# Paper 76


Proceedings of the Eleventh International Conference
on Computational Structures Technology,
B.H.V. Topping, (Editor),
Civil-Comp Press, Stirlingshire, Scotland

# Detection of Localized Damage for Beams using a Frequency Based Method

**F. El Khannoussi[1], A. Khamlichi[1], A. Hajraoui[1] and A. Limam[2]**
**[1] System of Communications Laboratory**
**Faculty of Sciences at Tetouan, Morocco**
**[2] Civil and Environmental Engineering Laboratory**
**Institute of Applied Sciences at Lyon, Villeurbanne, France**

## Abstract

Dynamic models enable describing how structures respond to applied loads with and without the presence of damage that is likely to occur. These models provide vibration data that can be analysed to identify changes in mass or stiffness. Diagnosis of damage encompasses three major items: detection, localisation and quantification. In this paper, the focus is on the elastic homogeneous and isotropic beams for which damage is assumed to be a localised loss of mass. Three dimensional modelling is considered in order to assess how in the system first frequencies shift according to various damage scenarios. Then the ability for detecting damage and its localisation is discussed.

**Keywords:** structural health monitoring, damage detection, localized damage, frequency based method, beam, modal analysis, finite element method.

# 1 Introduction

In real structures, it is essential to detect damage as earlier as possible before it reaches a critical phase of growth. Spectacular failures, such as the in-flight loss of the exterior skin of an airplane, have focused on the need of structural health monitoring to ensure endurably safety of structures [1]. This is particularly important for some essential facilities such as those of offshore oil industry or for diagnosis of high technology systems like space shuttles.

Structural damage detection can be performed by various non-destructive testing (NDT) techniques including optical, microscopy, acoustic emission, ultrasonic, radiography, eddy-current, thermal or electromagnetic wave based methods. All of these need that the damage location is already known and that the part of the structure where it is located can be accessed. These techniques are not however effective all the time especially for complex structures where some parts are inaccessible, furthermore they are reputed to be time-consuming and costly.

Vibration based methods seem to be more adequate as they are low cost and may enable to monitor damage detection where the conventional techniques can not perform well. Vibration based approaches are initiating from the changes that could occur on the commonly measured modal parameters consisting of frequencies, mode shapes and damping. Detectable changes in these modal properties can be produced when significant changes of the physical properties of the structure happen such as reduction in stiffness, due to the apparition of cracks or in mass like those resulting from oxidation. Changes in modal properties can be used as indicators of damage. As modal changes suffer from poor sensitivity to small damage, vibration based methods can be used fairly to detect damage exceeding some critical size.

Damage represents any change that can happen in a system and which is able to affect its future performance. Depending on the level of damage, the system may not show all the adverse effects. The concept of damage holds then implicitly a comparison between the initial undamaged state and the likely damaged states. Detecting these changes will not always be possible within the framework of modal analysis, as there are some limitations inherent to this method. These consist mainly in restrictions in system identification process such as the difficulty to identify all the modes from measured time-history responses and complications that could result from eventual coupling between modes that are closely spaced in frequency [2]. This happens especially at the higher frequency portions of the spectrum and because of system sensitivity to the environmental condition during the test. Other huge problems that can affect vibration based method are associated to the fact that damage is usually a local phenomenon. A local response is captured however only through higher frequency modes while in practice it is more difficult to excite higher frequencies of the structure.

Several previous works have dealt with vibration damage detection; some of them were reviewed in reference [3]. One finds mainly two approaches that have been introduced: methods that are based only on changes in the measured data and methods that need a finite element model.

In this work, level 2 of damage monitoring according to the damage level classification proposed in reference [4] is considered. For this level, one is interested in knowing whether damage has occurred in the structure and determining its geometric location. The methodology used for damage diagnosis is based on modal frequency changes. Salawu [5] presented a review on this approach and discussed the option of its utilization. The main question arising is related to the lowest damage level that can be detected, damage that is able to generate significant frequency shifts. The possibility to identify multiple structural changes is also an important issue that should be resolved.

In this work, several damage scenarios are postulated. Damage identification is performed using frequency based methods. A highly accurate model of the structure is built in order to compute frequency shifts of the first modes for both the undamaged structure and all the postulated damage scenarios [6]. For the candidate structure, the shifts of all the frequencies are used to compute an index function. If noise is assumed to have limited effect on the system and the actual damage is considered to lie within the assumed class of damage scenarios, the likelihood of damage is keyed on the index error function. The correct damage is that for which the index error reaches a minimum.

## 2 Assessing frequency shifts resulting from damage scenarios

Let us consider a cantilever beam made from an elastic homogeneous and isotropic steel material for which Young's modulus is $E = 2\times10^{11}\,Pa$ and Poisson coefficient is $\upsilon = 0.3$. The material density is $\rho = 7800\,kg.m^{-3}$. The beam length is chosen to be $L = 1m$ and the cross section is assumed to be rectangular with height $h = 1.2\times10^{-2}\,m$ and depth $d = 3\times10^{-2}\,m$.

The beam is expected to suffer from a damage consisting of thickness loss due to oxidation and which is located somewhere on the beam length. To define a database of damage events, the beam is subdivided into 8 sectors that will serve to generate the incorporated damage scenarios. Each sector has a length of $0.125\,m$. The loss of thickness is assumed to be uniformly distributed over the affected zone and the related amount of damage is taken to be significant to ensure sensitivity of frequency shifts. The lost mass is fixed at $\Delta m = 1.755 kg$. The damaged beam thickness is then $h_d = 6\times10^{-3}\,m$ if damage is supposed to affect a single sector of the beam having the length $L/8$ and $h_d = 3\times10^{-3}\,m$ if the damage is to affect the length $L/4$ of the beam on two separate sectors. This loss of thickness affects both rigidity and mass distribution of the beam. Figure 1 shows the beam with a localized damage zone.

The possibility of having a variable loss-of-thickness and more than two sites of damage is not investigated here.

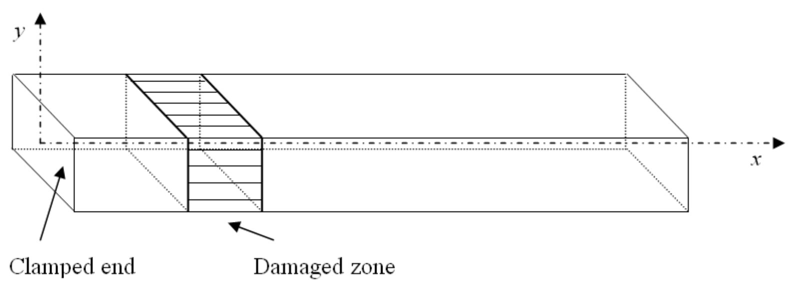


Figure 1: Clamped free beam with a single localized loss-of-thickness damage

Assuming that damage extends over 1/8 of beam length, figure 2 shows two possible damage scenarios. The total number of combinations for damage scenarios of this kind is then 8. The numbering of these scenarios will be continuous beginning from the left. Figure 2 shows scenarios 1 and 6.

Assuming now that damage extends on two sites extending each on 1/8 of beam length, figure 3 shows two possible damage scenarios. The total number of damage scenarios of this family is then 28. The numbering of these scenarios will be conforming to lexicographic order beginning from 9, as an example the scenarios shown in figure 3 have respectively the numbers 10 and 24.

In the following only damage scenarios resulting from the 8 plus 28 combinations are considered (the total number is then 36). The damage scenarios can be easily enriched in order to include more possible damage patterns. The limitations considered here are only for clearness reasons.

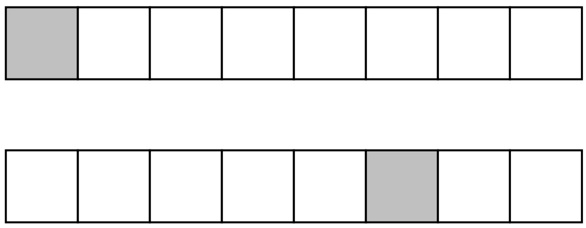

Figure 2: Two damage scenarios when assuming that damage extends uniformly over $1/8$ of beam length; scenario 1 (top) and scenario 6 (bottom)

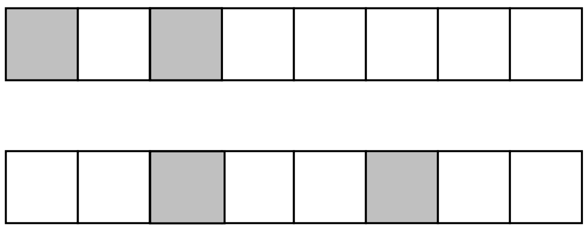

Figure 3: Two possible damage scenarios when assuming that damage extends uniformly on to separate sites representing each $1/8$ of beam length; scenario 10 (top) and scenario 24 (bottom)

Only the 12 first frequencies of the beam are considered in this analysis. The finite element modelling is performed by using 3D elements C3D8I (8-node linear brick with incompatible modes). The other characteristics of the finite elements model are mesh size equal to $0.003m$ and Lanczos method to compute the eigenvalues.

Figure 4 shows the surface giving frequency as function of mode order and damage scenario. One can see that frequencies vary as function of damage scenario, but globally their variations are not large even for a relatively large damage that was considered here. As the high frequencies are not easy to measure in practice because of damping, only the first modes have considerable importance. Figure 5 gives the absolute frequency shifts with regards to the undamaged state for the first three modes.

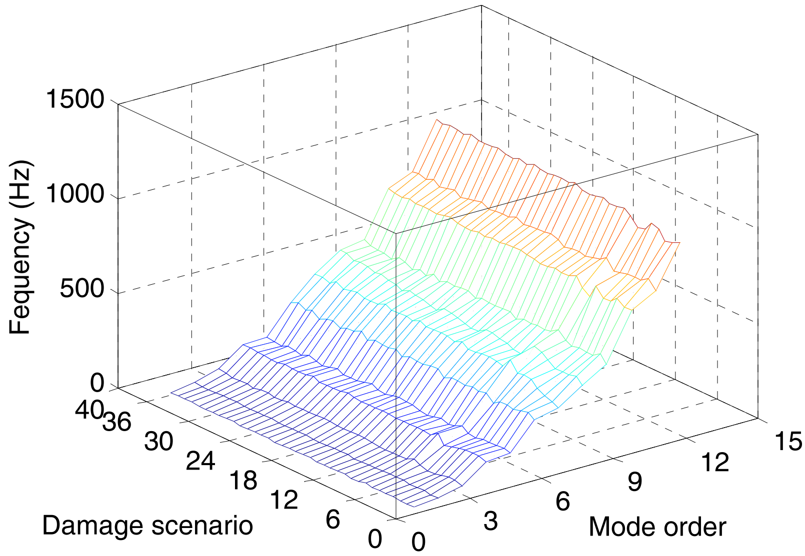


Figure 4: Frequency as function of the mode order and damage scenario

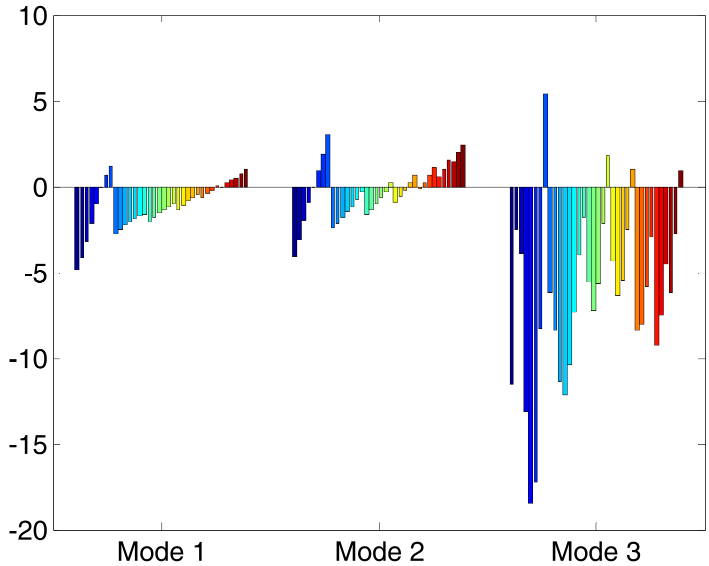


Figure 5: Frequency shifts for the first three modes as function of the considered 36 damage scenarios

If the amplitude of damage coincides with that one considered in establishing damage scenarios, then frequency shifts could be used to locate the damage. To do this, the following index error function is introduced

$$Error(i) = \sum_{k=1}^{N\,modes} \frac{\left|F(i,k) - F_{experimental}(k)\right|}{F_{experimental}(k)} \tag{1}$$

where $F(i,k)$ is the frequency for mode number $k$ and damage scenario $i$ and $F_{experimental}(k)$ is the measured frequency for mode number k.

Having calculated the index error function as defined in equation (1), one minimize the obtained vector to identify the damage scenario.

An important problem that is necessary to make clear is related to the influence of the total number of selected modes $N\,modes$ on the minimization process. It will be advantageous if the first modes are sufficient to identify the correct damage scenario. Another important issue is the ability to detect damages having the same extent but which are associated to a loss-of-thickness that is different from that included in the actual damage scenarios. These questions will be discussed in the following.

# 3 Results and discussion

To test the procedure presented in section 2 and which consists in minimizing the error index function defined by equation (1), we have considered the damage scenario number 2 to be the experimental existing damage experienced by the beam.

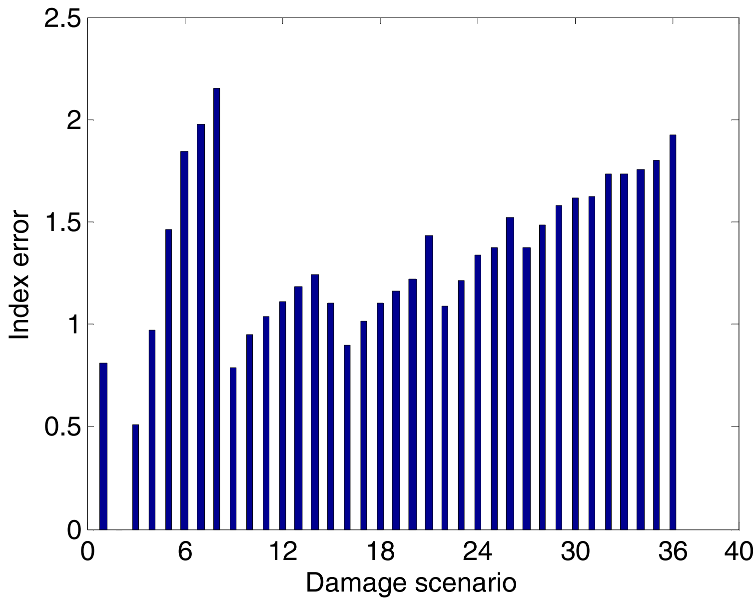


Figure 6: Damage index error as function of the damage scenario, $N\,modes = 12$

Evolution of the calculated index error as function of the damage scenario is presented in figure 6. This figure shows that the minimum is reached for damage scenario number 2, which is the exact solution. $N\,modes = 12$ has been used.

Figure 7 gives a comparison between the index error as function of damage scenario for $N\,modes = 12$ (blue) and when using only one mode $N\,modes = 1$. If the number of selected modes is comprised between 1 and 12 than the index error value will be bounded for each damage scenario by the values associated to $N\,modes = 1$ and $N\,modes = 12$. One can see that selecting only the first mode is sufficient here to localize the endured damage.

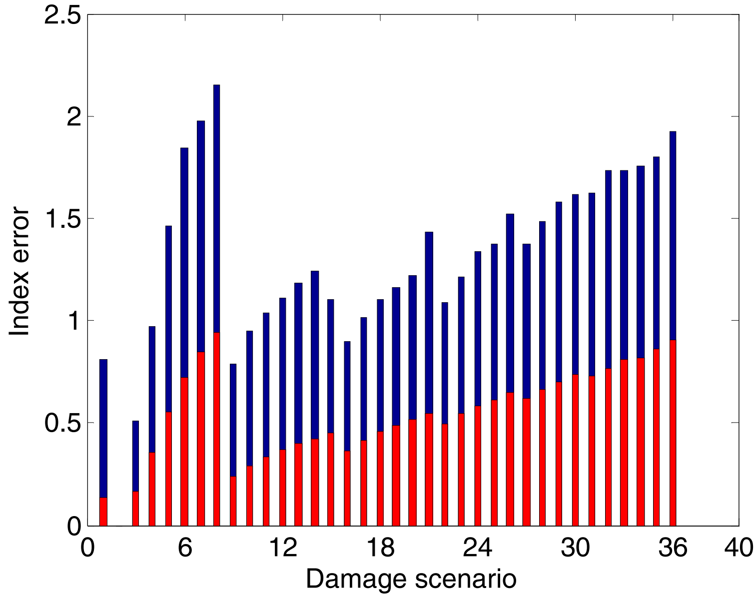


Figure 7: Damage index error as function of the damage scenario, comparison between $N\,modes = 1$ in red and $N\,modes = 12$

Injecting now damage scenario number 34, the obtained damage index error is shown in figure 8 where a comparison is made between $N\,modes = 1$, $N\,modes = 3$ and $N\,modes = 12$.

In this case one mode is theoretically sufficient to localize damage. It should be mentioned however that damage scenario 7 and 33 are not far form the minimum and that experimental errors in measuring the actual frequencies can yield to a wrong localization when using only one mode, figure 9. The situation is better when using $N\,modes = 3$ even if the risk still exists. This problem is less disquieting when taking $N\,modes = 12$ as the separation between damage scenarios is theoretically more obvious, but at the necessity to measure accurately the first 12 frequencies balances the advantage.

Figure 9 shows that the candidate damage scenarios 7 and 33 are close to the exact damage (scenario number 34). These have almost the same effect on the first mode frequencies for the considered beam.

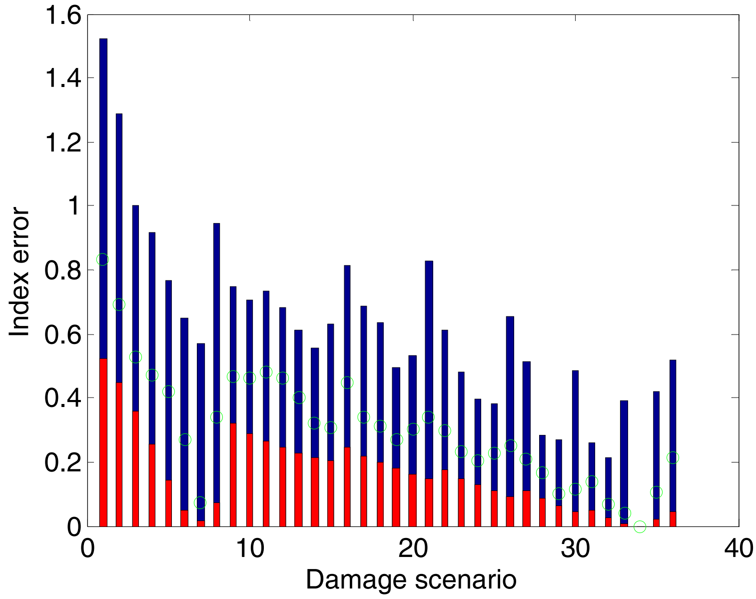


Figure 8: Damage index error as function of damage scenario, comparison between $N\,modes = 1$ in red, $N\,modes = 3$ (green circles) and $N\,modes = 12$ in blue

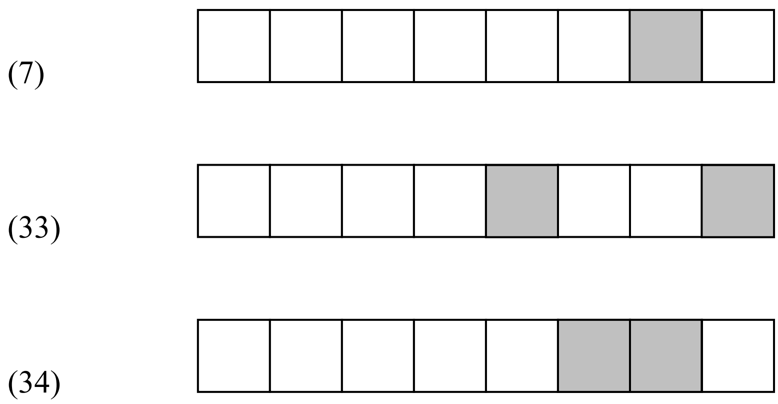


Figure 9: Damage scenarios having respectively the numbers 7, 33 and 34

To investigate whether the procedure continues to enable determining damage location if the damage extent is among the considered scenarios but with a different loss-of-thickness value, let us consider that the actual damage is similar to scenario 27 but with $h_d = 6\times10^{-3}\,m$, figure 10. This is different from $h_d = 3\times10^{-3}\,m$ that was included in our damage database.

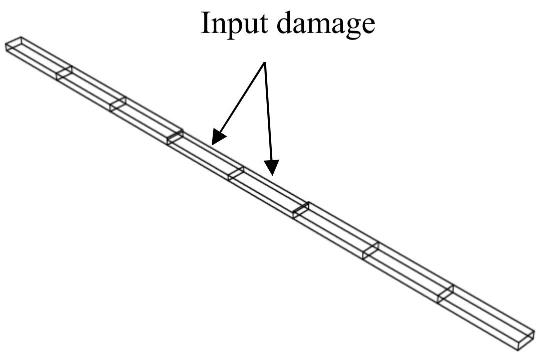


Figure 10: Experimental damage scenario showing a localized damaged extending over the 4th and 5th beam sector

The obtained results shown in figure 11 indicate that, in this case, the minimization procedure fails to localize exactly damage. Index error does not vanish for scenario 27 and the minimization gives scenario 4. This is only an approximation of damage location (fourth sector of the beam) instead of beam sectors number 4 and 5 associated to the input damage.

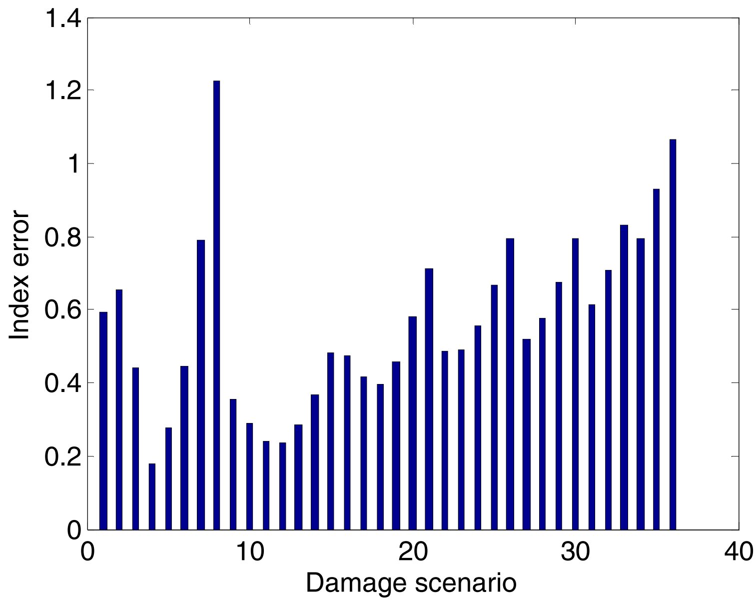


Figure 11: Damage index error as function of the damage scenario for $N\,\mathrm{mod}\,es = 12$, the input damage is shown in figure 10 and has $h_d = 6\times10^{-3}\,m$

For damage scenario 27, as defined in figure 10, taking loss-of-thickness value to be only $h_d = 1.5\times10^{-3}\,m$ does not enable to find the exact solution. The identified damage is in this case scenario number 30, figure 12, which corresponds to sectors 4 and 8.

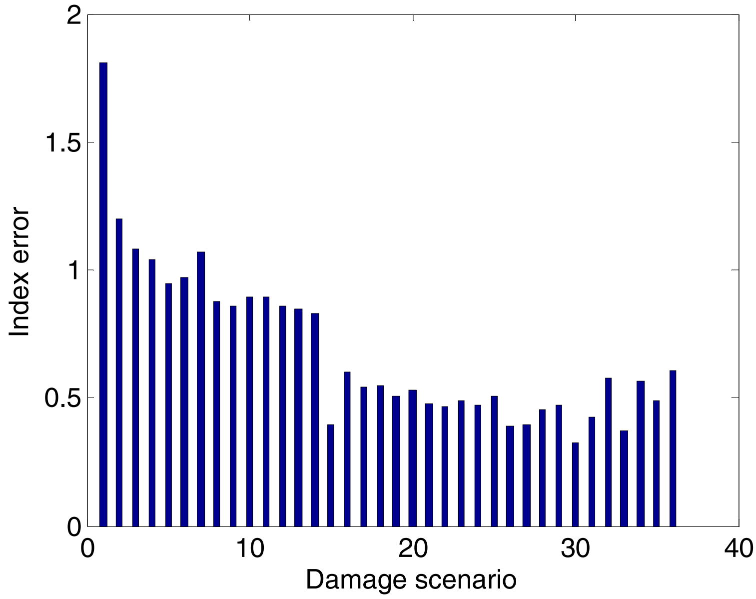


Figure 12: Damage index error as function of damage scenario for $N\,\mathrm{mod}\,es = 12$; the input damage is shown in figure 10 and has $h_d = 1.5 \times 10^{-3}\,m$

From these results one can see that identification of damage location could not be achieved exactly if the right damage scenario was not included in the damage data basis used for evaluation of damage index error function. Even, when this damage scenario is included, sufficient modes should be selected in order to obtain an index damage that enable distinguishing various close damage scenarios.

The proposed method can however be useful if one is able to enrich the damage scenarios by including those which are habitually diagnosed in the considered beam. In our case for example, more sectors can be introduced as well as more loss-of-thickness values to enlarge damage scenarios database. A spline interpolation of frequencies as function of the loss-of-thickness could also be performed to enable identifying the actual damage loss-of-thickness.

One should note however that damage should be sufficiently large to be detectable.

# 4 Conclusions

A frequency based damage identification method was presented in this work for beams by considering the minimisation of a special damage index error function. The results obtained have shown that the procedure of localising damage works well if the actual damage magnitude and extent were assumed as possible damage scenarios during the derivation of a frequency shift database. Attention should be however given to the correct number of frequencies to be measured. The method presented continues to work approximately for some damage characteristics that are close to the considered damage patterns indicating only their overall location. A possible way to generalise this method consists of enlarging the damage scenarios by varying their forms and amplitudes.

## References


[1] A. Morassi, F. Vestroni, “Dynamic methods for damage detection in structures”, Springer Verlag, ISBN 978-3-211-78776-2, 2008.

[2] D.J. Ewins, “Modal Testing: Theory and Practice”, John Wiley and Sons, New York, 1984.

[3] S.W. Doebling, C.R. Farrar, M.B. Prime, “A summary review of vibration-based damage identification method”, Shock and Vibration Digest, 30(2), 91, 1998.

[4] A. Rytter, “Vibration based inspection of civil engineering structures”, Ph.D. Dissertation, Department of Building Technology and Structural Engineering, Aalborg University, Denmark, 1993.

[5] O.S. Salawu, “Detection of structural damage through changes in frequency: a review”, Engineering Structures, 19(9), 718, 1997.

[6] M.I. Friswell, J.E.T. Penny, D.A.L. Wilson, “Using vibration data and statistical measures to locate damage in structures”, Modal Analysis: the International Journal of Analytical and Experimental Modal Analysis, 9(4), 239, 1994.