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On the Challenges of Upscaling Damage Monitoring Methodologies for Stiffened Composite Aircraft Panels

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ABSTRACT

Health management methodologies for condition-based maintenance are often developed using sensor data collected during experimental tests. Most tests performed in laboratories focus on a coupon level or flat panels, while structural component testing is less commonly seen. As researchers, we often consider our experimental tests to be representative of a structure in a final application and consider the developed methodologies to be transferrable to these real-life structures. Yet, structures in their final applications such as wind turbines or aircraft are often larger, more complex, might contain various assembly details, and are loaded in complex conditions. These factors might influence the performance of developed diagnostic and prognostic methodologies and should therefore not be ignored.

In our work, we consider the aspects of upscaling structural health monitoring (SHM) methodologies for stiffened composite panels with the design of the panels inspired by an aircraft wing structure. For this, we examine two levels of panels, namely a single- and multi-stiffener composite panel, where we consider the single-stiffener panel to be a representative lower-level version of the multi-stiffener panel. Multiple SHM sensors (acoustic emission, Lamb waves, strain sensing) were installed on both composite panels to monitor damage propagation during testing. We identify and analyse challenges and further discuss considerations that must be taken during upscaling of diagnostics and prognostics, and with that, aid in the development of health management methodologies for condition-based maintenance.

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INTRODUCTION

Health management methodologies such as diagnostic and prognostic algorithms for composite materials are often developed by researchers based on data collected during laboratory tests. These tests are often performed on smaller specimens, such as coupons or small-sized panels, while keeping in mind the final application of the study such as the aircraft or wind energy industry. Yet in these industries, the final structures are large and complex – for instance, an aircraft wing or wind turbine blade – and differ from the tested specimens during research. In structural testing, we often follow a building-block approach (BBA) [1] in which we test many smaller specimens under different conditions and fewer when moving upward in the structural testing pyramid. Namely, testing many full-scale structures under in-service conditions is not always feasible due to the corresponding expenses and required infrastructure. Therefore, in the BBA, we assume that the small research coupon is representative of the large-scale structure. Studying such research coupons provides us information about the mechanics of full-scale structures.

The transfer of knowledge and understanding of fracture mechanics in structures can be accomplished due to similarities in features such as material and lay-up. Similarly, in the field of structural health monitoring (SHM) we must also consider how to transfer developed diagnostic and prognostic methodologies to higher-level structures. Currently, a variety of damage diagnostic and prognostic techniques is developed for different levels (i.e., detection, localization, type, severity, and remaining useful life estimation) using data from different SHM techniques (e.g., acoustic emission (AE), guided waves (GW), or strain sensing) for lower-level structures under simplified loading conditions (e.g., only impact, static, or varying environmental conditions) [2-4]. Yet for a successful implementation in-service, its application must be suitable for higher-level and full-scale structures under realistic combined loading conditions. As it is not possible to test a variety of full-scale structures under in-service conditions, it is required to investigate how upscaling of SHM methodologies can be accomplished.

Studies into the development of methodologies using data on lower-level structures and applying them to higher-level structures under combined loading conditions remain open in the field of SHM for composite aircraft structures. To our knowledge, only one study investigated SHM upscaling for a limited number of levels (damage detection and localization) under a simplified loading condition (impact) [5]. In this work, we investigate the challenges that may be faced when performing such studies and identify several aspects to consider. As a subject case, we employ the upscaling of a single- to a multi-stiffener composite aircraft panel, whose details are provided in the next section "Stiffened panels". This is followed by the section "Knowledge transfer in upscaling" in which we discuss which knowledge can be gathered from lower-level structures for application in higher-level structures. Subsequently, section "Challenges in upscaling" considers several aspects that are of importance when upscaling, including the physical aspects of the structure and the sensing system.

STIFFENED PANELS

Two type of stiffener panels are employed in the study on upscaling: 1) a single-stiffener panel and 2) a multi-stiffener panel. The panels' design has been based on an aircraft wing panel design by Embraer to obtain generic and representative stiffened panels for aircraft structures. The two panels, including the attached sensors and their dimensions, are shown in Figure 1 and consist of a skin panel and one or multiple T-stiffeners. In essence, the multi-stiffener panel is a scaled-up version of the single-stiffener panel.

They were manufactured by Optimal Structural Solutions and both were made from the same material, that is, carbon fiber-reinforced epoxy unidirectional prepregs (IM7/8552). Moreover, the lay-ups of the two panels are equal with the skin having a lay-up of $[45/-45/0/45/90/-45/0]_S$ and the stiffeners of $[45/-45/0/45/-45]_S$. During manufacturing, one resin block was added to each side of the panel to allow for a proper compressive load introduction during fatigue testing.

Both panels were tested in fatigue compression after impact (FCAI) tests, which is a representative loading case for such aircraft structures. The panels were impacted to create a barely visible impact damage (BVID) that is non-detrimental to the load-bearing capacity of the structure, thereby simulating a potential foreign object impact event during in-service usage such as a tool drop. However, when a composite panel containing a BVID is loaded under fatigue loads, damage might grow, potentially leading to a failure of the panel. Therefore, after impacting a panel, it was subjected to compression-compression fatigue loading to initiate further damage growth.

To monitor damage initiation and propagation, multiple SHM techniques were employed. These techniques include AE, strain sensing using both distributed fiber optic

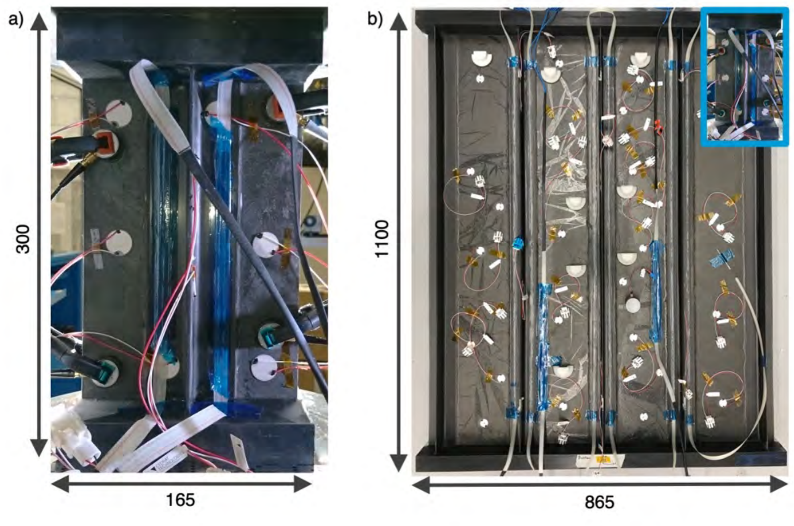

Figure 1. Two stiffened sensorized panels used in the upscaling study: a) single-stiffener panel and b) multi-stiffener panel, including their dimensions in mm. Note that the main images of a) and b) are not to scale. Therefore, to indicate the dimensionality change between the two panels, b) includes a to-scale image of the single-stiffener coupon.

strain sensing (DFOS) and fiber Bragg gratings (FBG), GW, and vibration mode analysis using FBGs. Additionally, the monitoring techniques were occasionally expanded by employing the following techniques: digital image correlation (DIC), a normal camera, a portable hand-held C-scan, thermography, and thermocouples.

KNOWLEDGE TRANSFER IN UPSCALING

The key in SHM upscaling is the potential for knowledge transfer from the lower- to the higher-level structure: what can be learnt from simplified generic lower-level structures that can help in the monitoring of damage in complex higher-level structures. Moreover, it includes the concept of developing and training diagnostic and prognostic methods using data collected during testing of the lower-level structure and subsequently applying it for SHM of the higher-level structures. To accomplish these objectives, a relation between the two structures must be established. In the stiffened panels of this work, there are several direct similarities between the single- and multi-stiffener panels: they are made from the same composite material and lay-up, both contain T-stiffeners, and the loading type conditions are similar in terms of FCAI testing. However, several differences can also be identified such as the obvious dimensional change, number of stiffeners, changes in sensor system (both number of sensors and technologies), and applied fatigue load values. In the aim of knowledge transfer, these similarities and differences must be comprehended as they will affect the development and performance of SHM methodologies.

Testing at a lower-level structure allows for the understanding of structural behavior such as: How does a panel act under different loading? How does damage initiate and propagate? How does stiffness degradation occur and affects damage propagation? What is the failure mechanism of the panel? The studying of lower-level structures thus provides more insight in the behavior of higher-level structures and allows one to anticipate what can be expected. Utilizing this structural knowledge, effective diagnostic and prognostic methodologies using different SHM techniques can be developed that are based on the gathered experience from lower-level structures and are applicable to such higher-level structures in which similar structural behavior will be observed. This may include the development of damage detection models up to the development of health indicators for damage prognostics. For instance, for the previously discussed stiffened panels, it may include the development of damage sizing algorithms based on collected GW data from the single-stiffener panel. It can also include the understanding of wave propagation for GW or AE in the single-stiffener panels, which can be used for the development of damage localization algorithms. Subsequently, such models can be (almost directly) applied to the multi-stiffener panel as the wave propagation between the structures will be comparable given the similarities in the structures' material, lay-up, and stiffeners, with only limited effects by new boundary conditions. In essence, the SHM knowledge transfer from lower- to higher-level structures allows one to not start from zero when assessing health methodologies for higher-level structures.

CHALLENGES IN UPSCALING

Upscaling of structures and the corresponding SHM methodologies comes with several points of attention and corresponding challenges. Based on the case study of the stiffened composite structures, we discuss several of these in this section, along the lines of physical differences in the structures to changes in the sensor system and the considerations for diagnostic and prognostic methodologies.

Physical Structural Aspects

Moving from the single- to multi-stiffener panel, similarities and differences are observed in the structure. On the one hand, aspects such as the material, lay-up, manufacturing process, bonding between stiffener and skin are similar for both panels. On the other hand, aspects such as the dimensions (length and width) and number of stiffeners change between the panels and new features, such as the distance between stiffeners, are introduced. Besides these evident alterations, there are additional – more concealed – aspects regarding the physical structural behavior that show variation. Two of those identified elements, the buckling behavior and the structural response to damage, are discussed in more detail next as they may influence the performance of health management methodologies.

During the test campaign, we observed that the single- and multi-stiffener panel display different buckling behavior. Whereas the single-stiffener panel buckles in a single half wave, the multi-stiffener panel buckles in 7 half-waves in longitudinal direction. As illustration, an indication of the post-buckled state using DIC measurements is presented in Figure 2. Changes in buckling behavior may affect damage growth in the panel, in particular disbond growth along the stiffener feet. Whereas for the single-stiffener panel, the predominant mode along a stiffener foot is constant as being either mode I (opening) or mode II (in-plane shear), the presence of multiple half waves in the multi-stiffener panel causes the predominant mode to shift

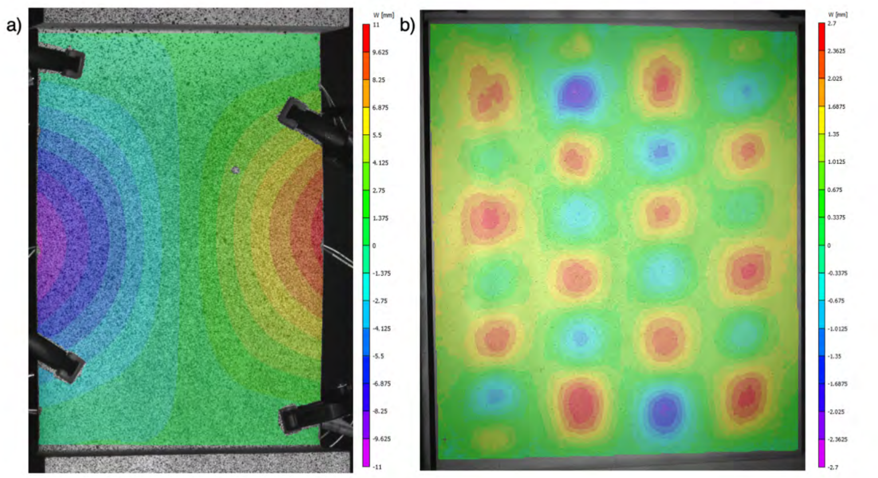

Figure 2. Out-of-plane displacement field of the skin for the a) single-stiffener panel and b) multi-stiffener panel obtained using DIC and showing the differences in buckling and number of half waves.

between mode I and mode II longitudinally along each stiffener foot. From previous studies [6, 7], we know that the disbond is more likely to propagate under mode I and in the case of the single-stiffener panel, this means that the disbond can grow freely in longitudinal direction. For the multi-stiffener panel, this is no longer the case causing the propagation of the disbond to change, for example by declining or having the disbond propagate to the other stiffener foot where mode I is observed. The buckling alteration between the two panels can thus have a powerful effect on the disbond propagation, and consequently, on the health management methodologies as further discussed in the third sub-section “Structural Health Methodology Aspects”.

The changes are not only observed in disbond propagation between the single- and multi-stiffener panel, but also in the effect of damage on the structural integrity of the panels. For the single-stiffener panel, an impact damage located near the skin-stiffener bond where mode I is dominant may lead to final failure of the panel under fatigue loads in an FCAI test [6, 7]. However, for the multi-stiffener panel, an equally sized impact damage located in a similar area under comparable loading conditions may not lead to a loss in load-bearing capacity in an FCAI test. For example, in an FCAI test performed on a multi-stiffener panel, an initial impact damage was created at the stiffener foot that resulted in a disbond, as confirmed using a C-scan measurement. Yet after 1,125,000 cycles of fatigue loading after impact, disbond propagation was only observed immediately after the impact event and subsequently came to a halt. Additionally, a residual strength test after the FCAI test did not indicate a loss in load-bearing capacity due to the impact and fatigue loads. The example presented here shows that an equally sized damage at a similar location and under comparable loading conditions, might have a different effect on the integrity of different structures: a damage that is detrimental for one, might not be for the other. This poses challenges when upscaling structures and mapping learned behavior and trends under damage. Its consequences for the health management methodologies are described later in this section.

Sensor System Aspects

Besides the structural and damage mechanics aspects, also sensor systems change from one structure to the other when scaling up. This relates to the number of sensors, but also to the placement and optimization of sensors. Both are discussed in more detail next.

For smaller and simpler structures, less sensors are needed to cover the full structure to perform damage monitoring. For example, in the case study presented in this work, only one stiffener is present in the single-stiffener panel in contrast to five stiffeners in the multi-stiffener panel which are additionally over 4 times longer. For the strain-based optical fiber measurements, this consequently means that longer optical fibers are needed to cover a longer stiffener length, as well as multiple stiffeners. In our case, three out of five stiffeners of the multi-stiffener panel were monitored over a length of 840 mm for each foot whereas the single-stiffener panel only a length of 140 mm was monitored for each foot. Consequently, the required optical fiber length for the multi-stiffener panel was 18 times longer than that of the single-stiffener panel. Similarly, an increase in number of sensors is seen for other SHM techniques such as the PZT sensors for GW.

Besides the increase in sensor numbers for spatial coverage aspects, the experience from the lower-level structure can also help to optimize the sensor network for the higher-level structure. For example, knowledge can be gathered to reduce the number of sensors and only employ those sensors that provide a significant and meaningful contribution to the monitoring of damage. Less effective sensors can be either moved to more optimal locations or removed completely. The latter can also contribute to a second aspect that becomes more important with higher structural levels, namely: data dimensionality. With higher-level structures containing an increased number of sensors and techniques, the size of SHM datasets will increase exponentially. The option to monitor every aspect of the structure might become infeasible; studies on lower-level structures can help in optimizing sensor placement, the development of improved diagnostic and prognostic methodologies, and with that study data dimensionality reductions and prevent issues in SHM dataset dimensions at higher-level structures.

Structural Health Methodology Aspects

Previously we have identified effects of the SHM upscaling for the stiffened structures in terms of the physical structural and sensor system aspects. The upscaling will correspondingly also affect the employed damage monitoring techniques: both the diagnostic and prognostic algorithms. Two examples of such changes are discussed next in more detail.

For the stiffened panels discussed in this work, we previously saw how the buckling behavior varies between the single- and multi-stiffener structures. The change in buckling pattern with now multiple half waves present in the multi-stiffener panel will affect the strain measurements and correspondingly the algorithms based on those measurements. A strain-based health indicator relying on certain trends in the data under damage, such as the ones presented in [6, 8, 9], may be affected when mode I and II are both predominantly present along the same stiffener foot. Consequently, it necessitates an adaption in its methodology to handle the simultaneous presence of both modes as well as a new inclusion of an approach on how to deal with the transfer-region between both modes.

Another example where the diagnostic or prognostic methodology is affected, can be seen in the use of AI-based methodologies in which training datasets are employed. For example, in cases where a diagnostic methodology is developed and an algorithm is trained using SHM data collected during lower-level testing and one wishes to apply such algorithm directly to data coming from a higher-level structure. However, the latter structure might be outside the training domain due to the previously mentioned aspects of sensor network adjustments and structural differences. Such aspects may require the introduction of transfer learning methods into the diagnostic and prognostic methodologies that were not previously needed for lower-level structures, although their application to composites is scarce and remains to be studied [10].

CONCLUSIONS

The concept of upscaling damage monitoring methodologies for stiffened composite aircraft panels and its challenges were discussed in this work. Upscaling requires a lower- and higher-level structure and in this work the case study consisted of a single- and multi-stiffener composite aircraft panel monitored using multiple SHM techniques. Similarities between different level structures, such as material, lay-up, and design, allow for SHM upscaling as it permits the study of fracture mechanics in the structure and the development and training of diagnostic and prognostic methodologies. The knowledge gathered during testing of lower-level structures can then be transferred and applied to higher-level structures. Yet several challenges may affect a successful implementation of SHM upscaling, such as changes in sensor networks, differences in structural behavior and, with that, in the way damage propagates, and in methodological challenges including higher-level structures potentially laying outside the training domain of an AI-based SHM algorithm. The aspects identified in this work will benefit researchers in the development of SHM upscaling techniques for composite aircraft panels. In future work, we will implement the concept of SHM upscaling to the presented case study and its challenges will be further addressed to enhance the methodological performance.

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REFERENCES

1. Rouse, M., D. C. Jegley, D. M. McGowan, H. G. Bush, and W. A. Waters. 2005. "Utilization of the Building-Block Approach in Structural Mechanics Research," in *46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, AIAA 2005-1874.
2. Amafabia, D. M., D. Montalvão, O. David-West, and G. Haritos. 2017. "A review of structural health monitoring techniques as applied to composite structures," *Structural Durability and Health Monitoring,* 11: 91-147.
3. Gomes, G. F., Y. A. D. Mendéz, P. D. S. L. Alexandrino, S. S. da Cunha, and A. C. Ancelotti. 2018. "The use of intelligent computational tools for damage detection and identification with an emphasis on composites – a review," *Composite Structures,* 196: 44-54.
4. Saeedifar, M. and D. Zarouchas. 2020. "Damage characterization of laminated composites using acoustic emission: a review," *Composites Part B: Engineering,* 195: 108039.
5. Yue, N., Z. Sharif Khodaei, and M. H. Aliabadi. 2021. "Damage detection in large composite stiffened panels based on a novel SHM building block philosophy," *Smart Mater. Struct,* 30: 045004.
6. Broer, A., G. Galanopoulos, R. Benedictus, T. Loutas, and D. Zarouchas. 2021. "Fusion-based damage diagnostics for stiffened composite panels," *Structural Health Monitoring*, April 2021.
7. Broer, A. A. R., G. Galanopoulos, R. Benedictus, T. Loutas, and D. Zarouchas. 2021. "Damage Diagnostics of a composite single-stiffener panel under fatigue loading utilizing SHM data fusion," in *Proceedings of the 10th European workshop on structural health monitoring (EWSHM),* P. Rizzo, A. Milazzo, eds. Cham: Springer International Publishing, pp. 626–635.
8. Milanoski, D. P. and T. H. Loutas. 2020. "Strain-based health indicators for the structural health monitoring of stiffened composite panels," *Journal of Intelligent Material Systems and Structures,* 32(3): 255-266.
9. Milanoski, D. G. Galanopoulos, A. Broer, D. Zarouchas, and T. Loutas. 2021. "A strain-based health indicator for the SHM of skin-to-stringer disbond growth of composite stiffened panels in fatigue," in *Proceedings of the 10th European workshop on structural health monitoring (EWSHM),* P. Rizzo, A. Milazzo, eds. Cham: Springer International Publishing, pp. 616–625.
10. Gong, Y., H. Shao, J. Luo, Z. Li. 2020. "A deep transfer learning model for inclusion defect detection of aeronautics composite materials," *Composite Structures,* 252: 112681.