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CALIBRATION OF A DIGITAL TWIN FOR STRUCTURAL TESTING

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ABSTRACT

An efficient physical test of a composite structure shall provide a maximum of information while the efforts for preparation, testing, and evaluation shall be minimized. To deliver deeper insight into the structural behavior, a test-accompanying simulation through a virtual test rig and a model of the specimen is a state-of-the-art procedure. Typically, the specimen in this analysis is a nominal model representing the specimen as-designed. To improve the accuracy, the nominal model can be replaced by a digital twin (DT) of the individual specimen. This DT digitally represents the specimen as a physical entity. The present work presents a particular DT creation method for the purpose of structural testing. A DT shall be created from a nominal model by optimizing the deviations between the measurement data obtained from the physical entity and the respective values in the virtual space. This adoption of the DT concept is new to the field of structural composite testing and permits us to increase the accuracy of a test-accompanying simulation.

The developed concept of the DT for structural testing follows the original idea of a DT as proposed by Grieves [1]. Already in the white paper introducing the DT, he described it as the virtual representation – in our case a finite element model – of a physical product – in our case the test specimen. This representation is updated by a data flow from the real space to the virtual space, as depicted in Figure 1. The particular feature of this method is the usage of the readily available data from the experiment to conduct the calibration. This differs from the typical approaches to creating a DT of a composite structure. A "typical" DT of a composite structure is created at the same time as the physical entity is manufactured and optionally updated throughout the life of the structure, as Jones et al. [2] outline. The updating process can even utilize real-time data, like it's included in the definition of Singh et al. [3]. Still, the information flow from the real space to the virtual space is achieved through particular measurements of a certain state, for instance, the actual geometry. Eventually, there are always remaining factors of uncertainty causing unknown deviations. A test setup and the test procedure add further uncertainties that can hardly be quantified previously.

The proposed DT shall minimize these deviations through a calibration based on the measured data during the test. We achieve this through three steps:

1. Determination of the crucial uncertainties
2. Rough quantification of the uncertainties and their influence on the results
3. Implementation of the uncertainties as regression parameters within an optimization procedure

The vital step of this procedure is already the selection of the significant uncertainties. The once-chosen parameter space limits the achievable improvement and might easily lead to a mathematically optimized model without any improvement of the physical phenomenology. Any numeral parameter in the finite element model of the specimen can possibly be a regression parameter. The actual optimization of these uncertain parameters is achieved through a least squares approach (LSQ). The LSQ algorithm minimizes the residuals resulting from the difference between the virtual and the real space. Due to the unknown correlations between the parameters and the result values, we employ a nonlinear LSQ method building on the linear Taylor surface f^0 approximating the real function F^0:

$$f^{0}(x,\beta) = F(x,\beta^{0}) + \left.\frac{\partial F}{\partial \beta}\right|_{\beta^{0}} (\beta - \beta^{0}) \tag{1}$$

An iterative solution can be found through the Jacobian matrix J^0 containing the gradients of the Taylor surface (the gradients of each residuum with regard to each regression parameter). Each iterative step reduces the uncertainty in the regression parameters.

$$\Delta\hat{\beta} = \left(J^{0^T} J^{0}\right)^{-1} J^{0^T}\left(y - F(x,\beta^{0})\right) \tag{2}$$

To improve the accuracy and the performance of the calibration, the basic nonlinear LSQ method is modified to a weighted, sequential, and damped LSQ method. The developed method is applied to create a DT for a stiffened CFRP panel which was subjected to a quasi-static compression test (cf. Figure 1). It is employed to improve the model accuracy in the elastic load range and to identify local stiffness degradations that possibly indicate local damage. Also, a damage identification supporting a structural health monitoring system is being tested. Beyond that, the presented DT extends the existing DT methods, and the combination with, for example, a geometrical DT is expected to further increase the performance.

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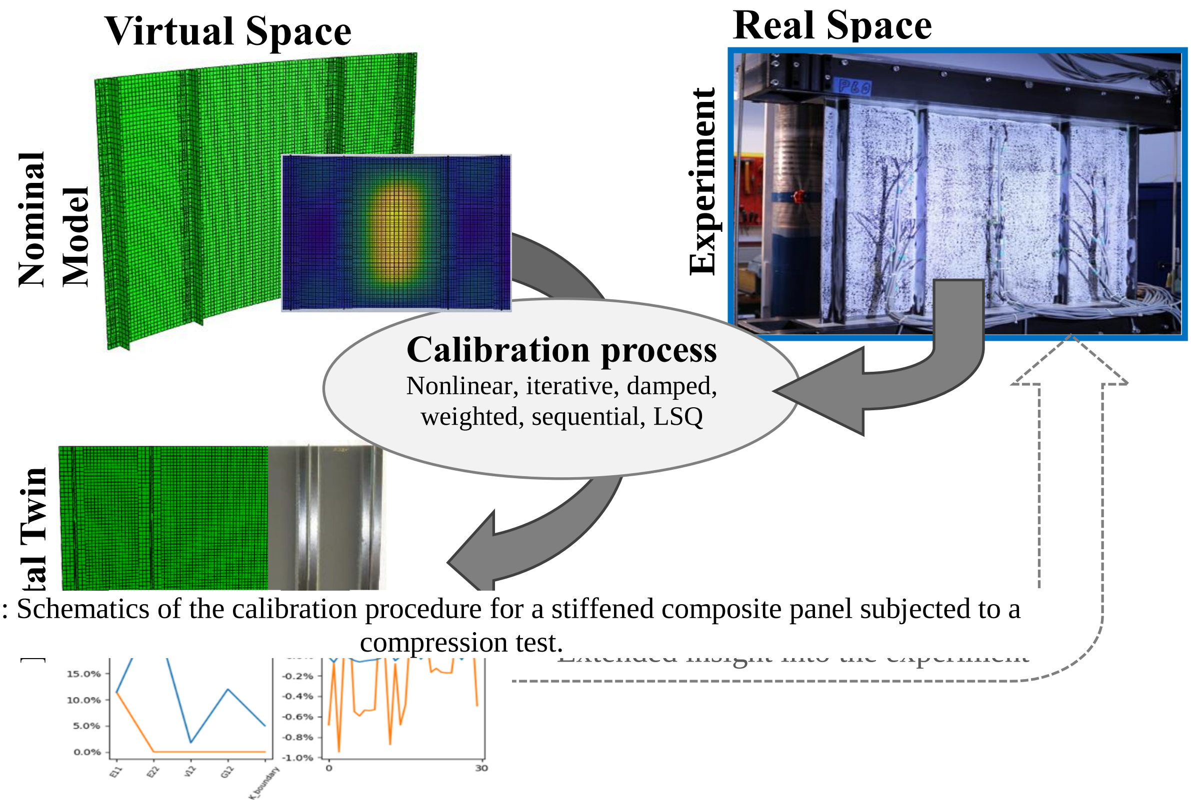

Figure 1: Schematics of the calibration procedure for a stiffened composite panel subjected to a compression test.

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