SHAPE AND LAYER OPTIMIZATION FOR THE DYNAMIC CHARACTERIZATION OF CARBON FIBER PLASTICS

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Abstract

A method is proposed for determining the optimum size and layer structure of dynamic test specimens made of carbon fiber reinforced plastics for shaker testing. In order to simulate the fatigue strength of high performance structures, detailed knowledge of their dynamic material properties is required. The quality of the test specimens is mainly influenced by their shape and, in case of carbon fiber materials, by their layer structure and fiber orientation. The design goals of the optimization are to increase test accuracy and to reduce testing time. While the accuracy increases with higher amplitudes and equal stress distribution in the specimen, the time efficiency decreases with higher amplitudes . Especially with the introduced method, dynamic testing provides highly accurate results and can be used to validate the stiffness parameters which are mostly derived from static testing. The natural frequencies for a given shape depend only on the material stiffness parameters and the material density. Using classical laminate theory, the stiffness parameters are optimized in a best-fit approach and can thus be used to minimize the error of measurement of the static material characterization.

Keywords

Dynamic Characterization; Carbon Fiber Reinforced Plastics; Parameter Optimization

NOMENCLATURE

Abbreviations

DOE	Design of Experiment	
FE	Finite Element	
Hz	Hertz	1/s
UD	Unidirectional	

1. INTRODUCTION

The process of structure design and manufacturing is relying increasingly on simulation to reduce the necessity of material and part testing and therefore reducing development costs. While approaches like Design of Experiment (DOE) aim to decrease the amount of tests necessary, the method described in this paper aims to reduce testing time and increase quality. Ideally both approaches are applied together to reduce the test amount and time to its minimum while ensuring the desired quality of the product. Test results often show the necessity of redesign, conducting tests which deliver fast and reliable results can reduce the uncertainty of the design process and, as shown in figure 1, is most beneficial at early design stages.

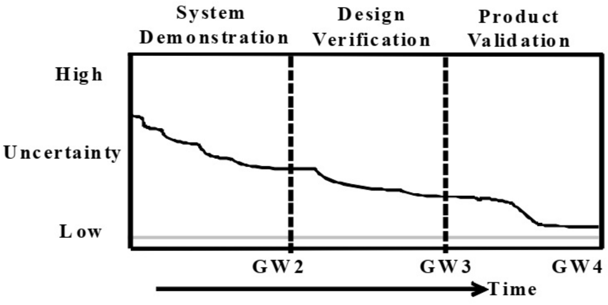

FIG 1. Design uncertainty [1]

The following chapters will describe the process to define the shape and layer structure of the dynamic test specimen. The results will be validated to proof the optimization quality. Finally the results of the dynamic characterization will

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be compared with the static test results and improvements will be proposed.

2. VIBRATION TESTING

In order to predict the fatigue limits of a structure, the material dependent dynamic strength limits need to be measured. The established test procedure to measure the dynamic material property is vibration testing and is well documented for metals and other isotropic materials. The measured response determines the resonance frequencies, while usually only the first order, and the dynamic fatigue strength of the tested material. Since the test is performed under a defined environment and the test geometry may be different from the part geometry the results are used in later simulations to give an estimate of the parts fatigue life.

2.1. Shaker

The vibration test facility used for the described tests is a standard shaker setup. The test equipment consists of a shaker table with a mount to clamp the test specimen, a acceleration sensor to measure the response frequencies, a cooling nozzle to avoid overheating and a distance laser to measure the occurring amplitudes. Figure 2 shows the test setup.

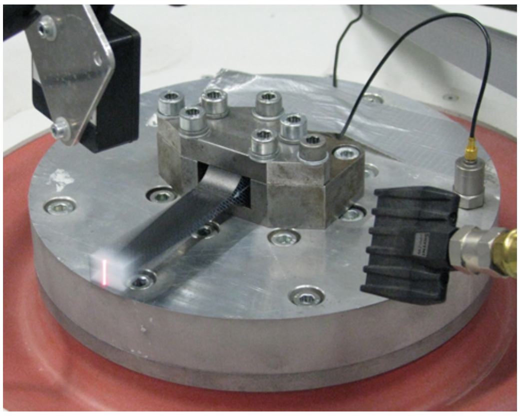
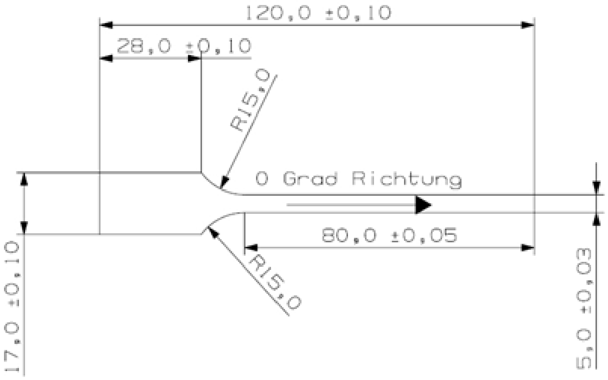


FIG 2. Vibration test facility

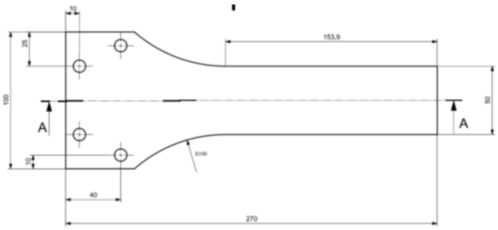
For most applications, including the work at scope, the dynamic fatigue strength is defined as the strength remaining after ten million cycles, for parts with high frequency loading, the fatigue strength definition may be increased to ten billion cycles. According to [2], the deviation of the frequencies, depending on the fiber direction can be between five to ten percent. This deviation is usually only taken into account in the evaluation of the measurement results and must be determined on the basis of the failure curve. Here it helps if as many samples as possible are examined to determine a regularity.

2.2. Test specimen geometry

For isotropic materials the direction of testing is by their isotropic definition irrelevant, therefore the specification of the test specimen geometry can be reduced to one optimum geometry. Fiber composites, however, have direction-dependent properties which can differ considerably depending on the laminate structure, as well as fiber and matrix characteristics. To determine the dynamic strength, the subsequent loading direction of the component must be taken into account. Since it is not possible from an economic point of view to test every direction, only orthogonal properties are determined and the intermediate values are approximated. For fiber composite components, loading in the thickness direction should be avoided, since the material has advantages over metallic materials mainly for thin-walled components.
Examples for different test specimen shapes are shown in figure 3.



(a) Specimen A



(b) Specimen B

FIG 3. Specimen geometry examples

While specimen A was designed to determine the dynamic strength after a milling process which leaves open fiber ends on the component surface, specimen B has a more common geometry to determine the dynamic strength in fiber direction. This example shows the necessity to use different shapes for different applications. The shape definition is a time consuming process since different requirements need to be fulfilled. The choice of the correct shape is crucial to determine the correct fatigue life of the later application. The shape design is conducted via FE simulations, where the eigenform and the location of the maximum stresses are the most important factors. To reduce the development time an automatic process for the test specimen design was developed and is explained in the following chapter.

3. PARAMETER OPTIMIZATION

Parameter Optimization is the high level description for a set of optimization methods. Generally parameter optimization works by varying over a set of control parameters to find an optimum for one or more specified goal values. The challenge for the optimizer is to find the optimum, most optimization methods are minimization problems, in the fastest way, with as less data as possible. There exist countless of different optimization algorithm for example deterministic, evolutionary or stochastic methods. These algorithms work best for different optimization problems. For the optimization problem at hand an evolutionary algorithm was chosen since the advantage of this method is to find the global optimum with a higher accuracy as for example gradient descent. The amount of free parameters is not very high so optimization time and training data are not the critical aspects. The optimization process is divided into two steps, layer optimization and shape optimization. The layer definition is limited by the later application since the amount of layers for the vibration testing should not exceed the later application layer setup. After the layer definition is finished, the shape optimization can be conducted. The design process is shown in figure 4.

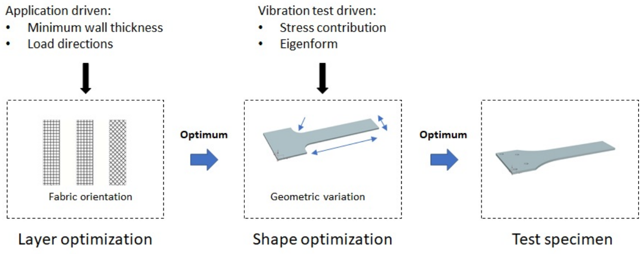


FIG 4. Optimization process

3.1. Layer optimization

The layer optimization of the test subject was restricted by the later application to consist of fabric layers with 50 percent warp and weave. The material properties of the fabric layers are derived from various static tests as described in [3]. The layer optimization uses two advanced failure models, namely Puck and Tsai-Wu [4], therefore the fabric layer needs to be broken down into to unidirectional (UD) layers. Since single fiber and matrix properties are difficult to measure and iterative method developed in [5] is used to determine the stiffness properties of the UD layers (figure 5).

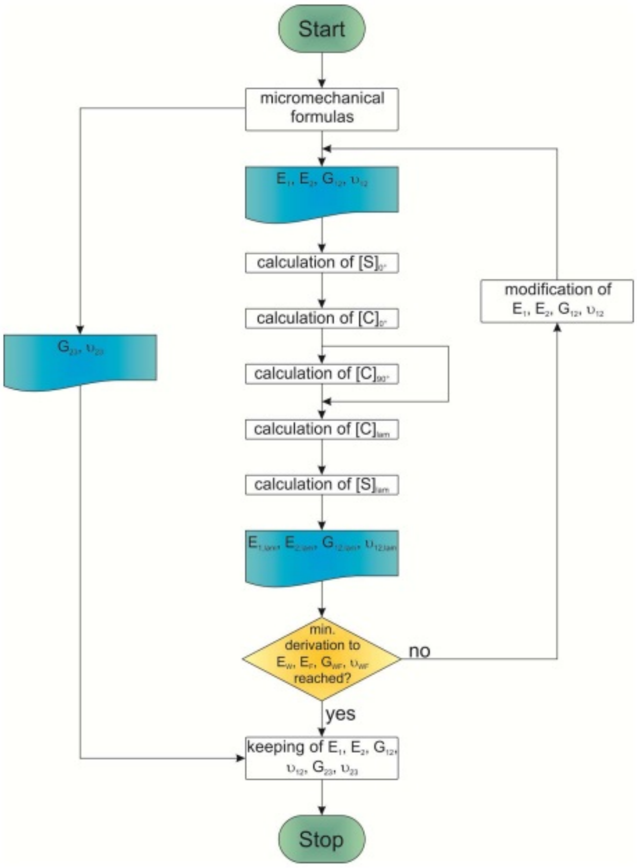


FIG 5. Analytic stiffness calculation[6]

The missing strength parameters are calculated using an algeabric approach [6]. The ud layers can again be stacked in packets of 0/90 as one fabric layer and then stacked in varying orientations until the desired laminate thickness is achieved. The optimizer varies the orientations until the failure criteria reach their minimum. The loads applied in the testcase originate from an engine bypass strut and consist of different load cases. The resulting fiber orientation for this use case is the standard layup for turbine blades, with fabric layers stacked in packets by (0/45/-45/0).

3.2. Shape optimization

For the test case of the shape optimization, the geometry B in figure 3 was chosen, since the application is a thin-walled structure and the fatigue strength should be predicted in the fiber plane. As optimization parameters the wideness, length and the radius to the mount are optimized with the goal to achieve pure bending modes while reaching a frequency with a minimum of 200 Hz and to achieve an concentrated stress distribution, which is located outside of the clamping mount. A pure bending mode is necessary to measure the excitation amplitude with high accuracy, this results except in rare cases to a symmetric geometry regarding the length axis. The characterization of the mode shapes is carried out automatically. The minimum requirement for the eigenfrequencies comes from the need to make the test time as time-efficient as possible. An upper limit for the eigenfrequencies is generally not necessary, yet the specifications of the test facility for the amplitude detection limits the possible frequency, since with higher frequency the fatigue amplitude drops. The length and wideness show high influence on the eigenfrequency. The eigenfrequency requirements proved to be difficult to achieve, since the laminate thickness for the application are only 8 UD layers. To reach the desired frequency it is possible to measure the second eigenfrequency during the vibration test, as long as the pure bending requirement is still met. The amplitude of torsion modes can not be measured accurately yet the resonance frequency can be detected and used for the validation of the test results in chapter 4. Figure 6 illustrates the level of the first three eigenfrequencies and their mode shapes.

The option to use the second bending mode for the vibration testing reduces the testing time by nearly 80 percent.

4. RESULT VALIDATION

The optimization method as well as the simulations need to be validated. The optimization results can be compared directly with the vibration tests by analyzing the deviation from calculated to measured eigenfrequencies and also by visual inspection to validate the predicted failure location. Since the calculated eigenfrequencies are mainly influenced by the material stiffness parameters, the corrected eigenfrequencies can be approximated by tuning the material stiffness properties. Especially the measurement of the torsion mode reduces the possible property combinations, to give the equation system an unique solution in most cases. In the final step these parameters are compared with the static test results of the static test program. If the proposed material properties are within the uncertainty of the measurements, the adjusted material properties can be used for the later simulation of the component model.

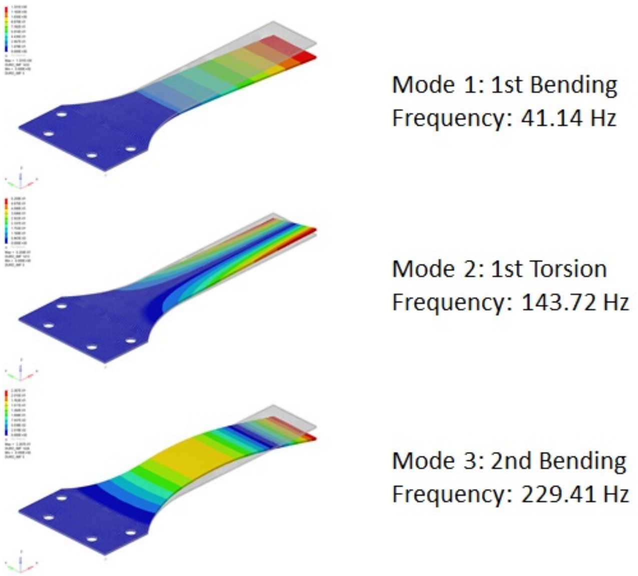


FIG 6. **FE simulation of the final optimization member**

4.1. Test results

The capability of the used solver PERMAS are not discussed here, the accuracy is proven for example in [7]. The vibration test results for the eigenfrequency location of specimen B differ only slightly from the simulation results. All test samples showed a failure at the radius outside of the mounting clamp as predicted by the FE-simulations. The differences in the eigenfrequency values could stem from the damping properties of the mounting clamps, therefore a more detailed FE-model was built. The results of the detailed model show a slightly better fit to the experimental results.The different FE-models are displayed in figure 7.

A variation over the stiffness properties of the simulation allows a better representation of the real physical phenomena in future simulations.

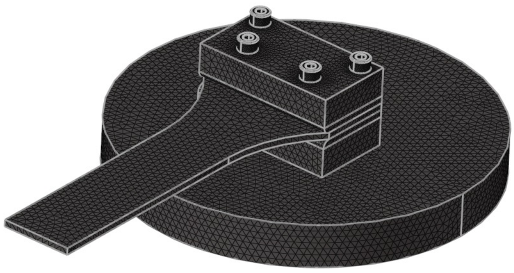


FIG 7. Detailed FE model with mount for data validation

This approach can also reduce errors made by the simplification of fabric layers by two UD-layers. The optimization approach is already described in [3] and is an iterative approach to find the best fitting material description to match the measured eigenfrequency results.

4.2. Comparison with static tests

The calculated material properties need to be checked against the measured results of the static characterization. The changed material properties of the UD layer are used in a FE simulation of the static test specimen. The results of the static behavior to the applied loads and the comparison with the measured values lie within the expected measurement uncertainty of the static test campaign.

5. CONCLUSION

A method was proposed to automatically generate fitting layer architectures and specimen geometries for vibration testing. The approach can be used for different fiber and matrix combinations as well as fabric or UD-layers. The approach was validated against a vibration test program to ensure the quality of the underlying FE-simulations. To increase the accuracy of following simulation steps, a comparison between measured and calculated results was made and a method proposed to improve the agreement specifically of the eigenfrequencies. The final check against the measured material properties of an earlier static characterization ensures the validity of the made assumptions.

References

[1] K. Tahera, C.F. Earl and C.M. Eckert. *Integrating Physical and Virtual Testing to Improve Confidence in Product Design*. Trinity College, University of Cambridge, 2012.

[2] B. Drees, N. Forsthofer. *Material- und Komponententests für CRISP2*. DLR, IB 435-2015/76, 2015.

[3] N. Forsthofer, C. Reiber. *Structural Mechanic and Aeroelastic Approach for Design and Simulation of CFRP Fan Blades*. DLRK, ID420132, 2016.

[4] VDI-Fachbereich Kunststofftechnik. *VDI2014 Blatt 3: Entwicklung von Bauteilen aus Faser-Kunststoff-Verbund*. Beuth Verlag GmbH, Berlin, 2006.

[5] P. Dreher. *Enhancements of the static CFRP failure analysis with PERMAS for applications with fabrics*. DLR, IB 435-2015/76, 2015.

[6] P. Dreher. *Static CFRP Failure Analysis with PERMAS for a CROR Blade*. DLR, IB 435-2015/83, 2015.

[7] INTES GmbH. *PERMAS Product Description Version 18*. INTES GmbH, Stuttgart, 2019.