A Scenario-Based Damage Identification Framework

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Abstract
Damage has a direct impact on the modal parameters of structures. However, finding the location and severity of the damage from the modal parameters is a challenging task. This is because damage identification problems are in general highly undetermined, i.e. the number of potential damage locations is much higher than the size of the experimental data set. The presented damage scenario-based framework overcomes this problem by both increasing the size of the experimental data set and reducing the number of investigated damage locations.
The key component of the damage-scenario based approach is an FE-model of the undamaged structure that has been updated in a physically correct way, i.e. no equivalent parameter changes were made to update the model. Such a model can be obtained by correcting the FE-geometry using a high fidelity geometrical description of the test structure, before updating the mass and stiffness parameters. The updated FE-model can provide relevant information on the damage scenarios that can be expected and this for a relatively wide frequency range. Furthermore, as no equivalent parameter changes were made during updating, the updated model can also be used to predict the effect of these damage scenarios on the modal parameters. As such, the damage detection problem can be redefined as a decomposition problem: decompose the observed shift of the modal parameters into the contributions of the considered damage-scenarios.

1. Introduction
Although damage has a direct impact on the modal parameters of a structure, solving the inversion problem, i.e. identifying the location and level of damage from the modal parameters, has proven to be a challenging task. If no prior knowledge is available about the damage location and level then damage identification problems are hard to solve because of the limited size of the experimental data set in combination with a potentially high number of identification parameters. As such, damage identification problems are over-determined identification problems and therefore provide a multitude of possible solutions.

1.1 Traditional Solutions
Increasing the size of the experimental data set is less straightforward as it may seem. Measuring more modes on the structure must be considered although using higher order modes for damage detection requires an FE-model that is capable of predicting those modes in a reliable way. An alternative solution is to increase the number of response locations and thus increase the resolution of the modes shapes. However, this approach reduces the amplitude difference between the modal displacements of two adjacent measurement points and thus decreases the signal-to-noise ratio of derived quantities like modal curvatures that are normally used for damage detection. This problem has been observed by the authors [1] and has been confirmed by others [2].
Using a model updating approach, damage is identified by modifying the element properties in a local, i.e. element-by-element, manner. A reduction of element stiffness is then an indicator for the presence of damage. Threating all the element properties as individual parameters leads to over-determined problems and thus multiple mathematical solutions. The number of updating parameter can be reduced by grouping the elements in sets in which the properties remain homogeneous [1], or by introducing additional relations between the element properties [3]. Although these relations improve the conditioning of the problem, they also reduce the resolution of the damage identification technique. A very local damage might not be detected as it will be 'redistributed' over the area covered by the element set or parameter relation.

1.2 Scenario-based Solution
The damage identification approach suggested in this paper is based on the assumption that there is a priori knowledge about the types of damage that can be expected. In theory, the damage can be located anywhere in the structure. However, most of the damage patterns that are theoretically possible are unlikely to appear in reality. It therefore makes sense to, instead of

grouping or linking the updating parameters in an arbitrary/systematic way, reduce the number of parameters by defining a number of likely or expected 'damage scenarios'. As such the number of identification parameters can be reduced to the number of considered damage cases. The damage identification routine now has to determine the probability that a particular damage scenario is present. Note that a damage scenario can be present with a varying damage level, e.g. the size of a crack. The identification routine should thus indicate the probability that a certain damage scenario is present for each of the considered damage levels. By selecting the right set of damage scenarios the number of identification parameters can be reduced without compromising on the spatial resolution of the damage identification algorithm.

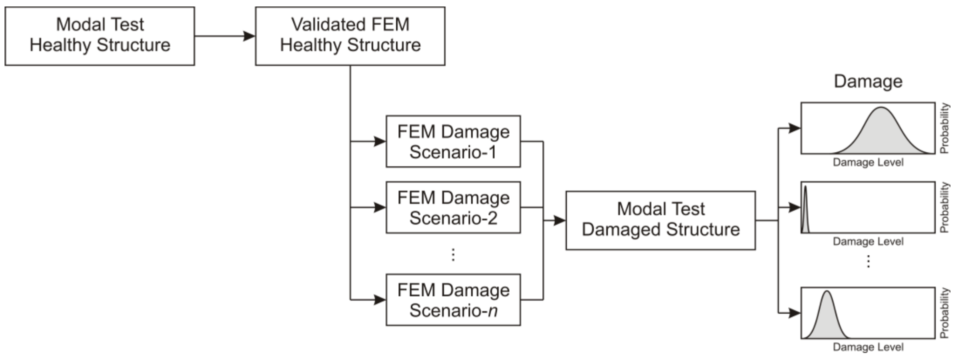


Fig. 1 The scenario-based damage identification technique.

Note that the simulations required to quantify the impact of each damage scenario requires a validated model that was updated without making any equivalent parameter changes. Such a model can also be used to reliably predict the modes in an extended frequency range. This makes it possible to use a higher number of experimental modes and thus further increases the performance of the damage identification routine.

2. The FE-model of the Undamaged Structure

A key step of the scenario-based damage identification technique is the generation of a high-fidelity model of the undamaged structure. Such a model can be obtained using an accurate geometrical description of the considered structure. This section discusses and illustrated the various steps that are required to create a high-fidelity model using a lantern housing. A more detailed description of the process can be found in [4] and [5].

2.1. Measuring the Geometry

The first step consists of obtaining an accurate geometrical description of the structure, as-built. In the case of the considered lantern housing this was done using a combination of optical scanning and photogrammetric techniques. The optical scanning was performed using a GOM ATOS I scanner. Because the lantern housing is too large to fit the scanning volume of the scanner, photogrammetric techniques were applied to combine partial scans. Photogrammetry uses photographical images of multiple marker systems to merge optical scans of different regions of the lantern housing. Fig. 2 shows pictures of the lantern housing during the scanning process. A white spray is applied to reduce reflections. Small marker stickers are used for local optical scanning. Large stickers and two reference bars on the ground are used for the merging software. Triangulation techniques can be applied to reconstruct a point cloud from these images based on the distance and angle between the cameras, the projected grid information and the photogrammetry pictures.

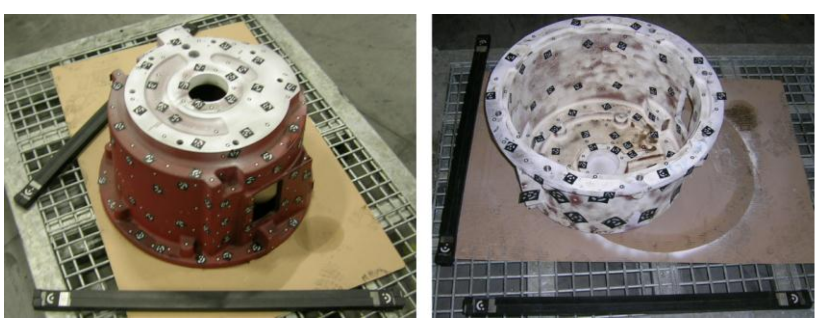


Fig. 2 The lantern housing during the digitizing process.

2.2. Creating the Mesh

2.2.1. Reference Approach

The point cloud data can be triangulated and converted into a triangle facet surface mesh representation. In case of the lantern housing, the minimal geometrical accuracy of this facet model, taking into account scanning and point cloud post-processing, is approximately 0.2 mm. However, the facet model resulting from the digitization process is not suitable to generate an FE mesh because it is not watertight. Therefore, the model was corrected with the STL fixing, design & meshing software package 3-matic [6].

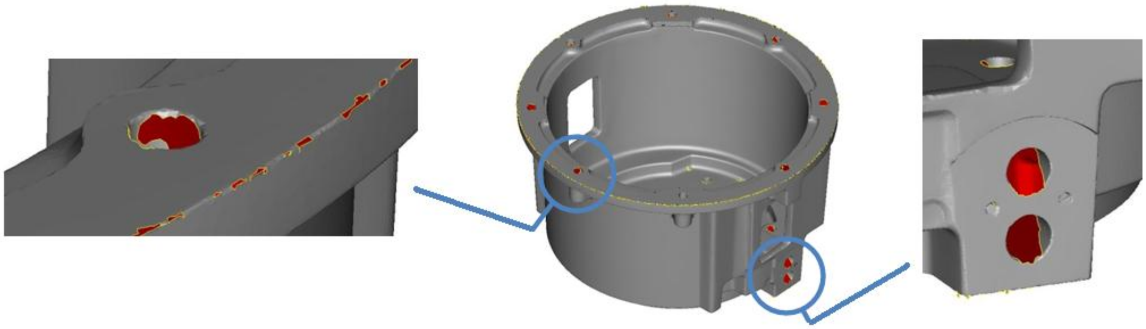


Fig. 3 Detail views of typical scan surface mesh imperfections: non-watertight edges (left) and incomplete hole or slot information (left and right).

Once the facet model is watertight, the enclosed volume can be meshed using as standard tet-mesh generator. A section of the final volume mesh of the lantern housing is shown in Fig. 4.

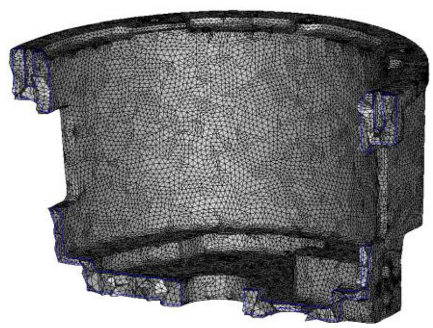


Fig. 4 Resulting 10-noded tetrahedron mesh

2.2.1 Alternative Approach

The procedure described above works fine for damage inspection on a particular piece. However, the procedure is not suitable for application in manufacturing quality control where this process would have to be repeated for many pieces. In this case an alternative procedure can be followed where a full geometry scan of a random selection of pieces is used to identify how the geometry of the real structures differs from the CAD geometry. Using this information, the geometry of the test pieces only has to be measured in only a limited number of locations. The customized mesh for each piece can be obtained by correcting the mesh based on CAD geometry using these discrete geometry measurements. In [5] the authors show that this is feasible using standard mesh morphing techniques. This procedure can be performed much faster compared to the reference approach and is therefore more suitable for applications that require a unique and updated mesh for a larger number of inspected pieces.

2.3. Validation

Although an FE-model generated with the procedure described above has the exact same geometry as the actual structure, there might still be discrepancies between the resonant frequencies computed with the model and those measured on the structure. These discrepancies are caused by a mismatch between the properties of the numerical model and the test piece. Typical model parameters that still need to be validated include material properties and joint stiffness.
The validation process starts by performing an experimental modal analysis (EMA) on the test structure. The EMA should aim at identifying as many modes as possible. Note that FE-models based on high-fidelity geometry measurements have a broader frequency range in which they can reliably predict the resonant frequencies than 'conventional' FE-models. Due to this increased reliability range, the damage identification technique will be able to use all the modes identified by the EMA.

A higher number of experimental modes will eventually lead to a better performance of the damage identification technique. In the case of the lantern housing considered in this paper, 18 modes could be identified [4].
The model parameters of the FE-model can now be validated and updated using the mode shapes and resonant frequencies provided by the EMA. It is important that updated parameters are selected in such a way that the updating procedure only makes physically correct modifications to the parameters. The updating procedure should not make equivalent parameter modifications to compensate the effect of mechanisms that are not included in the FE-model. This is a demanding requirement but a feasible one that can be satisfied if no equivalent parameter modifications have to be made to compensate for geometrical inaccuracies – the geometry of the FE-model has already been validated. In the case of the lantern housing, updating the overall Young's modulus and mass density resulted in an average frequency discrepancy between FEM and test of 0.14% [5]. Note that the residual frequency differences have to be significantly smaller than the impact of the damage scenarios on the frequencies of the structure. Otherwise the damage identification algorithm might identify these discrepancies as damage.

3. Damage Scenarios

3.1. Selecting the Damage Scenarios

The damage scenarios are damage cases that are expected to appear, or that are potentially dangerous and therefore have to be detected by the damage detection algorithm. The damage scenarios can be selected based on damage patterns that have been observed on similar structures, or can be derived from numerical stress or fatigue analysis. The selection of the damage scenarios is a critical step as a damage scenario that is not included cannot be detected by the routine.
Every damage scenario has to be simulated in order to know its impact on the resonant frequencies of the structure. Depending on how the damage is modeled, this might require one or more FE-models. For example, if the damage is modeled by a local reduction of the stiffness and/or mass density, different degrees of damage can be modeled with the same mesh but different material parameters. However, if a crack is modeled by a discontinuity in the mesh, i.e. disconnected adjacent elements, increasing crack lengths will have to be modeled with different meshes. The way the damage is modeled does not have an impact on the complexity of the damage detection algorithm. However, it is important that the damage scenarios are modeled as realistic as possible in order to have a reliable estimate of the impact of the considered damage scenario on the structure's response.
To test the scenario-based damage detection algorithm, eight different damage scenarios were considered for the lantern housing. All damage scenarios represent cracks, which were modeled by a local reduction of the Young's modulus of the material. Although this is not the most realistic way to model a crack, it is considered a sufficient way for a preliminary evaluation of the performance of the scenario-based identification technique. As the performance of the algorithm is tested with simulated 'test data' the way the damage is modeled does not have an impact on the results (which would certainly not be the case when real test data is used). Fig. 5 provides an overview of the considered damage scenarios; the blue regions are the areas where the stiffness is reduced for that particular damage scenario.

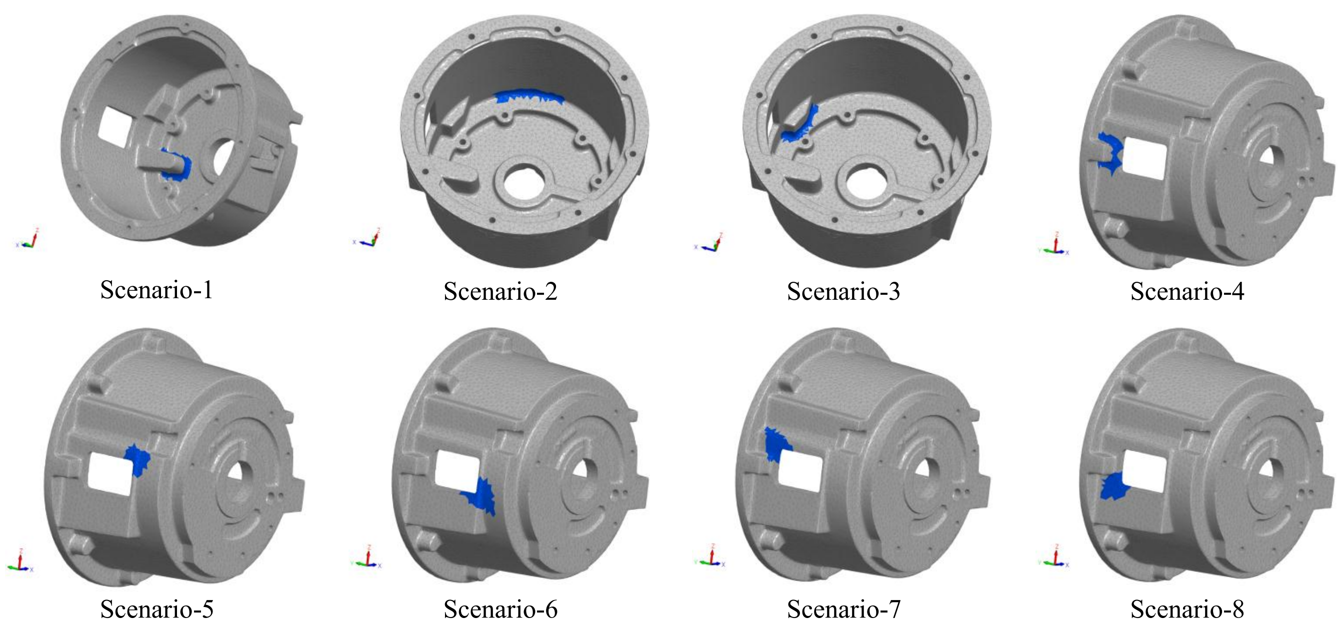
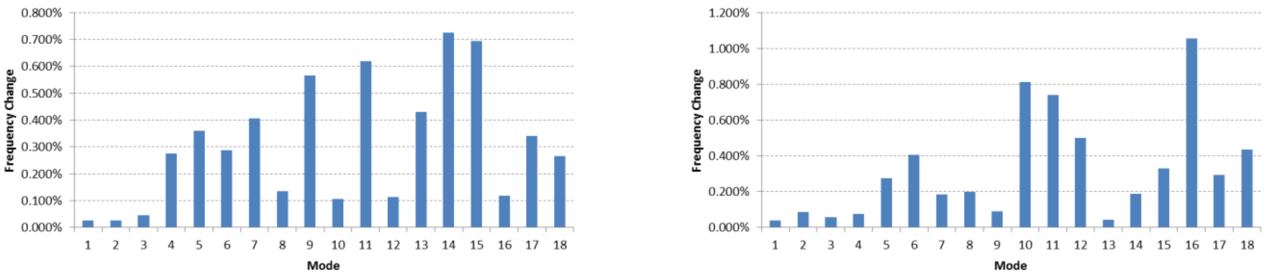


Fig. 5 Eight damage scenarios (damage area marked in blue).

3.2. Damage Scenario Fingerprints

Fig. 6 shows the impact of two arbitrarily chosen damage scenarios on the resonant frequencies of the structure. This figure illustrates that the impact of every damage scenario results in a very particular 'fingerprint'. Recognizing one of these patterns in the frequency differences of the structure in its current and undamaged state indicates the presence of that particular damage scenario.



Scenario-2 Scenario-5

Fig. 6 The impact of two damage scenarios on the frequencies on the structure.

The link between the frequency impact patterns and the level of damage is likely to be non-linear. Fig. 7 shows the impact of damage scenario 2 on the frequencies of the first five modes of the lantern housing for a local decrease of the material stiffness by 10%, 20%, 30%, 40% and 50%. This illustrates that, even when the damage is modeled as a simple local decrease of the Young's modulus, the relation between the damage level and resonant frequencies is slightly non-linear. Although this non-linearity is small, it has to be taken into account for damage identification purposes. Because the impact of damage on the frequencies of the structure is relatively limited, ignoring the non-linear impact of the damage scenarios might lead to incorrect results. Therefore, the various damage scenarios have to be modeled for increasing levels of damage. The number of levels for which the frequencies have to be evaluated depends on the degree of non-linearity exhibited by damage scenario.

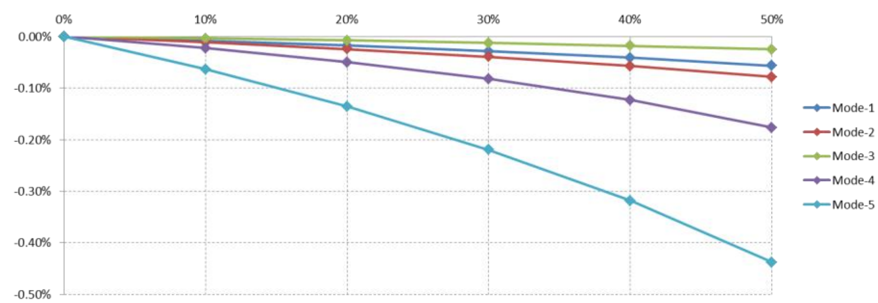


Fig. 7 Illustration of the non-linear relation between the resonant frequencies and the level of damage.

4. Damage Identification

The main goal of the work presented is to investigate if it possible to identify the correct damage case from a set of frequencies using the suggested scenario-based approach. The damage was identified using a three-step approach. First, it is considered that only one type of damage is present. In a second step, the signatures for the considered damage scenarios are computed for all damage levels between 1% and 50% using a damage level step of 1%. This is done by interpolating the base signatures computed for damage levels of 10%, 20%, 30%, 40% and 50%. The interpolated signatures are subtracted from the frequencies measured on the damaged structure and the frequency residuals with the undamaged structure are computed. Finally, in the third step the sum of the squared frequency residuals is computed as a scalar measure for the frequency fit. On the plots, the inverse of the frequency residuals (IFR) are shown because it provides a more intuitive graph. Peaks in these plots indicate the presence of a damage scenario. The whole damage identification analysis was performed using scripts developed with the FEMtools CEA software platform [7].

4.1. Test Case 1

For the first test case the damage combination of Table 1 was used to compute the 'test' frequencies of the damage structure. The low levels of damage for scenarios 2 to 8 are used to introduce noise into the test data.

Damage Scenario	Damage Level	Damage Scenario	Damage Level
Scenario-1	34%	Scenario-5	2%
Scenario-2	2%	Scenario-6	1%
Scenario-3	3%	Scenario-7	3%
Scenario-4	4%	Scenario-8	2%

Table 1 The damage composition of test case 1.

The left-hand side plot of Fig. 8 shows the IFR for all the damage levels of the eight considered damage scenarios. In this plot, high the values imply low frequency residuals and therefore indicate a good match between the signature of the considered damage scenario/ level and the observed frequency shifts. The graph clearly indicates that the damage exhibits a frequency pattern similar to that of damage scenario 1. The damage level is estimated at 38%, i.e. the point corresponding with the minimal overall frequency residuals. Fixing the damage level of damage scenario 1 to 38% and re-evaluation the IFR for all the other damage scenarios provides the right-hand side plot of Fig. 8. It indicates that all other damage cases are present with very low damage levels. The conclusion is that the structure is damaged according to scenario 1 with a medium to high intensity; which is a correct evaluation.

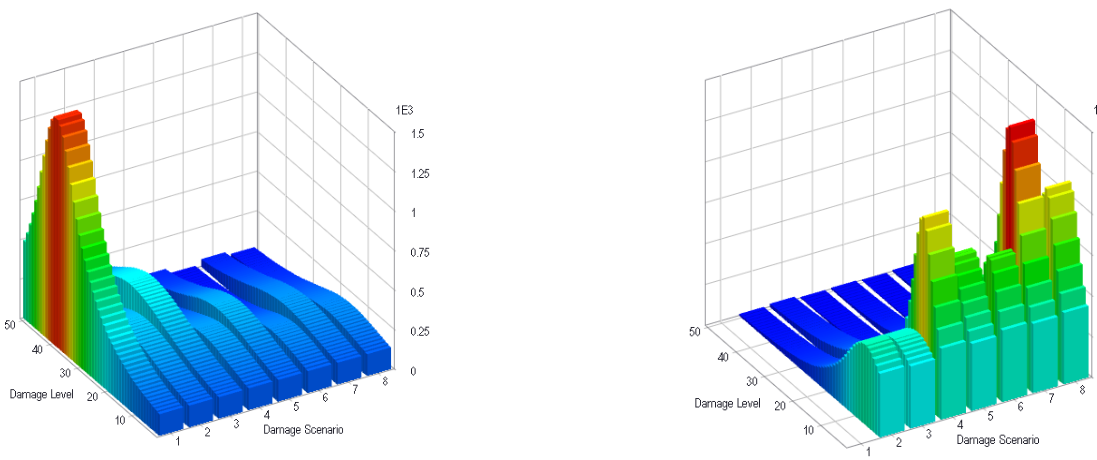
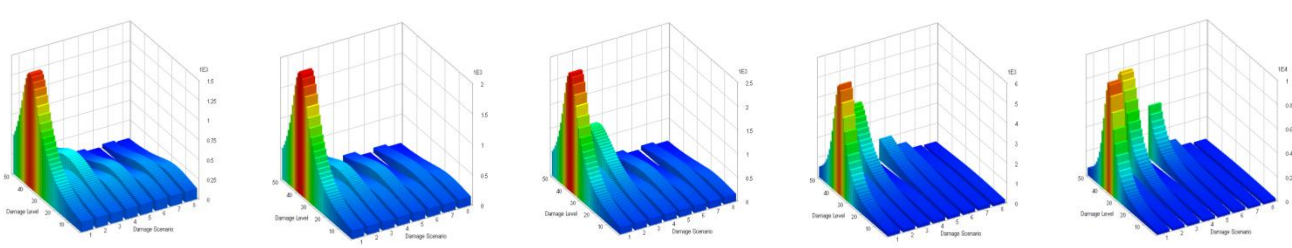


Fig. 8 The IFR of all damage scenarios (left) and the IFR while assuming a damage level of 38% for damage scenario 1.

The results presented in Fig. 8 were obtained using the resonant frequencies of the first 18 modes of the lantern housing. The analysis can be repeated with a decreasing number of frequencies to investigate the importance of the size of the experimental data set. Fig. 9 presents the results obtained with decreasing number of frequencies.



18 modes | 15 modes | 12 modes | 9 modes | 6 modes

Fig. 9 IFR of all damage scenarios in function of the size of the experimental data set.

The analysis with 18 and 15 modes clearly indicate that scenario 1 is the only damage scenario that is present. The analysis with 12 modes still identifies scenario 1 as the most important one, but also seems to indicate that damage scenario 3 is present. The importance of scenario 3 increases when the number of modes is further reduced. When only 6 modes are used, scenario 3 becomes as important as scenario 1. This indicates that the size of the frequency set is a key factor in successfully identifying the correct damage scenario. It is equally important to use a FE-model that is properly validated so that the higher order modes can be included into the damage identification.

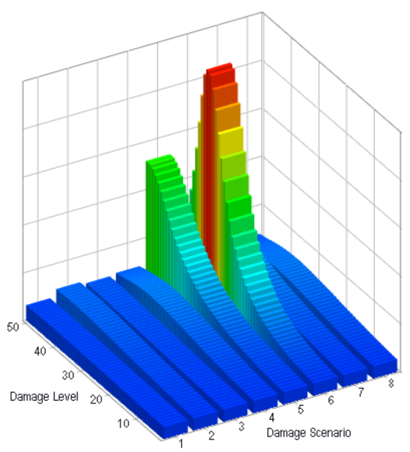
4.1. Test Case 2

The second test case is more challenging than the first one as there are now two types of damage present that exhibit about the same damage level.

Damage Scenario	Damage Level	Damage Scenario	Damage Level
Scenario-1	1%	Scenario-5	24%
Scenario-2	2%	Scenario-6	28%
Scenario-3	1%	Scenario-7	1%
Scenario-4	4%	Scenario-8	2%

Table 2 The damage composition of test case 2.

Fig. 10 (left) shows the IFR in the presence of one damage scenario. This analysis indicates that both scenarios 5 and 6 are present. Evaluating the frequency residuals for all damage level combination of scenario 5 and 6 provides the right-hand size plot of Fig. 10. Minimal frequency residuals are obtained for a damage level of 30% for scenario 5 combined with a damage level of 27% for scenario 6. This is a slight overestimation of the actual damage which is the result of the noise introduced in the test data. However, the general conclusion that the damage is a combination of scenarios 5 and 6, both at a medium damage level, is correct.



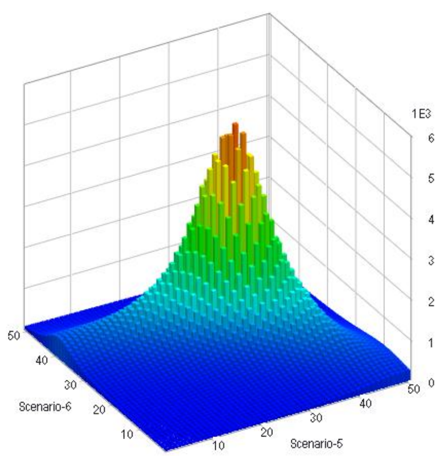


Fig. 10 The IFR of all damage scenarios (left) and the IFR for all the damage level combination of scenarios 5 and 6.

5. Conclusions and Future Work

5.1. Conclusions

A scenario-based damage identification framework has been introduced. The technique starts with the creation of a carefully validated FE model of the undamaged structure. Next, this model is used to simulate the effects of a number of damage scenarios. Eventually, the identification routine detects the 'fingerprints' of the damages scenarios in the frequency pattern of the damaged structure.

The scenarios-based damage identification framework has been evaluated and showed promising results. It appears to be possible to decompose the measured frequency pattern into the signatures of a series of pre-defined damage scenarios. The scenario-based approach seems to be capable of not only identifying the location of the damage but also the degree of damage. The efficiency of the identification procedure was not considered and needs to be further improved. Scanning the data for the considered damage scenarios requires a significant computational effort that increases quickly when more than one type of damage is present.

5.2. Future Work

An efficient scenario-based damage identification routine will require a true decomposition of the observed frequency shifts into the contributions of the damage scenarios. This is a point that has not been addressed in this paper and still has to be resolved. Bayesian updating or a genetic optimizer could provide a solution.

Linear interpolation is certainly not the optimal approach to obtain the 'fingerprint' for the intermediate damage levels. Fast reanalysis techniques such as Structural Dynamics Modification (SDM) can increase both the accuracy and the computational efficiency. However, an SDM approach will only be feasible in cases where the mesh does not change in function of the damage level. In those cases a response surface approach could be used.

Finally, the scenario-based damage identification problem should be integrated into a probabilistic framework in order to provide true 'damage probabilities' for each damage scenario and level.

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