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STRUCTURAL HEALTH MONITORING OF SANDWICH STRUCTURES WITH LATTICE CORES IN AIRCRAFT DESIGN: CHALLENGES AND POTENTIAL

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Abstract

Sandwich-type structures are among the most weight-efficient structures used in lightweight applications due to their high bending stiffness. Metallically printed sandwich lattice core structures are an emerging technology in aeronautics with a high potential to improve the manufacturing processes, impact behavior and environmental resistance of such structures. With the development of additive manufacturing technologies, it is possible to build a full metallic sandwich with a lattice core.

However, little research has been done in the certification of this kind of structures. Structural health monitoring (SHM) is an emerging new technique due to its benefits in enhancing safety, reducing maintenance costs and more importantly, in accelerating the certification process of new materials and designs. SHM refers to the process of monitoring the current state of a structure and measuring damage-sensible data from the sensors that are typically permanently installed on the structure. Nowadays, there are a lot of promising SHM methods, such as strain, vibration, elastic wave, electromechanical impedance and etc. However, there is no such a SHM method that fits all kinds of structural systems or damages.

The goal of the paper is to evaluate the usage potential of an integrated SHM system concept for an aircraft with lattice core structures. For this, a system consisting of several SHM methods accounting for the new materials and designs is developed. The main damage types considered for this application are impact, corrosion, fatigue and overload. For the impact and corrosion, a global damage assessment of the whole structure is needed as their location is quite random. In the case of the fatigue-induced cracks and overload, a local damage detection is needed, because the stress concentration area and load carrying parts are known in the design phase. In our concept, the weight and power consumption of the system are considered too due to their importance in airborne applications.

Keywords: Structural Health Monitoring, Additive Manufacturing, Sandwich Structures, Lattice Core

1. Introduction

The importance of monitoring the loads and damages arises since these structures might experience unexpected changes in their operational and environmental conditions, which are not always considered during the design. To guarantee a safety operation, structures are designed adding a safety factor against an ultimate limit load, which is the maximum load ever experienced by a structured. This is known as safe-life design. Designing a structure against this load, however, results in an oversized and heavy structure [1].

Aircraft structures, specifically in commercial aircraft, are designed to be damage-tolerant. This means that the structure is designed to withstand certain damages up to a defined size without compromising the overall integrity of the structure [2]. The allowable size limits within which structures can operate safely are calculated from structural and fracture mechanics analyses. Above these limits, the safety operation of these structures cannot be guaranteed. For example, in the case of cracks, a crack propagation analysis can be carried out to evaluate the number of cycles that the structure can operate without the crack reaching a critical size. Designing under damage-tolerance has allowed structures to become much lighter when compared to the traditional safe-life design [1, 3].

Thus, inspection intervals are needed to constantly evaluate the state of the structures. Most of the inspections are done visually, by non-destructive inspection (NDI) techniques such as eddy current or ultrasonic testing [2]. During these inspections, cracks or other type of damages are detected, and depending on their magnitude, the structures must be repaired. Inspections are time-consuming and require a big effort, especially when the inspected locations are not accessible and multiple components need to be disassembled. This requires an aircraft to be out of operation for a significant time. All of these translates into a big economic impact.

SHM is the integration of sensors and actuator devices to be part of the structure, allowing a constant monitoring of the structure state. Constantly monitoring the state of the structures allows an optimal use of the structure, a minimized downtime, and the avoidance of failures. It also allows a better understanding of the structure operation, which can lead to improvements of the designs. It reduces the maintenance labor, by aiming to replace scheduled and periodic maintenance inspections with performance-based inspections, in which inspections are done only when necessary. It minimizes the human interactions, and consequently reducing labor and human errors, which in turn can improve the safety and reliability [4]. Furthermore, SHM can also be used to monitor the state of the structures after manufacturing. Therefore, the certification of new materials and designs can be accelerated.

In off-line SHM systems, the monitoring of the structure state is performed when the aircraft is not in operation. These SHM systems aim to reduce the aircraft maintenance costs by reducing the frequency of maintenance inspections and the labor involved in them. By looking at Figure 1, it is clear that the inspections in aircraft maintenance represent the highest cost, even more than the repairs themselves.

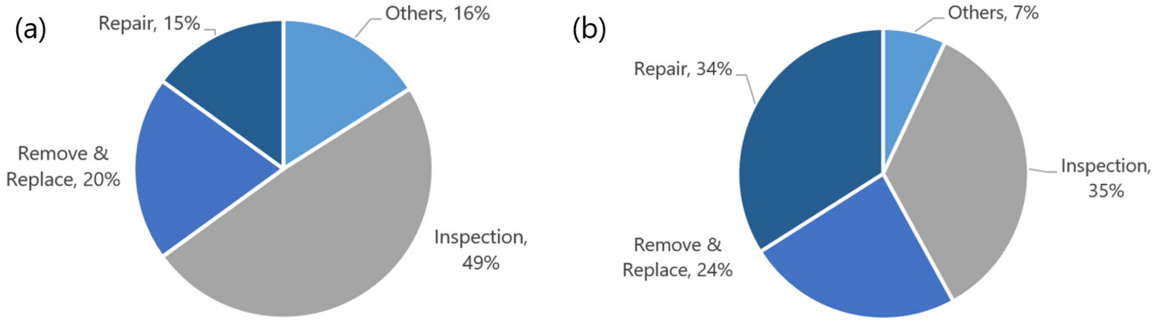

Figure 1 – Aircraft maintenance costs. (a) Maintenance action distribution (b)Maintenance manpower distribution [5].

SHM methods require the observation of a structure over time, where the dynamic response of the structure is obtained by using periodical measurements from an array of sensors, and damage sensitive features are extracted from these measurements to evaluate the state of the structure.

These methods are usually divided into local and global methods, depending on the relation of the characteristic length of the waves or vibration pattern with respect to the defect size and the overall structure dimensions. Local methods use high frequency ultrasonic waves with wave lengths smaller than the damage size to be detected. In this case, there is a need of estimation of the damage location beforehand.

On the other hand, global methods use the fact that the local damage, which causes a reduction of a local stiffness, has an influence on the global behavior of the whole structure. These methods can work with a much coarser sensor network, which is usually distributed over the whole structure. There is no need of knowing the zones where damage is likely to occur [6, 4].

Therefore, the SHM methods are classified depending on the operation over a broad spectrum of frequencies, which spans from low frequency vibrational response of the structure to the ultrasonic regimes [5]. These methods are classified as vibration-based monitoring, guided waves monitoring and ultrasonic monitoring. This study focuses on vibration-based techniques, therefore a more detailed description on these techniques is given in the next section. Figure 2 shows the classification of the dynamic-based SHM techniques on the basis of its frequency range.

Sandwich with lattice cores (SLC) is promising in aerospace application as they have high poten-

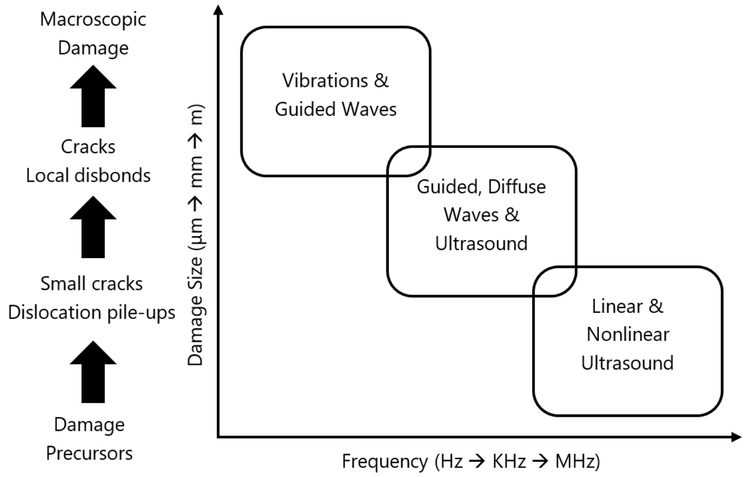

Figure 2 – Classification of dynamics-based SHM techniques on the basis of frequency of interrogation of the dynamic behavior of the system [5].

tial to improve the manufacturing processes, impact behavior and environmental resistance of such structures. However, as the mechanical properties and typical damages for this kind of structure is not clear yet, the application of SLC is limited.
Structural Health Monitoring (SHM) refers to the process of measuring and interpreting data from sensor systems distributed around a structural system to objectively quantify structural conditions [7, 8, 9]. A broad goal of the SHM system is to identify early damage events that may ultimately result in the failure of a single component or system. The damage identification results determined by monitoring can then be used to inform the decision making of the remediation work. Beside, SHM has the potential to accelerate the certification process of new materials and designs.
This paper will first review the state of the art of the vibration and strain based SHM methods. Then the principle of a typical vibration based method is explained. After that, the vibration and strain based method is validated with numerical simulations.

2. State of the Art

2.1 Vibration Based SHM

The basic idea of vibration-based damage identification is that changes in structural physical properties (mass, damping, and stiffness) caused by damage will result in detectable changes in modal properties (natural frequency, modal damping, and modal shape) [10, 11]. For example, the reduction in stiffness is caused by the occurrence of cracks. Therefore, the characteristic information contained in the structural damage can be recognized by analyzing the changes in the vibration signal characteristics of the structure.
Vibration based methods can be divided into two categories: data-based methods and model-based methods. Data-based methods use statistical tools for pattern recognition, while model-based methods use models and physical relationships for damage detection.
Three main aspects of model-based methods when developing a vibration-based SHM method need to be considered. First, the accurate measurement of the damage sensitive data and the preprocessing of the raw data, such as the extraction of modal parameters. Second, a reliable reference model (if the approach is not baseline-free). And third, an algorithm which extracts the damage parameters based on the information from the reference model and the measured data [6]. This study focus on the reference model and the damage detection algorithm. The experimental part is not covered. Figure 3 shows the main aspects of model-based approach in vibration-based SHM.
Vibration-based methods are classified depending on the modal parameters that are used for damage identification. These methods are classified in natural frequency-based methods, mode shape-based methods, mode shape curvature (MSC)-based methods, modal strain energy-based methods and modal flexibility-based methods. A more detailed description of the MSC-based methods is given in

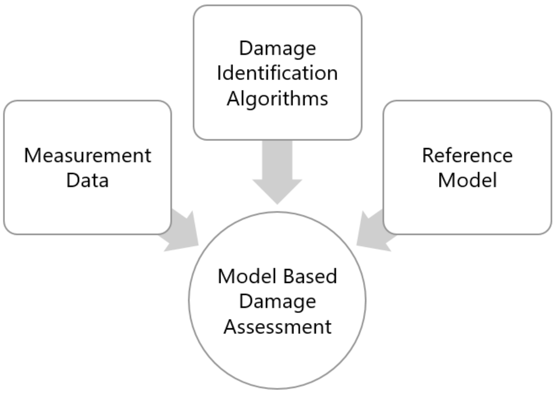

Figure 3 – The three basic pillars of model-based damage assessment [6].

the next section as it is the selected method for damage detection for the additively manufactured lattice core sandwich structure.

Doebling et al. [12] presented an extensive review of vibration-based damage identification methods up to 1996. A summary review on their previous work was presented by Doebling et al. [13] in 1998. Farrar et al. [14] then presented an updated version up to 2001. Carden and Fanning [15] presented a review with particular emphasis on structural engineering applications. Yan et al. [16] introduced the development of modern-type vibration-based methods using modern signal-processing techniques and artificial intelligence.

Fan and Qiao [11] comprehensively reviewed the modal parameter-based damage identification methods for beam-type and plate-type structures and conducted a comparative study of five algorithms. Das et al. [17] presented a review through a comparative study among different vibration-based damage detection methods. And Kong et al. [18] presented a more systematically review of the state of the art of vibration-based damage identification, focus on a step-by-step implementation.

2.2 Strain Based SHM

Strain-based SHM methods adopt the fact that the damages, such as cracking, crushing, yielding, bowing, and so on, will lead to anomalies in the strain distribution [19]. Thus, by monitoring the strain near the critical locations, the health state of the structure can be acquired. The strain-based methods are especially suitable for monitoring the local changes in some critical areas [20]. Moreover, with the help of a high-fidelity finite model, the detail of the damage can be acquired.

Typical strain-based SHM techniques utilize strain gauges and fiber optic sensors. Strain gauges are widely used in SHM systems as they are inexpensive, easy to install. However, the cables will add the total weight of the structure significantly when a large number of strain gauges are adopted. On the other hand, fiber optics sensors can integrate many monitoring points in one single fiber [21].

3. Structural Health Monitoring of Lattice Core Structures

3.1 The principle of MSC-TEO Method

The extension of the MSC method to plate-type structures was formulated by Zhong and Yang [22], which was based on the work of Pandey et al. [23]. In 1-D structures, the curvature consists only of the longitudinal direction component U_{xx}. For plate-type structures, the MSC consists of three components, longitudinal U_{xx}, transversal U_{yy}, and torsional U_{xy}. In order to take the effect of all the three components into account, the total MSC is expressed as:

$$Uc = \sqrt{U_{xx}{}^2 + U_{xy}{}^2 + U_{yy}{}^2} \tag{1}$$

Damages in the plate will alter its MSC. To indicate the presence of damage, the damage index is calculated by comparing the MSC of the undamaged plate $Uc_{h,i}$ and the damaged one $Uc_{d,i}$. The damage index magnitude will show peaks in the presence of damage. It is calculated as follows:

$$DI_i = Uc_{h,i} - Uc_{d,i} \tag{2}$$

The longitudinal and transversal components of the MSC are calculated as follows:

$$U_{xx}(x_i, y_j) = \frac{U(x_{i+1}, y_j) - 2U(x_i, y_j) + U(x_{i-1}, y_j)}{{H_x}^2} \tag{3}$$

$$U_{yy}(x_i, y_j) = \frac{U(x_i, y_{j+1}) - 2U(x_i, y_j) + U(x_i, y_{j-1})}{{H_y}^2} \tag{4}$$

Where $U(x_i, y_j)$ is the amplitude of the mode shape displacement of the plate, H_x and H_y are the uniform spacing of the grid points in the x and y directions.
The determination of the torsional component of the MSC is completed in two steps. First, Eq. (5) is used to find the torsional curvature of all grid spaces formed by grid lines as shown in Figure 4, where k corresponds to each of the spaces.

$$T_k = \frac{\frac{U(x_{i+1}, y_{j+1}) - U(x_{i+1}, y_j)}{H_y} - \frac{U(x_i, y_{j+1}) - U(x_i, y_j)}{H_y}}{H_x} \tag{5}$$

Second, the torsional curvature at each grid point (x_i, y_j) is obtained by taking an average of all the T_k values of the grid spaces that share that common grid point. In Figure 4, a color code is shown to indicate the three different calculations depending if the grid point is located either at the corner, the edge or inside the plate. As an example, the following formulations show the three possibilities:

$$U_{xy}(1,4) = T_1 \tag{6}$$

$$U_{xy}(2,4) = \frac{T_2 + T_3}{2} \tag{7}$$

$$U_{xy}(2,2) = \frac{T_7 + T_8 + T_{12} + T_{13}}{2} \tag{8}$$

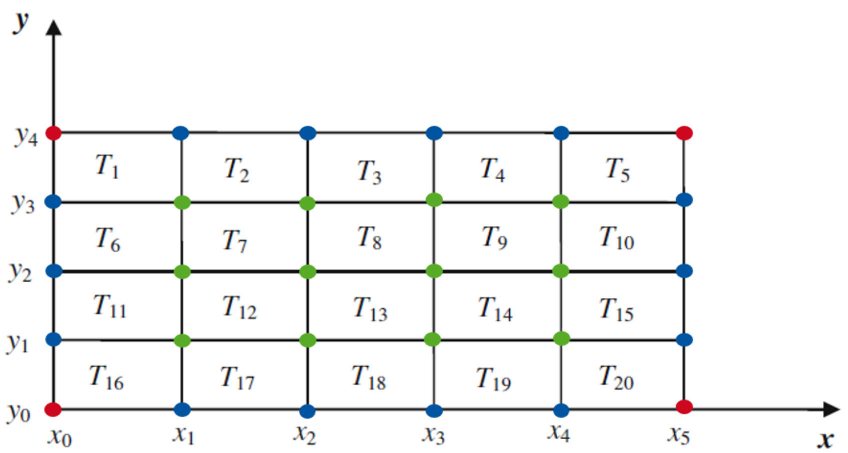

Figure 4 – Schematic plot of measurement grid for torsional curvature calculation [22].

An improvement in the damage detection can be done by post-processing the damage index using the Teager Energy Operator (TEO). This approach has been used along with several damage identification methods. Li et al. [24] demonstrated that the peaks at the damaged areas are intensified while the global fluctuations are suppressed when a signal is processed by the TEO. Additionally, Cao et al.[25] identified that the damage detection method based on MSC has low sensitivity to measurement noise and this drawback can be overcome by using the TEO. The TEO was defined by Kaiser [26] and it is used to calculate the instantaneous energy of a temporal signal. It was deduced from a harmonic signal, but has been extended to a generalized discrete signal. Let x_n be samples of a cosine signal, given by the following:

$$x_n = Acos(\Omega n + \phi) \tag{9}$$

where A is the amplitude, Ω the digital frequency, ϕ the arbitrary initial phase, and n the temporal sampling point. The signal values at three successive points are:

$$x_{n-1} = Acos(\Omega(n-1) + \phi), x_n = Acos(\Omega n + \phi), x_{n+1} = Acos(\Omega(n+1) + \phi) \tag{10}$$

From trigonometric identities, one can obtain:

$${x_n}^2 - x_{n-1}x_{n+1} = A^2 sin^2(\Omega) \tag{11}$$

As stated by Kaiser [26], the left side of above equation is defined as the Teager energy, which is a measure of the instantaneous energy of a temporal signal. It can be seen that the Teager energy of a harmonic is a particular constant (right hand side of the equation) over its duration. Furthermore, when Ω is restricted to a small value that satisfies $\Omega \approx sin(\Omega)$, the Teager energy can be approximated by:

$$E_n = {x_n}^2 - x_{n-1}x_{n+1} = A^2 sin^2(\Omega) \approx A^2\Omega^2 \tag{12}$$

For a generalized discrete signal $f[n]$ not limited to a harmonic, the Teager energy can be calculated using the TEO defined by the following:

$$\Psi[f[n]] = f^2[n] - f[n-1]f[n+1] \tag{13}$$

The principle of TEO is introduced to the damage index obtained from Eq. (2). Instead of temporal instantaneous energy, a MSC-TEO damage index, DI^*, for a series of spatial sampling points can be calculated as:

$$DI^*(n) = DI^2(n) - DI(n-1)DI(n+1) \tag{14}$$

Figure 5 shows a flowchart with an overview of the SHM method implementation. The implementation of the SHM method is carried out based on the modal displacements of the structure. The modal displacements are obtained from a modal analysis using a numerical model developed in ABAQUS. As shown in Figure 5 , a baseline model and a damaged model are created. The baseline model represents the undamaged structure. The damaged model one takes into account the core debonding and the face sheet damage. Lectures of the modal displacements are taken from both models to calculate the total structure curvature. Since the structure is 2-D, the total curvature (Eq. (1)) consists of the longitudinal (Eq. (3)), transversal (Eq. (4)) and torsional curvature (Eq. (6), (7) and (8)).
Once the total curvature from both models is calculated, a damage index is calculated from the difference of total curvature between the baseline model and the damaged model (Eq. (2)). It is expected that the changes in the structure curvature due to the damage are localized in the damage zone. Therefore, the damage index will indicate the damage presence by showing peaks on these zones, where there is a high difference in the curvature between the baseline and the damaged structures, as compared to the low-to-null difference in the undamaged zones.

3.2 The principle of strain Based Approach

In the strain based approach two different structural damage indicators (SDIs) were investigated: the absolute strain difference and zero strain direction. The absolute damage indicator is calculated comparing the measured strain in the damaged model $X_{\text{dam}}(x)$ with the strain in the base model $X_0(x)$ as written in Eq. (15). The damage indicator in the zero strain direction is calculated determining the difference between the angles of the theoretical zero strain direction and the measured zero strain direction. The strain in zero strain direction $\tilde{\varepsilon}_{11}$ is calculated using Eq. (16), where ν is the Poisson coefficient of the used material and β (Eq. (17)) the theoretical zero strain direction [30].

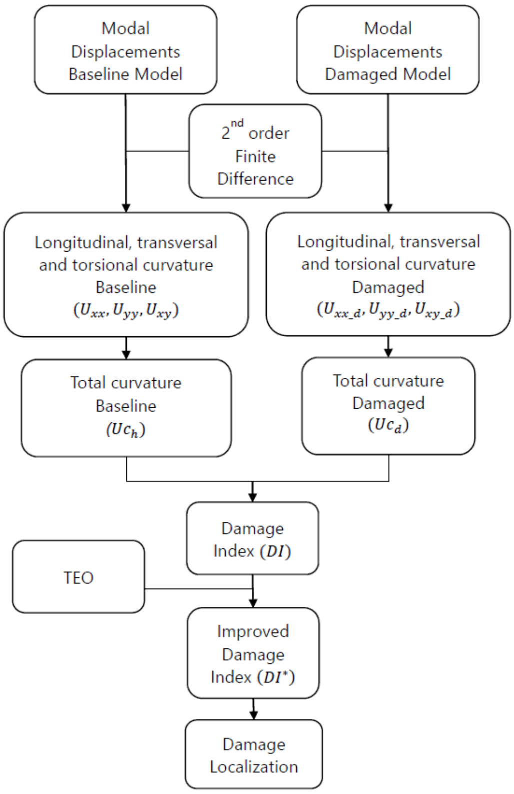

Figure 5 – Flowchart of implementation of damage identification algorithm.

$$\iota_{\text{abs}} = X_{\text{dam}}(x) - X_0 \tag{15}$$

$$\tilde{\varepsilon}_{11} = \frac{\varepsilon_{11} - \varepsilon_{22}}{2} + \frac{\varepsilon_{11} + \varepsilon_{22}}{2} \cos 2\beta + \varepsilon_{12} \sin 2\beta \tag{16}$$

$$\beta = \pm \frac{1}{2} \arccos \frac{\nu - 1}{\nu + 1} \tag{17}$$

4. Numerical Simulations

To investigate the different SHM-System approaches for monitoring sandwich structures, a representative flat panel is chosen. This panel consists of a ten by ten grid of tetrahedral pyramids, as shown in the unit cell in Fig. 6. The core thickness t_c and the face thickness t_f are set to $t_c = 2.0$ mm and $t_f = 0.5$ mm. The struts are assumed to be circular with a diameter of $d = 0.5$ mm. The relative strut angle is $\omega = 45°$. This leads to a panel size of approximately 42 mm by 42 mm.

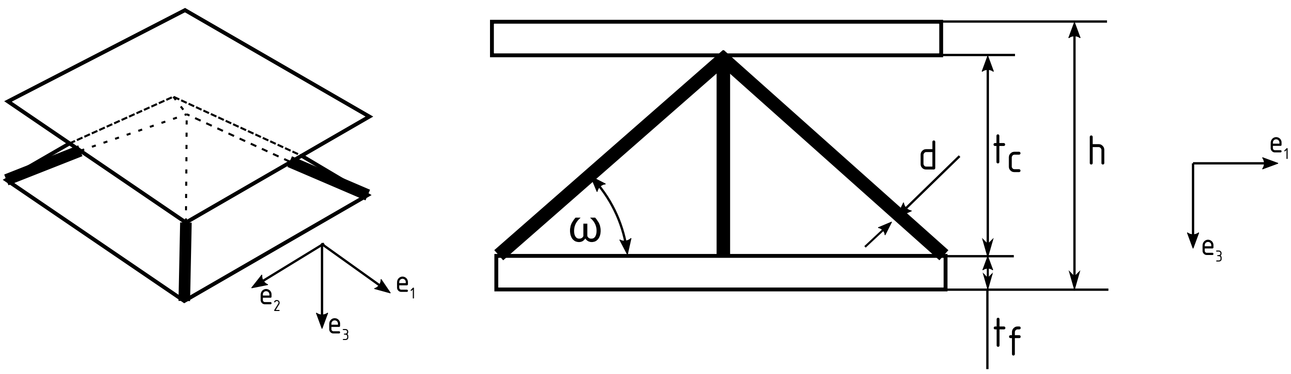

Figure 6 – Unit cell and plate used for the investigations.

The panel is modelled using the Finite-Element software ABAQUS using two layers of shell elements for the faces and beam elements for the struts. Each unit cell consists therefore of 16 shell elements and 4 beam elements.

From the previous studies performed in [27] two load states were identified as critical: in plane normal loads and out of plane loads. In plane normal loads lead to a failure of the faces and out of plane loads lead to a failure of the strut or the connection between the strut and the face (delamination). Therefore, face sheet and connection damages were modelled to investigate the different SHM approaches. The simulated defects are shown in Fig. 7. The smallest defect on the face sheets (A1) consisted of a 25% reduction in the stiffness of four adyacent shell elements, which corresponds to a zone of approximately 2 mm x 8 mm. The larger defects with a 25% stiffness reduction in rectangles of 4x8 elements and 8x16 elements are shown in A2 and A3. Last, the case with three small defects of 1x4 elements is shown in A4. In a similar way, defects in the connection between the face sheets and the struts were also modelled. In cases B1, B2 and B3 the connection between the face sheet and the struts in 1, 2 and 4 units cells respectively was removed. B4 represents the case with three not adyacent connection defects.

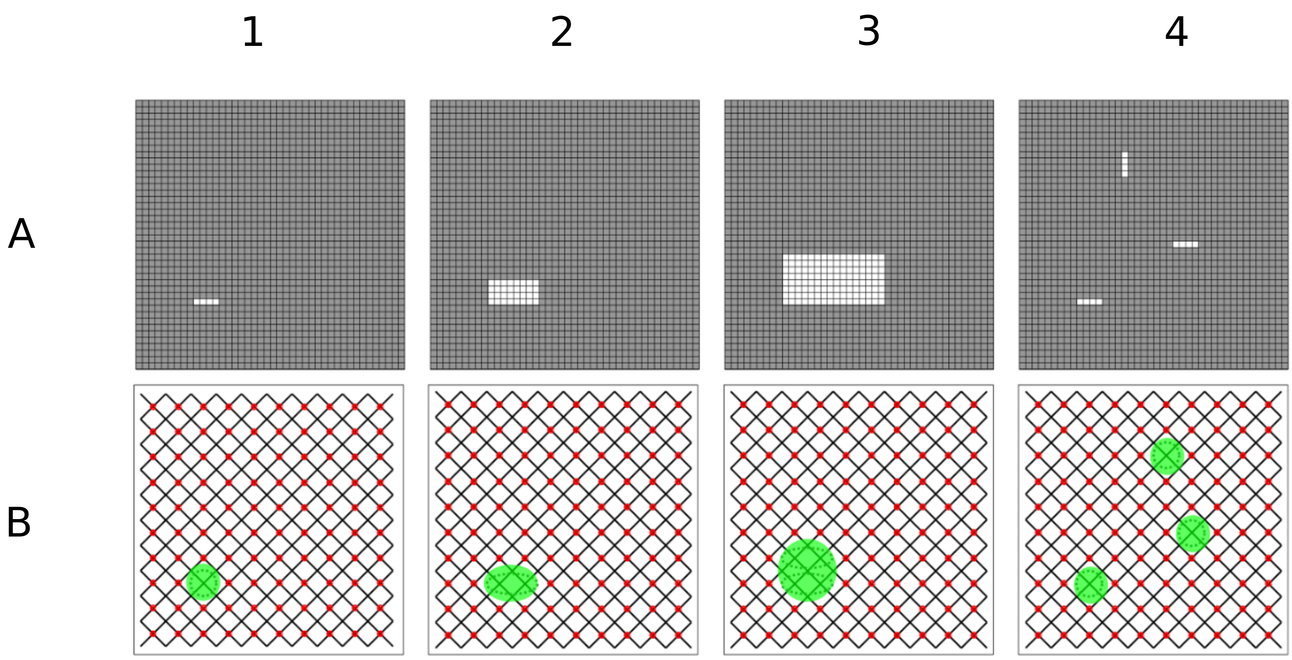

Figure 7 – Simulated defects on the face sheets (row A) and connection the between the face sheets and the struts (row B) with different damages sizes (column 1 to 3) and number od defects (column 4).

For each of these damage cases an FE simulation is performed. The results are then compared with the plate without defects. For each SHM approach different strategies of measuring the defects are evaluated: shape and modal frequency in the vibration based approach and strains in the strain based approach. Also, sensitivity studies varying noise levels and measurement distance are performed to evaluate the suitability, amount needed and requierements towards the different sensors to be used.

4.1 Vibration Based Approach

The numerical model is created using the commercial Finite Element Analysis (FEA) software, ABAQUS. The model consists of a squared-shape plate of 42x42 mm with 40 cells. Each cell contains four struts that form a pyramidal lattice core. The struts are modeled as second order beam elements of type B32. The pyramidal lattice core structure is discretized into 400 beam elements. The face sheets are modeled as first order shell elements of type S4 and discretized into 1764 1x1 mm elements. The interface between the face sheets and the pyramidal lattice core is done by sharing a single node at the connection point and using a tie constraint. The material is AlSi10Mg. Figure 8 shows the complete model and its dimensions. The beam profile and the shell thickness are rendered in the pictures.

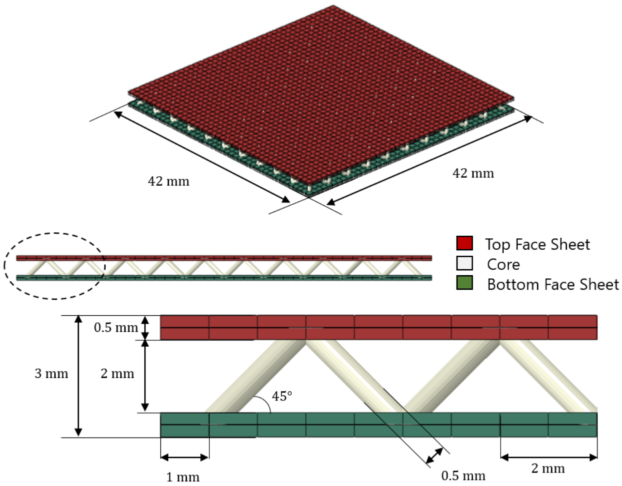

Figure 8 – Finite Element Model (FEM) developed in Abaqus.

Regarding the boundary conditions, both the top and the bottom face sheets are fully clamped at its four edges. This type of boundary condition is selected based on the conclusions from Lou et al. [28], in which they state that the presence of local damage could be more easily detected by imposing fully clamped boundary conditions, compared to others like cantilever. Natural frequencies and mode shape displacements are obtained by running a linear perturbation analysis using the Subspace eigensolver.

The MSC-TEO method is tested for multiple face sheet damages. Figure 9 shows the results of multiple face sheet damages and multiple cells with core debonding, using mode 1.

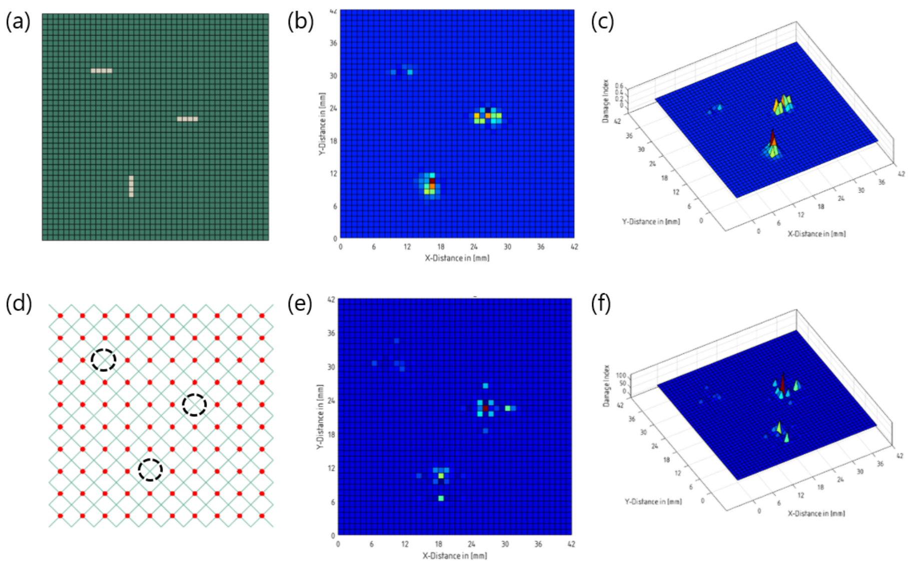

Figure 9 – Damage location and 2D and 3D damage index plots of (a-c) multiple face sheet damages and (b-f) multiple non-adjacent cells with core debonding using Mode 1.

Results show that the multiple damages were detected and located. It is observed in both damage cases that the damage index of the upper left damage is smaller than the one from the other two damages. This is due to the other two damages are located in a zone of higher flexural displacement and similar to the findings from Tian et al. [29]. Thus, damages closer to the center will result in a higher damage index.

4.2 Strain Based Approach

For the strain based simulations the same finite element model as in the vibration based simulations is used. The calculations are performed with the ABAQUS Standard static solver with a linear elastic material model.
Using the strains calculated with the simulations different damage indicators are compared. It is observed that in the load cases with normal loads, the zero strain-direction damage indicator is most suitable. As shown in Figure 10, the damage index plot of the zero strain direction SDI is more sensitive to the simulated damage than the absolute SDI.

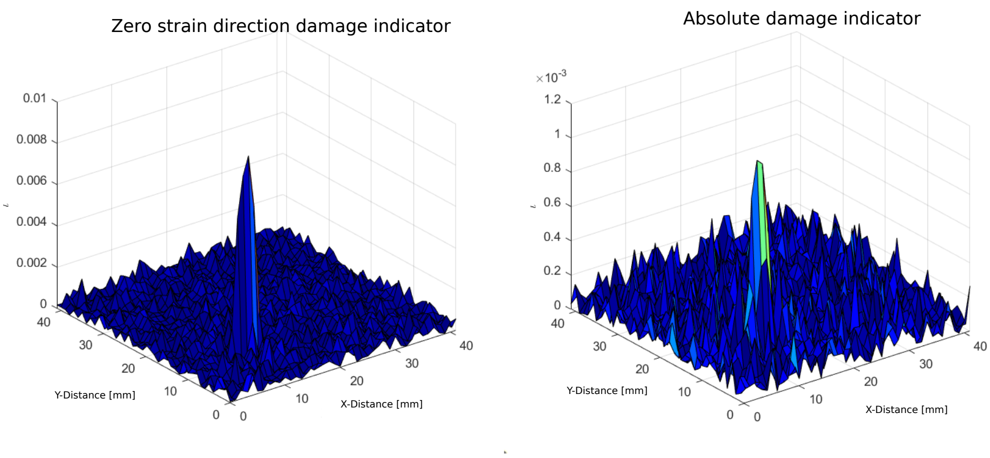

Figure 10 – Comparision between absolute strain and zero strain direction damage indicators

To investigate the sensitivity of the SDIs considering sensor distance and measurement noise further studies are performed. Noise is simulated adding to each measurement point a normally distributed random number with a standard deviation of a percentage of the measured strain. Different sensor distances are simulated only taking into account measurements in a predefined distance. Figure 11 shows the regions where Level 1 (damage detection) and Level 2 (damage location) health monitoring can be performed. As expected, with increased noise and measurement distances it is more difficult to accurately assess a damage. The size of the dotted regions in the figure showcases that facesheet damage can be recognized more easily than delamination damage: the maximum sensor distances to detect the damage are 12 mm (delamination damage) and 16 mm (facesheet damage). Similarly, sensor distances of no more than 2 mm (delamination damage) and 6 mm (facesheet damage) are needed to locate the damage. The measurement noise should not be larger than 10% in order to detect a damage.

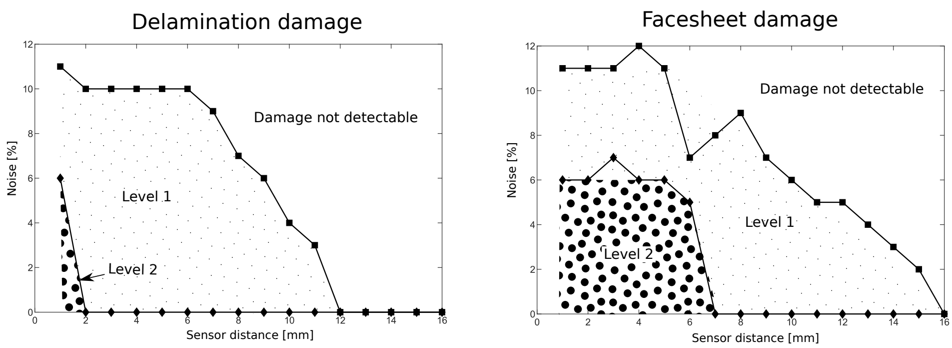

Figure 11 – Damage location (Level 2) and detection (Level 1) regions for different sensor distances and measurement noise

5. Conclusion

This paper reviews typical vibration and strain based SHM methods. The advantages and disadvantages of several vibration-based SHM methods were reviewed. The Mode Shape Curvature (MSC) method was selected as a damage detection method. Numerical models of the structure in an undamaged state and a damaged state were developed. The Mode Shape Curvature (MSC) was derived in MATLAB using the modal displacements of the numerical models. an improvement in the damage index was done by suppressing global fluctuations originated when the normal damage index was computed. The improvement was done through a post-processing of the damage index using the Teager Energy Operator (TEO), which resulted in a more localized and readable damage index. The MSC-TEO method was effective and robust in detecting damages in the additively manufactured structure. It was able to detect and locate both type of damages with different extents. Additionally, it was proved that the method was capable to detect damages even with less number of measurement points. To evaluate the strain based methods similar numerical models were employed. The zero strain direction damage indicator was found to be more suitable than the absolute strain damage indicator to detect and locate damage, and facesheet damage could be more easily detected than delamination.

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8. Copyright Statement

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