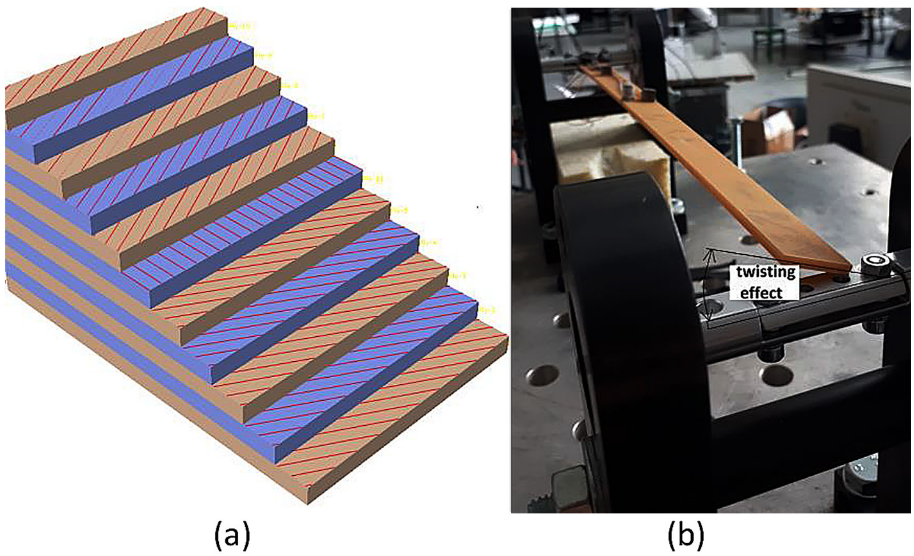

Figure 5. The stacking sequence set of composite beams (a) and the visible pre-twisting effect on the beam at asymmetric set of fibre layers (b)

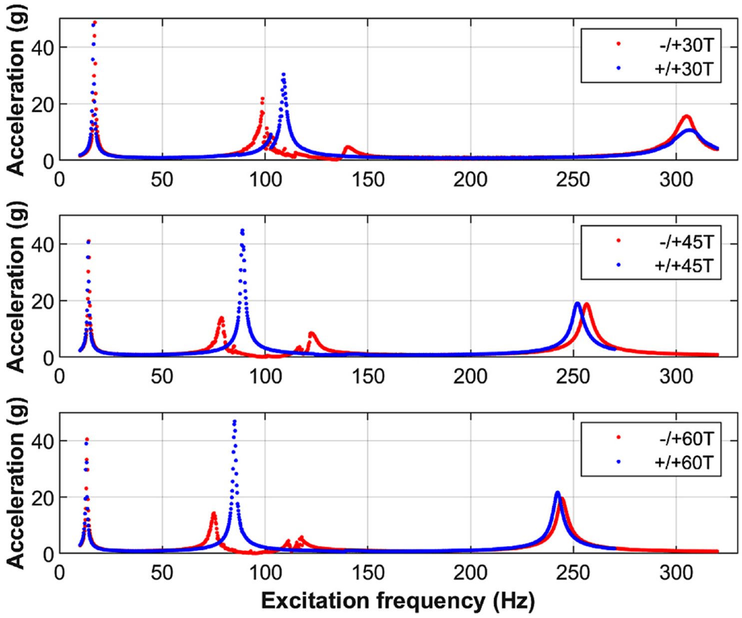

Figure 6. Amplitude – frequency response at the free end of the cantilever beam before exposition to temperature shocks of asymmetric (-/+) and symmetric (+/+) layer configurations for corresponding fiber sets 30°, 45° and 60°

fibre configuration properties. The anti-symmetric beams behave more softly in the second resonance zone, appearing as smaller double picks. This is connected with the composite structure: the anti-symmetric stacking sequence of fibres introduces an effect of pre-twisting moment which displays such responses. The initially analysed influence of conditioning and comparisons of the first resonance zone range resulted in no important changes as shown in Figure 7, but at the higher excitation frequency, the differences are clearly visible. Figure 8 presents the results of the second resonance zone. Figures 8a and 8c correspond to the asymmetric beams, and 8b and 8d to the symmetric beams. Output amplitudes of new structures are plotted without the influence of conditioning effects '0 m' as well as with conditioned samples '2 m', '4 m' and '6 m', which correspond to the time-period in months. The experimental investigations demonstrated the significant effect of conditioning on the composite structure, which causes weakening of beam stiffness in general. This is observed both in the second and in the third resonance. It is revealed by the amplitudes which are raised for all stacking sequence of fibres sets as well as the resonance shifts to the

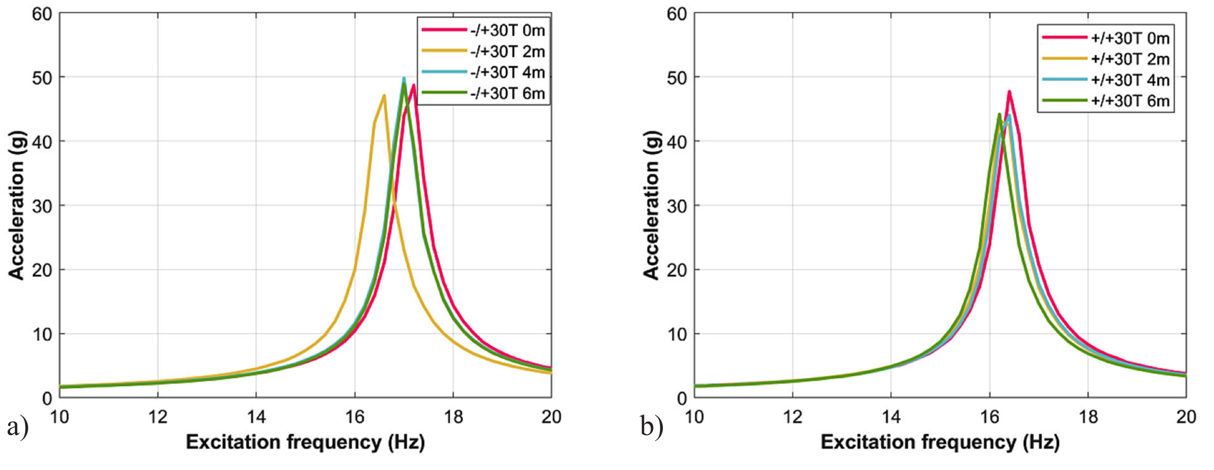

Figure 7. Amplitude – frequency response in with fibre set configuration 30°, exposed to temperature shocks in the vicinity of the first resonance zone of asymmetric (a) and symmetric (b) beams

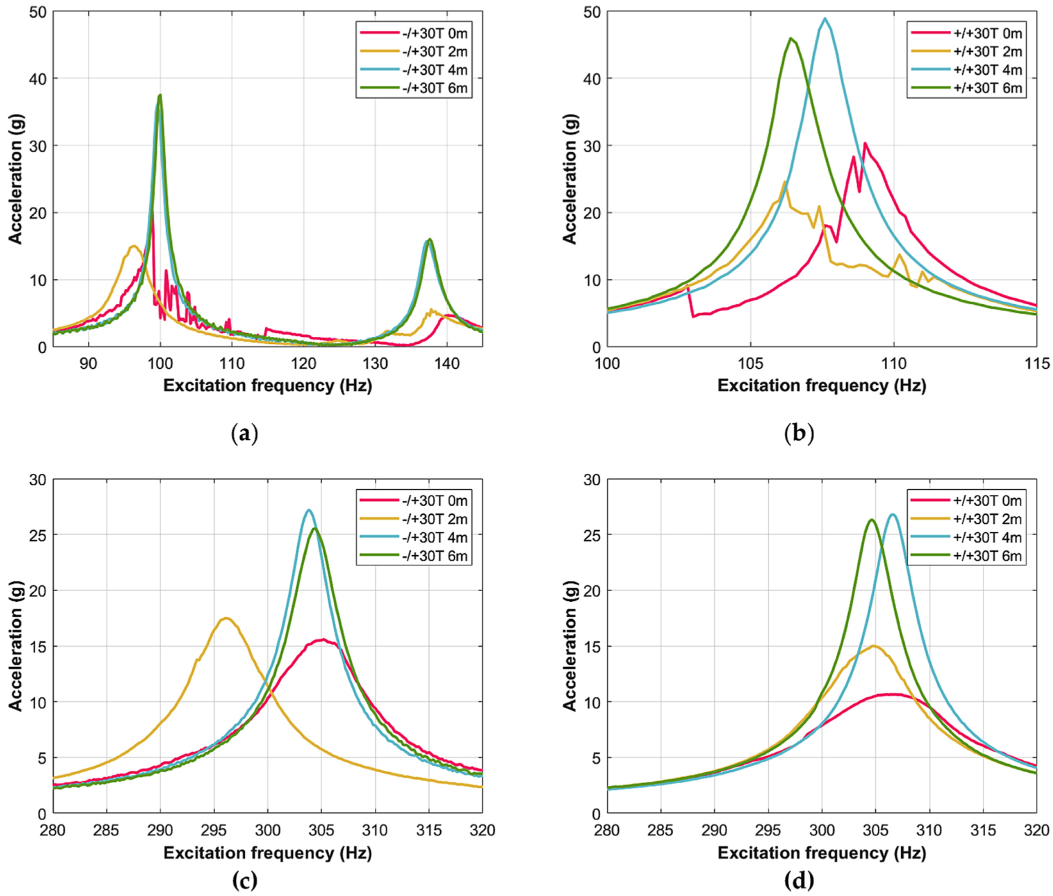

Figure 8. Amplitude – frequency responses of the cantilever beam with fibre set configuration 30°, exposed to temperature shocks in the vicinity of the second (a, b) and the third (c, d) resonance zones, respectively

lower frequency (Figure 8b) while the exposure to conditioning is extended. One can notice the first effect of shock temperature, which corresponds to two months conditioning influence on the composite, significantly weakens the structure, which is presented by characteristics in the Figures 8a and 8c yellow curves. The longer effect of temperatures reinforced the structure and the resonance picks back to points closer to the original pick resonance (blue and green plots). Analysing the results of composite beams of fibres set at 60° the structure achieved the opposite features.

Analysing the results of composite structure beams with a fibre set configuration at 60° (Figures 9a and 9c), the behaviour is similar to that observed in structure sets at 30°. However, in the case of symmetric sets (Figures 9b and 9d) the dynamics of the beams achieved opposite features. Conditioning of the composite structures influenced by hardening their stiffness, the amplitude consequently decreasing while simultaneously shifting the resonance pick to the higher frequencies. Reporting the investigation of the temperature shocks affect, the behaviour of the composite material significantly depends on the structures applied in context of the layer configurations. By means of a sequence of fibre stacking, it is possible to obtain the (amplitude – frequency) characteristics of the applied composites, which are required for industrial applications for use in specific environmental conditions.

UV conditioning

The second set of results regard the cantilever beams exposed to the UV radiation. Figure 10 presents the output amplitudes in the frequency ranges for three sets of fibre configurations before the conditioning by UV radiation. The results include the range of frequency excitation for three transverse resonance zones; the rotational modes for the chosen frequencies were not observed. Comparing these plots to the output amplitudes of the beams conditioned by the temperature shocks, similar behaviour is visible. The first resonance fits in both the symmetric and asymmetric

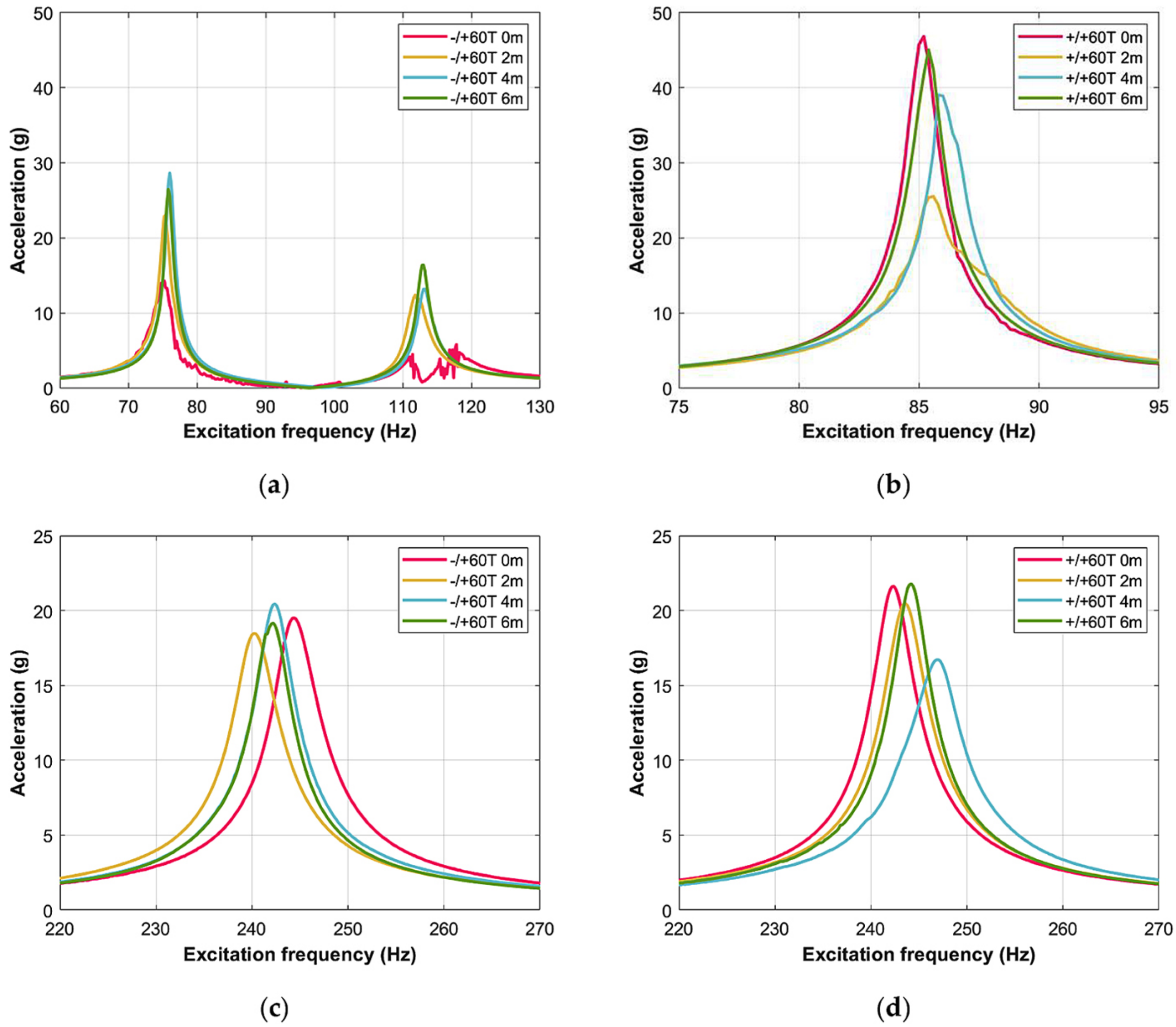

Figure 9. The amplitude – frequency responses of the cantilever beam with fibre set configuration 60°, exposed to temperature shocks in the vicinity of the second (a, b) and the third (c, d) resonance zones, respectively

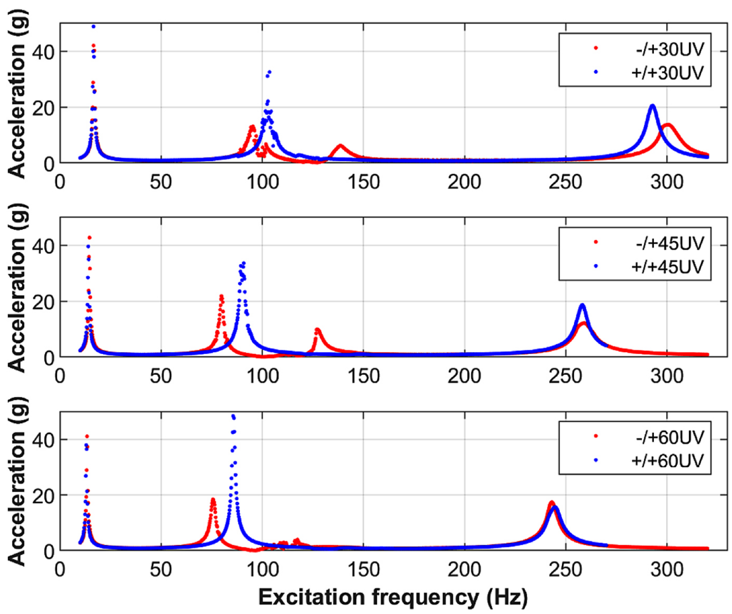

Figure 10. Amplitude – frequency response at the free end of the cantilever beam before UV radiation of asymmetric (-/+) and symmetric (+/+) layer configurations for corresponding fiber sets 30°, 45° and 60°

configurations, but the second and the third reveal discrepancies. The symmetric set (+/+) results in a single pick around the frequency at 100Hz, but the asymmetric (-/+) set branched off into two smaller resonance picks. This indicates some geometrical nonlinearities of the asymmetric structures.

For discussion in detail, two sets of fibre configuration only have been chosen: 30° and 60°, because the middle case, 45°, reported dynamic behaviours closer to the case of 60°. The crucial excitation frequency in the vicinity of 100Hz revealed the significant influence of the UV radiation on the composite structure. Figure 11a shows that the output amplitudes gradually increased at extended exposure to UV radiation. A new structure is characterised by relatively high stiffness, the output acceleration does not exceed 15 g in the vicinity of 95 Hz, but when exposed to UV the material loses stiffness by an amplitude of 35 g at 6 months of conditioning. The same behaviour is observed at the frequency 130–140Hz. The symmetric beams appear to be resistant to the UV conditioning process (Figure 11b). A significant weakening of stiffness appeared at 6 months' time only, when the amplitude increased, while the earlier time effect does not change the output amplitude compared to the "unused -new" material (0 m).

In the third resonance zone presented in Figures 11c and 11d, the dynamics of the structure indicate its asymmetric configuration, that first stage of the UV radiation conditioning definitely increased the beam stiffness which shifted the resonance point approximately 10Hz down. Applying the next stages of UV conditioning, the composite structure was reinforced, then the behaviour repeated the characteristics as new structure holds. In case of symmetric beams, the reinforced affect also appears but at the last stage of conditioning, which corresponds the 6 months'

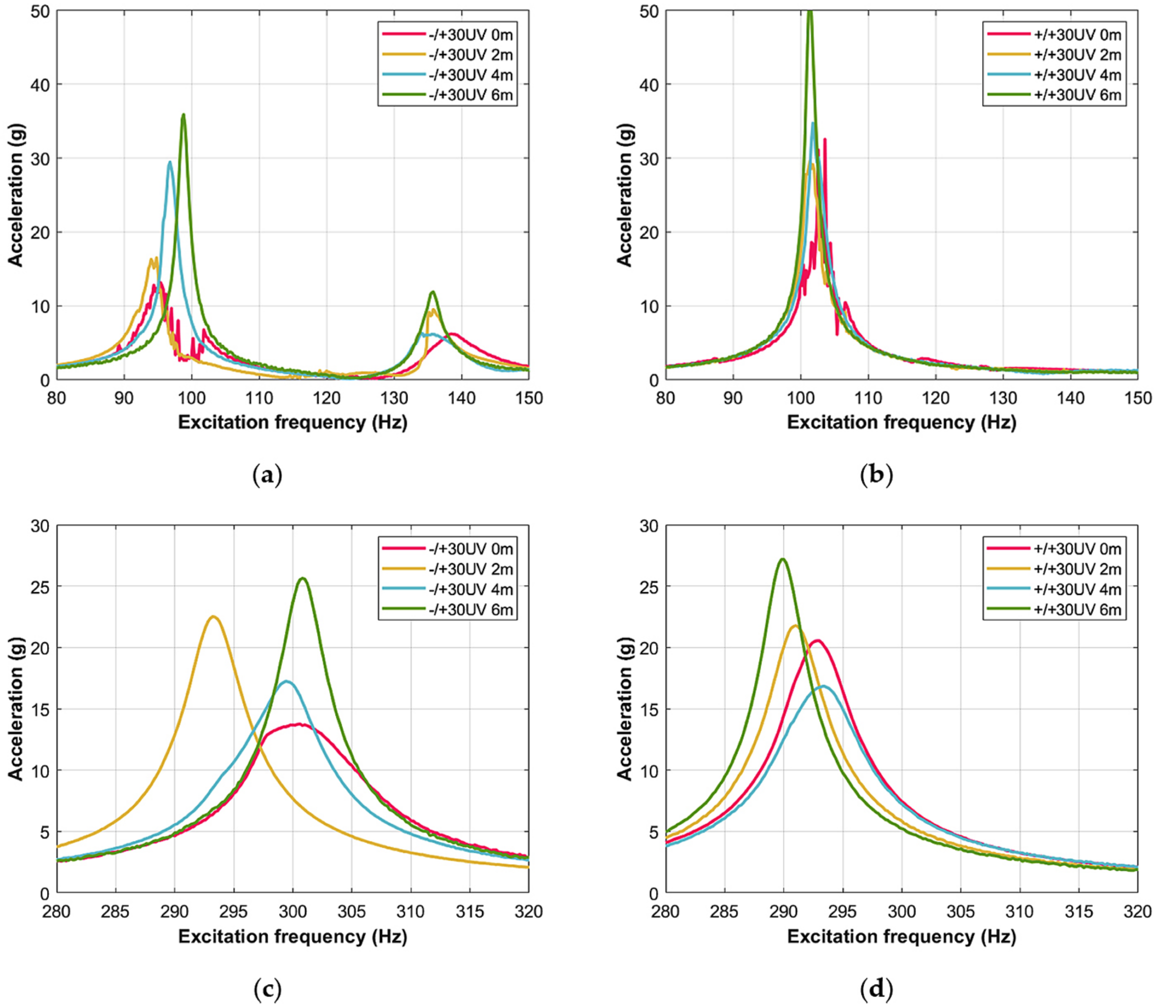

Figure 11. The amplitude – frequency responses of the cantilever beam with fibre set configuration 30°, exposed to UV radiation in the vicinity of the second (a, b) and the third (c, d) resonance zones, respectively

time conditioning. The shorter exposure times of two and four months continuously increased the beam stiffness, as is indicated in Figure 11d. The experimental investigation of symmetric and asymmetric beam structures revealed the fibre configurations relates to how the structure undergoes the time stage of the conditioning exposure. Analysing the set of 60° fibre configurations, the UV radiation conditioning definitely weakens the beams' structure, especially in the case of asymmetric configurations (-/+), as presented in Figures 12a and 12c (green lines). The final time of conditioning, which corresponds to 6 months, indicated resonance amplitudes shifted to the lower ex-citation frequency; the symmetric fibre configuration is resistant to the conditioning effects. The amplitude – frequency responses hold the resonance zone at each time period of UV radiation exposure (Figures 12b and 12d). This suggests that the symmetric structures are more stable than asymmetric ones against environmental conditions.

Finally, the experimental results of maximal output amplitudes of asymmetric and symmetric cantilever beams were juxtaposed in Figures 13 to expose their relations. Figure 13a shows the asymmetric samples of both conditioning approaches, temperature shocks (T) and UV radiation (UV), respectively. For these sets, the structures exposed to the temperature shocks as well as UV radiation conditioning displayed relatively convergent behaviour. For each of the fibre configuration sets, 30°, 45° and 60°, the structures reached the stiffer characteristics during the first exposure time. The maximal amplitudes decreased during the first period of conditioning (2m), then increased during the second period (4m) and finally decreased again at 6m, reaching

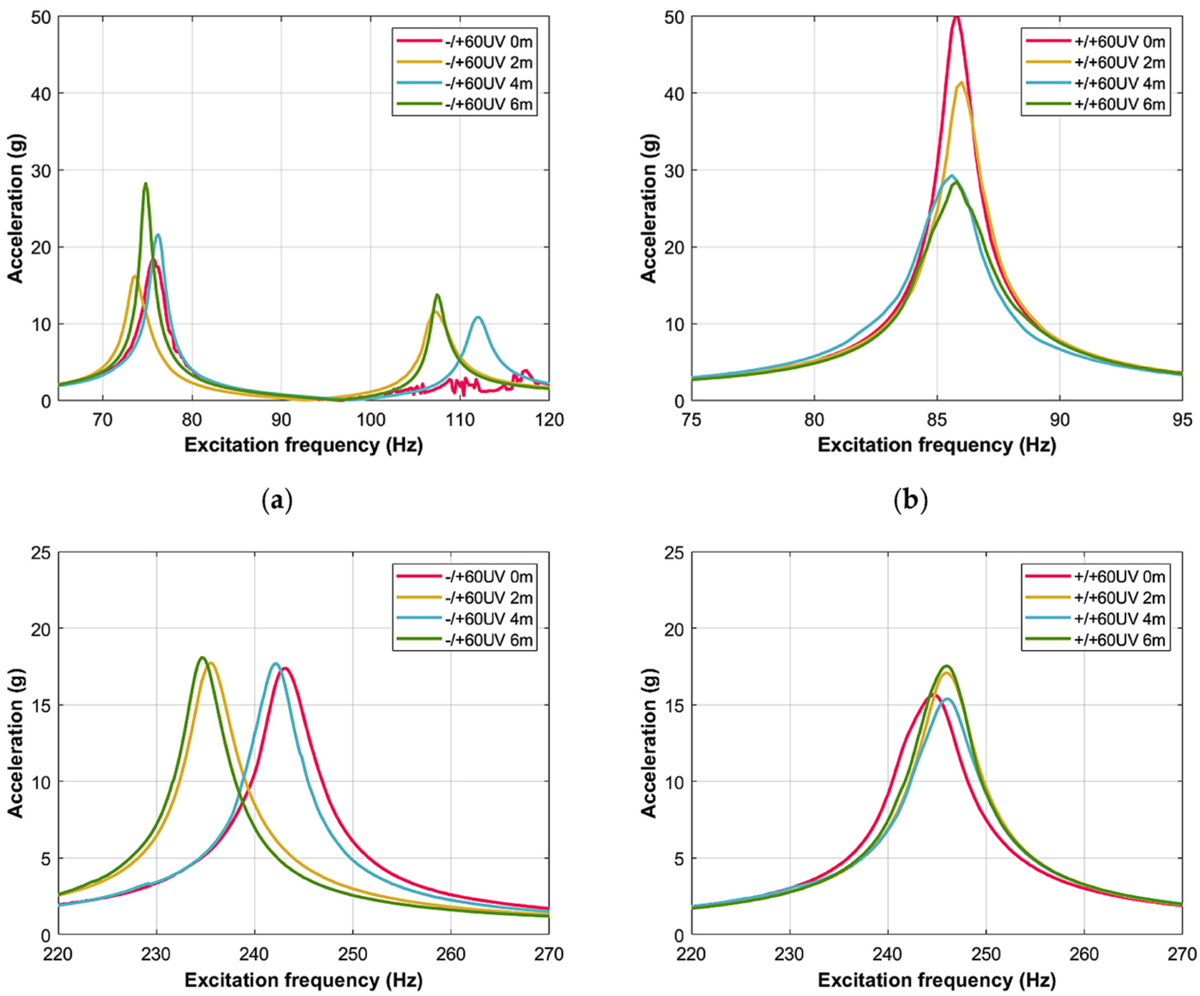

Figure 12. Amplitude – frequency responses of the cantilever beam with fibre set configuration 60°, exposed to UV radiation in the vicinity of the second (a, b) and the third (c, d) resonance zones, respectively

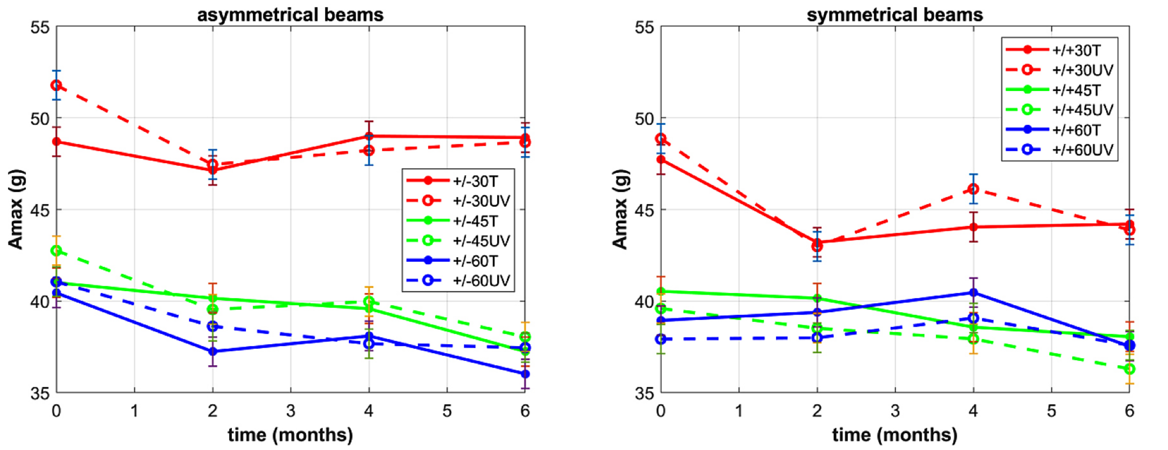

Figure 13. Maximal amplitude expressed by gravity acceleration (g) attained of all compared composite structure via time expressed by months periods of conditioning for asymmetric (a) and symmetric cantilever beams (b)

a higher stiffness of the structure in comparison to the new samples. This is observed for both types of conditioning to which the beams were exposed. It reports the dynamical behaviour of the analysed composite has no unequivocal trends while degradation is progressing. It reveals the complexity of the structure which has symptoms of dynamical nonlinearities.

In Figure 13b, the symmetric samples are presented. Note that in case of composites at 30° fibre sets, after the first period of conditioning which corresponded to two months, the maximal amplitudes decreased in both cases of conditioning, but at two more months of exposure the beams under UV effects reached higher amplitudes than those exposed to temperature shocks. This means the analysed composite structure is more susceptible to UV radiation conditioning than to temperature shocks. The other analysed fibre configuration sets, 45° and 60°, behaved in convergent ways. For the 45° set, one can observe similar behaviour in both conditioning approaches. The amplitude slightly increased up to the 4th month, and finally decreased to the initial level, which indicates that the structure is first weakened and then stiffened. In the case of the 60° set, convergence effects are also observed for both kinds of conditioning, but the amplitudes fall from the beginning of the conditioning tests. This means the structure is consistently stiffened. In general the first period of conditioning, causes initially reinforced of the structure while for the longer exposition on UV radiation or temperature shocks, the structure becomes weakening again and finally after the third period of the conditioning, the structure manifests cracking features which is caused by applied the thermosetting epoxy resin in manufacturing the composite structures.

CONCLUSIONS

The results obtained from the experiment revealed the complex behaviour of the analysed composite structures. The two types of stacking sequences were exposed to environmental conditions, asymmetric and symmetric sets of three selected fibre configurations, respectively. The applied experiment of the conditioning by means of temperature shocks and the effects of UV radiation introduced structural changes in the materials. Identification of the dynamic changes in the behaviour of these structures is a new achievement reported in this paper. The tests performed in this experiment provide the manufacturers of composite shells with important details concerning the structures. The conditioning reported in the time intervals, especially indicated the stiffness of the materials was significantly changed. This was manifested by the shift of the resonance points from the original values related to new materials, unexposed to conditioning, and the output amplitudes were altered. The features of composites materials indicated are crucial and valuable in manufacturing the shell bodies used in constructions such as aircraft, where such conditioning occurs. The next step is to apply the investigation to the composite structures with fibre configurations that are much more varied from each other and select the optimal variant to achieve a structure impervious to such environmental conditions, which makes the structure more safe.

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