Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Damage detection and probability of detection for a Structural Health Monitoring system based on optical fibres applied to a stiffened composite panel

Problem area
Aircraft require regular costly inspections to guarantee their safety. During the last century, 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 the undamaged state and the current damaged state. 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.

Description of work
A SHM system design tool is presented with which the number and position of optical sensors can be determined for a general composite or metallic structure to enable the detection of damage. The damage detection algorithm is hereby based on a modal approach and is able to detect the presence and location of the damage. The SHM design tool is highly automated and allows for automatic damage insertion in the finite element model, which is a requirement for a fast design.
A numerical approach is presented and applied to the stiffened panel to determine the damage detection capability (reliability) of a SHM system.

Results and conclusions
Results were shown for a three stringer aircraft panel of successful detection for different damage scenarios, even for small damages. 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, assuming a signal-to-noise ratio.

Applicability
The SHM system design tool is implemented around the finite element tool Abaqus and can therefore be applied to a wide range of problems for which a SHM system has to be designed based on strain sensors

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Damage detection and probability of detection for a Structural Health Monitoring system based on optical fibres applied to a stiffened composite panel

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Summary

In this paper a SHM system design tool is presented with which the number and position of optical sensors can be determined for a general composite structure to enable the detection of damage. The damage detection algorithm is hereby based on a modal approach and is able to detect the presence and location of the damage. The SHM design tool is highly automated and allows for automatic damage insertion in the finite element model, which is a requirement for a fast design. The tool is demonstrated on a stiffened composite aircraft like panel for which several damage scenarios are analysed, such as stringer debonding and impact damage. A numerical approach is presented and applied to the stiffened panel to determine the damage detection capability (reliability) of a SHM system.

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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 century, 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 operational availability. For this, various types of sensors exist to monitor the condition of the structure and to signal in time 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.

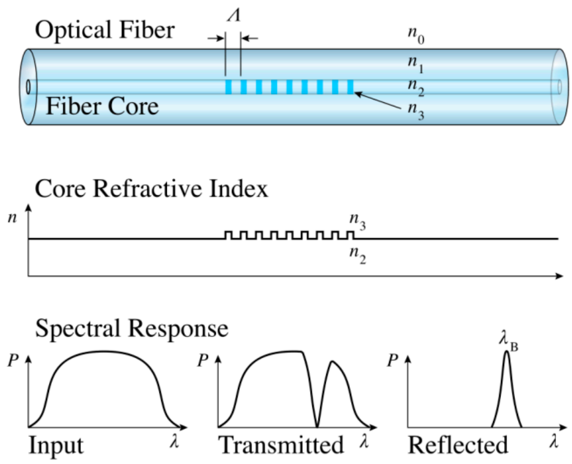


Figure 1: Principle of a Fibre Bragg Grating sensor, from Wikipedia

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, although these can be operated in the mid to high frequency range as well.

In this paper a SHM system design tool will be presented with which the number and position of the optical sensors can be determined for a general composite structure 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 herein is based on a modal (vibration) approach and is able to detect the presence and location of the damage. The damage size can be determined as well but only when a large number of sensors is applied. 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. The objective therefore is to minimise the number of sensors.

The SHM design tool is highly automated and allows 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 stiffened composite aircraft panel for which several damage scenarios are analysed, such as impact damage, stringer debonding or a combination of both. Stringer debonding is believed to be a promising application 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 will be presented and demonstrated for the stiffened composite panel, including its confidence

bounds. 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 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.
The paper addresses the SHM design tool in chapter 2 including an application on a three stringer aircraft panel. In chapter 3 the model assisted POD characterisation is described and applied to the same stiffened 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 are altered due to the presence of damage causing local changes in the stiffness of the structure. For both states the modal frequency response is calculated for the lowest modes at every sensor location for a given sensor network. In a real application the frequency 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 (OMA).
The FBG sensor measures the strain in the direction in which it is oriented. 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) are determined. Examined damage indicators are:

- Changes in natural frequencies
- Changes in mode shapes
- Changes in modal assurance criterion
- Changes in modal strain energy

Depending on the value of the damage indicator, damage is signalled or not. As will be demonstrated in section 2.3, the changes in natural frequencies are small for small damages and as such not very suitable to detect small damages. This is true for the changes in mode shapes and modal assurance criterion as well. Moreover, it is also complicated to extract the damage location for these indicators.

The modal strain energy 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 small damages. Furthermore, the damage location is directly provided as well, see section 2.3.3.

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 a damaged area. Furthermore, damaged material properties have to be specified in case of impact damage for impacted region. Based on the polygon description, the elements inside and/or overlapping the polygon are assigned damaged material properties.

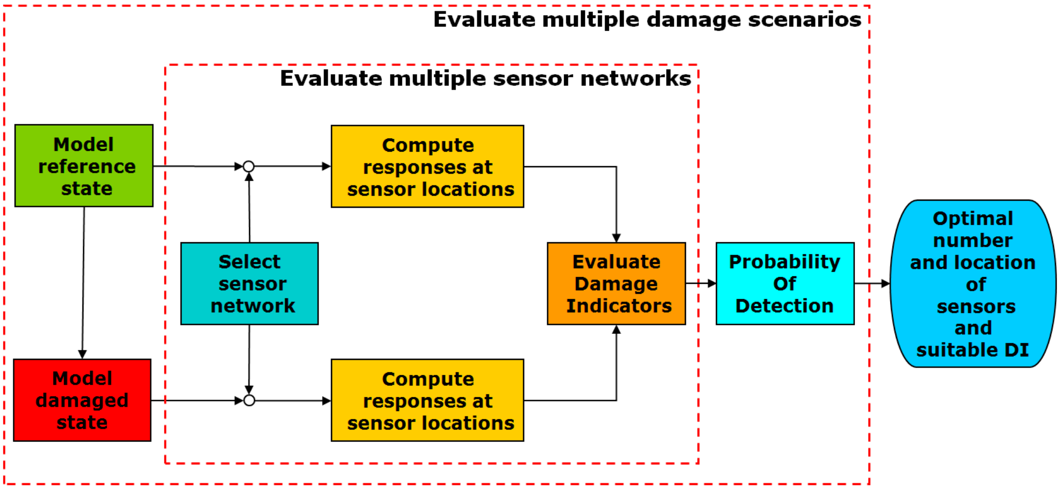


Figure 2: Flow diagram of the SHM design tool

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 fully automatically insert the (impact, debond) damage in the finite element model, even for complex models, and as such generate the damaged model, compute the modal frequency responses, extract the strain value at the sensor location 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

Papers [1] and [2] each provide a good overview of developments in the field of vibration-based damage identification methods. One of the methods is the modal strain energy. Stubbs [3] formulated the modal strain energy damage indicator and successfully applied it to a steel bridge using a beam formulation. The modal strain energy (MSE) is given by:

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

in which *EI* is the flexural rigidity, *l* the length of the beam and φ_i the i-th mode shape. Cornwell [3] later on used a plate formulation:

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

where D is the bending stiffness of the plate given by $D = Eh^3/12(1-\nu^2)$, 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. 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 (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.
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.
Various authors, [3] to [8], have demonstrated that the modal strain 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.

2.3 Application

2.3.1 TAPAS stiffened panel

In this section the SHM design tool is demonstrated on a composite panel depicted in Figure 3 developed by Fokker Aerostructures in the TAPAS (Thermoplastic Affordable Primary Aircraft Structure) project. The panel is made of thermoplastic material. Thermoplastics are polymers consisting of macromolecules which are held together by weak secondary bonds. A thermoplastic will never reach a fully crystalline state, but the material is at most semi-crystalline. Sophisticated thermoplastic polymers can withstand high temperatures and show good mechanical properties. The high-performance and ultra-polymers, such as polyphenylenesulfide (PPS), polyetheretherketone (PEEK) or polyetherketoneketone (PEKK) are therefore typically used in fibre reinforced parts for aerospace applications. The strength and stiffness in the composite is provided by reinforcing fibres, for instance glass or carbon. The thermoplastic matrix material binds the fibres and transfers loads between the fibres.
The advantages of thermoplastic composites over their thermoset counterparts are improved fracture toughness, potential for recycling and the possibility to reshape or remould the product

at elevated temperatures. Thermoplastic composites enable a much more complex geometry in combination with rapid processing techniques, such as stamp forming or rubber pressing, as well as novel high-tech bonding techniques such as induction welding and ultrasonic welding. Also the material has excellent fire, smoke and toxicity performance.
The TAPAS panel consists of a tailored skin with varying thickness as depicted in Figure 4. A finite element shell model was built in Abaqus depicted in Figure 5, where the different colours denote the various layups. The thickness varies from 8.14 mm (59 layers) to 5.24 mm (38 layers). Inhere free boundary conditions are applied, but simply supported and clamped have been analysed as well, providing similar results. The mesh consists of 9417 nodes and 8882 linear shell elements with a total of 56502 degrees of freedom.

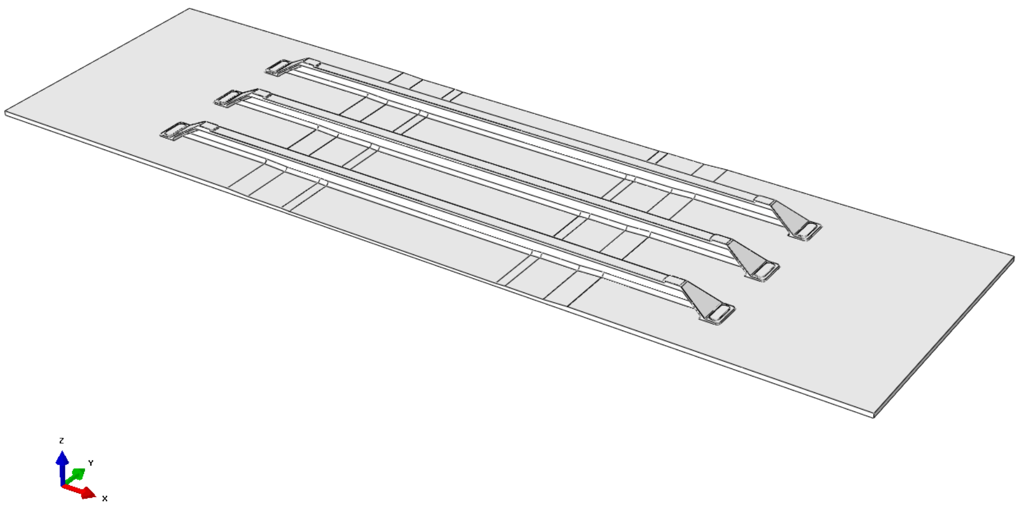


Figure 3: 3-stringer thermoplastic composite panel

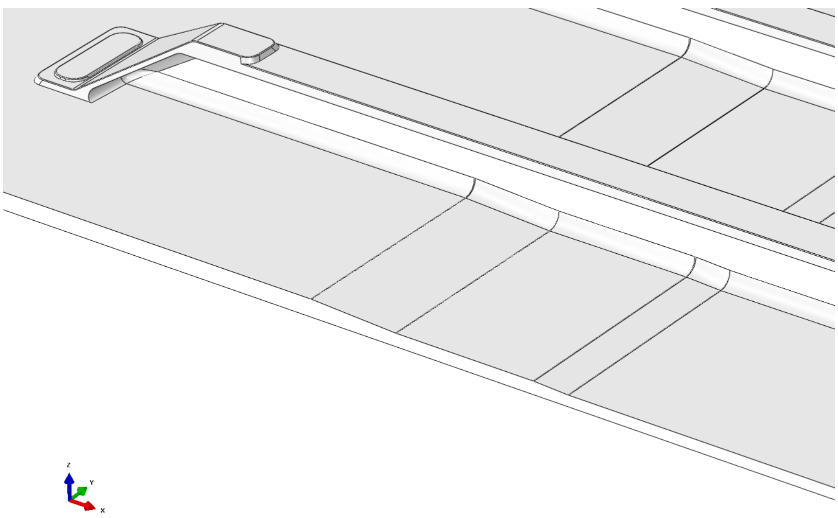


Figure 4: 3-stringer thermoplastic composite panel detail

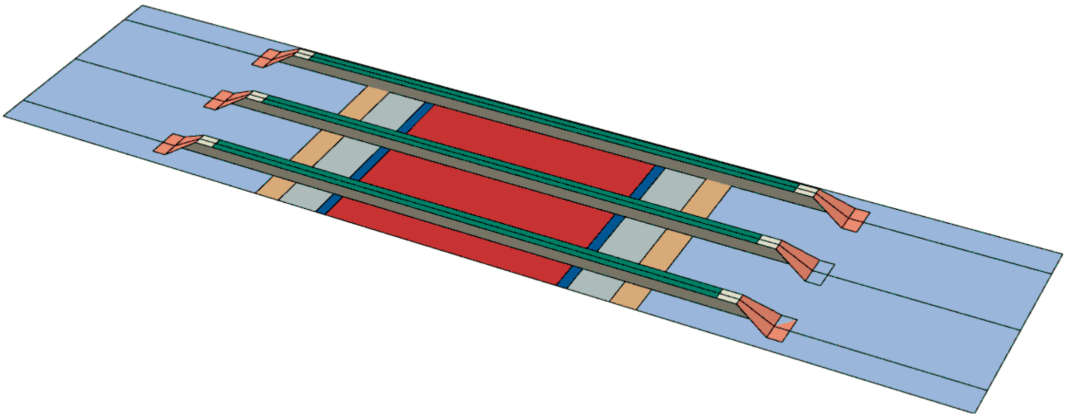


Figure 5: FE model of 3-stringer thermoplastic composite panel

2.3.2 Modal properties

The eigenfrequencies of the undamaged panel are listed in Table 1, up to 1000 Hz. This is the frequency range taken into account in the damage detection. Figure 6 shows the corresponding first 8 lowest eigenmodes.

Table 1: TAPAS panel eigenfrequencies

Mode	Eigenfrequency	Mode	Eigenfrequency
1	38.2	15	548.1
2	58.3	16	605.6
3	101.0	17	635.5
4	127.0	18	653.8
5	184.1	19	680.9
6	202.3	20	738.0
7	273.1	21	744.7
8	285.1	22	798.2
9	331.6	23	834.7
10	359.1	24	849.9
11	376.5	25	913.2
12	443.5	26	926.4
13	453.0	27	967.0
14	498.2	28	990.9

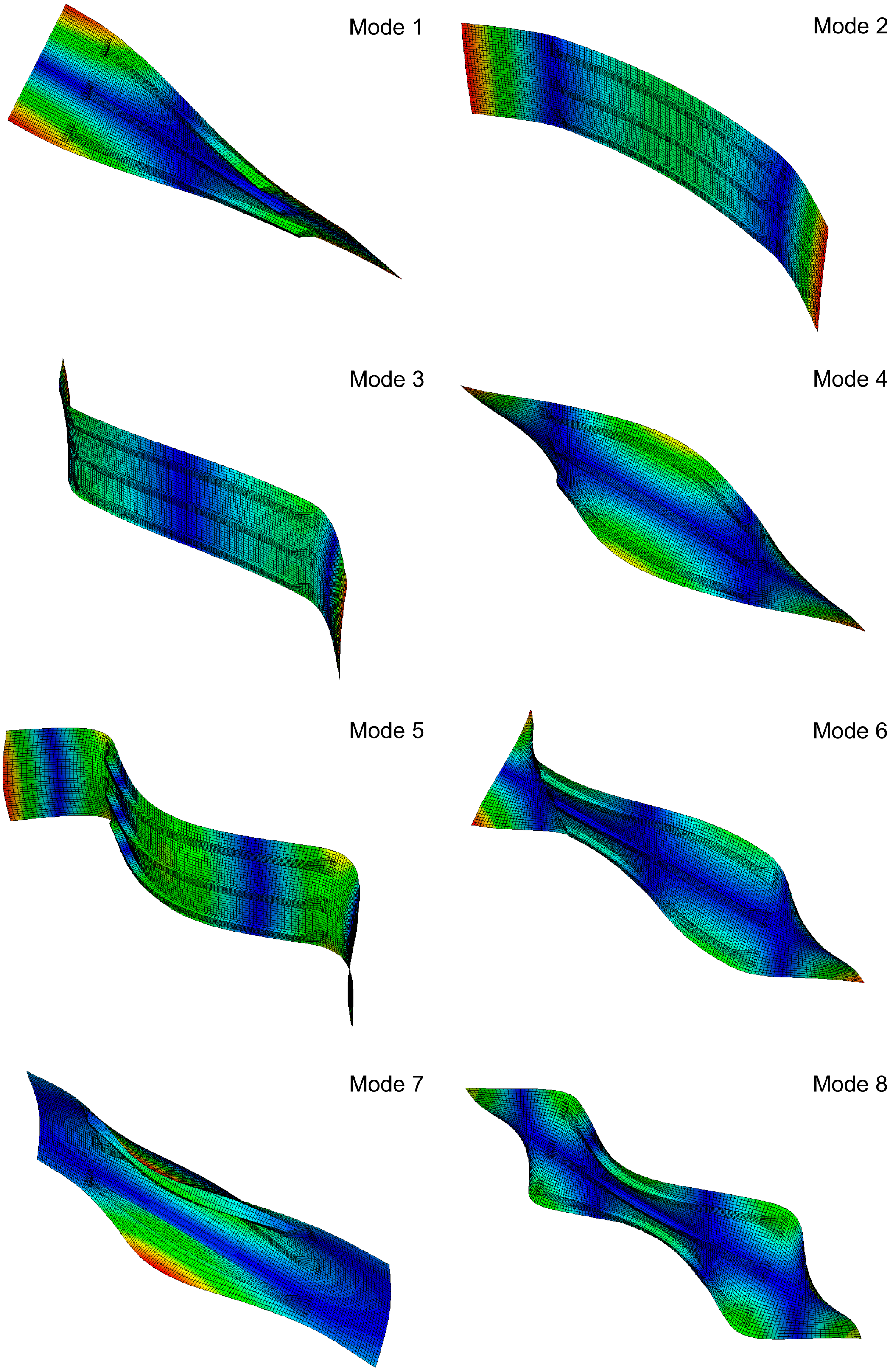


Figure 6: First 8 mode shapes of the 3-stringer thermoplastic composite panel

2.3.3 Damage scenarios

With the SHM design tool the effectiveness of various sensor networks in detecting damage can be easily examined. Sensor networks were analysed consisting of 3, 4 and 5 optical fibres times 8 FBG sensors per fibre, different FBG directions (0º, 90º, ply direction), surface mounted or embedded at different thickness fractions or plies.

In all cases several damage scenarios were analysed:

1. Stringer runout debonding
2. Stringer debonding away from the runout
3. Single skin impact damages
4. Impact of a stringer without debonding
5. Impact of a stringer with debonding
6. Impact after a previous debond
7. Debond after a previous impact
8. Double impact damages

The first five scenarios are different single damages consisting of a debond, an impact or a combination of both. Scenario 6 and 7 are to examine whether a new damage can be detected after a previous damage. The previous damage situation then becomes the new initial state and can for example represent a repaired structure. Scenario 8 consists of two simultaneous impacts to examine the capability of the SHM system in detecting both damages. An important area for application of a SHM system based on optical fibres is hot-spot monitoring. Debonding of the stringer run-out is an example of such an application.

In case of a stringer debonding the damage is modelled by a local decoupling of the stringer from the skin panel. An impact damage is modelled by a reduction in the local stiffness properties of the material(s). The user can specify the material properties of the damaged material. In the analysis presented in here a 25 % reduction in the modulus of elasticity as well as the shear modulus is assumed.

In all scenarios, the sensors are surface mounted at the inside of the panel (inside the aircraft) and oriented in the x-direction, see Figure 8, i.e. measuring the strain in this direction.

Figure 7 depicts the corresponding frequency shift, which is less than 1 Hz for most of the eigenmodes and as such not very sensitive.

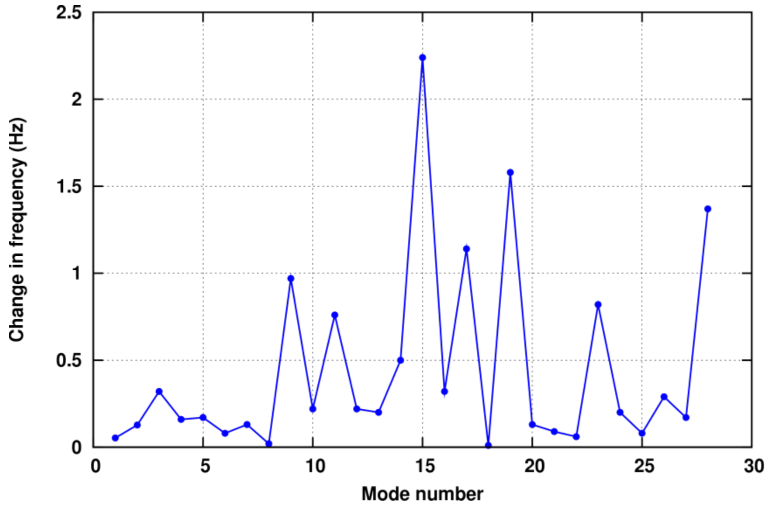


Figure 7: Frequency shift for stringer runout debonding, 3x8 sensors

In Figure 8 a typical automatically generated output result is shown for the MSE DI for a FBG sensor network consisting of 3 optical fibres with 8 FBGs each running along the stringers. The dark grey area indicates the debonded area and the coloured elements denote the location of the sensors inside the element. The colour refers to the value of the damage indicator. A sensor near the damage is signalling a high value of 4.6 indicating the presence and location of damage.

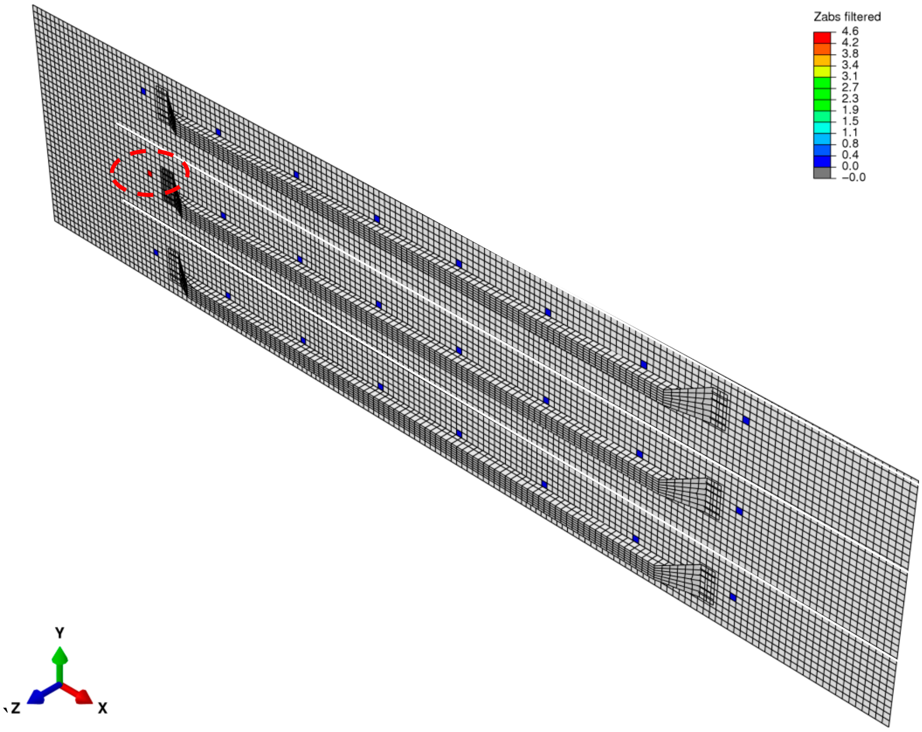
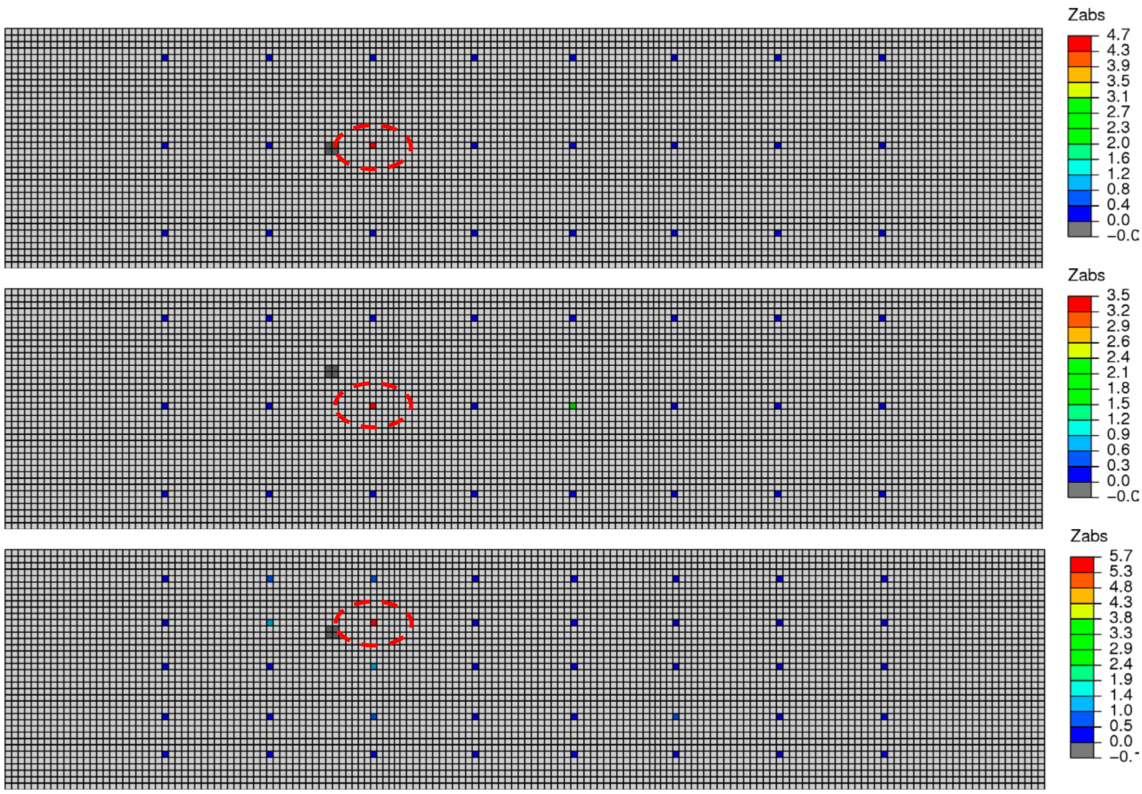


Figure 8: MSE DI for stringer runout debonding, 3x8 sensors

Figure 9 shows the results for a number of other scenarios for the same sensor network. The stringers have been left out for visibility. The first picture shows the MSE DI for a small stringer debond away from the runout (located at the grey area). The red sensor again correctly signals the debond. The second picture reflects a small impact damage. The third picture is the same impact damage, but now with a finer sensor network (5x8) showing a more pronounced (5.7 instead of 3.5) MSE DI value at the damage location. The fourth picture is a similar case, but now a previous runout debond of Figure 8 is present defining a new initial state. Picture five shows a stringer runout debond after a previous impact damage. The sixth picture reflects a double impact scenario in which both damages are detected. In all cases the SHM system is capable to correctly detect the damage. Some other nearby sensor might show some response (green colour) as well. These lower insignificant values (e.g. z < 2) can be filtered out of the plots to prevent a wrong interpretation by the operator.
The numerical results show that damage detection can be successfully accomplished even for small damages and low number of sensors, however, in a realistic application noise will be present on the measurement signal. This is further discussed in section 3.1.



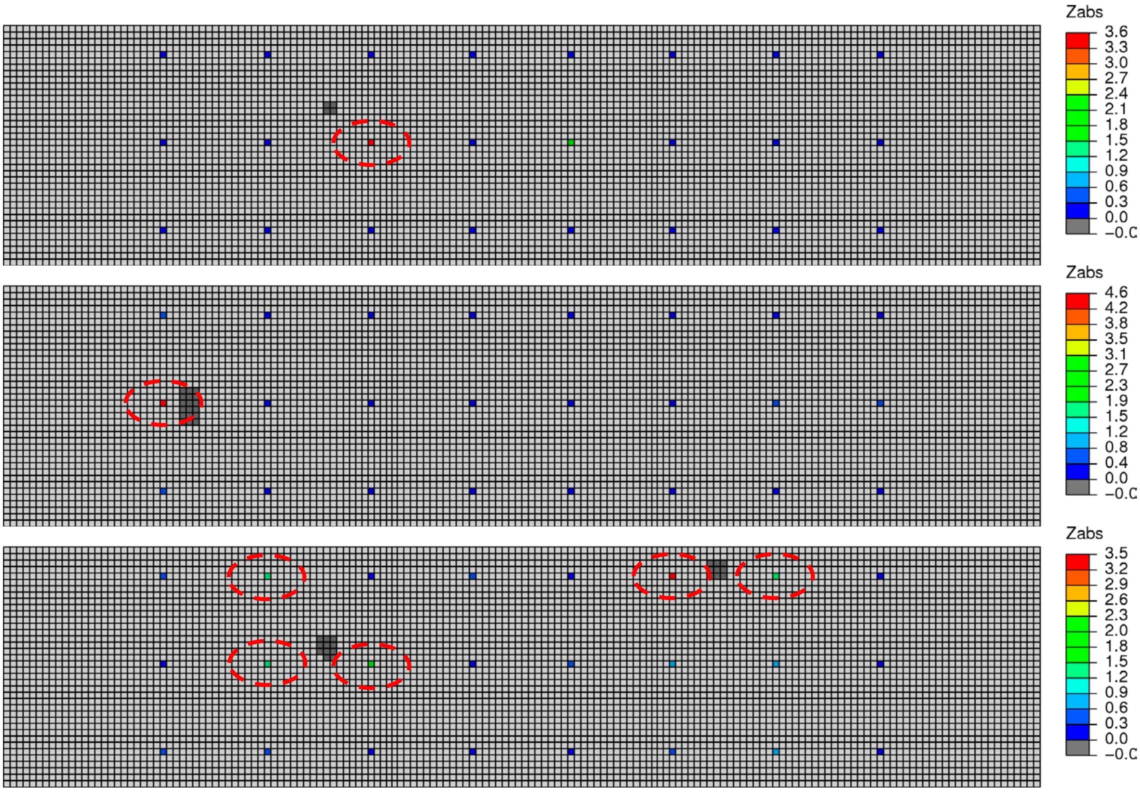


Figure 9: MSE DI for 1) stringer debond, 2 and 3) single impact, 4) single impact after initial stringer runout debond, 5) stringer runout debond after initial single impact, 6) double impact

3 Probability of Detection

3.1 Approach

In manual operated non-destructive inspection (NDI) methods the operator plays an important role in the accuracy of the system, i.e. in the chance of finding a damage of certain size. For an NDI system the reliably detectable damage size is defined as the one 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. 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 structure to be inspected 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 of the system in finding a damage of certain size at a certain location. For instance, a damage located 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 structure now has to be manufactured instead of a representative part in case of a manual NDI system. Furthermore, for each damage location a new structure has to be manufactured in which the damage size can be gradually increased to generate different size data. 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.

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 are randomly generated throughout the structure. For the latter a predefined area can be specified where damages are expected to occur.

A noise component is added to the computed responses ε_{sim} to simulate a signal-to-noise ratio (SNR) present in a realistic application according to:

$$\varepsilon = \varepsilon_{sim}\left(1 + random.Gauss(0.,\frac{1}{SNR})\right) \quad (5)$$

The noise component is assumed to have a standard normal distribution. Other sources of uncertainty can be easily added as well.

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

For the TAPAS panel a first POD analysis is run for a sensor network, as depicted in Figure 10, consisting of 5 optical fibres running in lengthwise direction with 8 FBG sensors per fibre. If a sensor signals a damage then it is assumed that a manual NDI inspection is performed around the sensor to determine its exact location and size. The area in which the NDI inspection is performed is depicted in Figure 10 as well. If the damage is not (partly) located in this area it remains undetected (a miss).

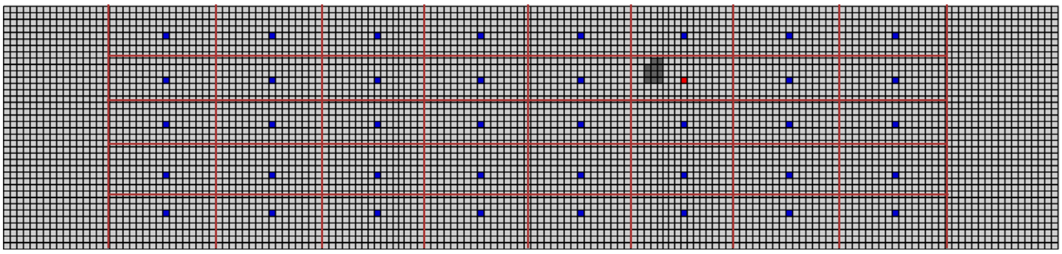


Figure 10: NDI inspection areas per sensor

A simulation was run for 150 randomly generated impact damages. A SNR of 100 was assumed in the analysis. The resulting hit-miss data was subsequently used to determine a lognormal fit by means of the maximum likelihood estimation, depicted as the blue-line in Figure 11. The red-lines represent the 95% lower and upper confidence bound, which will narrow for increasing number of simulations. Figure 12 shows an overview of the randomly simulated damages. The true POD strongly depends on the SNR. In general, the more sensitive the damage indicator the more sensitive it is for noise as well.

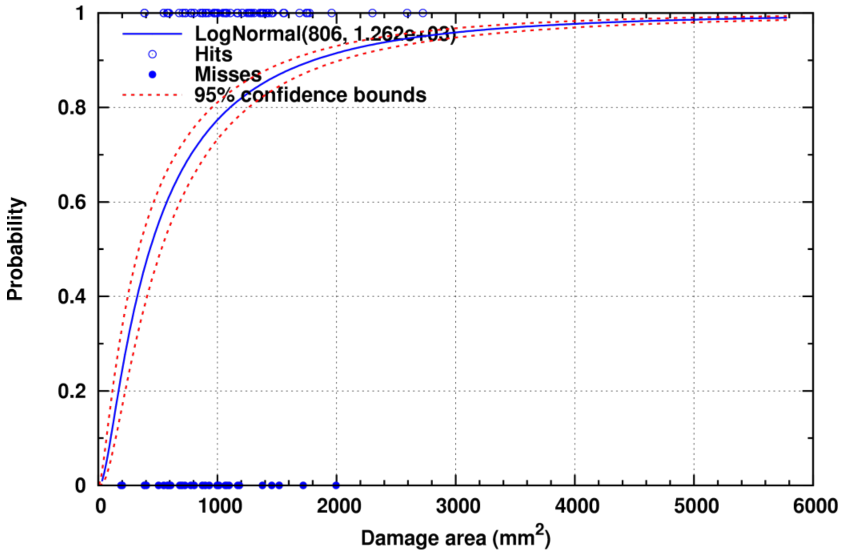


Figure 11: Computed POD distribution for 5x8 sensor network

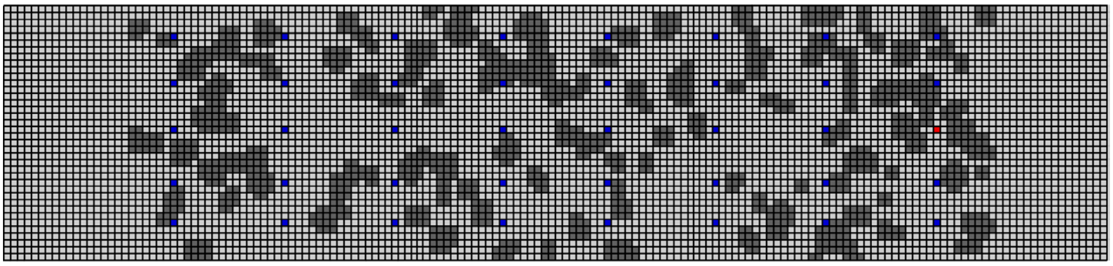


Figure 12: Randomly simulated impact damages

4 Conclusions and outlook

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 three stringer aircraft panel of successful detection for different damage scenarios, even for small damages. 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, assuming a signal-to-noise ratio.
An experimental programme on the TAPAS panel is planned to validate the numerical results presented. The Deminsys interrogator depicted in Figure 13 [10] will be used to obtain the strains from the FBGs. Deminsys is a fast multi-sensor/multi-channel FBG interrogator which can interrogate signals up to 20 kHz with high accuracy of a few micro strain. The applicability of the MSE DI depends on the obtained signal-to-noise ratio that can be reached in a practical application.

Figure 13: Technobis Fibre Technologies Fibre Bragg Grating interrogator

5 Acknowledgements

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