Combined environments - challenges and potentials in the realistic component testing

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Abstract

Structural components can be exposed to extreme environmental conditions during operation over their service life. For this reason, they have to pass corresponding tests during development and certification in which they are tested for these loads. However, those tests are carried out separately, while in practice the loads occur in combination. This paper discusses the challenges arising from this, using the example of sandwich structures under combined mechanical and thermal loads and cylinder shells under combined mechanical loads. For this purpose, existing investigations, procedures and approaches are analysed, the necessity for combined testing is shown and a possible approach for a structured and reproducible procedure for testing components under combined loads is described.

Keywords

Combined Loads, Combined Environments, Environmental Engineering, Structural Testing, Lightweight Structures

1. Introduction

Products and their components are exposed to a range of different loads over their life cycle and are influenced by their environmental conditions due to the place of use. Particularly with regard to service life and reliability, the type of prevailing influences and the intensity and duration of these are decisive factors in component design and testing [1]. The environmental influences can affect components either directly or indirectly, with mechanical loads and hygrothermal influences being the best-known groups.

Both, during development and in the certification of safety-relevant components, especially in the aerospace industry, corresponding test evidence has to be provided so that fault-free function in operation can be ensured [2]. Despite the existing knowledge about the presence of interactions between different load types, the tests are performed in practice both experimentally and numerically mostly separately for each type of loading [3, 4]. However, it has already been proven in a large number of investigations that these superpositions of loads can have a significant influence on the system behaviour, which cannot be derived from the isolated considerations [5–7].

2. State of the art

Combined environmental conditions are understood to be the simultaneous impact of several influences, usually predetermined by the environment [8]. The best-known environmental influences generally cover:

- Mechanical static loads: e.g., axial load, bending, torsion
- Mechanical dynamic loads: e.g., vibration, shock
- Thermal stress: temperatures, temperature changes
- Humidity
- UV-radiation

The separation of these influences offers some advantages with respect to testing. Test rigs have a comparatively low complexity and offer a good approximation of the respective load for the specific application. By specifically avoiding or minimising other loads, the cause can be clearly identified in the event of a failure of the test specimen. For some test conditions, such as those listed in DO-160, a key standard for aviation in the field of environmental simulation, there are no interactions between load types present. In these cases, tests with isolated loads are quite reasonable and sometimes even necessary. A combined test for tightness against moisture and dust, for example, would not fulfil the desired purpose in combination. However, it is known that environmental conditions also exist that can have a strong interaction. Some examples are:

- Combined mechanical loads
- Mechanical-thermal loads
- Hygrothermal loads
- Mechanical-pressurised loads
- Thermal-pressurised loads

The influence of superimposed test conditions is occasionally taken up by industry and offered by testing laboratories. Particularly in automotive engineering and the development of electrical and electronic systems, the influence of combined loads is taken into account and specified in the ISO 16750 standard [9] as an example. For general applications, IEC 60068 and DIN EN 60068, which has been adapted to German-speaking countries, were supplemented in 2011 by the chapter on combined climatic and dynamic tests [10]. These are intended to provide a guideline for carrying out tests with combined mechanical and climatic conditions.

On the subject of combined testing, the standards refer to the parameters of the respective separated conditions, like the DO-160 [2] and MIL-STD-810 [11] standards known in aviation, and thus assume a linear relationship of the conditions [2, 10]. However, the intended test conditions only correspond to the real installation situation to a limited extent, since in most cases different loads occur in combination. In order to take into account this unknown influence, the combination by conservative interpolation between isolated load cases with the aid of safety factors is partially taken into account in design guidelines [12, 13].

There are also critical voices on combined environmnetal testing. In addition to the most common argument, that test rigs and test procedures become too complex, it is also argued that combined testing can lead to overstressing, which does not occur in reality and must therefore be avoided [8, 14]. Almost no quantitative studies can be found on the frequently mentioned time and cost savings, Seager et al. [14] only state that a time saving potential of less than 20% can be assumed.

In case of structural components like cylindrical shell elements, the varying combinations of different mechanical loads that may occur over the service life of such load-carrying structures are also of major concern during the design phase. Current design guidelines like the NASA SP-8007 [12] or the Eurocode 3: EN1993-1-6 [13] make explicitly conservative assumptions regarding the load-carrying capacity under combined loads, which are justified by the lack of experimental data [12, 15]. Indeed, testing procedures and the test rigs necessary to conduct reliably reproducable tests with combined mechanical loads, in the following also referred to as multiaxial loads, are much more complex than for conventional, isolated tests [16]. Although several numerical and a few experimental studies exist, that show nonlinear load interaction curves between critical load cases [5, 16, 17], no comprehensive approach to account for this has been developed.

Under the aspects of possible cost efficiency and realism, a more detailed investigation into combined testing with structural components should be sought. In particular, this opens up the possibility of achieving a further reduction in safety factors, thus leading to better exploitation of lightweight construction potential. Up to now, however, the need for special test rigs and the system behaviour influenced by interactions have presented complex challenges in the design, implementation and evaluation of such tests. This raises the question of how to conduct tests with combined loading in order to systematically and reproducibly verify load-specific interactions and to take them into account from the conceptual design to the evaluation.

3. Approach to testing with combined load conditions

It becomes apparent, that the so far predominantly theoretical approaches and investigations of this research area contradict industrial practice. Furthermore, the use of global safety factors due to a lack of research into the actual load interactions represents a decisive weakness in the design of lightweight structures. Consequently, support is needed for the accurate and load-appropriate design of structural components, taking into account occurring load conditions. A possible approach is outlined in Figure 1, which includes the identification of the occurring interactions and their influences on the system behaviour under combined loads.

For this purpose, sub-component tests on a low complexity level with isolated loads as well as with predefined combinations of the investigated loads must first be carried out. From the analysis of occurring interactions, conclusions can be drawn about the quality of previous interpolation methods and their applicability can be critically reviewed. In addition, it is possible to draw consequences for the choice of safety factors and the reduction potential of these. In the case of non-linear interactions, additional combined tests are to be carried out at component level to analyse the system behaviour, whereby the realistic load conditions eliminate the need to consider uncertainties regarding load interactions. Depending on the practical application and the respective safety and reliability requirements, this allows the use of minimised knock-down and safety factors.

Consequently, in addition to a load-optimised design that is suitable for lightweight construction by avoiding unnecessarily conservative assumptions, this also potentially results in a reduction of the testing effort, since combined tests only have to be carried out in relevant cases at higher levels of the product-component-test pyramid.

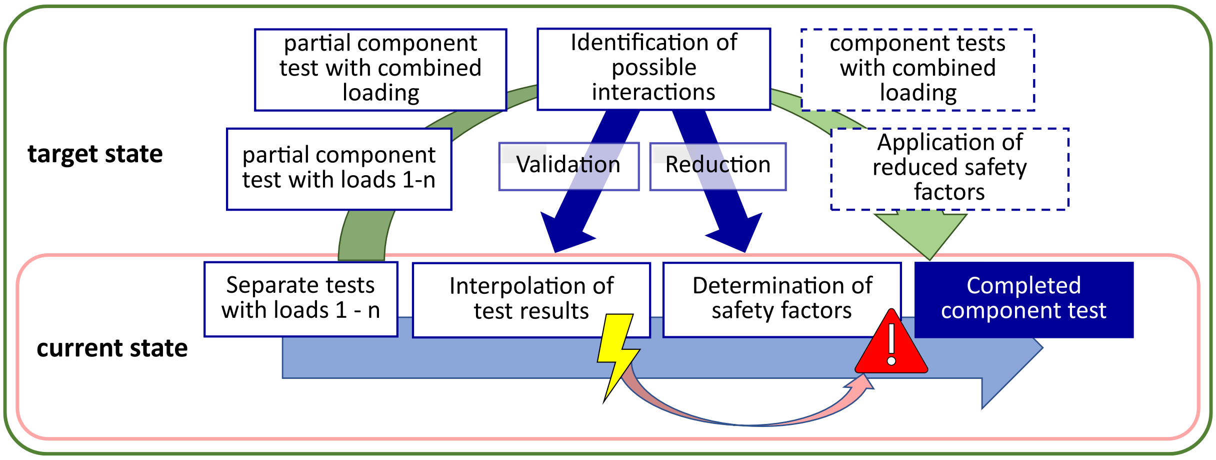

Figure 1: Approach to combined testing for lightweight design structures

4. Application examples of the approach

The two cases presented below as examples show that existing approaches for taking combined loads and their interactions into account are mainly based on theoretical and numerical investigations. However, validation through physical tests is only available in a few individual cases. The examination of the existing test data shows that a clearly non-linear interaction occurs with certain load combinations.

4.1. Environmental testing of lightweight structures

In the following section, the previously presented approach is applied to the testing of structural components using the example of sandwich structures. It will be shown that a combination of environmental conditions is also useful in the area of structural components.

4.1.1. Initial situation and objectives

Scientific literature in the field of aviation components on this topic is rare. However, numerous studies on the material level or less complex structural level of sandwich structures used in aviation show that a changed system behaviour can be observed through the superimposition of environmental influences [18]. The best-known influencing conditions for aerospace structural components are temperature, humidity and pressure, with the combination of mechanical and thermal loads being the most frequently investigated. Although there is a significantly larger number of studies with static loads, i.e., the superposition of static forces with environmental conditions, the following will only deal with the superposition of dynamic loads in combination with environmental conditions. In these publications, mostly free vibrations are dealt with. Forced vibrations, as required by standards, are hardly ever used.

The most significant effect associated with a changing ambient temperature is the shift in the natural frequencies of a sandwich structure in the frequency domain [6, 7, 19, 20]. In all investigations, it was found that a lowering of the natural frequency can be observed with increasing temperature. This is exemplified in Figure 2, where Kisa et al. [7] investigated a GFRP composite panel at different temperatures.

When investigating the structural behaviour of composite structures in cold regions, the opposite behaviour can be observed [21], Thus, it can be stated that the system behaviour of structural components is temperature-dependent, but does not behave linearly to the ambient temperature and additionally exhibits a frequency dependence [19].

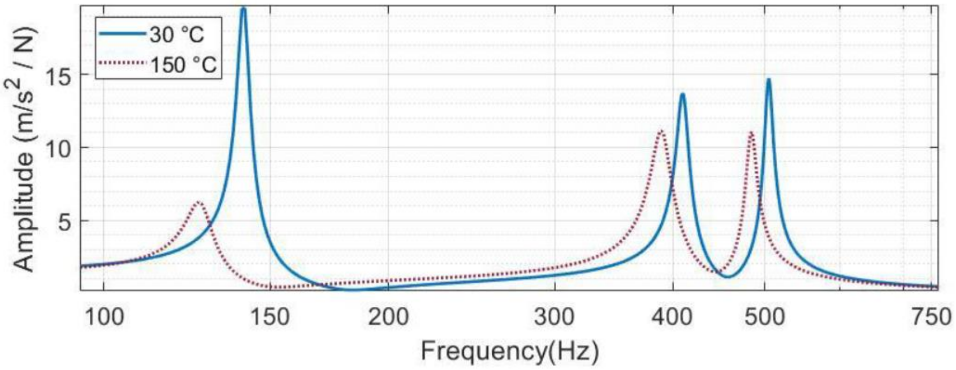

Figure 2: Investigation of a GFRP composite panel at different temperatures [7]

This becomes more evident the greater the temperature fluctuations are and the more frequent temperature changes occur. If a vibration is combined with temperature changes, it is to be expected that fatigue will progress more quickly due to this additional load. Another aspect to consider when investigating structural elements is the occurrence of mode-jumping effects, as mentioned in numerous publications, e.g, [22, 23]. In this case, eigenmodes distributed over the frequency spectrum are influenced to varying degrees by the ambient temperature. As a result, a natural frequency can shift significantly faster to a lower spectrum than another natural frequency that was previously below the first one, and both swap their positions. With regard to the safety requirements of structural components in the field of aviation, knowledge of such effects is imperative.

As a further environmental influence, humidity also affects the structural behaviour of sandwich components. Due to the close thermodynamic connection, however, these investigations are often carried out in combination with thermal influences, whereby the system behaviour does not change linearly with temperature and humidity change [19]. With increasing moisture content of the sandwich structure, all publications consulted observe a decrease in the natural frequencies. The changes associated with an increasing moisture content of the sandwich structure are justified with a reduction of the structural stiffness [24]. However, test specimens have to be specially prepared, and hardly any differences are observed with changes in the relative humidity of the ambient air.

Investigations of sandwich structures under variable ambient pressure are not very present in the literature selection. In addition, sandwich components for special applications that are exposed to a specific pressure difference have mostly been investigated. These include, for example, pipes with different internal and external pressures or the aerofoil of an aircraft, which are subjected to different pressures on the upper and lower sides, as well as changes in air density and associated force effects. Mohammadi et al. [25] show that in the case of cylinders, external pressure leads to greater flexibility of the sandwich structure and the natural frequencies decrease as a result. In contrast, internal pressure increases the stiffness of the structure, shifting the natural frequencies to higher frequency ranges.

Based on the research results presented, there is a need to also test products and structures with higher complexity under combined loading in order to be able to derive information on how the system behaviour of these components changes under combined environmental conditions.

4.1.2. Application of the approach

The approach to testing with combined environmental conditions forms a basis for the realistic testing of structural components. It can be supported by the approach presented by Schwan et al. [26] for transferring boundary conditions with the help of the product-component-test pyramid. The aim of this approach, shown in Figure 3, is to manage the number of boundary conditions, which also increases with lateral component complexity [26]. These are usually specified from the real installation situation of the component and define the structure of the test rig, as illustrated by point 1 in the figure. In addition, detailed physical and virtual research results at the material level, which were summarised in section 4.1.1, can be included in the investigation (point 2).

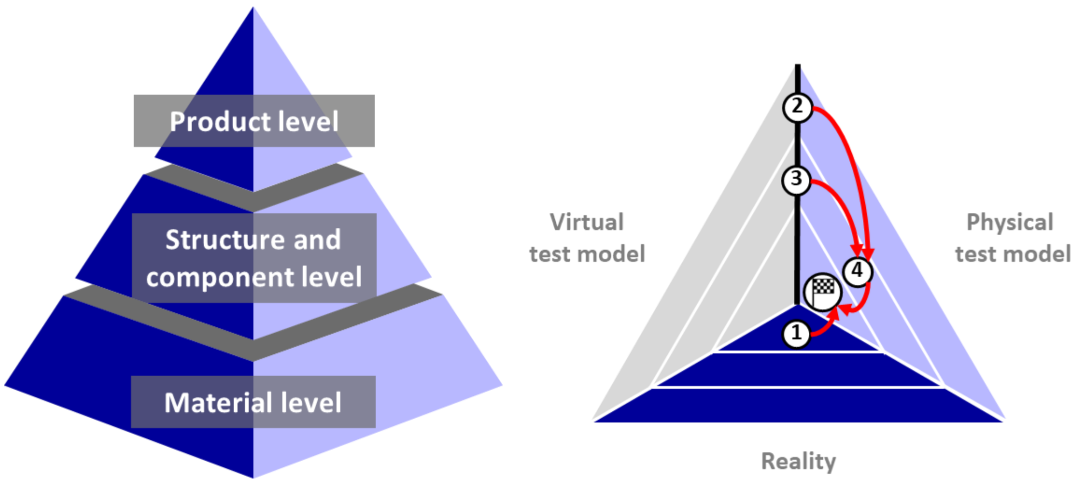

Figure 3: Adapted depiction of the Product-Component-Test pyramid by Schwan et al. [26]

As outlined in section 3, for a systematic and reproducible investigation simplified structural tests must first be carried out with isolated loads. This can be done both physically and virtually according to point 3 in the figure. Through these tests, knowledge about the basic structural behaviour of the component under investigation can be expanded. With the information obtained, the same simplified structure can then be tested under several environmental influences simultaneously, in order to analyse the system behaviour. This is initially done on a physical level (point 4), since in the area of co-simulations and multi-physical simulations of sandwich structures there is initially a need for further basic research in order to produce reliable results. From the analysis of the combined test, it can be checked whether a linear interpolation between the individual tests and a correction of the safety factors is possible. In the case of non-linear interactions, which can be inferred from the presented investigations of sandwich structures at material and structural level, tests at product level should be carried out subsequently after the initial separate tests. Only in this way can a detailed analysis of the real system behaviour in the installed state be done, although a comparison with the results at the structural level should be made for further system analysis.

4.2. Cylindrical shells under multiaxial loading

In the following section, it is illustrated that the challenges of combined testing are not only of relevance for certification, but also during the design phase of lightweight structural components on the example of buckling sensitive cylindrical CFRP shells. Thin-walled shells are commonly used as structural elements, e. g., in aerospace applications. In practice, the shells are often subjected to combined mechanical loads in these cases.

4.2.1. Initial situation and objectives

Thin-walled cylindrical shells exhibit sudden structural failure by buckling in critical load cases such as axial compression, bending, torsion or external pressure [12]. For structural elements, these load cases tend to occur in various combinations in practice, depending on the specific application and the environmental conditions. The current general guideline for designing such structures is the 1968 published NASA SP-8007 [12] which recommends a linear interpolation of the load carrying capacity for any combination of different buckling-critical loads. More recent guidelines are the Eurocode 3: EN 1993 and the derived national standard DIN EN 1993-1-6, the two of which show some slight differences in certain steps of their recommended procedures [13, 27]. Although a nonlinear interaction between different loads is considered here, the design guideline introduces purposefully conservative assumptions based on the insufficient amount of empirical data [15]. Numerous approaches exist to achieve precise predictions of buckling loads under pure uniaxial compression load, whereas buckling due to combined loading has not been thoroughly investigated. Studies concerning multiaxial loading are carried out mostly numerically or purely theoretically, without experimental validation of the results. While it is known that nonlinear interactions do exist between the different separate load cases, the exact shape of the interaction curves is dependant on numerous factors, e.g., the shell dimensions and material parameters [15].

4.2.2. Application of the approach

Motivated by the lower complexity of necessary test rigs and test set ups, buckling experiments with cylindrical shells are usually carried out under isolated, uniaxial loads. However, there are some experimental studies in which the buckling behaviour under combined loading, e.g., axial compression and torsion, is investigated [5, 17]. One study by Bisagni and Cordisco [17] also considers the influence of sequential and simultaneous application of the different mechanical loads. With regards to the product-component-test pyramid in Figure 3, virtual and physical tests with unstiffened cylindrical shell elements correspond to the points 3 and 4, as these shells can be considered sub-components or simplified components. Both, Meyer-Piening et al. and Bisagni first tested the shells under pure axial compression and pure torsion, before subsequently doing a number of tests with predefined combinations of those loads. This procedure corresponds to the first steps of the proposed approach, as visualised in Figure 1. In both studies, the experimental results showed a significantly nonlinear behaviour over the different load combinations. The results of the tests with eight different shells investigated by Meyer-Piening et al. are given exemplary in Figure 4.

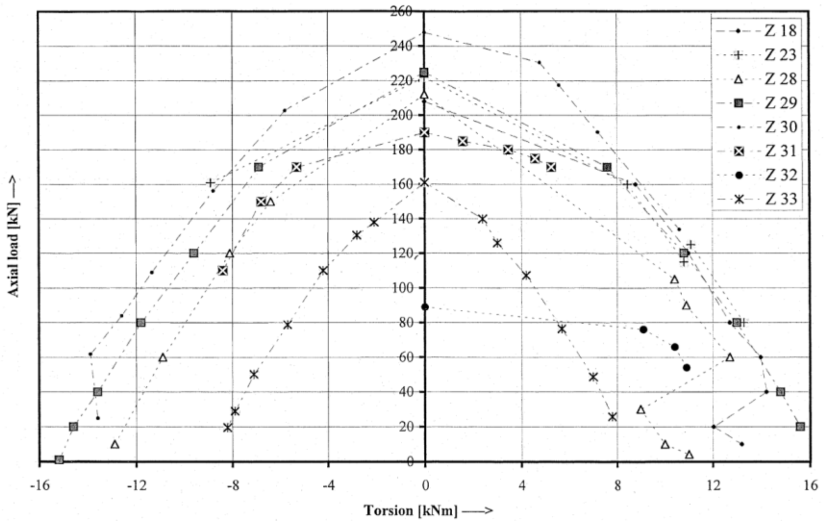

Figure 4: Buckling loads from tests with combined axial compression and torsion by Meyer-Piening et al. [5]

It is apparent, that the found interaction curves are well above the linear interpolation provided by the NASA SP-8007. Furthermore, numerical simulations of these shells under the same load cases yield almost identical load-interaction curves [5]. A similar behaviour can also be observed for the combination of axial compression and bending, which further highlights the overly conservative assumptions made by the current design guideline. Following the proposed approach from Figure 1, the next step is to find a way to better characterise the observed load interactions, be it by means of the development of a new design approach or by defining improved knockdown factors for the shell specifications investigated. Finally, with the transfer from sub-component and component level up to the product level, an additional test is to be carried out with the realistic load ratios, as it has been shown that accounting for each load case separately delivers inaccurate results for this example.

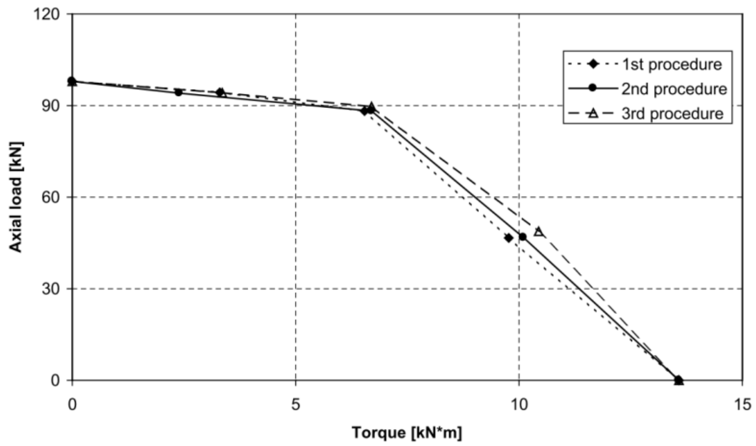

Figure 5: Comparison between buckling loads achieved with three different loading procedures [17]

As a contrary example to the interaction between different mechanical loads with respect to to load ratios, the tests carried out by Bisagni found no significant influence of the loading sequence [17]. As shown in Figure 5, only minor differences in buckling load occur whether torsional or axial load is applied first to a preset level (1st and 2nd procedure) or both loads are applied simultaneously (3rd procedure). Consequently, in this exemplary case the established assumptions for the loading procedures in physical and virtual tests are validated by the experiment. Thus, no further experiments need to be carried out at higher complexity levels of the product-component-test pyramid with variation of the loading sequence.

5. Summary and outlook

It can be summarised that up to now no tests with combined environmental conditions have taken place in the field of structural components due to complex test set-ups. There is a lack of appropriate procedures and guidelines that enable test engineers to systematically and reproducibly examine structural components under combined loads. Here, it is first necessary to determine which interactions are decisive for the respective application and thus need to be investigated in more detail.

As a further step in this field of research, a detailed approach must be developed which, through quantitative criteria, makes it possible to synthesise relevant influences depending on the application, to identify interactions and to derive test parameters corresponding to reality for combined tests. Furthermore, comparable tests have to be carried out on different levels of the product-component-test pyramid in order to show ways to carry out tests up to the product level in a time- and cost-efficient way. For this purpose, a procedure must first be developed to transfer the boundary conditions corresponding to reality between the levels of test specimen complexity.

Acknowledgements

The research results on which this publication is based on are part the LuFo VI-1 project CERTEV (New Cost-Effektive & Reliable Test Environments) that is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the project ProMultAx (Experimental investigation and probabilistic analysis of the buckling load of cylindrical shells subjected to multiaxial load cases) that is funded by the German Research Foundation (DFG). The statements and information in this contribution do not necessarily represent the opinion of the BMWK and DFG.

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