Numerical Vibration Analysis of Impacted CFRP Specimens Using COMSOL Multiphysics®

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Abstract: Non-destructive testing (NDT) of carbon fiber reinforced composites (CFRP) structures can be fairly time consuming and expensive. The question at hand is if defects in CFRP materials can be detected via modal testing in a first step to determine whether it is necessary to apply more thorough methods like ultrasound and x-ray. Therefore the intent of this work is to simulate how vibration modes are altered by delamination, which are defects resulting from an impact.

In order to obtain a first insight into the vibration behavior of CFRP with and without defects, simple specimens have been modeled in COMSOL Multiphysics. The specimens are rectangular laminates with different layups. In this process COMSOL Structural Mechanics Module and Solid Mechanics Interface have been used to conduct an Eigenfrequency Study. Different parameters such as fiber angle or geometrical dimensions have been adjusted to give accurate results which were validated by experimental examination of the specimens. In the further process, the specimens were impacted to yield the desired defects. As the defects are not quantified in detail by the time of this submission, their exact size and geometry are approximated and the material stiffness is altered in this region of the COMSOL model.

For the samples without defects, the results of the simulation yield eigenfrequencies that are accurate within about 5% over a broad frequency range, compared to the experimental results. In a first step, impact induced delamination is approximated by elliptic areas of reduced stiffness in each layer of the models. For these models, simulation and experimental results correlate acceptably only for the lower mode numbers. Therefore, the model of the damaged samples is subject to further development.

Keywords: Non-destructive testing, modal analysis, vibration analysis, CFRP, delamination, impact damage

1. Introduction

Striving for lower energy demand due to ecological and economical considerations, automotive, aerospace and other manufacturers are increasingly using lightweight materials such as CFRP [1]. In order to ensure production quality and efficiency as well as operational safety, adequate non-destructive testing is of fundamental importance. However, the same heterogeneous and anisotropic structure that gives CFRP its specific strength also leads to challenges for established NDT methods such as ultrasound, thermography and computer tomography. With these methods, achieving precise and reproducible measurement results with an appropriate probability of detection can be time consuming and expensive. For this reason, it can be useful to apply more simple techniques like vibration and modal analysis in a first step for a preliminary good/bad decision and general assessment of the part's dynamic behavior. To fully understand the influencing factors on the detectability of delamination in composites by modal analysis, a numerical study is conducted and supported by experimental data.

The capability of vibration analysis to detect and even to roughly locate damage to CFRP plates was shown fairly early [2]. Later on, vibration analysis was described to specifically detect impact-induced delamination in CFRP by measuring significant shifts of the natural frequencies. In this study, early stage finite-element models were already used to predict the sample behavior [3]. Additional numerical investigations on the detection and localization of damage in CFRP beams using modal parameters were conducted by Sanders et al. [4]. In recent years, this topic has repeatedly gained more attention [5] [6].

2. Real CFRP Samples and COMSOL Model

For this study, five CFRP sample plates of different lay-ups are available including detailed information about the material properties like Young's and shear moduli, Poisson's ratio and density. The external geometry of the samples is given in Table 1.

Table 1: External geometry of the samples.

Sample no.	Size	Thickness
1 & 2	150x100 mm	3.3 mm
3 & 4	150x100 mm	1.92 mm
5	300x200 mm	1.92 mm

In order to achieve quasi-isotropic properties of a CFRP part, layers of unidirectional fiber orientation are placed on top of each other at a certain angle, most commonly +45°, -45°, + 90° and -90°. Figure 1 shows the cutting edge of sample no. 2, visualizing the innermost layers at 0° surrounded by a number of layers at +45° and -45°.

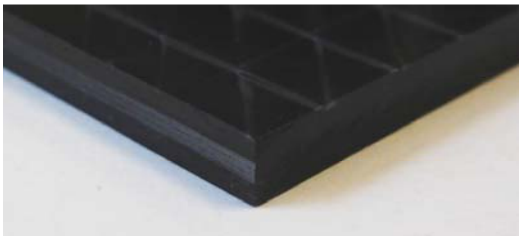

Figure 1: Visible differences in fiber orientation along cutting edge of sample no. 2.

The given lay-ups are recreated as a 3D model using the COMSOL geometry modeling and CAD tools. For modeling different fiber orientations, rotated coordinate systems are used and the respective material properties are assigned to each layer. As the grammage [g/m²] is given as twice as large as for the outside layers, double layer thickness is assumed for the inner layers. Figure 2 depicts these differences in the 3D model including a mesh consisting of prism elements.

For the validation of the simulation, an experimental modal analysis of the samples is conducted using an affixed acceleration sensor and an impulse hammer. Parts of the experimental setup are shown in Figure 3, where the white dots on the sample indicate the points of excitation while the sensor position is fixed. Previous measurements have shown a slight influence of the sensor mass when the weight of the sample is very low. In order to integrate this effect into the considerations, a model containing a sensor mass is created (s. Figure 4).

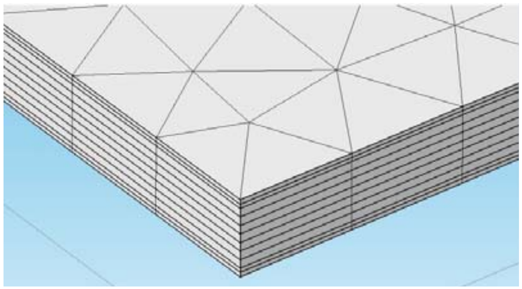

Figure 2: Differences in layer thickness assumed for the 3D-model.

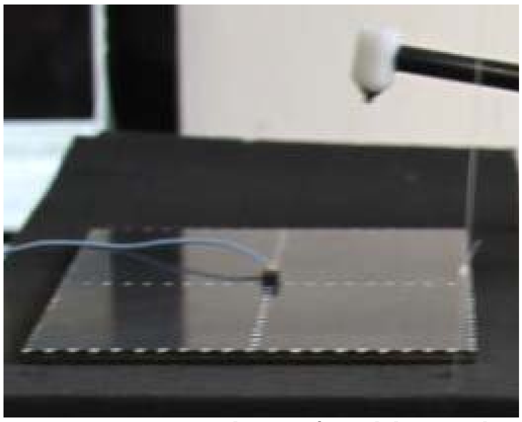

Figure 3: Experimental setup for validation (white dots: excitation grid; right: impulse hammer; center of the sample: acceleration sensor).

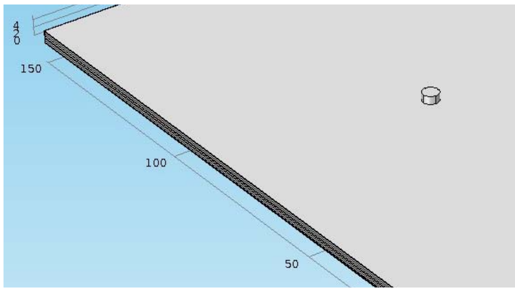

Figure 4: Approximation of sensor mass on a sample in the 3D model.

The experimental validation is conducted before and after an impact damage is induced using different impact energies (5-10 J). The exact shape and location of the resulting delamination inside the sample is unknown at this point of the study. However, it is known that the shape of impact-induced delamination in each layer is similar to a double lobe, with the main axis following the local fiber orientation [7]. For this reason, an approximation is done in the 3D model using elliptic shapes as areas of reduced stiffness, representing delaminated areas in a first step. The size of the ellipses is determined from a visual inspection of the top and bottom layers and a linear interpolation in between, as shown in Figure 5. The actual size of the approximated delaminated area on sample 3 is given in Figure 6.

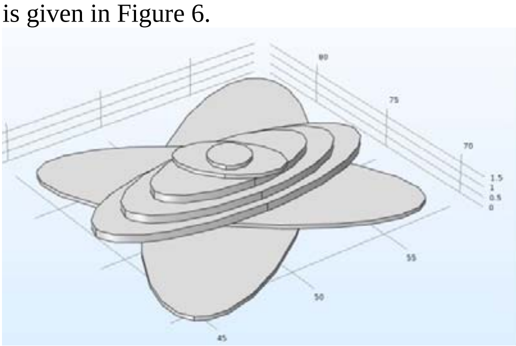

Figure 5: Approximation of delamination in 3D-model through all layers.

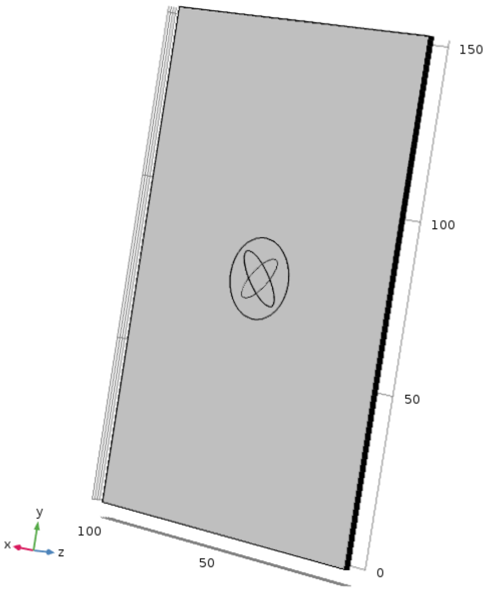

Figure 6: Size and position of the delamination approximation.

3. Results

Using the models described in the previous section, an eigenfrequency study is conducted with the COMSOL structural mechanics module. Eigenfrequencies and mode shapes are then compared to the experimental results of the undamaged samples. Below, sample no. 3 is used as a representative example for the entire investigation. Figure 7 shows the experimental mode shape no. 7 at 1823 Hz. The seemingly poor resolution is due to the limited number of measuring points. In this case, approx. 294 measuring points were used, each averaging five single measurements. Detailed information on the conducted measurements can be found in [8].

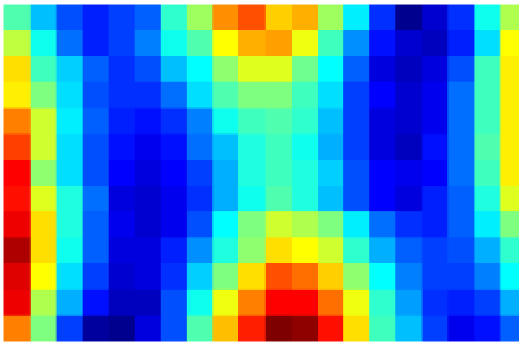

Figure 7: Experimental mode shape no. 7 (1823 Hz) before impact damage.

Figure 8 shows the corresponding simulated mode shape no. 8 at 1825 Hz. The correlation between experiment and simulation is evaluated using the modal assurance criterion (MAC). Figure 9 shows the result for sample no. 3 before impact damage. For most of the mode shapes, experiment and simulation correlate by a coefficient of larger than 0.9.

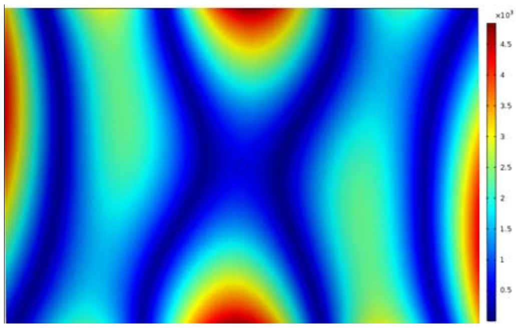

Figure 8: Simulated mode shape no. 8 (1825 Hz) before impact damage (scale: total deformation).

Non-correlating mode shapes in Figure 9 and other results not depicted here may result from measurement inaccuracy, theoretical modes that are not measurable or other disturbance impacts.

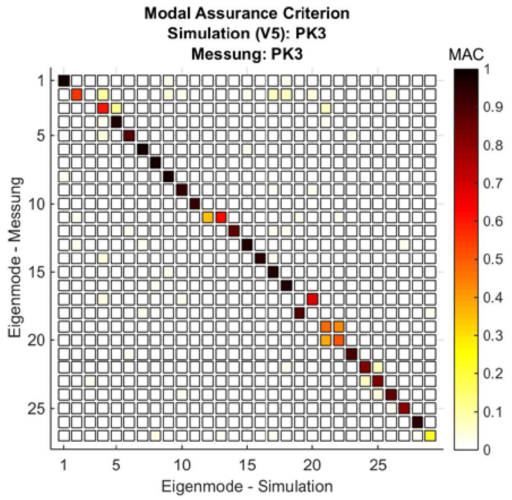

Figure 9: MAC for comparing experiment and simulation of sample 3 before impact damage.

When detecting damage in CFRP using modal analysis, a possible shift in natural frequencies before and after damage may be considered. Figure 10 shows the frequency difference versus the mode shape number, comparing simulation and experiment of sample no. 3. Hardly any difference can be noted for the lower mode shape numbers, whereas both simulation and experiment detect partly significant shifts for higher mode shape numbers.

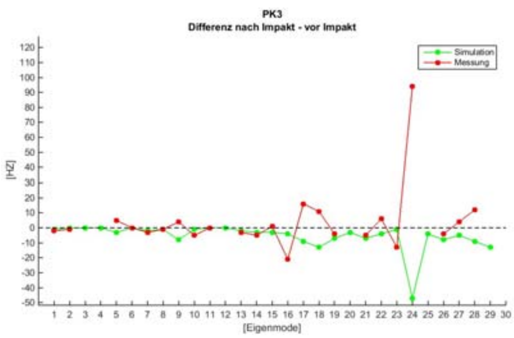

Figure 10: Differences in eigenfrequencies [Hz] before and after impact damage for experiment (red) and simulation (green).

However, the non-correlating direction of the shift indicates insufficient model quality. For this reason, the model is subject to ongoing improvement. Detailed information about this study can be found in [9].

4. Conclusions

Purpose of this study is to investigate possibilities and limits of vibration and modal analysis to detect damage in CFRP. For this, a COMSOL model was created for both damaged and undamaged samples. The results of the simulation were compared to experimental data, showing correlation coefficients of mostly larger than 0.9 for the case of undamaged samples. However, there are a number of factors yet limiting the capability of the model for the damaged samples. Firstly, the necessary material properties for a complex structure like CFRP have to be available in detail. Secondly, location and exact dimension of the delaminated has to be assessed by means of other methods of non-destructive testing. Finally, the critical damage dimension for an adequate probability of detection has to be studied in order to push ahead the practical use of modal analysis in NDT.

5. References

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