Transferability of Boundary Conditions in Testing and Validation of Lightweight Structures

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Abstract

In the product development process testing and validation is necessary to certify the function of the product, but it is time and cost extensive. A high ratio between output and input effort has to be aimed. To reach this effect a hierarchy of test levels is sensible. This paper shows an approach to describe and map the transferability of boundary conditions between these scale levels and model layers. The chosen scale levels are material, structure and product level and the model layers are reality, physical and virtual models. The challenges of the transferability of boundary conditions will be shown for three research topics, static testing for cylinders, optimization of sandwich inserts and dynamic testing of cabin interior.

Keywords: Transferability, Boundary Conditions, Testing, Lightweight Structures

1 Introduction

Lightweight aspects are important design criteria in the aviation and aerospace sectors, since reducing the mass increases the exhilaration and makes a system more fuel-efficient. To certify a design testing and validation is necessary, but there is always a discrepancy between reality, test and simulation. In testing and validation, the environment of the test object has to be replaced as accurate as possible to receive utilizable results. Mechanical boundary conditions have a significant influence on the mechanical behavior of the test object. In static tests the results can differ whether the clam is articulated or fixed for each degree of freedom. In dynamic testing furthermore the inertia, stiffness and damping of the system has to be considered.

Lightweight structures are mostly optimized to few exact loading conditions and that way they are sensitive to not planned loading conditions. Since boundary conditions influence the internal loading state of the test object they have to be modeled for lightweight structures with even more precision.

This paper shows the challenge of transferability of virtual and physical test results to the reality, as well as the transferability from the material level, to the structure and the product level. The transferability of boundary conditions is shown for three research topics, static testing for cylinders, optimization of sandwich inserts and dynamic testing of cabin interior.

2 Approach

A hierarchy of test levels is common in the context of testing, since there is a high discrepancy between testing of materials and products. Testing of the real product can certify the usability of a product, but can be much more extensive for testing each change. Testing on lower levels is less extensive but cannot self-acting be transferred to the whole product.

In materials science a multiscale analysis is used to group different levels of scale, from atomic, over nano-, micro-, meso- and macroscale to the structural level. In the field of aerospace, the focus is on higher scales. A well-established description for testing of structural elements is given by the Building Block Approach [1]. It is used to certify a design step by step either by test or analysis. By moving upwards, the testing complexity and the effort per test increase while the number of tests decreases. The final proof has to be by testing the full-scale structure of the product [1].

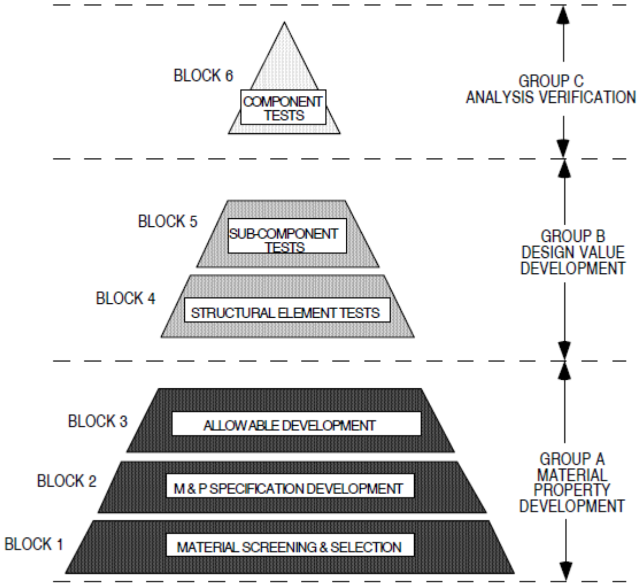

Figure 1: Building block approach [1].

Cox et al. [2] are focusing on virtual testing and the possibilities to reduce testing effort this way. They say that a virtual test must be a system of hierarchical models, engineering tests, and specialized laboratory experiments [2]. To reduce the effort for a large fraction of real tests a link between physical and virtual models has to be created. For validation and certification there has to be as well the link to the reality, since test results of a virtual or physical model are not self-acting transferable to a real application.

Based on the usability of the building block approach [1] and the test pyramid shown by Seemann [3] and Krause et al. [4], this approach adds layers to show the transferability between reality, physical and virtual models. The resulting three-dimensional testing pyramid is shown in Figure 2. Shown are different levels of structural scales and the material, structure and product level. The separation in static and dynamic testing is not necessary, but recommended, since the transferability of boundary conditions from static to dynamic testing is problematic. The dynamic behavior is affected by mechanical interactions, like eigenfrequencies leading to varying and non-stationary mechanical properties. On top the inertia, stiffness and damping of the system has to be considered in dynamic testing.

The shown approach in Figure 2 shows the links between different layers and levels and tries to aware of difficulties for the transferability between them.

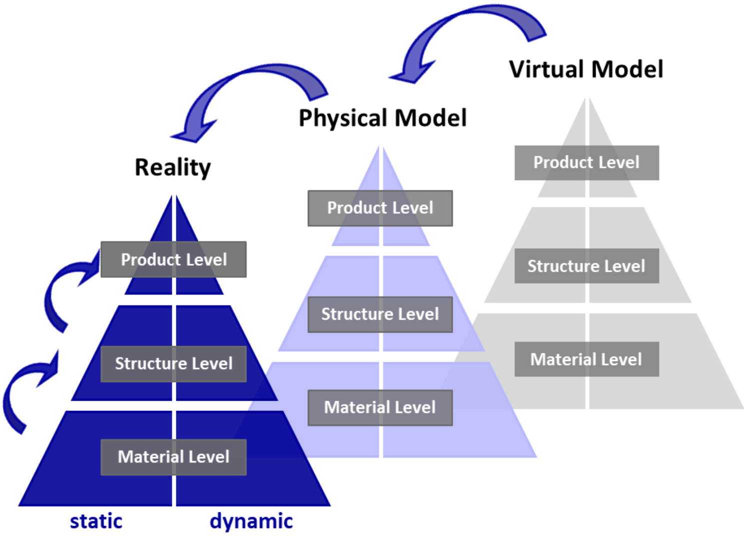

Figure 2: Static and dynamic testing pyramid showing the reality, experiment and simulation layers over product, structure and material levels.

The transferability of test results has to be shown for each step, by layer to layer and level to level. It is recommended to do one step at a time and to validate for each step the transferability. The links between the levels of scale, like material, structure and product level depend on the defined interface for each case. Overall a smooth classification is shown here. For this case the material level includes the atomic-structure until the basic lamina and laminate for composite materials. At structure level a distinction between structural elements, sub-structures and components can be made, for a sandwich structure this could be a panel or insert element. The product level is the scale of the product and can be a galley out of sandwich panels or even the whole airplane. Transferability of test results can be distinguished into bottom-up and top-down testing, the arrows in Figure 2 show the transferability bottom-up, top-down is possible as well.

Products and applications have to show their usability in reality, in the product development process disturbance values have to be considered. The reality has to be modeled as accurately as possible to receive utilizable results. Mechanical boundary conditions for the layers can differ, virtual models generally use ideal exact degrees of freedom and restrictions, while boundary conditions in physical models have to deal with the mechanical properties of the test setup. Virtual test methods reduce the test effort by a synergistic combination of testing and analysis methods. By integrating the insights from lower levels into the next higher one, a higher informational value of the developed overall model is achieved as shown by Seemann for sandwich joints [3].

3 Challenges of transferability of boundary conditions for lightweight structures

In this chapter the challenges of the transferability of boundary conditions will be shown for three research topics, static testing for cylinders, optimization of sandwich inserts and dynamic testing of cabin interior.

3.1 Static testing of thin-walled CFRP Cylindrical shells under axial loads

In aerospace engineering thin-walled cylindrical shells are a commonly used structure. One recent example is given in Figure 3 with the interstage of the falcon 9 from SpaceX. The critical load case is axial compression and due to the high radius-thickness-ratio these structures prone to buckle.

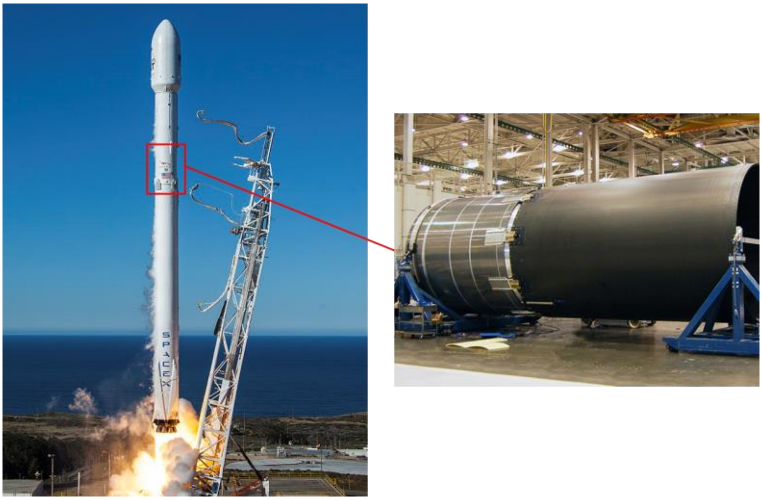

Figure 3: Falcon 9 (left) and interstage of the Falcon 9 (right) [5]

In the design process a high discrepancy between the analytical and experimental buckling load has to be handled. Imperfections like geometric and load imperfections introduce varying boundary conditions. In order to achieve a reliable design (reality) and a valid transfer from the virtual analytical model to the real product an experimental knockdown factor was determined based on various experiments (physical model) on metallic cylinders under different boundary conditions [6]. However, for cylindrical shells made of CFRP this proposed transferability is not given and the knockdown factors lead to conservative designs [7], that is why new guidelines should be developed.

Furthermore, the boundary conditions during the experiments have a significant influence on the buckling load and differ from the real ones. Most test rigs use a displacement controlled test procedure whereas the real application is more like a force controlled procedure [8]. Therefore, the transferability of boundary conditions is not given.

For testing cylinders, a connection between the cylinder and the test rig has to be realized. Obviously, this connection also influences the test results. After clamping one cylinder, the radial wave modes of the geometric imperfections are reduced [9]. Nevertheless, this reduction has only a small influence compared to the other imperfections [10]. Another more important parameter while testing cylindrical shells are the degrees of freedom (DoF) between the clamped cylinder and the test rig. For instances, Schillo proposed two different connection and chooses a ball-and-socket-connections which allows tilting of the cylinder [11]. With fixed connection the introduced lateral forces are smaller and the reached buckling loads are higher [10]. Compared to real applications both connections differ because the stiffnesses of the adjacent structures are missing.

Introduced lateral forces have a big impact on the buckling load. These lateral forces are mostly induced by boundary conditions of the test rig, which always vary between different tests and the transfer to the real application is difficult. The hexapod test rig at the TUHH enables a hybrid control so that in radial direction the force can be controlled almost to zero whereas in axial direction a displacement-controlled procedure can be used. Applying the hybrid control reduces the lateral forces significantly. However, one drawback is that the test rig runs out of the middle of the specimen so that a transferability to other tests and simulations is not given [12].

Most relevant parameters of a cylindrical shell are only known after manufacturing and testing these shells. Therefore, the transferability between the virtual and physical model is determent. One possible solution to handle the transferability between the virtual and physical model is the RBCB-Method proposed by Schillo [13]. This method considered the uncertainties of the virtual model and uncertainties of the physical model. Furthermore, it used the Bayesian updating for information after testing new specimens which improves the transferability from the virtual to the physical model. Furthermore, the transferability from the material level to the structural level is a topic itself, because most material parameters are determined with two-dimensional specimens in contrast to the three-dimensional structure.

3.2 Testing and optimization of load introduction points in sandwich structures

For modern aircraft cabin monuments lightweight sandwich structures are used, which have a variety of different load application points. These are needed to connect the individual sandwich panels, to connect the monument to the primary structure via attachments as well as to secure components such as trolley and standard units, for example via retainers and bumper strips. Inserts are inserted into the sandwich structure to realize these interfaces [14]. To check the structural mechanics of the individual inserts a static verification test must be carried out. From a large number of different variants ensues a high number of necessary tests, for example due to different connection concepts and different core or face sheet thickness. This results in a high effort in the development and design phase. To minimize the testing effort and to be able to compare the test results directly with each other, these tests represent an abstraction of reality. Thus, relatively small specimens are used, since mainly the inserts are tested and only a small section of the surrounding sandwich structure is represented. Furthermore, to compare the insert concepts, the installation situation is abstracted. For example, in the pull-out test where the insert is pulled out perpendicular to the sandwich panel, the specimen is limited using a bracket with a circular opening [15] .

A method for virtual testing of sandwich joints on the component level was developed by Seemann [16, 17]. Their introduction in product development would mean a reduction of the testing effort. However, for evidence on the product level, a real full-size test still has to be carried out. To extend the virtual testing and allow a transfer to the product level, the influence of the considered system boundary has to be investigated. Also, a suitable level of detail has to be selected to ensure that while considerably increasing the model size a critical failure of the individual inserts is still considered on the product level. The associated increased modeling effort could be reduced by a semi-automated generation of models from CAD data. Validated test models on component level already allow a first simplified optimization of the insert, since e.g. different concepts, number of layers and bonding can be varied locally and examined numerically.

However, the transferability to reality reaches its limit when innovative concepts are investigated. For example, additive manufactured cores or large-scale inserts with local load path reinforcement [18] or load path-optimized face sheets with local reinforcements can only be inadequately designed by these simple tests. The problem is that the used tests abstract the boundary conditions too far [19]. As long as the individual force introduction point is only considered locally in a simple sandwich structure, these simplifications make sense. However, as soon as a larger area of the panel can be adapted, the specific connections of the panel play a decisive role in load path reinforcement. An optimization based on a simple test could no longer be transferred to reality because the boundary conditions differ too much [20].

There is currently no test for individual sandwich panels where a realistic installation situation is used. Therefore, a conflict arises between the simple standardized test for inserts and the optimization of the load introduction points, which takes the exact installation situation of the individual panel into account. One solution could be validated virtual optimization models, which allows the virtual verification of individual load application points with reduced test effort. A continuous, digitalized product development process, similar to that developed for modular lightweight design [21] , should be used to establish a parameterized product development process whose defined steps can be easily and quickly repeated with slightly modified parameters.

3.3 Dynamic testing of cabin interior with adjustable mechanical properties at the boundary conditions

Aircraft interiors are exposed to dynamic loads, these loads bring high energies into the structure, the resulting vibrations are a crucial design criterion [22]. At the present time, testing of aircraft interior components is mostly done with rigid connection elements [23]. This way a certification of a virtual model by a physical model is possible, but the transferability to the reality is problematic. In reality the connection elements have mechanical properties that can even be varying and non-stationary. This non given transferability of boundary conditions leads to deviations between physical tests and the real system, since the rigid design of the connection elements differs to the ones of the system's operation environment [24].

Boundary conditions with adjustable mechanical properties could face this problem, by being able to reproduce the properties of the real system's operation environment. Related to this Adjustable Impedance Elements are introduced, they are shown in Figure 4 at the right side. These are machine elements, which consist of an Adjustable Stiffness Mechanism and an Adjustable

Damping Mechanism [24–26]. These elements act as connections between the test object and the test rig and represent the mechanical properties of the real connection elements. This way the lack of transferability in testing of aircraft interior components can be tackled. Figure 4 shows the set-up for testing of aircraft interior components on the hexapod test rig at the TUHH. The Adjustable Impedance Elements are located between the test specimen and the load cell of the test rig. This way the boundary of the test system can be extended, by including the connection elements themselves.

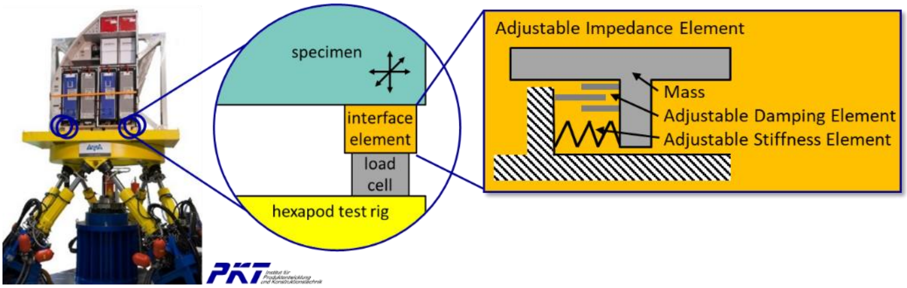

Figure 4: Adjustable Impedance Elements on hexapod test rig.

In the DFG and SNF funded project AIProVE Adjustable Impedance Elements are developed, these can lead to more realistic interface behavior in testing of aircraft interior without using individual connection elements for each test case. Therefore, optimization of interface elements gets feasible, since the extensive effort in testing is largely decreased [27]. By direct adjustment of stiffness and damping parameters it is possible to validate simulation models with mechanical properties like stiffness and damping at their boundaries.

In a first step Adjustable Impedance Elements should be developed with adjustable properties that are constant over time, position, velocity and acceleration. This way they can be used for the transfer of boundary conditions from the physical layer to the reality layer, under predetermined conditions that the real connection has one stationary impedance. In future an active control of the adjustment could even be used to represent boundary conditions for a non-stationary impedance. The combination of more than one Adjustable Impedance Element could even represent boundary conditions consisting of more than one mechanical interaction.

3.4 Conclusion

For the three research topics the transferability of their boundary conditions is mapped in levels and layers of the three-dimensional testing pyramid. The classification helps to cluster their challenges. Figure 2 of the pyramid sets the focus on the links between the levels and layers, this way it helps to solve the transferability step by step and makes sure that none are skipped.

Especially lightweight structures are sensitive to not planned loading conditions and their boundary conditions have to be modeled precise. This paper tries to aware of the difficulties to set the boundary conditions right and takes in account that test results in most cases are depending significantly on their boundary conditions. The boundary conditions have to be chosen realistic to reach usable test results.

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