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SHM system design tool for damage detection and probability of detection

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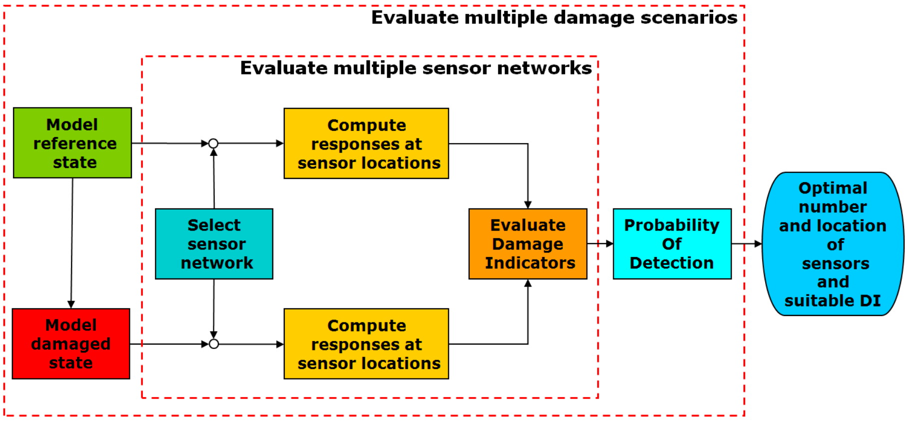

Problem area

Structural Health Monitoring (SHM) systems are a way to reduce the maintenance costs of aircraft and increase the safety. Optical sensing based on Fibre Bragg Gratings strain sensors are one type that has a number of appealing advantages for application in aircraft structures.

Description of work

A highly automated SHM system design tool is presented that allows a fast design of a strain sensor network for damage detection based on a modal approach and is able to detect the presence and location of the damage. The tool is demonstrated on a stiffened composite aircraft fuselage panel analysed for skin-stringer debonds. With the presented tool also the detection capability of the SHM system can be largely determined by means of a model approach.

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Results and conclusions

Results of successful damage detection were shown for a four stringer aircraft fuselage panel for different damage scenarios. Furthermore, the probability of detection curve was computed for different error levels caused by noise in the signal, which is a measure of the reliability of the SHM system.

Applicability

The highly automated SHM system design tool allows a fast design and evaluation of a strain sensor network for damage detection based on a modal approach.

GENERAL NOTE

This report is based on a presentation held at the NATO Specialist Meeting AVT-305, Athens, December 11-13, 2018.

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Summary

Structural Health Monitoring (SHM) systems are a way to reduce the maintenance costs of aircraft and increase the safety. For this, various types of sensors exist to monitor the condition of the structure and to provide a timely detection that damage is present. Optical sensing based on Fibre Bragg Gratings (FBGs) are one type of sensor that has a number of appealing advantages for application in aircraft structures. In this paper a highly automated SHM system design tool will be presented that allows a fast design of a strain sensor network for damage detection. The damage detection algorithm is hereby based on a modal approach and is able to detect the presence and location of the damage. The tool will be demonstrated on a stiffened composite aircraft fuselage panel analysed for skin-stringer debonds.

A main issue with SHM systems is their accuracy and reliability in timely detection of any damage before it becomes critical. This can be characterised by the system's Probability of Detection (POD), expressing the chance to detect a damage of a certain size within the structure, which is an important quantity for the certification of the SHM system. An experimental assessment of the POD is very expensive, because of the large number of damages that have to be tested to obtain a statistically valid data set. A model assisted approach to determine the POD curve will be presented and demonstrated for the composite fuselage panel. The entire POD curve can be used in a risk analysis to determine the SHM system's reliability. Moreover, the POD curve can be used in the SHM design as the objective function to optimise the number and position of the sensors.

Contents

Abbreviations

ACRONYM	DESCRIPTION
FBG	Fibre Bragg grating
MSE	Modal strain energy
NDI	Non-destructive inspection
POD	Probability of detection
SHM	Structural health monitoring
SNR	Signal-to-noise ratio

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1 Introduction

Aircraft require regular costly inspections to guarantee their safety, which currently mainly relies on manual non-destructive inspection (NDI) methods. During the last decades, a lot of research has been dedicated to more automated systems called Structure Health Monitoring (SHM), which consists of a network of sensors to detect changes in the physical and/or geometric properties of a structure from data gathered at two different states, an initial reference state, considered as the undamaged state, and the current damaged state. Changes can be caused by damage present in the structure. Especially in composite structures damage may go easily undetected by visual inspection, like debonding of stringers or impact damage often not causing substantial plastic deformation and delamination. SHM techniques can be operated on-line during the flight or off-line on the ground and can be focused on global inspection of large surface areas or on local inspection of highly critical areas (hot spots).

The main objectives of SHM are to reduce the cost of ownership and to improve the system's operational availability. For this, various types of sensors exist to monitor the condition of the structure and to timely detect that damage is present, such as acoustic and ultra-sonic sensors. These operate in the mid to high frequency range. A sensor that can operate in the low frequency range is the Fibre Bragg Grating (FBG). An FBG is a small segment in an optical fibre in which a periodic variation of the refractive index is inscribed by an ultraviolet laser. The segment reflects particular wavelengths of the light and transmits all others, as depicted in Figure 1. Stretching the fibre causes a shift of the transmitted wavelength. The reflected wavelength can be correlated with a strain value by means of calibration.

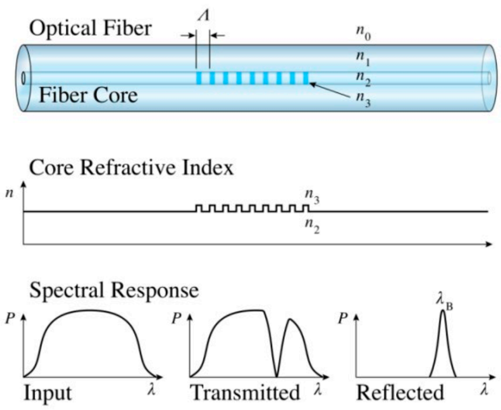

Figure 1: Principle of a Fibre Bragg Grating sensor, from Wikipedia

Optical sensing based on FBGs has a number of appealing advantages for application in aircraft structures, such as light weight, tolerant for harsh environments, long term stability, completely passive and no interference with other signals. The optical fibres can be embedded in the (composite) structure or surface mounted. The latter has the big advantage that a sensor can be installed at any time during manufacturing and operational life and that a broken sensor can be replaced. The FBG sensors are applied here in the lower frequency range (up to 1 kHz), although these can be operated in the mid to high frequency range as well with a suitable interrogator.

In this paper a SHM system design tool will be presented with which the number and position of the optical (or any other strain) sensors can be determined for a composite fuselage panel to enable the detection of damage. In general, four consecutive levels of damage identification can be distinguished of increasing complexity:

1. Determination that damage is **present** in the structure
2. Determination of the **location** of the damage
3. Quantification of the **severity** of the damage
4. Prediction of the **remaining service life** of the structure

The damage detection algorithm presented herein is based on a modal (vibration) approach and is able to detect the presence and location of the damage. In principle, the damage size can be determined as well but this requires much more sensors. This is unrealistic for a commercial SHM system and is therefore not pursued. Instead it is expected that when the SHM system signals damage at a certain location, an inspector will inspect the structure in the vicinity of the signalling sensor by means of a suitable NDI technique to locate the exact position and size of the damage before a structural repair is performed. The objective therefore is to minimise the number of sensors.
The damage indicator compares modal data from a reference measurement and a measurement of the current state of the aircraft. The reference measurement can be replaced by the latest measurement after, for instance, a structural repair or to compensate for some structural degradation over time. Measurement can be performed during flight, especially random (white-noise) gust loads in multiple locations are ideal for this, or on the ground by means of a small shaker, e.g. portable (inertia) shaker.

The SHM design tool makes use of finite element analyses and is highly automated, for instance allowing for automatic damage insertion in the finite element model, which is a requirement for a fast design. The tool will be demonstrated on a realistic composite aircraft fuselage panel for skin-stringer debonds. Stringer debonding, being invisible from the outside, might be one of the promising applications of a SHM based on optical fibres for aircraft panels.

A main issue with SHM systems is their accuracy and reliability in timely detection of any damage before it becomes critical. This can be characterised by the system's Probability of Detection (POD), expressing the chance to detect a damage of a certain size within the structure, which is an important quantity for the certification of the SHM system. An experimental assessment of the POD is very expensive, because of the large number of damages that have to be tested to obtain a statistically valid data set. A model assisted approach in which the damage detection is simulated can alleviate the costs significantly and only requires a limited amount of experimental data for validation. Such a model assisted approach to determine the POD curve, including its confidence bounds, will be presented and demonstrated for the composite fuselage panel. The POD curve can be used in the SHM design as the objective function to optimise the number and position of the sensors.
With the probabilistic model assisted approach also the number of false calls can be determined, where the system signals a damage which is not present. For a reliable SHM system the number of false calls should be minimised to reduce the costs of unnecessary inspections and affected aircraft availability, which is another important characteristic for acceptance of such a system. Also the effect on the damage indicator of variations in boundary conditions, temperature and other properties can be simulated by adding a probabilistic layer on top of the analysis. For this, a general probabilistic tool can be applied, like the NLR-tool RAP++ (Reliability Analysis Program).

The paper focusses on the numerical simulation and introduces the SHM system design tool in section 2. This includes an example of a sensor network design for a composite fuselage panel. Only single damage at a time is considered herein and a new reference can be selected after the damage. Simultaneous multiple damages can be detected as well if they are in different areas. Whether simultaneous nearby damages can always be detected successfully remains to be investigated. Also the damage indicator still needs to be validated by means of tests on a realistic component.
In section 3 the model assisted POD characterisation is described and applied to the same composite fuselage panel.

2 SHM system design tool

2.1 Approach

A flow diagram of the damage detection algorithm is depicted in Figure 2. The algorithm is based on comparing the modal characteristics of the initial (undamaged) state with a damaged state of the structure. The modal characteristics of the structure are altered due to the presence of damage causing local changes in the stiffness of the structure. For both states the modal frequency strain response is computed for the lowest modes at every sensor location for a given sensor network. In a real application the frequency strain response of the structure due to some external load, for instance a broadband random load or sine-sweep, can be determined by measuring the response as well as the load. In theory, under certain conditions, the frequency response can be determined even when the external load is unknown by means of operational modal analysis.

The FBG sensor measures the strain in the direction in which it is oriented, which is also applied in the simulations. Hence, only limited information about the modal behaviour of the structure is available in reality. Based on the strain response measured by the sensor network in the initial and current state, a number of damage indicators (DI) can be determined. Depending on the value of the damage indicator, damage is signalled or not.

A general SHM design tool has been programmed in Python implementing the flow diagram of Figure 2. The program functions as a shell around the finite element program Abaqus in which both the responses of the undamaged and damaged structure are computed. Abaqus provides an extensive Python and C++ API suitable for this purpose. The SHM tool only requires a limited amount of input:

- The finite element model of the reference structure.
- The sensor network, specified by the location, position and orientation of the sensors. A sensor can be embedded or surface mounted, specified by the layer number or its position in thickness direction.
- A description of the damage(s). A simple versatile polygon description is applied to specify the contours of a damaged area. Furthermore, new material properties have to be specified in case of impact damage for the impacted region. Based on the polygon description, the elements inside and/or overlapping the polygon are assigned the new (damaged) material properties.

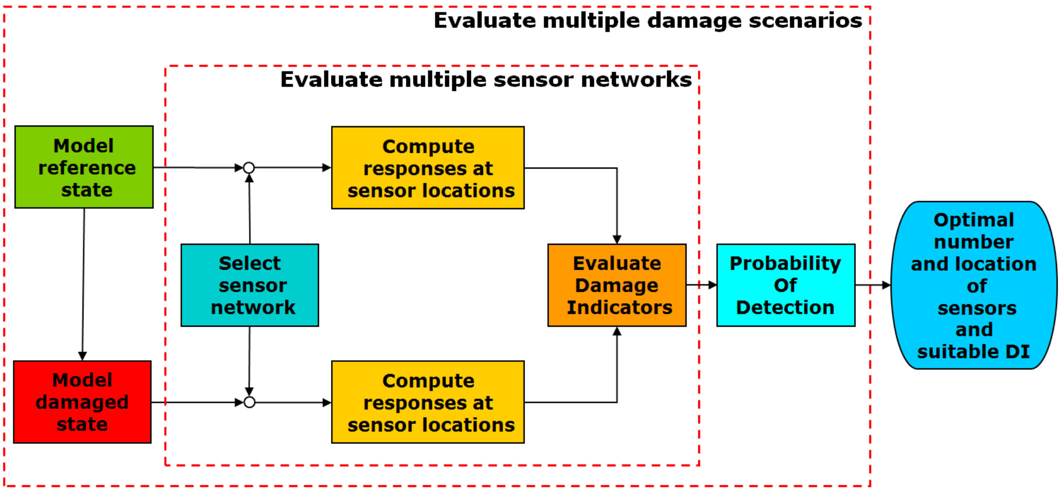

Figure 2: Flow diagram of the SHM design tool

Additionally, a number of analysis parameters can be specified such as the frequency range, the number of active modes, damage indicator thresholds and some tolerances for the applied numerical algorithm.
The tool is capable to automatically insert the (impact, debond) damage in the finite element model, even for complex models, as the one discussed in this paper, and as such generate the damaged model, compute the modal frequency responses, extract the strain value at the sensor location and orientation and derive the damage indicators. Results are automatically generated and consist of plots and pictures of the structure including the DI values at the sensor network, depending on the damage indicator applied.

2.2 Modal strain energy damage indicator

Based on the modal strain response measured by the sensor network in the reference and current (damaged) state, several DIs can be determined. Papers [1] and [2] each provide a good overview of developments in the field of vibration-based damage identification methods. The changes in natural frequencies are very small for small damages and as such not very suitable to detect damage. This is also true for the changes in mode shapes and modal assurance criterion. Moreover, it is also complicated to extract the damage location for these indicators. The modal strain energy (MSE) criterion on the other hand is much more sensitive to small changes in the stiffness of the structure making it a suitable indicator to detect smaller damages. Furthermore, the damage location is directly provided as well, see section 2.3.3.

Stubbs [3] formulated the modal strain energy damage indicator and successfully applied it to a steel bridge using a beam formulation. The MSE is given by:

$$U_i = \frac{EI}{2}\int_0^l \left(\frac{\partial^2 \varphi_i}{\partial x^2}\right)^2 dx \qquad (1)$$

in which *EI* is the flexural rigidity, *l* the length of the beam and φ_i the i-th mode shape in terms of displacements.
Cornwell [4] later on used a plate formulation:

$$U_i = \frac{D}{2}\int_0^b \int_0^a \left(\frac{\partial^2 \varphi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \varphi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \varphi_i}{\partial x^2}\right)\left(\frac{\partial^2 \varphi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \varphi_i}{\partial x\, \partial y}\right)^2 dx\, dy \qquad (2)$$

in which *D* is the bending stiffness of the plate $D = Eh^3/12(1-\nu^2)$, *a* and *b* the plate dimensions and ν the Poisson's ratio. The last term in (2) corresponds to twisting of the plate and the other terms to pure bending of the plate.
The second derivatives represent the curvature in x-, respectively, y-direction and are represented by the strain in the corresponding directions. In a real application the measured signal has a noise component. Therefore, if the displacement φ is measured this causes significant numerical problems in calculating the second-order derivatives, certainly for a coarse sensor network. To avoid this, a sensor directly measuring the strain, like an FBG, is highly preferred.

The formulation of Stubbs is limited to one-dimensional curvature, but has successfully been applied to 2D and 3D structures as well, which essentially is application of the formula of Cornwell and neglecting all the terms which are not measured. This also applies to a SHM system of FBGs for a 3D structure where each sensor only measures the strain in one direction.

Various authors, [3] to [7], have demonstrated that the modal strain energy damage index (MSE-DI) is one of the most promising indicators. Especially in the lower frequency range corresponding to global modes, damage can cause a distortion of the displacement and strain field in a larger area.
By subdividing the structure in *n* regions, the above formula can be obtained by summing the contributions U_{ij} of all the regions, where U_{ij} is the modal strain energy associated with sub-region *j*.
The damage index (MSE-DI) is now given by:

$$\beta_j = \frac{\sum_{i=1}^{m} \frac{U_{ij}^d}{U_i^d}}{\sum_{i=1}^{m} \frac{U_{ij}^u}{U_i^u}} \tag{3}$$

which is the ratio of the sum of the fractional energy for the *m* lowest modes in a sub-region of the damaged and undamaged structure. This formulation does not require any normalisation of the modes. It is indirectly assumed that the individual modes can be determined, which restricts the method to the low frequency domain having a low modal density. Variations in the definition of the MSE-DI can be found in [8].

The β_j can be further normalised by assuming that the β_j values for the different sub-regions are normally distribute:

$$z_j = \frac{\beta_j - \mu_\beta}{\sigma_\beta} \tag{4}$$

The value of *z* represents the number of standard deviations away from the mean μ_β. For larger values ($z > 2$) this provides an indication of the presence of damage.

2.3 Application

2.3.1 Composite fuselage panel

In this section the SHM design tool is demonstrated on a composite panel depicted in Figure 3 developed by Airbus. The panel is 1.0 m long and 0.8 m wide and consists of a composite skin with 4 hat-stringers and 2 aluminium Z-frames with additional reinforcements (green colour) at the edges for testing purpose. Material properties are proprietary. The applied boundary conditions are depicted in Figure 3 in red. The panel is fully clamped at its edges. The edges of the frames and four edge clips are constrained in the radial and angular direction. A finite element shell model was built in Abaqus depicted in Figure 4. The complete mesh consists of 77114 nodes and 74796 linear quadrilateral shell elements with a total of 462684 degrees of freedom.

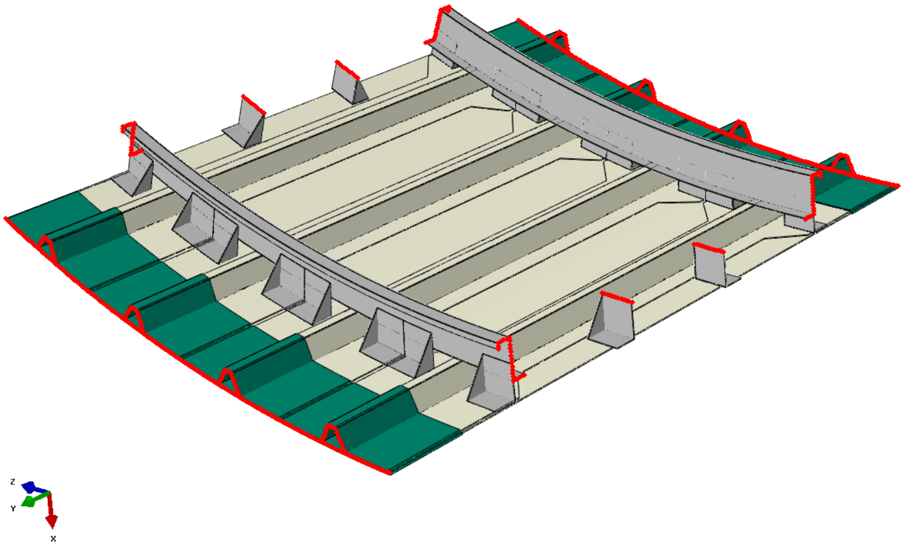

Figure 3: Airbus composite fuselage panel

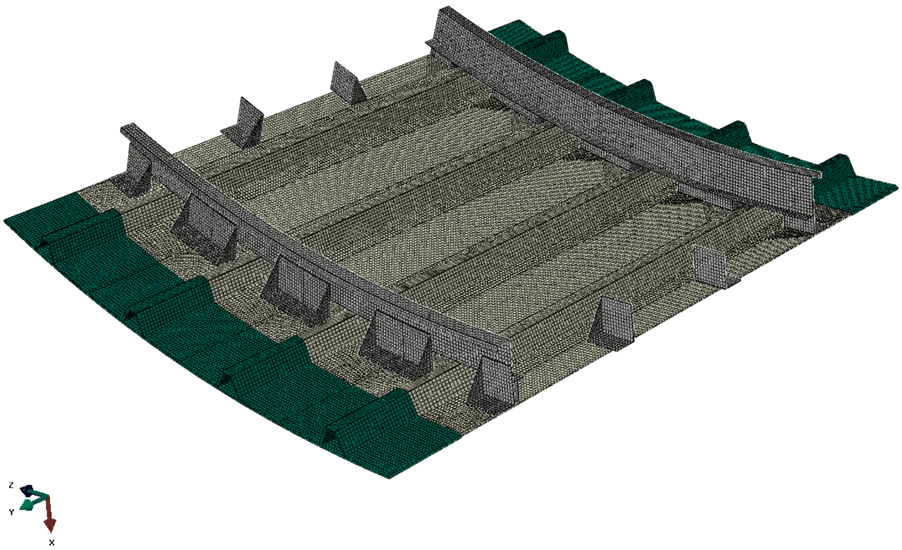

Figure 4: FE model of the composite fuselage panel

2.3.2 Modal properties

The eigenfrequencies of the undamaged panel up to a 800 Hz, taken into account in the damage analyses, are listed in Table 1. Three different mode shapes can be distinguished: skin modes showing deflection of the skin, frame modes showing mainly deflections of the frames and edge modes showing deflections of the skin edge only. Figure 5 shows the first 4 lowest skin mode shapes. Figure 6 shows an example of a frame and edge mode shape, which are both not relevant for the damage detection and left out.

Table 1: Top fuselage panel eigenfrequencies

Mode	Frequency		Mode	Frequency	
1	274	Skin	17	592	Edge
2	276	Skin	18	594	Edge
3	354	Skin	19	600	Edge
4	370	Skin	20	616	Frame
5	381	Frame	21	629	Frame
6	399	Frame	22	644	Frame
7	458	Skin	23	692	Skin
8	493	Frame	24	696	Skin
9	513	Edge	25	710	Skin
10	538	Edge	26	719	Skin
11	541	Edge	27	729	Frame
12	548	Edge	28	746	Frame
13	550	Edge	29	749	Frame
14	560	Skin	30	765	Frame
15	587	Edge	31	783	Frame
16	592	Edge	32	794	Frame

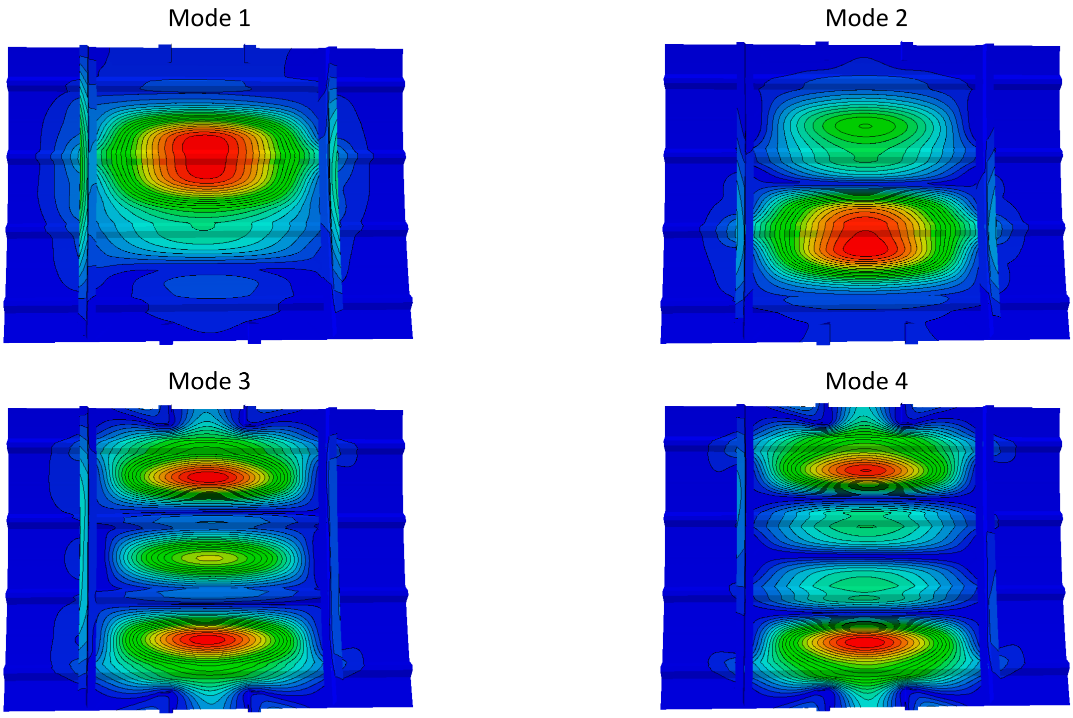

Figure 5: First 4 skin mode shapes of top fuselage panel

2.3.3 Damage scenarios

With the SHM damage detection design tool presented in section 2.0, the effectiveness of a number of sensor networks in detecting damage was analysed. Within the project it was decided that the main objective was the detection of skin-stringer debonds and to install surface mounted FBG sensors, enabling the replacement of broken fibres, on both lower feet of the two middle stringers (i.e. 4 optical fibres), oriented in the direction of the stringer measuring the strain in flight direction, see Figure 7. This corresponded to the situation in a test set-up. The only remaining choice was the number of FBG sensors per bay area. The requirement was that the sensor network should be able to reliably detect a stringer debond of 20 mm over the full width in one of the middle stringer feet. Analyses revealed that 8 FBG sensors per bay (i.e. one optical fibre per stringer foot) area sufficed. Normally FBG sensors would be installed on the two outer stringers as well. Additional simulations have been run for such a full sensor network, which could successfully detect all damages. Initial test results on a fuselage panel show that a vibration energy level of 4 to 7 g suffices to derive suitable frequency response functions from FBG time data.

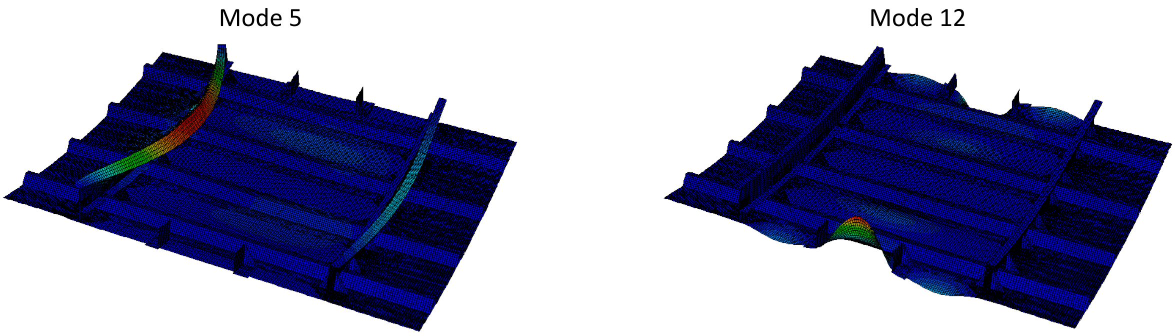

Figure 6: Example of a frame and edge mode

Due to symmetry of the structure, only damages in a quarter of the panel needed to be evaluated. The stringer debond locations were all selected in between the sensors, being hardest to detect. A stringer debond is modelled by a local decoupling of the stringer feet from the skin of the panel.

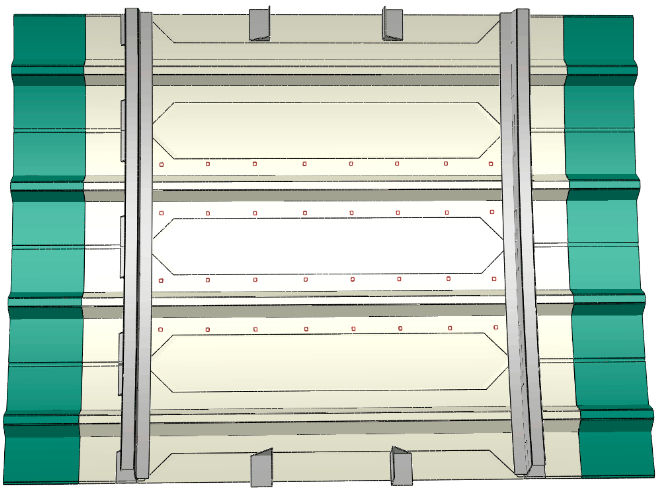

Figure 7: FBG sensor network (red dots) consisting of 4 optical fibres with each 8 FBG sensors

Figure 8 is an example picture for a stringer debond scenario that is automatically generated by the SHM design tool. The dark grey area represents the stringer debond area. The figure depicts the values of the MSE-DI for the different FBG sensors. The red-coloured sensor shows a MSE-DI value more than 5 standard deviations away from the mean, correctly signalling the presence and location of the damage. Some other nearby sensor might show a significant (e.g. $|z| < 2$) MSE-DI response as well. The lower insignificant values are filtered out of the plots to improve readability by the operator.

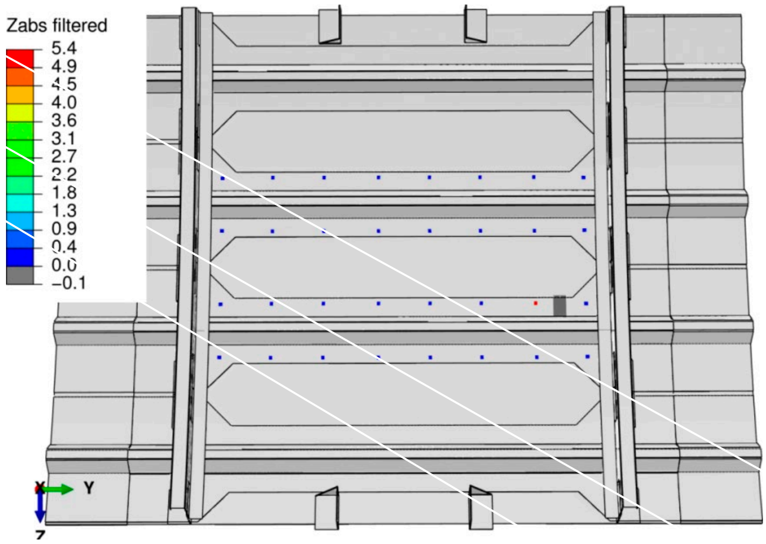

Figure 8: MSE DI at the FBG locations (coloured dots) for a skin-stringer debond (dark grey area)

For all locations along the stringers a 20 mm debond over the full foot width was simulated. Figure 9 shows the results for all middle stringer debond scenarios, which are all correctly detected by one or two nearby sensors. To improve visibility, only part of the panel is depicted. As indicated above, normally FBG sensors would be installed on both outer stringers as well.

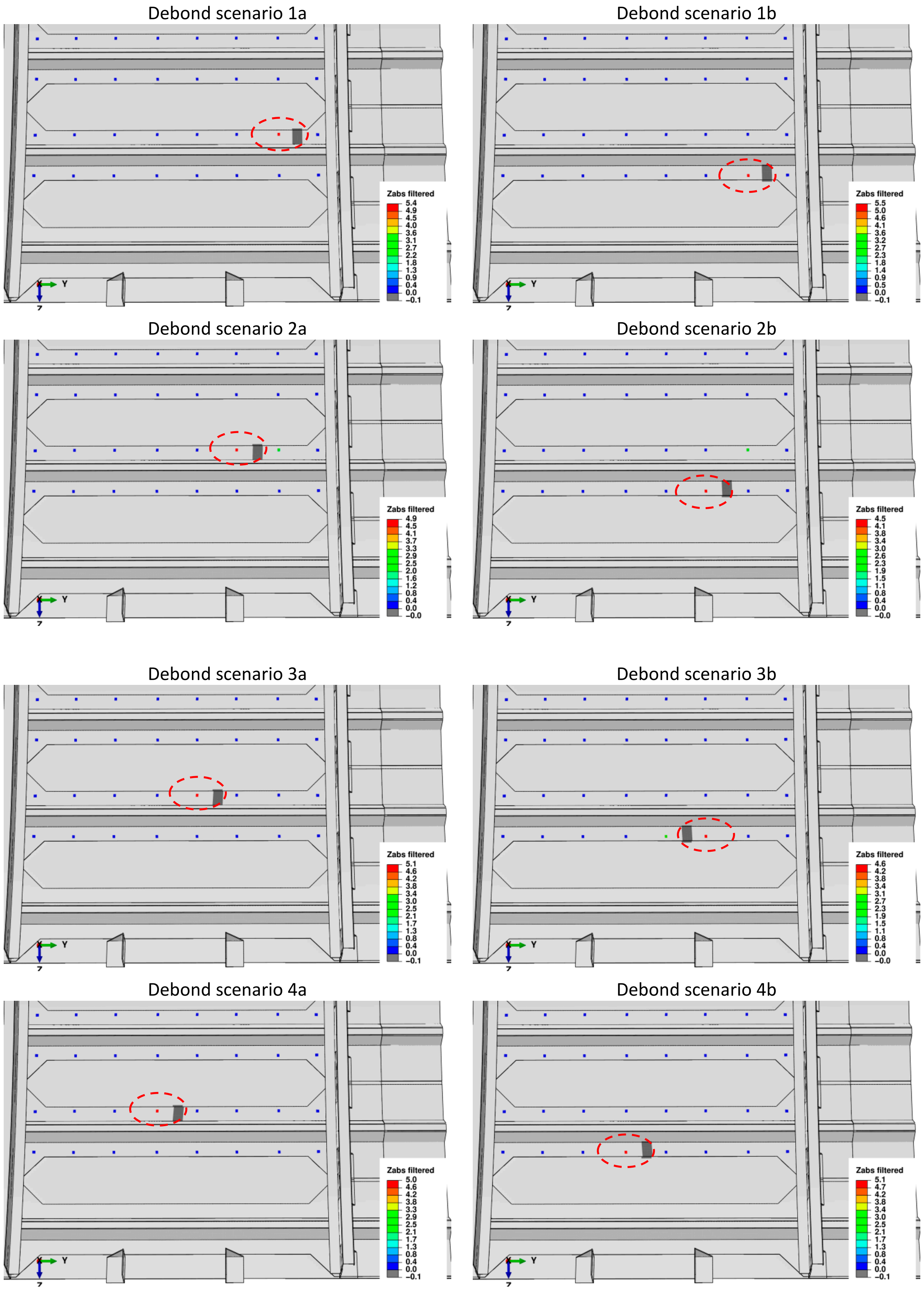

Figure 9: Modal strain energy damage indicator for the middle stringer scenarios

3 Probability of Detection

3.1 Approach

The previous analyses results are based on the assumption that even small strains can be measured very accurately without any noise component. In reality this will not be the case and noise will be present in the FBG time signals. Most of this noise will be averaged out by transferring to the frequency domain, by taking a time-average, of which the results are used to compute the damage indices. However, due to the remaining noise some damages may go undetected in reality. The signal-to-noise ratio (SNR) present in a realistic application may be simulated by adding a noise error component to the computed responses. Other sources of uncertainty can in principle be added as well. The noise component influences the SHM system accuracy and reliability in detection of a damage before it becomes critical. This can be characterised by the system's POD, expressing the chance to detect a damage of a certain size within the structure, which is an important quantity for the certification of the SHM system.

In manually operated NDI methods the operator plays an important role in the reliability of the system to detect a damage, i.e. in the chance of detecting a damage of certain size. For an NDI system the reliably detectable damage size is defined as the size that can be found with a 90% probability and 95 % lower confidence level. Besides the capability of the NDI system this, amongst others, depends on the training level, experience and alertness of the inspector. The human factor hereby plays an important role. Damages can be found or missed and based on a population of damage sizes found and missed a POD distribution function can be determined [9]. Constructing such a statistical data set is expensive. Various test articles representative of the structural detail must be manufactured containing damages of various sizes sufficiently mimicking operational conditions. These have to be inspected by several inspectors yielding the final data set.

In case of a SHM system the same principle can be applied. However, the human factor is no longer present. Missed cracks are only due to the capability and accuracy of the system in finding a damage of certain size at a certain location. For instance, a damage located further away from a sensor will in general be harder to detect than a nearby damage. A SHM system consists of a network of sensors and signal processing capability designed for a specific structure. To determine the detection capability, the complete structural component now has to be manufactured instead of a representative part in case of a manual NDI system. Within one test structure various damage locations can be examined in which the damage size per location can be gradually increased to generate different size data as well. Nevertheless, several of these components are necessary to obtain a sufficiently large statistical data set. Experimental validation of the detection capability of a SHM system is therefore very expensive.

On the other hand, in the absence of the uncertain human factor, which is hard to model, the detectability can to a large extent be computed. Such a model assisted approach, in which the damage detection is simulated, can alleviate the costs significantly and only requires a limited amount of experimental data for validation of the numerical analyses.

To simulate this, a probabilistic framework has been set-up to determine the probability of detection (POD), as indicated in Figure 2. For a given sensor network damages of random size and location are generated throughout the structure. For the latter a predefined area can be specified where damages are expected to occur, as well as a damage range.

A white noise error component is added to the computed responses in the frequency domain ε_{sim} to simulate a signal-to-noise ratio (SNR) present in the time signal in a real application. Here it is assumed that the error scales with the magnitude of the response peak in the FRF and can be easily adapted:

$$\varepsilon = \varepsilon_{sim}(1 + random.\,Gauss(0.\,, \epsilon)) \tag{5}$$

The noise component is assumed to have a standard normal distribution.
The result of the probabilistic simulation is a similar data set of found and missed damage sizes as in the case of an NDI system. Based on this hit-miss set a POD distribution can be fitted [9]. The POD curve can be used in the SHM design to optimise the number and position of the sensors.

3.2 Application

A simulation was run for 250 randomly generated skin-stringer debond damages for four different noise levels, equal to three times the standard deviation of the Gaussian distribution: 5, 7, 10 and 15%. The damages were random in location and in size (over the full width, according to the requirements) along the four stringer feet. Figure 10 shows a plot with all first 100 randomly simulated debonds. The colour indicates the order of the damage from blue to red. A damage was only considered detected when the nearest sensor showed the highest DI value, i.e. the damage should be found by an NDI inspection afterwards covering an area around the sensor of half the sensor distance. The resulting hit-miss data was subsequently used to determine a distribution fit by means of the maximum likelihood estimation, depicted as the blue-line in Figure 12 for a 7% error. The red-lines represent the 95% lower and upper confidence bound, which will narrow for increasing number of simulations. Figure 10 shows the POD curve as a function of the error. For a 10% error the SHM system is able to detect a damage of 20 mm in size, as indicated by the requirements, with a 90% probability, corresponding to the detectable crack size in an NDI system.

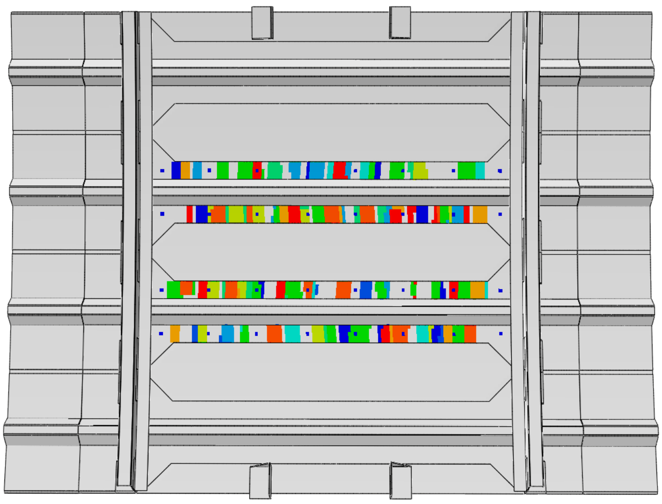

Figure 10: First 100 randomly simulated debond damages

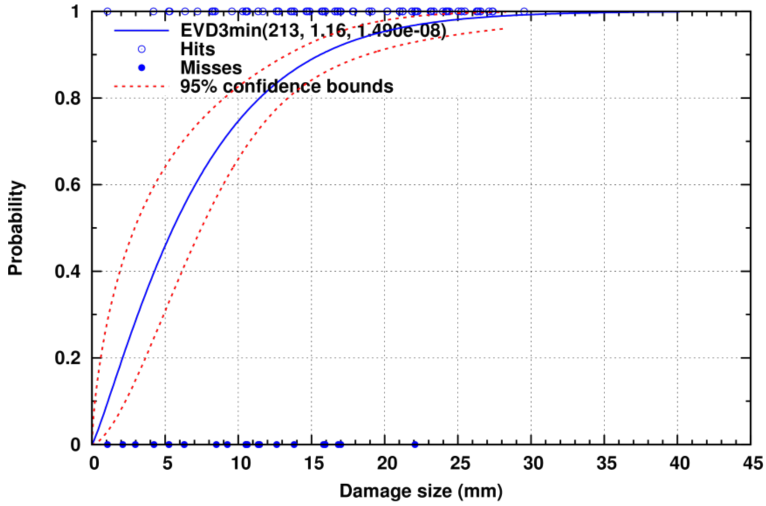

Figure 11: Computed POD distribution for a 7% error

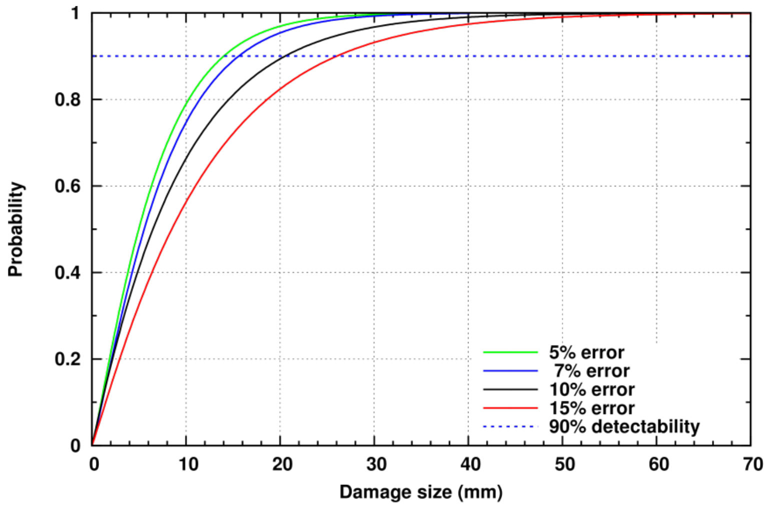

Figure 12: Computed POD distribution as function of the percentage error in the FRF peaks

4 Conclusions

A SHM design tool was presented with which an optical FBG sensor network can be quickly designed for any structure. The damage indicators are based on the changing modal characteristics between an initial and a damaged state. Results were shown for a four stringer aircraft fuselage panel of successful detection for different damage scenarios. An approach was presented and applied to the same panel to determine the detection capability of the SHM system reflected by the Probability of Detection curve, for an error present in the measured response signals.

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