FULL SCALE STATIC TEST OF A LIGHTWEIGHT COMPOSITE STRUCTURE

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Abstract

Simulations of modern complex lightweight structures become increasingly important due to challenging targets in terms of mass. In order to validate that simulations can predict accurately the structure under investigation, a large amount of measurement data is required. In order to be representative, the test specimen shall be loaded such that similarity is given between the loads of the tests and the loads the structure experiences during lifetime. Hence, the load magnitudes and the location and direction of the load introduction has to be calibrated by means of a constraint optimization problem, where the constraints consist in the strength requirements of the structure which shall not be exceeded, especially due to concentrated load introduction. In addition, an efficient strategy for monitoring has been developed in order to analyse the data in real time which permits an immediate identification of possible local damages. After completion of the test, the quality of the underlying model has been evaluated by comparing analysis and predictions at the measured positions.

1. Introduction

Many engineering fields, such as aviation or automotive industry, pose the challenging need for structures with low mass targets in order to be competitive with respect to efficiency, environmental protection, material costs, fuel consumption and hence costs. In order to meet these targets, complex and large Finite Element models are necessary which can predict the structural behaviour in an accurate way. In order to determine the degree of accuracy of the established model, experimental data of structural tests are indispensable. Tests at coupon or component level deliver valuable information in order to enhance and validate the underlying model and methods, but the information on the load path, structural behaviour and critical areas can only be confirmed by a full scale test of the investigated structure.

Clearly, a full scale test is very costly, for which reason the maximum amount of information has to be deduced from it. For that reason the first question is concerned with the representation of the actual flight condition in the test. In order to achieve this target, the applied loading has to be calibrated in order to mimic the flight condition in terms of internal forces and moments at certain locations. At the same time, an overloading of the structure due to concentrated load application has to be avoided. Mathematically speaking, a constrained optimization problem has to be solved where the difference between flight and test state variables has to be minimized while still fulfilling strength requirements. During the test, an efficient monitoring has to be performed in order to be able to react fast in case of an unexpected behaviour. This is mainly concerned with the evolution of strains and displacements at critical locations. For this purpose, warning thresholds have been introduced which are formulated in terms of absolute values and of critical slopes of the curves. Finally, after the performance of the test, the quality of the underlying model is evaluated by comparing the predicted and measured strains and displacements at many locations in order to obtain a full representation of the structural behaviour.

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This step also poses a challenge in terms of data handling since strain and displacement history curves have to be processed and compared with the respective predictions.

In this work, the different steps of preparation and performance of the full scale test of a lightweight structure are discussed. The theoretical background, the logic of the workflow and practical issues for the application in connection with the investigated structure will be addressed.

2. Test calibration and preparation

The first step of the test preparation consists in the determination of the loads with the goal of representing the investigated loading situation in the flight hardware. During the test, which is limited to static loading, the forces are introduced into the specimen by means of five yokes, where three loads act on each of them. Hence, a total of 15 load magnitudes are to be determined. The model of the test structure together with the setup of the load introduction is shown in Figure 1. The determination of the forces to be applied is based on the goal of achieving good correspondence of the section forces and moments at several defined locations (called stations) along the structure caused by the 15 point loads of the test and the target flight cases.

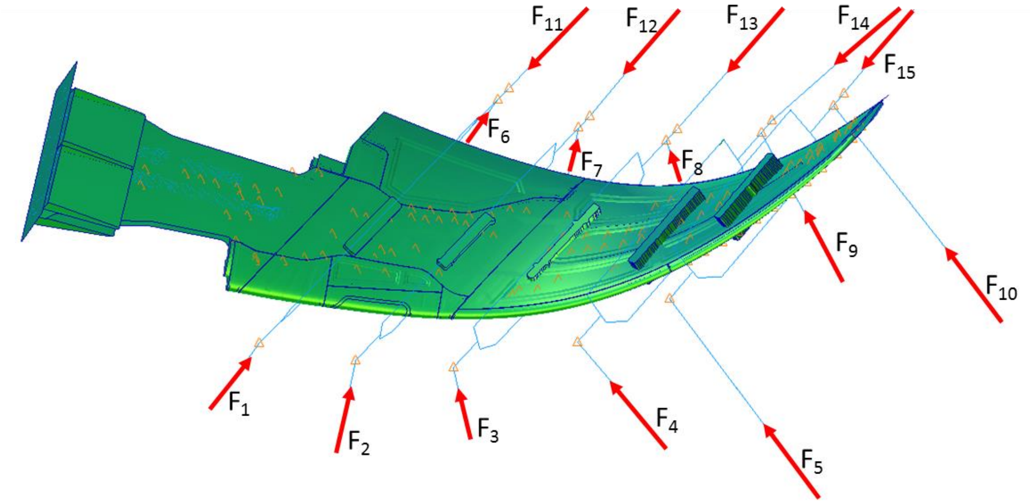

Figure 1. Model of the test specimen and load introductions

Mathematically speaking, a constrained optimization problem has to be solved where squared, summed up differences of the section forces and moments between test and flight are minimized. The constraints consist in the fulfillment of the strength requirements. Hence, the problem can be formulated as follows:

$$\sum_{i=1}^{n_{stations}} w_{i,force}\left(F_{i,flight}-F_{i,test}(x)\right)^2 + w_{i,moment}\left(M_{i,flight}-M_{i,test}(x)\right)^2 \rightarrow \min \tag{1}$$

where x denotes the magnitudes of the cyclinder forces, $n_{stations}$ is the number of considered stations, F_i and M_i are the section forces and moments in the three directions at the station i due to test and flight, respectively. The weights w_i are used in order to put emphasis on selected station points and types of section forces or moments during the optimization process.

Since the objective function involves the evaluation of a full FE model, the computational effort of the optimization problem is rather high. As a remedy, the concept of linear superimposition is used, where the structure is loaded by 15 unit cases and the effect of each load combination can be computed by a

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matrix vector multiplication, where the matrices are selected as outputs of a linear FE analysis. This operation is embedded into the optimization procedure carried out within MATLAB. The results of the optimization process are then used for a strength assessment of the structure and –if necessary– a new optimization loop with constraints regarding the strength analysis is started. Finally, a high level of agreement of the target section forces and moments is achieved where the strength requirements are fulfilled. Figure 2 shows exemplarily the comparison for the moment M_x along the 15 station points.

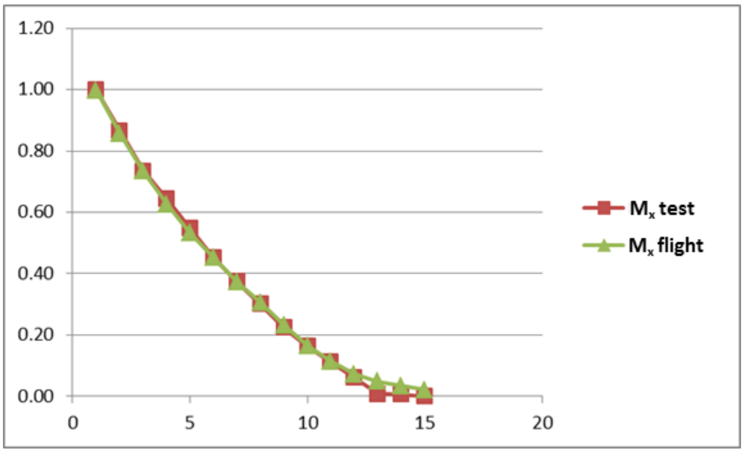

Figure 2. Comparison of the normalized moment M_x at 15 station points due to flight and test prediction

The test setup as mounted by the CoLT Test Facility in St. Martin im Innkreis (Austria) is shown in Figure 3, where also the complete test rig can be seen. In addition, also the cameras for the displacement measurements are visible, which are mounted on an independent frame. The displacements of the specimen was measured by a two non-contact sensors, which allows for the monitoring of reference points of the upper surface of the specimen which are pre-defined based on the FE analysis. In total, more than 200 points are analyzed three-dimensionally in the x, y and z direction.

Strain measurements are performed by about 500 strain gauges placed over the whole structure, with emphasis on the critical locations, as predicted by the FE analysis. All measured data was recorded by a dedicated software and analyzed in real-time in order to identify a possible local damage immediately. Three different strategies for analyzing the measured strains have been implemented, which consist of a warning and an error limit referring to the absolute value of the measured strains and a warning threshold related to the slope of the strain histories. The latter criterion shall identify a sudden drop of the stiffness in case of a local failure. In addition, critical strain gauge channels are visualized on a total of 20 screens to ensure seamless monitoring and recording of all processes.

The third and last part of data monitoring consists in the analysis of the load-displacement curves of the actuators, meaning that a comparison with the predicted curves is performed. For that reason, the applied load was measured and recorded by load cells installed at the end of each cylinder actuator and visualized on a separate screen in real-time.

These efficient strategies developed for analyzing the monitored data made it possible to run the tests without any additional interventions on the component under testing that would have become necessary. After successful completion of the different tests, the acquired measurement data are used for validating the underlying computational model and also for improving simulation parameters in order to obtain a more accurate model to be used for prediction. The results of this validation procedure will be discussed in the next section.

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Figure 3. Test setup (courtesy of CoLT Test Facility)

3. Evaluation of the measurements

The evaluation of the test data is performed by means of comparing the strains and displacements deriving from analysis and test. Both a linear and a geometrically non-linear analysis of the test load cases have been employed for the test prediction. The latter is especially needed for a correct modelling of the kinematics of the cylinder actuators during the test (i.e. loads following the movement of the actuator due to the displacement of the specimen) and due to the fact that some components exhibit non-linear behavior at higher load levels.

In order to correlate the measured values of all channels of the strain gauges to the analysis data, an automated tool has been developed which identifies the element in the underlying FE model which is closest to the location of the investigated strain gauge. In addition, the predicted strains have to be transformed into the direction of the strain gauge channel. Figure 4 shows two examples, where the measured strains of selected strain gauges are correlated with the respective analysis results. The strains are depicted as a function of the applied load level. A high level of agreement of the two curves can be seen which underlines the high quality of the computational model.

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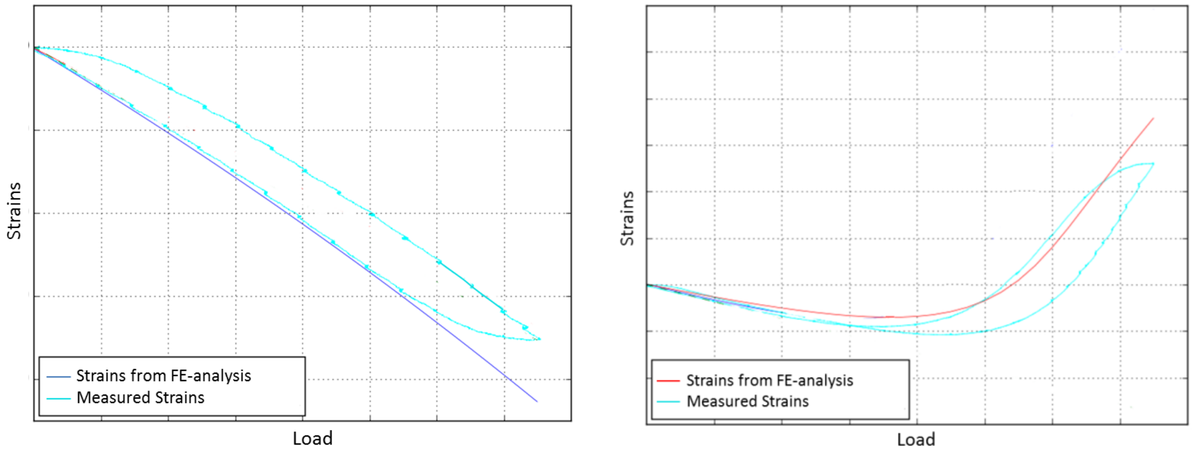

Figure 4. Test-analysis correlation for two selected strain gauge channels

As stated above, in total there are more than 500 strain gauges installed on the structure, which turns the task of classifying the model by visual check into a cumbersome action. Hence, a tool is needed in order to get a quick overview of all correlation results over some components of the test specimen.
At INTALES, an in-house visualization tool for dedicated results evaluation has been developed in the course of previous projects over the last years. In order to evaluate the test results, a plug-in has been added, which displays the ratios between the measured and the predicted strains at the locations of the respective strain gauge. Figure 5 shows an example of such a plot, where one component out of the test specimen is selected. At each location of a colored spot a strain gauge is installed and the colors of the closest element and those in the direct neighbourhood refer to the ratio of measured to predicted strain. The inclusion of the neighbouring element in this plot is motivated by the existence of high strain gradients in some locations which can be identified in this way.

Figure 5. Visualization of the ratio between measured and predicted strains at the locations of the strain gauges of one selected component

In addition to the deterministic evaluation of the correlation between test measurements and predictions, also stochastic methods have been used. This approach is motivated by the fact that the predictions derive from a deterministic model which is characterized by assumptions on the input parameters. For example, for the Young's modulus the mean value is used in the FE analysis, which is not necessarily the value exhibited by the actual structure. The test specimen might consist of some components where the Young's modulus varies within certain bounds. The same consideration applies to all other input parameters.
In order to quantify the uncertainties about the proposition of using certain parameters, the probabilistic approach is used. For that purpose, a sensitivity analysis of the established model is performed, where a total of 200 simulations are used (see Ref. [1] for the underlying theory). Some selected input parameters, like the Young's modulus and the fibre angle are varied within bounds defined by production tolerances. An example for a resulting histogram is shown in Figure 6, where the measured value is within the bounds of the scatter of the predicted strain if considering the above described uncertainties. Hence, the stochastic analysis can be used as a method for better understanding and judgement of some differences between the measurements and the respective predictions.

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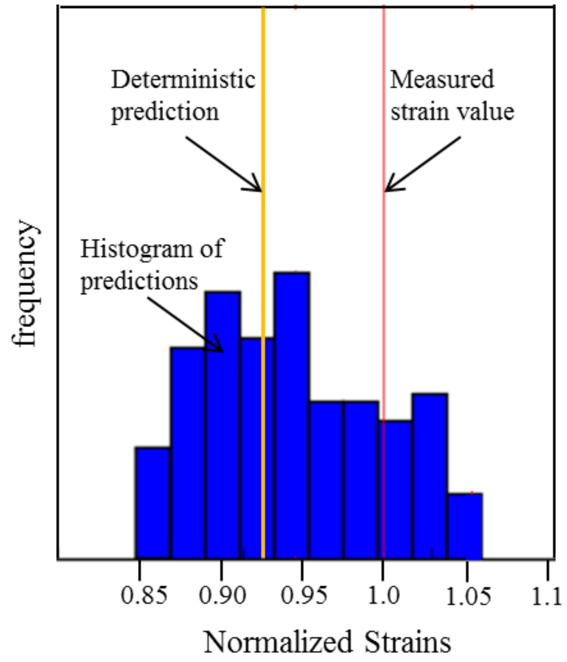

Figure 6. Example for the scatter of the strain value at the location of one selected strain gauge

4. Conclusions

In this paper, all steps needed for the performance of the full scale static test of a lightweight structure are described. The strategies developed for the calibration, monitoring and evaluation of the tests have been discussed which has led to the successful completion of the test campaign. A dedicated plug-in to an in-house visualization software has shown to be a suitable tool for obtaining a quick overview on the quality of the computational model with respect to the ratios of predicted and measured values.

Future development tasks are especially targeted towards the usage of the measurement data for improving the underlying numerical model in terms of parameter calibration. This poses challenges especially with respect to the computational efforts due to the large of complex FE model. In addition, also the scatter of the test data shall be considered in this model updating process.

Acknowledgments

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