Acta Scientiarum

http://periodicos.uem.br/ojs
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v45i1.63847

CIVIL ENGINEERING

A modified mode shape data-based method for beams structural damage detection

Will José de Lima Júnior* and **Wayne Santos de Assis**

Programa de Pós-Graduação em Engenharia Civil, Centro de Tecnologia, Universidade Federal de Alagoas, Avenida Lourival Melo Mota, s/n, Tabuleiro do Martins, 57072-900, Maceió, Alagoas, Brazil. *Author for correspondence. E-mail: will.junior@ctec.ufal.br

ABSTRACT. Damage detection methods based on changing modal parameters have received considerable attention in engineering applications due to the satisfactory results and the low associated cost compared with other techniques. The Mode Shape Data Based Indicator (MSDBI) is a damage indicator available in the literature, being used to identify damage in beam structures from the mode shape, mode shape slope and mode shape curvature, in the undamaged and damaged configurations of the element under study. However, in some situations, the configuration of the displacement mode shape of the i^{th} mode, of the undamaged structure compared to the damaged one, presents mirroring. The damage identification algorithm could be a better indicator when these situations occur. Them, this paper presents a proposal to modify this method, called MSDBIM. The proposed modified method (MSDBIM) and the traditional method (MSDBI) were applied in two numerical examples that were elaborated in commercial software of finite elements, namely a simply supported concrete beam and a fixed-end steel beam in different single and multiple damage scenarios with sensitivity studies. A new discretization for the fixed-end beam was performed to assess whether there is a direct influence on the damage identification method. The results show that the proposed method (MSDBIM) performs better than the traditional method (MSDBI).

Keywords: Damage identification; structural damage; modal analysis; numerical analysis; beams; mode shape data

Received on june 03, 2022.
Accepted on march 03, 2023.

Introduction

Structural health monitoring (SHM) is based on reliable and robust indicators that allow for detecting, locating, and quantifying damage, in addition to estimating the residual useful life of the structure after characterizing the damage whenever possible. These actions may provide important advantages, such as establishing criteria for the safe use of the structure and the ability to identify better when interventions in the structure are necessary so that maintenance can be properly carried out, contributing to the extension of the structure's useful life and cost reduction.

The Vibration-Based Damage Detection (VBDD) method considers changes in modal parameters and has shown to be a very promising method for engineering applications, allowing good results, especially after improvements in the technologies of vibration transducers (accelerometers), hardware, and software for data acquisition.

To consider applications of VBDD methods based on changing the modal parameters, the damage produces changes in the structure properties physical and, therefore, in its dynamic properties (which are correlated with mass, stiffness, damping, and boundary conditions). Thus, the damage in a structure changes its modal parameters, which include natural frequencies, natural modes of vibration, and damping factors. In this sense, the damage can be identified by comparing the initial (undamaged or intact) and the final (damaged) states. Several methods based on changing modal parameters have been proposed in the last decades to identify structural damage.

Allemang and Brown (1982) proposed a method to identify damage that considers a global statistical index called the Modal Assurance Criterion (MAC). This index measures the correlation between pairs of modal vectors of an integral structure and another damaged structure, and its value varies between 0 and 1. On this scale, 0 means that the modal vectors are orthogonal to each other (indicating that the structure possibly has damage), while the value 1 means that the modal vectors have complete agreement (indicating that the structure is possibly intact).

Lieven and Ewins (1988) defined a new method that follows MAC principles called the Coordinate Modal Assurance Criterion (COMAC). This criterion has a local character and measures the specific agreement among the various vibration modes of structures with and without damage. Its value also varies between 0 and 1, and as in MAC, 0 indicates complete orthogonality and 1 indicates complete agreement. The location of the damage, following the COMAC index, is found by observing which node has the greatest discrepancy between the vibration modes of structures with and without damage, and if all the nodes have a COMAC index equal to the unit, which indicates that the structure is possibly intact.

Pandey, Biswas and Samman (1991) presented a method of change in curvature, showing via finite elements that the absolute difference between the curvatures of vibration modes obtained through an operator of Central Finite Difference (CFD) of the undamaged and damaged structure is in the damage region and therefore can be used to identify and locate structural damage. The curvature of vibration modes is related to stiffness and flexibility; therefore, the greater the loss of stiffness, the greater the level of damage, and thus the greater the variation in curvature.

Pandey and Biswas (1994) proposed a method to identify and locate damage based on the difference between flexibility matrices, which is the inverse of the structure's stiffness matrix with and without damage. Since the damage causes a decrease in the structure's stiffness and, consequently, an increase in its flexibility, the difference between the flexibility matrices of the intact and damaged states indicates the damaged region. The results showed that in both analytical and experimental cases, the change in the flexibility matrix seemed to be a good indicator for identifying and locating the damage.

Samman and Biswas (1994a and 1994b) presented the Signature Assurance Criterion (SAC) and the Cross Signature Assurance Criterion (CSAC) in that same year, attempting to compare signals of Frequency Response Function (FRF), methods similar to MAC (Allemang and Brown, 1982) and COMAC (Lieven and Ewins, 1988). The difference between these methods is that MAC and COMAC use the obtained modal shifts, while the SAC and CSAC indexes consider the signals from the FRF. In the first study (1994a), the theoretical context of the proposed methods was described, and in the second study (1994b), some experimental results were presented. The SAC method allowed for obtaining the correct location of the damage in structures, as the CSAC was not successful in detecting the damage.

Ratcliffe, C. P. (1997) used a method called the modified Laplacian operator to identify the location of structural damage in a beam based only on the vibration modes of the damaged structure. The transverse displacements obtained through the vibration modes are applied to the formula (Laplacian function of finite differences) representing the node curvature of the determined mode. Considering that the damaged element presents less flexural rigidity (EI), it will consequently present a greater curvature than the adjacent elements, making it possible to identify the damage. The procedure was developed using a model of finite elements in a steel beam, with results that evidenced a certain limitation.

Shi and Law (1998) proposed a method for locating damage in a structure based on Modal Strain Energy (MSE). This method uses Modal Strain Energy Change (MSEC) in each structural element before and after the damage occurs. The information needed to apply the method is only the modes of vibration and the elementary stiffness matrix; it is not necessary to know the global stiffness and the mass matrix. Cases of damage to steel structures (beam and plane frame) were simulated with single and multiple damages, noise, and incomplete modes. The results obtained experimentally attest to the effectiveness of the method.

Kim and Stubbs (2003) proposed a method to locate the damage using a change in the structure's natural frequencies. According to the mathematical formulation, the change in modal deformation energy is directly related to the change in frequency, considering structures with and without damage. Thus, the method calculates the difference between two ratios for each element for a given mode of vibration. The method was tested experimentally on 16 steel beams with a rectangular section, different intensities, and single damage positions. The results showed that the accuracy of the single damage location can be improved as more modes are used.

Wang and Li (2012) developed a new method for locating and quantifying damage from the study of modal deformation energy that requires little information about changes in natural frequencies. To demonstrate the robustness of the damage estimation algorithm, numerical and experimental studies were carried out using a clamped-free beam and a two-dimensional plane frame. The results were good, thus validating the proposed method.

Moradipour, Chan and Gallage (2015) proposed an improved Modal Strain Energy (MSE) method to detect and quantify structural damage. The comparison between the method proposed by Shi, Law, and Zhang (2000) and the improved method employed numerical simulations using a fixed-end beam and a three-story frame, including single and multiple damage scenarios, in the absence and presence of up to 5% of noise. The improved method performed better.

Yazdanpanah, Seyedpoor, and Bengar (2015) proposed a new indicator for identifying damage to beams based on mode shape data, slope, and curvature of mode shapes. The evaluation of the method's robustness considered two numerical examples: a supported beam and a two-span beam, with single and multiple damage scenarios. The results showed the effectiveness of the method in most investigated cases.

Wu, Zhou, Rui, and Fei (2017) developed a new approach to identify structural damage in which the Modal Strain Energy Change method of Shi and Law (1998) was reformulated with strain modes. The method was tested numerically on a fixed-end aluminum beam with different scenarios of single and multiple damages and validated experimentally. The results showed that the proposed method performed better than the Modal Strain Energy method with incompletely measured vibration modes and the modal expansion technique (adopted to match the degrees of freedom between the analytical and experimental models).

From the reviewed literature, numerous studies have been developed based on the modification of modal parameters using mainly natural frequencies, modes of vibration derived from modes of vibration, energy of modal deformation, etc. The derivatives of vibration modes, such as curvatures of vibration modes, are sensitive to small disturbances and require information only from the vertical vibration mode, being promising from a practical and economical point of view for damage investigations (as found in: Pandey & Biswas, 1994; Roy, K. 2017; Yazdanpanah, Seyedpoor, and Bengar 2015).

This paper aims to modify the MSDBI method, which uses mode shape, slope and curvature of mode shapes, to improve the accuracy of the damage identification algorithm and provide a new approach to assist in the monitoring of structural integrity, which in turn aims to contribute to the extension of useful life, predict unexpected structural damage, and contribute to the safety of structures. The modified and traditional methods were applied in two numerical examples elaborated in commercial software of finite elements, namely a simply supported concrete beam and a fixed-end beam in different single and multiple damage scenarios. The results are compared and discussed.

Traditional MSDBI theory

A method called Mode Shape Data Based Indicator (MSDBI) was defined by Yazdanpanah, Seyedpoor, and Bengar (2015) to identify structural damage in beams using dynamic responses (mode shape, slope and curvature of mode shapes) in undamaged and damaged beams (Equation (1)).

$$MSDBI_j = \frac{1}{m}\sum_{i=1}^{m}\left|\left[\left|\Phi''_{d(j,i)} - \Phi''_{(j,i)}\right|\left(\phi_{d(j,i)}\right)^2\right] - \left[\left(\left|\Phi'_{d(j,i)}\right| - \left|\Phi'_{(j,i)}\right|\right)^2\left(\phi_{(j,i)}\right)\right]\right| \quad (1)$$

where $MSDBI_j$ – mode shape data based indicator of the j^{th} node;
$\phi_{(j,i)}$ – mode shape of the j^{th} node of undamaged structure at i^{th} mode;
$\phi_{d(j,i)}$ – mode shape of the j^{th} node of damaged structure at i^{th} mode;
$\Phi'_{(j,i)}$ – mode shape slope of the j^{th} node of undamaged structure at i^{th} mode;
$\Phi'_{d(j,i)}$ – mode shape slope of the j^{th} node of damaged structure at i^{th} mode;
$\Phi''_{(j,i)}$ – mode shape curvature of the j^{th} node of undamaged structure at i^{th} mode;
$\Phi''_{d(j,i)}$ – mode shape curvature of the j^{th} node of damaged structure at i^{th} mode;
m – number of mode shapes considered.

These slope of mode shapes of the undamaged and damaged structure can be calculated using the approximation of a Central Finite Difference (CFD) operator for the displacement of the *j* node at *i* mode shape (Equations (2.a) and (2.b)).

$$\Phi'_{(j,i)} = \frac{\phi_{(j+1,i)} - \phi_{(j-1,i)}}{2l} \quad (2.a)$$

$$\Phi'_{d(j,i)} = \frac{\phi_{d(j+1,i)} - \phi_{d(j-1,i)}}{2l} \quad (2.b)$$

where l – length of beam element.

Likewise, mode shape curvature of the undamaged and damaged structure can be calculated using the approximation of a CFD operator for the displacement of the j node at i mode shape ((Equations (3.a) and (3.b)).

$$\Phi''_{(j,i)} = \frac{\phi_{(j+1,i)} - 2\phi_{(j,i)} + \phi_{(j-1,i)}}{l^2} \quad (3.a)$$

$$\Phi''_{d(j,i)} = \frac{\phi_{d(j+1,i)} - 2\phi_{d(j,i)} + \phi_{d(j-1,i)}}{l^2} \quad (3.b)$$

Assuming that the set of MSDBIs of all nodes represents a population of a normally distributed random variable, the authors defined a normalized form of MSDBI as follows:

$$nMSDBI_j = max\left[0, \left(\frac{MSDBI_j - mean(MSDBI)}{std(MSDBI)}\right)\right] \quad (4)$$

where $mean(MSDBI)$ – mean of MSDBI of all nodes;
$std(MSDBI)$ –standard deviation of MSDBI of all nodes.

Modified MSDBI method formulation

When damage occurs to a structure, it can be represented as a disturbance in the original system, which is compatible with the intensity of the damage. In some situations, this disturbance causes the configuration of the displacement mode shape of the i^{th} mode of the damaged structure to mirror concerning the configuration of the undamaged structure (Figure 1).

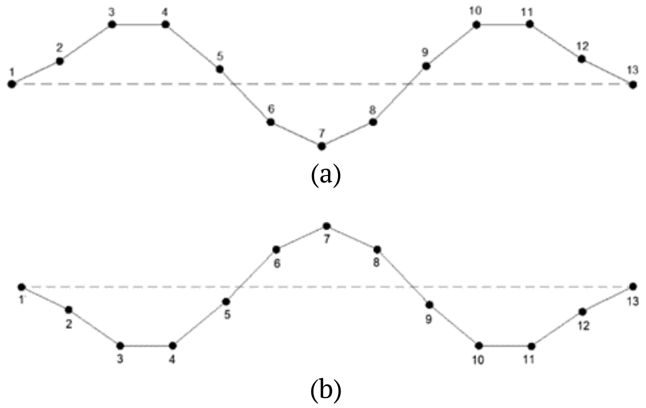


Figure 1. Configuration of the displacement mode shape for a mode: (a) undamaged and (b) damaged structures.

For these situations, the $\left|\Phi''_{d(j,i)} - \Phi''_{(j,i)}\right|$ portion of Equation (1) will not realize the difference in curvature of the i^{th} node referring to the mode that presents this scenario. For the illustrative example (Figure 1), the modal curvature of node 7 of the undamaged structure will have a positive value, while for the damaged structure, it will have a negative value. Thus, for this node (using Equation (1)), it will not be possible to realize the difference in the modal curvature in that portion.

Thus, the proposed idea for modifying the Mode Shape Data Based Indicator (MSDBI) is based on the absolute changes of absolute mode shape curvatures of structure in undamaged and damaged conditions (Equation (5)).

$$MSDBIM_{(j,i)} = \left|\left[\left|\left|\Phi''_{d(j,i)}\right| - \left|\Phi''_{(j,i)}\right|\right| \left(\phi_{d(j,i)}\right)^2\right] - \left[\left(\left|\Phi'_{d(j,i)}\right| - \left|\Phi'_{(j,i)}\right|\right)^2 \left(\phi_{(j,i)}\right)\right]\right| \quad (5)$$

where $MSDBIM$ is Modified Mode Shape Data Based Indicator.

In the modified method proposed here, in order to evidence the damaged location more accurately and safely, we suggest that if m vibration modes are used, the $\mathrm{MSDBIM_j}$ of the j^{th} node be defined as the average of the sum of MSDBIM_j^i for all normalized modes regarding the largest value of $\mathrm{MSDBIM^i_{máx}}$ in each mode (Equation (6)) (normalization similar to that proposed by Shi and Law 1998). It is usually recommended to use the first five modes of vibration.

$$MSDBIM_j = \frac{1}{m}\sum_{i=1}^{m} \frac{MSDBIM_j^i}{MSDBIM_{máx}^i} \quad (6)$$

The results of the damage indicator $\mathrm{MSDBIM_j}$ (Equation (6)) are normalized in the same way as the indicator $\mathrm{nMSDBI_j}$ (Equation (4)) since they will be compared in this paper, according to Equation (7).

$$nMSDBIM_j = máx\left[0, \left(\frac{MSDBIM_j - mean(MSDBIM)}{std(MSDBIM)}\right)\right] \quad (7)$$

It is expected that the MSDBI and MSDBIM methods will show significantly higher index values at certain consecutive nodes, characterizing a given element, indicating that damage occurs at that location, and relatively lower values in undamaged locations. A node with an index value equal to zero and another non zero node do not characterize a damaged element.

Numerical examples

For the applied investigation of the methodology, computational models of concrete and steel beams were constructed using the *commercial software* package for finite element analysis, Abaqus/CAE (2018), and beam data available in the specialized literature. In this context, the works of Pedro Paulo Martins de Carvalho carried out in 2015 at the Graduate Program in Civil Engineering (PPGEC) at the Federal University of Alagoas (UFAL) and Moradipour, Chan, and Gallage (2015) were of particular interest. Carvalho's work (2015) was chosen due to the author’s interest in the data obtained experimentally by the author and the possibility of evaluating whether another approach (based on the changing of modal parameters) would allow identifying the region where the author introduced damages. The work of Moradipour, Chan and Gallage (2015) was selected given the interest in modeling and the numerical results presented.

Initially, the computational beam models were discretized, with subsequent extraction of the vibration modes of the undamaged structure. This process was also repeated for damaged beam models. The obtained data were evaluated using a MATLAB code (R2014b).

This section will present the most relevant aspects of the aforementioned works, such as the discretization and the introduction of damages in the constructed computational models.

Physical and geometric properties of beams without damage

For the simply supported beam, the same material properties and the same geometric data as the work of Carvalho (2015) were used (Table 1).

Table 1. Properties of the simply supported undamaged beam.

Cross-sectional area	0.01 m^2
Second moment of area	$833.33 \cdot 10^{-8}$ m^4
Modulus of elasticity	$19.19 \cdot 10^9$ N/m^2
Mass density	2400 kg/m^3
Length of the beam	0.40 m

For the fixed-end beam, the same properties as in the work of Moradipour, Chan and Gallage (2015) were used (Table 2).

Table 2. Properties of the fixed-end undamaged beam.

Cross-sectional area	0.0016 m^2
Second moment of area	$3.4133 \cdot 10^{-9}$ m^4
Modulus of elasticity	$207 \cdot 10^9$ N/m^2
Mass density	7870 kg/m^3
Length of the beam	7.20 m

Discretization of beams

The models of the simply supported and fixed-end beams were constructed in two dimensions using the commercial software package for finite element analysis Abaqus/CAE (2018), with formulation B21, which refers to two-node linear beam elements in the plane, so that each node has three degrees of freedom.

The simply supported beam was discretized into 16 elements, each 0.025 m in length, 17 nodes, and 47 degrees of freedom (Figure 2).

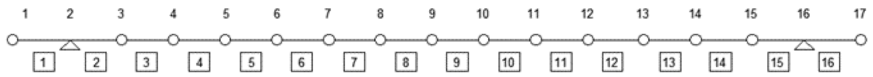


Figure 2. Model of the discretized simply supported beam.

The fixed-end beam was discretized in the same way as the one in the work of Moradipour, Chan and Gallage (2015), namely into 12 elements, each 0.60 m in length, totaling 13 nodes and 33 degrees of freedom (Figure 3).

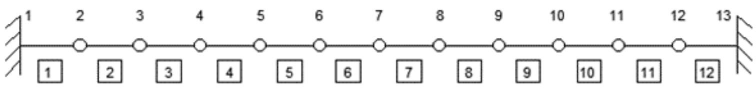


Figure 3. Model of the discretized fixed-end beam (Discretization I).

A new discretization for the fixed-end beam was used to assess whether there is any direct influence on the damage identification methods and consisted of 24 elements, each 0.30 m in length, totaling 25 nodes and 69 degrees of freedom (Figure 4).

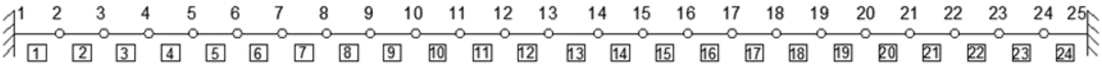


Figure 4. Model of the discretized fixed-end beam (Discretization II).

Introduction of Damage

In the models of the simply supported beam, a single damage was introduced in a region close to that where Carvalho (2015) tested (element 9 of Figure 2). Because the sensitivity of the proposed modified method will be assessed, different damage scenarios have been defined (Table 3).

Table 3. Damage scenarios in the simply supported beam model.

Scenario no.	Damaged element no.	Stiffness reduction (%)
1	9	5
2	9	10
3	9	15
4	9	20

For the fixed-end beam (Discretization I), in the case of single damage, the damage was introduced in element 6 of Figure 3, with a stiffness loss of 15%; in the case of multiple damages, the damage was made to elements 6 and 11 of Figure 3, with 10% stiffness loss in each element, similarly as that performed by Moradipour, Chan and Gallage (2015). Different damage scenarios were considered to assess the sensitivity of methods for single and multiple damages (Table 4).

Table 4. Damage scenarios in the fixed-end beam model.

Scenario no.	Damaged element no.	Stiffness reduction (%)
1	6	5
2	6	10
3	6	15
4	6	20
5	6 and 11	5 and 5
6	6 and 11	10 and 10
7	6 and 11	15 and 20
8	6 and 11	20 and 20

For the fixed-end beam (Discretization II), the same damage scenarios, single and multiple, were defined as for the fixed-end beam (Discretization I) (Table 4). However, in the case of single damage, the damage was introduced in element 11. In the case of multiple damages, the damage was introduced in elements 11 and 21, as illustrated in Figure 4. These elements were chosen so that the damaged regions in the beam models, in both situations (single and multiple damages), coincided with those investigated by Moradipour, Chan and Gallage (2015).

Results and discussion

This section presents the results obtained from the models of the simply supported and fixed-end beams (Discretization I and II) for the damage scenarios investigated (Tables 3-4). The modal data, obtained numerically, for the first five vibration modes were used simultaneously to identify the damaged site through the application of the traditional method MSDBI and the proposed modified method MSDBIM.

To study the sensitivity of the methods in the simply supported beam models, different damage scenarios (with stiffness reductions of 5, 10, 15, and 20% (Table 3)) were assumed for element 9. For all investigated scenarios (Figures 5 (a)-(d)), the proposed modified method (MSDBIM), despite not presenting null index values (nMSDBIM) in all nodes outside the damaged region, presents greater values in the damaged region (element 9), indicating that damage occurs in that element. The traditional MSDBI method, in turn, does not locate the damaged element at damage intensities of 10% (Figure 5 (b)) and 20% (Figure 5 (d)), in addition to erroneously presenting the existence of more than one damaged region. Thus, the greatest disagreement between the two methods occurs for these two damage intensities. A possible explanation for such disagreement is the fact that the results shown in Figures 5 (a)-(d) are from the simultaneous analysis of the first five vertical mode shapes, therefore, as the mode shapes are mirrored, the traditional method's damage identification algorithm is not a good indicator. Such an occurrence is verified for a damage intensity of 10%, in which two of the five vertical mode shapes (modes 1 and 5) have mirroring (Figure 6), and for an intensity of 20%, in which one of the five modes (mode 5) has mirroring (Figure 7).

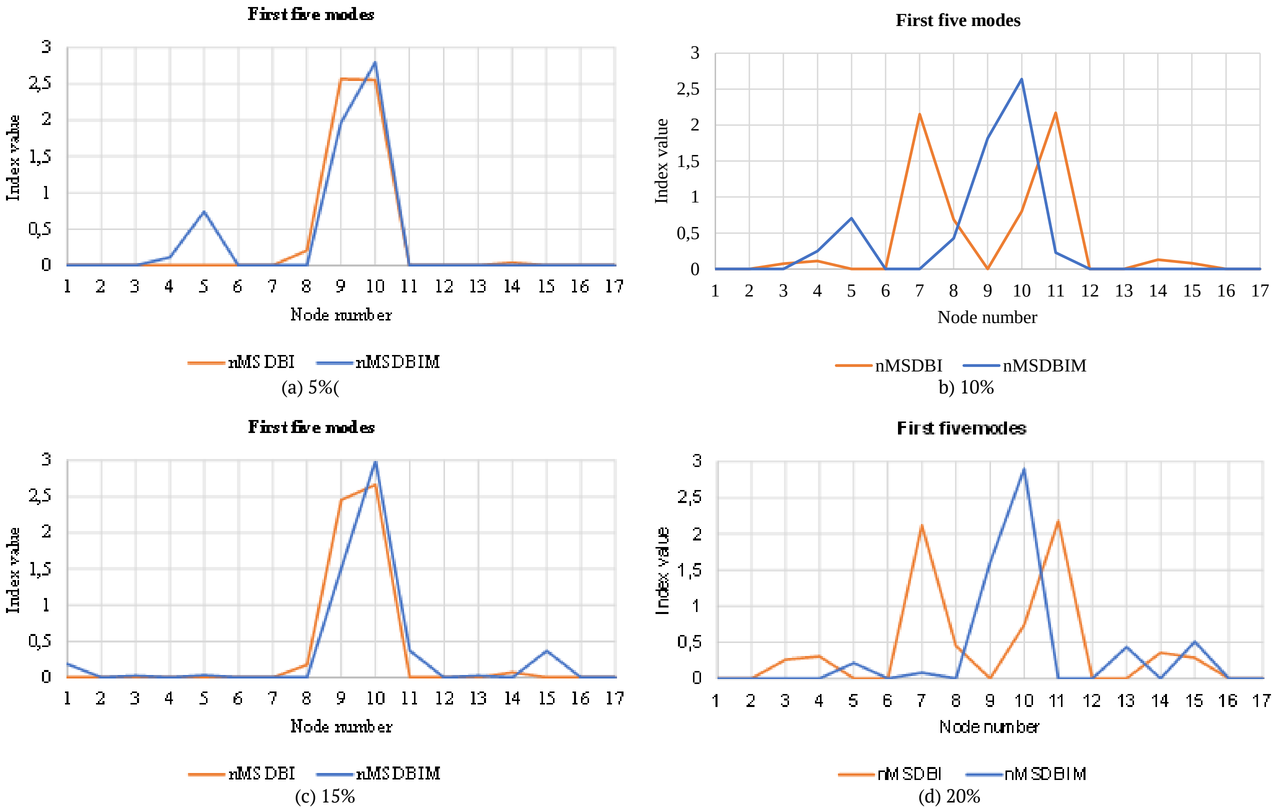


Figure 5. Damage identification in models of the simply supported beam for single damage scenarios.

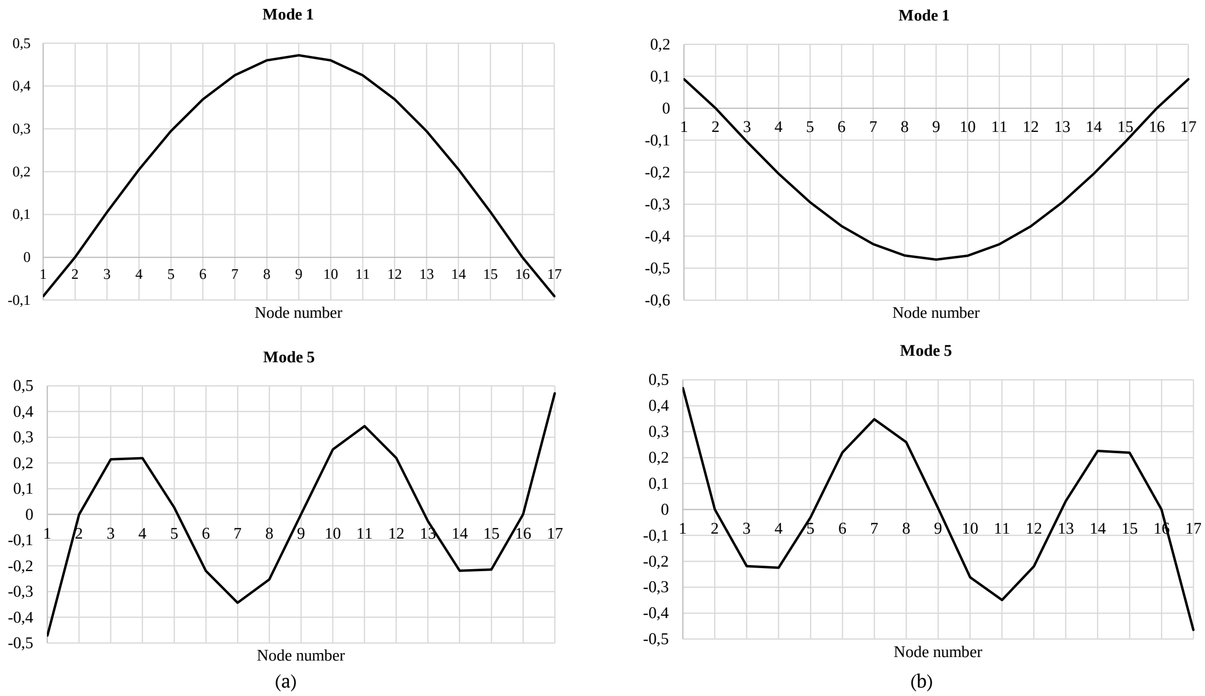


Figure 6. Displacement mode shapes in simply supported beam models (a) intact and (b) damaged, with a 10% reduction in flexural rigidity.

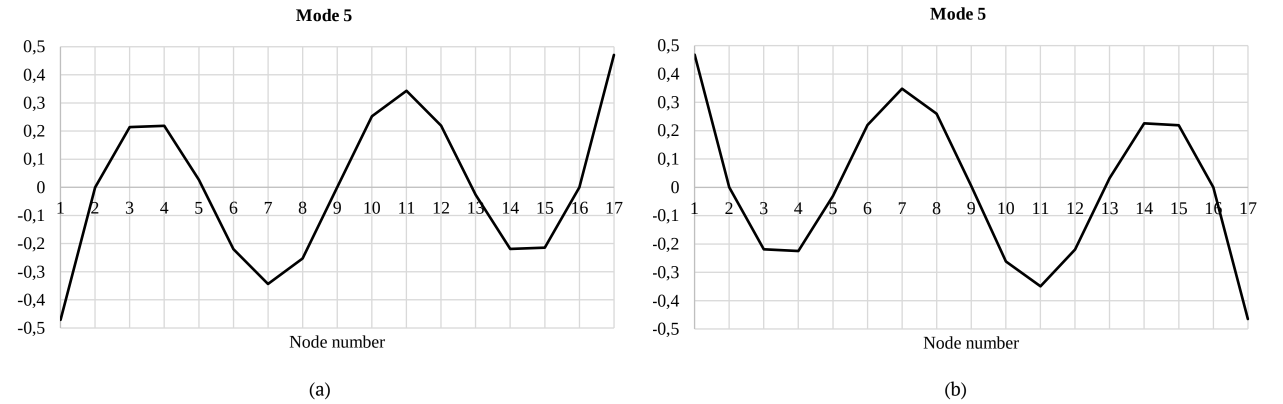


Figure 7. Displacement mode shapes in simply supported beam models (a) intact and (b) damaged, with a 20% reduction in flexural rigidity.

The single damage scenarios in the models of the fixed-end beam (represented by stiffness reductions of 5, 10, 15, and 20% in element 6) were investigated using the methods. For all damage scenarios (Figures 8 (a)-(d)), the modified MSDBIM method detects a region between elements 5 and 6 where the damaged element is contained. The traditional MSDBI method shows the existence of more than one damaged region for all scenarios (Figures 8 (a)-(d)). In this case, it is not a good indicator of damage.

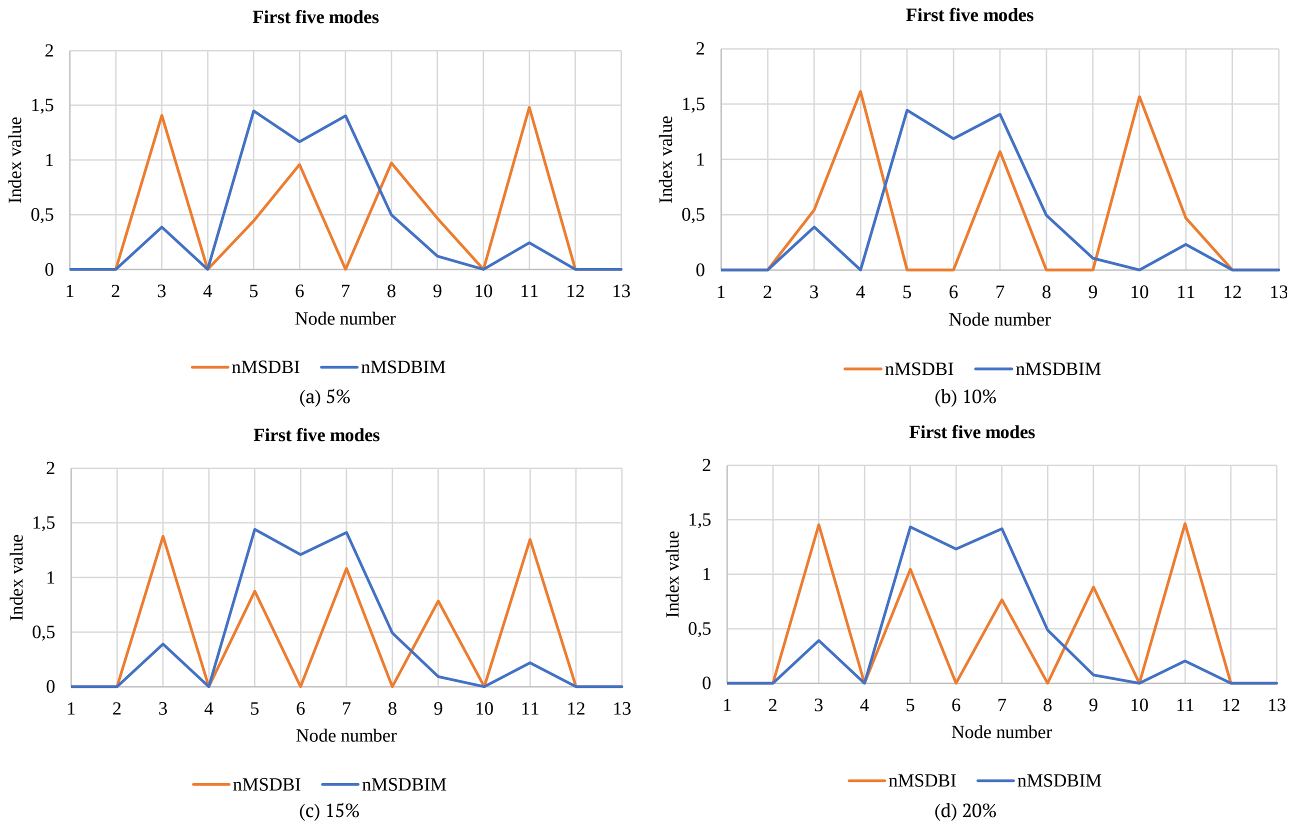


Figure 8. Damage identification in models of the fixed-end beam for single damage scenarios (Discretization I).

To study the multiple damage case in the models of the fixed-end beam, different damage scenarios are assumed for elements 6 and 11, with stiffness reductions of 5% and 5%, 10% and 10%, 15% and 20%, and 20% and 20%, respectively (Table 4). In all investigations (Figures 9 (a)-(d)), the MSDBIM method points to the existence of two damaged regions. In the first region, the damaged element can be 5 or 6, while the damaged element can be 9 or 10 in the second region. The MSDBI method, in turn, has more than two damaged regions.

When increasing the mesh refinement in the models of the fixed-end beam, the same single damage scenarios (stiffness reductions equal to 5, 10, 15, and 20%) were considered in element 11 to assess the sensitivity methods. For the investigated scenarios (Figures 10(a)(d)), the proposed modified method (MSDBIM) identifies the damaged element correctly and clearly. The MSDBI method, on the other hand, has more than one damaged region, reducing the number of indicated regions as the damage intensity increases.

Then, the worst scenarios for the MSDBI method are for a damage intensity of 5% (Figure 10(a)), in which three of the five vertical vibration modes (modes 1, 3 and 5) are mirrored (Figure 11), and for an intensity of 10% (Figure 10(b)), in which three of the five modes (modes 1, 3 and 4) are also mirrored (Figure 12). Added to the number of mirrored modes, their order (1, 2, 3, 4, and/or 5), and the intensity of the damage are factors that influence the damage identification algorithm.

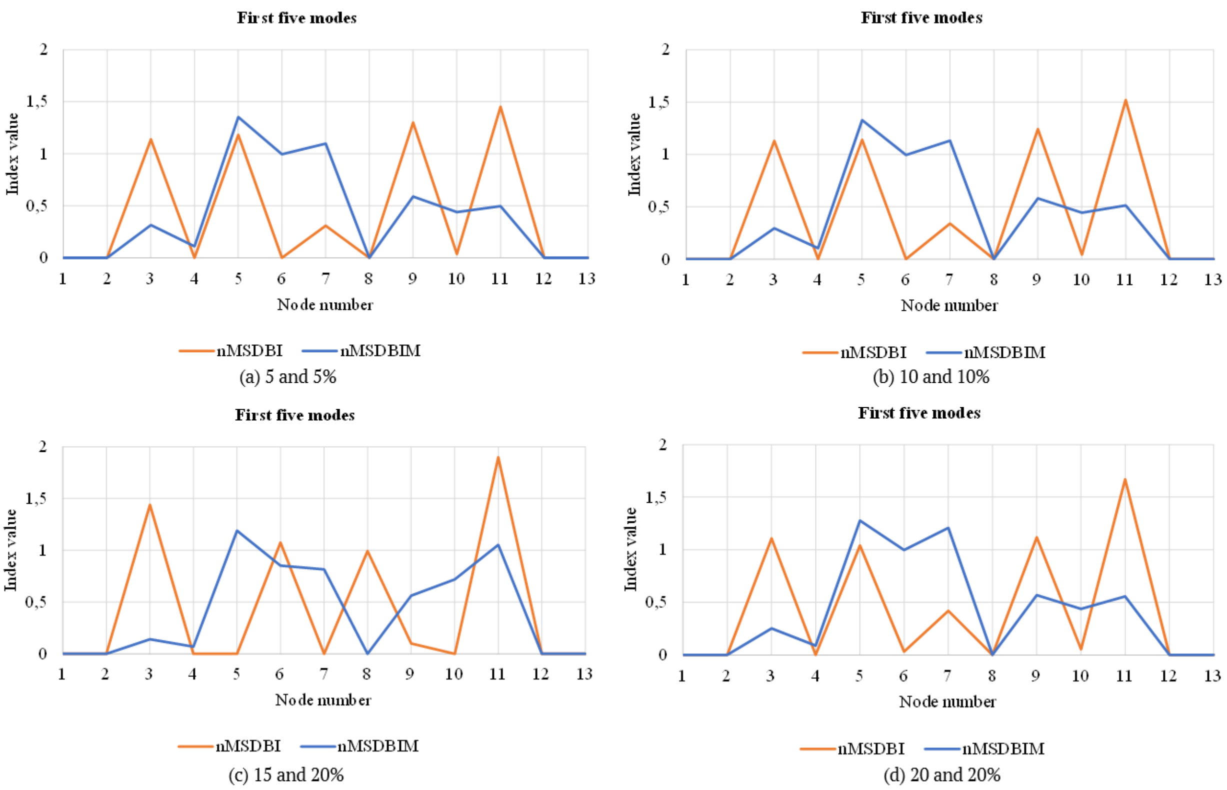


Figure 9. Damage identification in the fixed-end beam models for multiple damage scenarios (Discretization I).

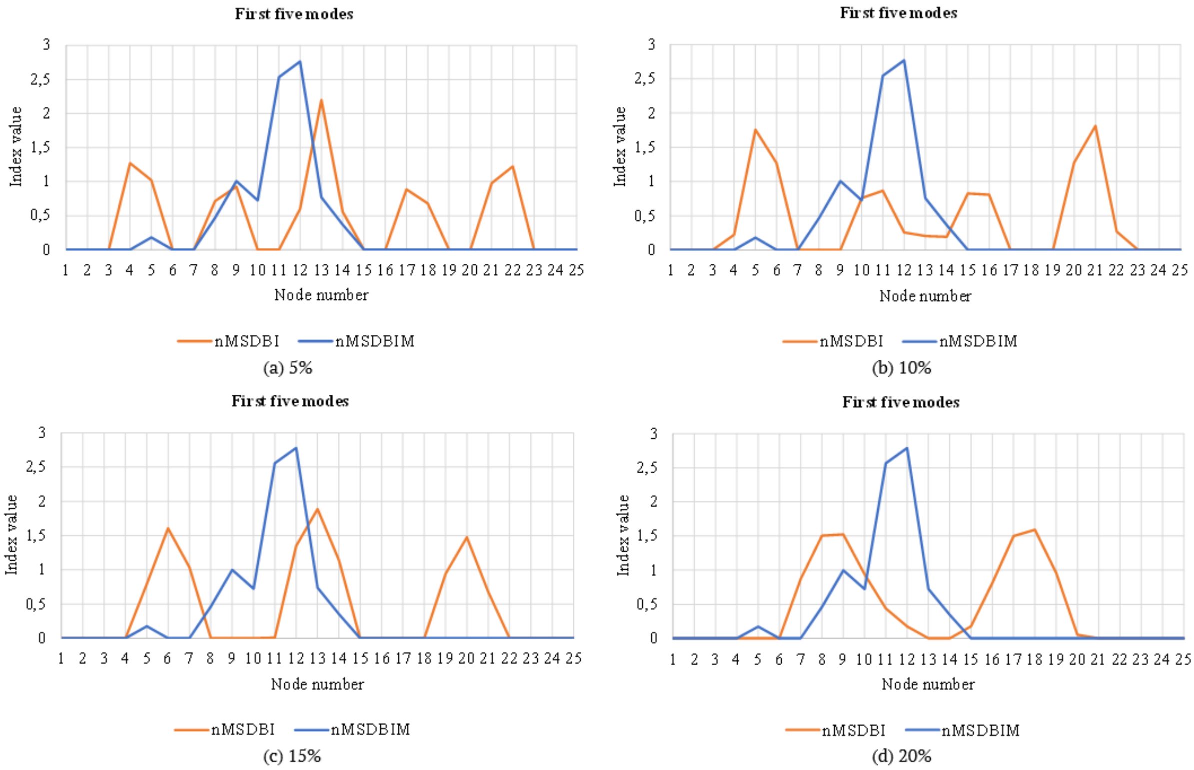


Figure 10. Damage identification in the fixed-end beam models for single damage scenarios (Discretization II).

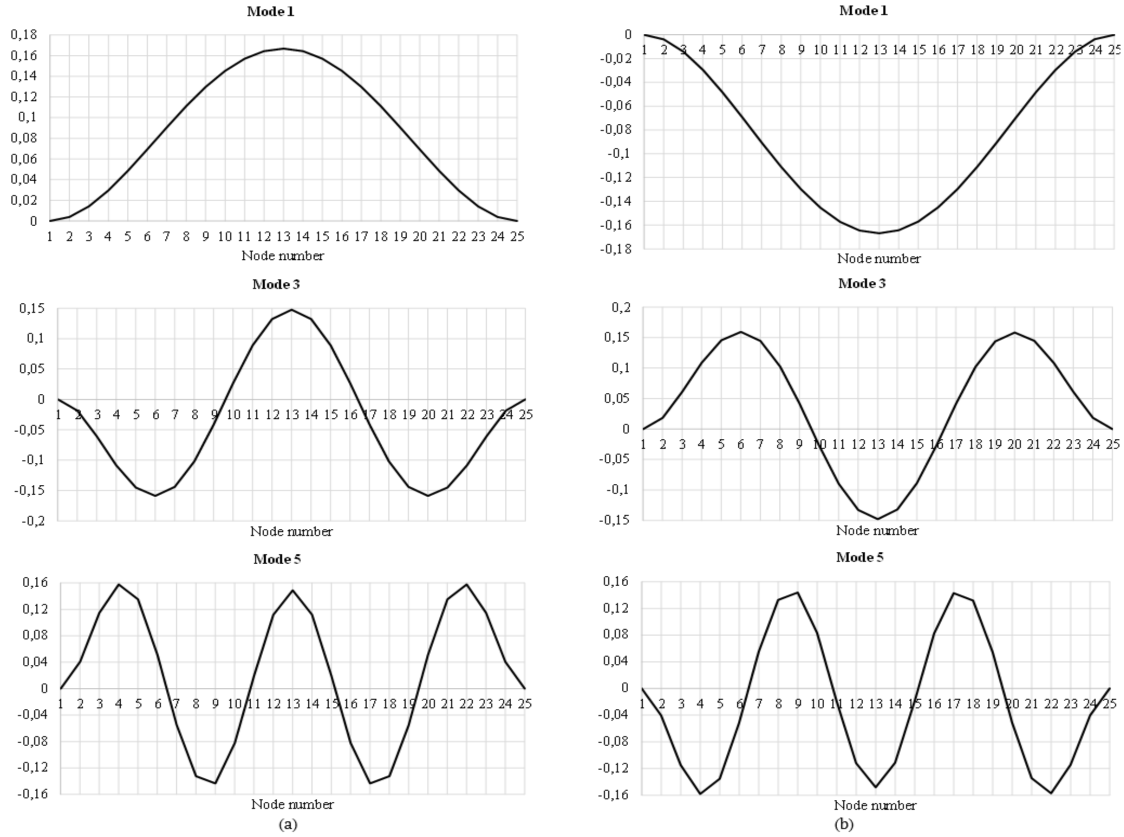


Figure 11. Displacement mode shapes in the fixed-end beam models (Discretization II) (a) intact and (b) damaged, with a 5% reduction of flexural rigidity.

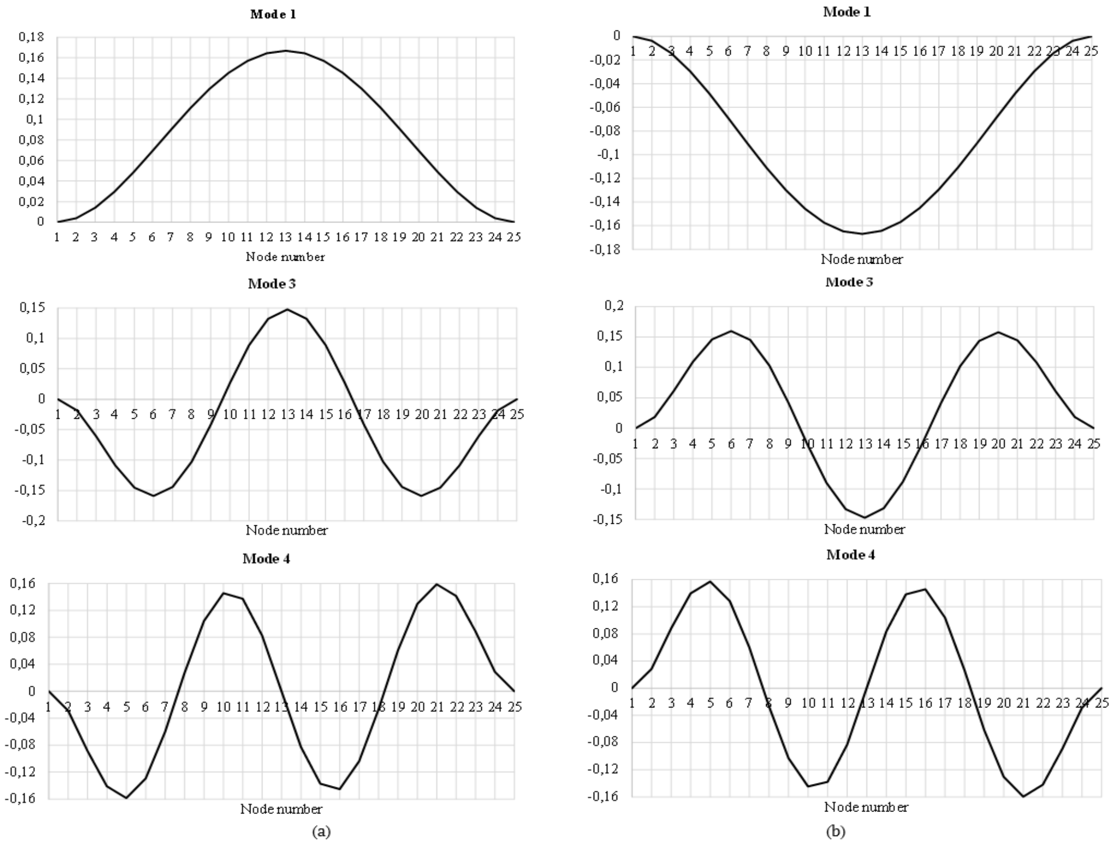


Figure 12. Displacement mode shapes in the fixed-end beam models (Discretization II) (a) intact and (b) damaged, with a 10% reduction of flexural rigidity.

To study the influence of the refinement mesh on the fixed-end beam models with multiple damages, different damage scenarios were assumed for elements 11 and 21, with stiffness reductions of 5% and 5%, 10% and 10%, 15% and 20%, and 20% and 20%, respectively. MSDBIM, the proposed modified method, identified the two damaged elements (11 and 21) in all damage scenarios investigated (Figures 13(a)-(d)). The MSDBI method detects more than two damaged regions in all damage scenarios examined. For all investigated scenarios, of the five modes of vibration, three modes have mirroring. For damage intensities, 5% and 5% and 10% and 10%, the modes that have mirroring are 3, 4, and 5 (Figures 14 and 15). For the damage intensities of 15% and 20% and of 20% and 20%, the modes are 2, 3, and 4 (Figures 16 and 17). In addition to the number of mirrored modes, their order and the intensity of the damage are factors that influence the damage identification algorithm.

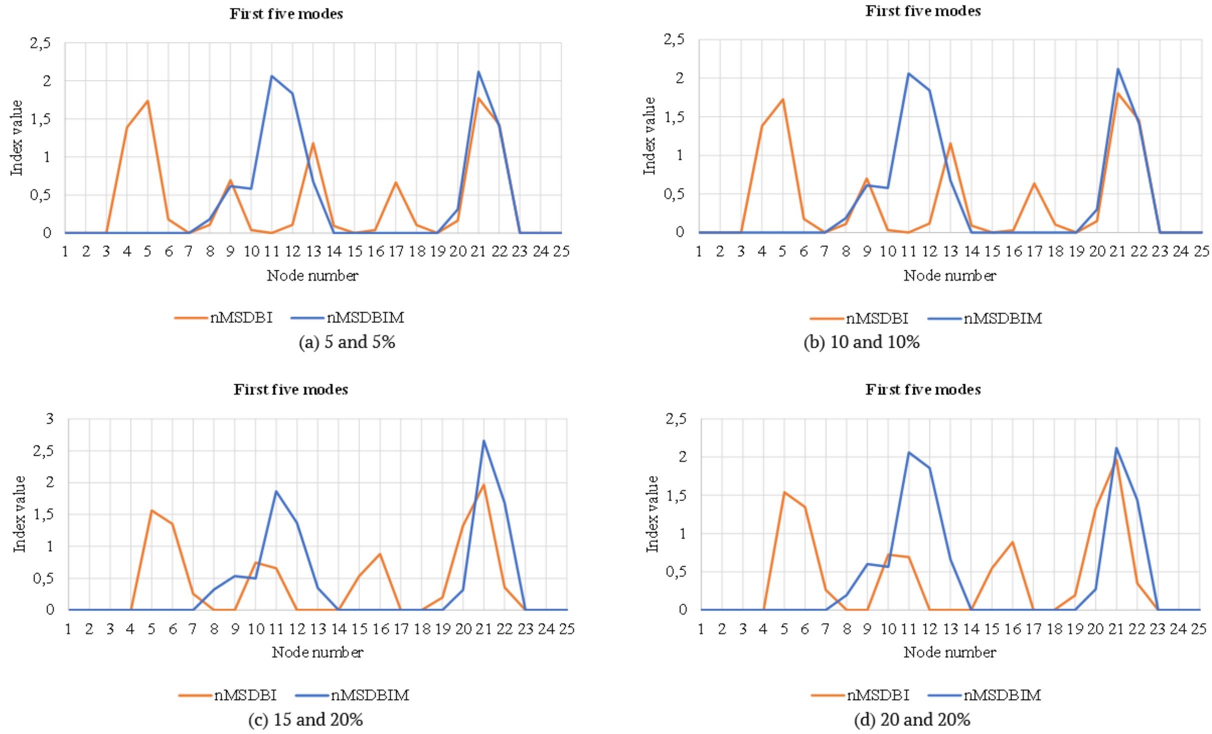
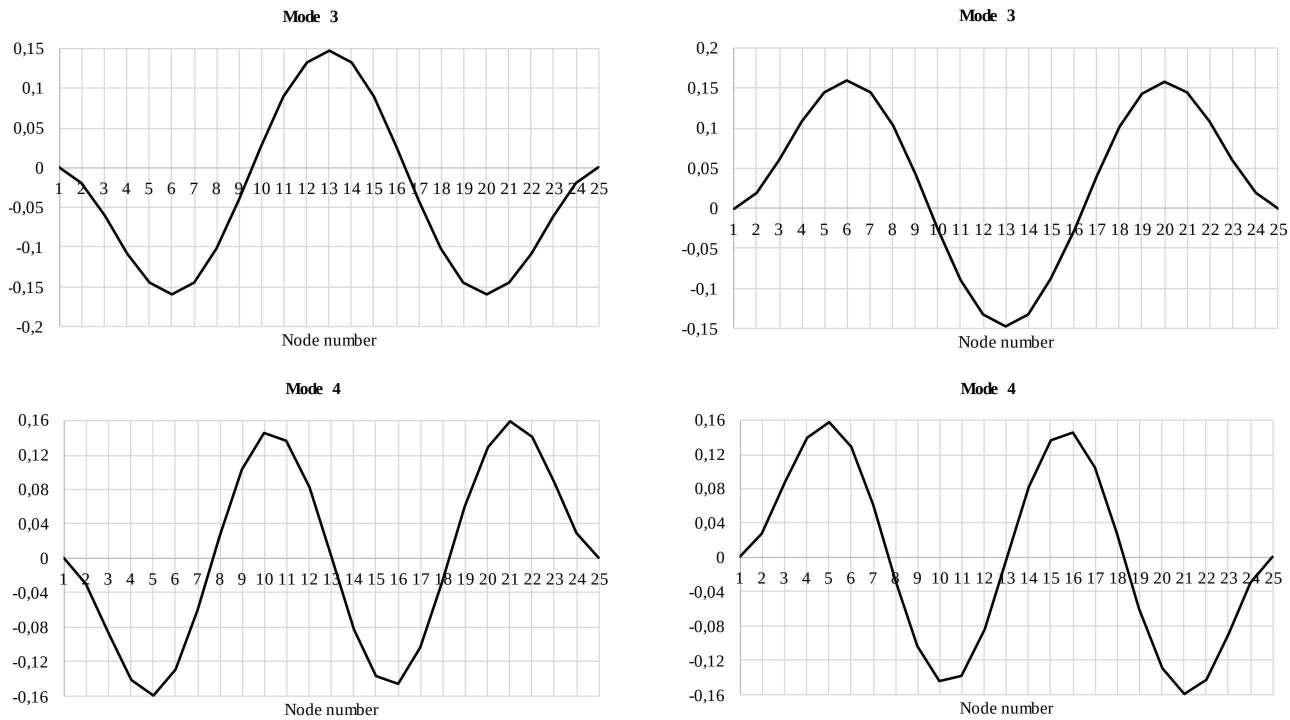


Figure 13. Damage identification in the fixed-end beam models for multiple damage scenarios (Discretization II).



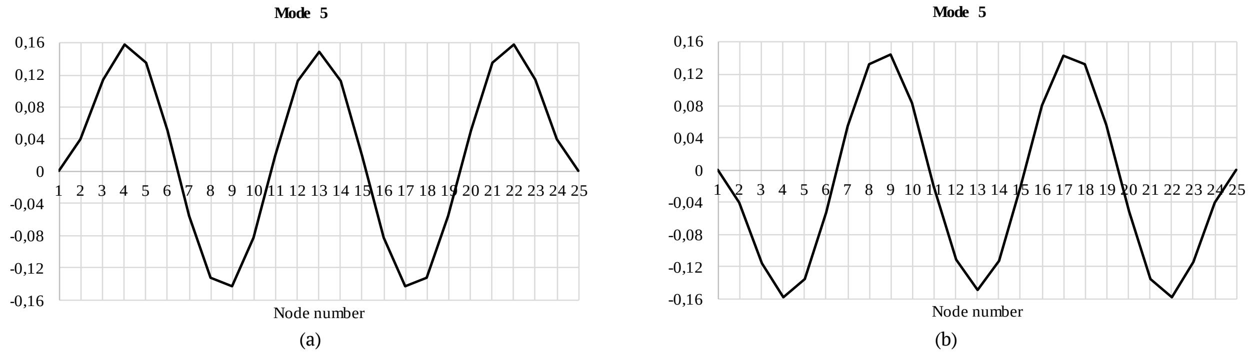


Figure 14. Displacement mode shapes in the fixed-end beam models (Discretization II) (a) intact and (b) damaged, with a 5 and 5% reduction of flexural rigidity.

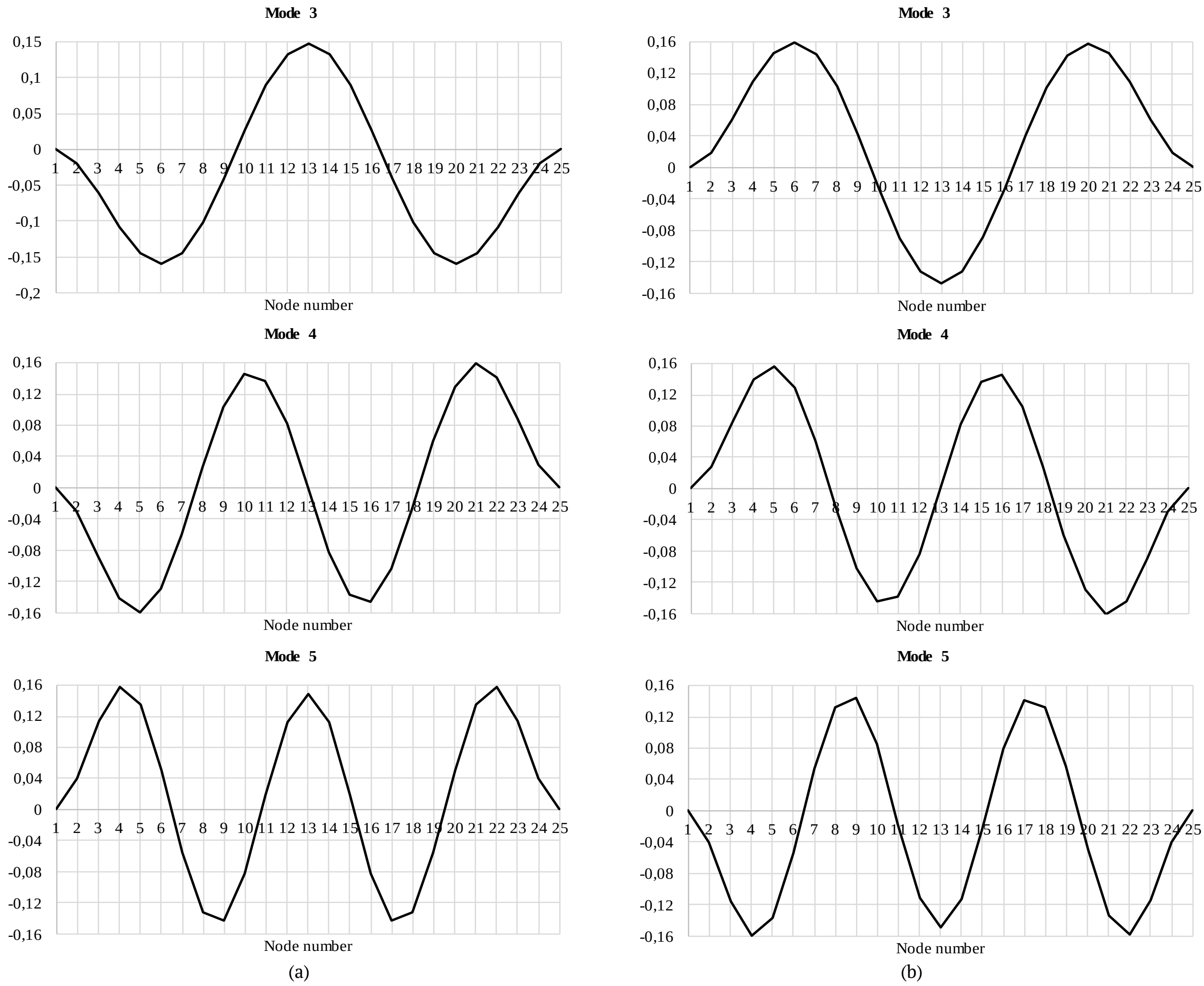
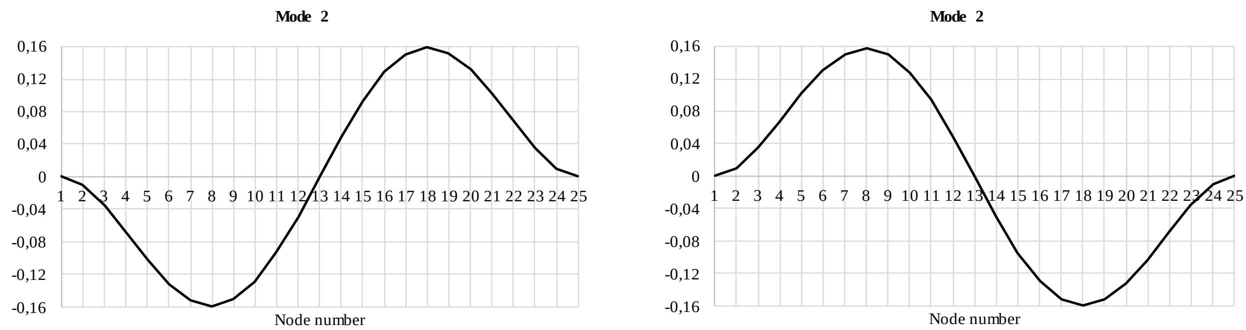


Figure 15. Displacement mode shapes in the fixed-end beam models (Discretization II) (a) intact and (b) damaged, with a 10 and 10% reduction of flexural rigidity.



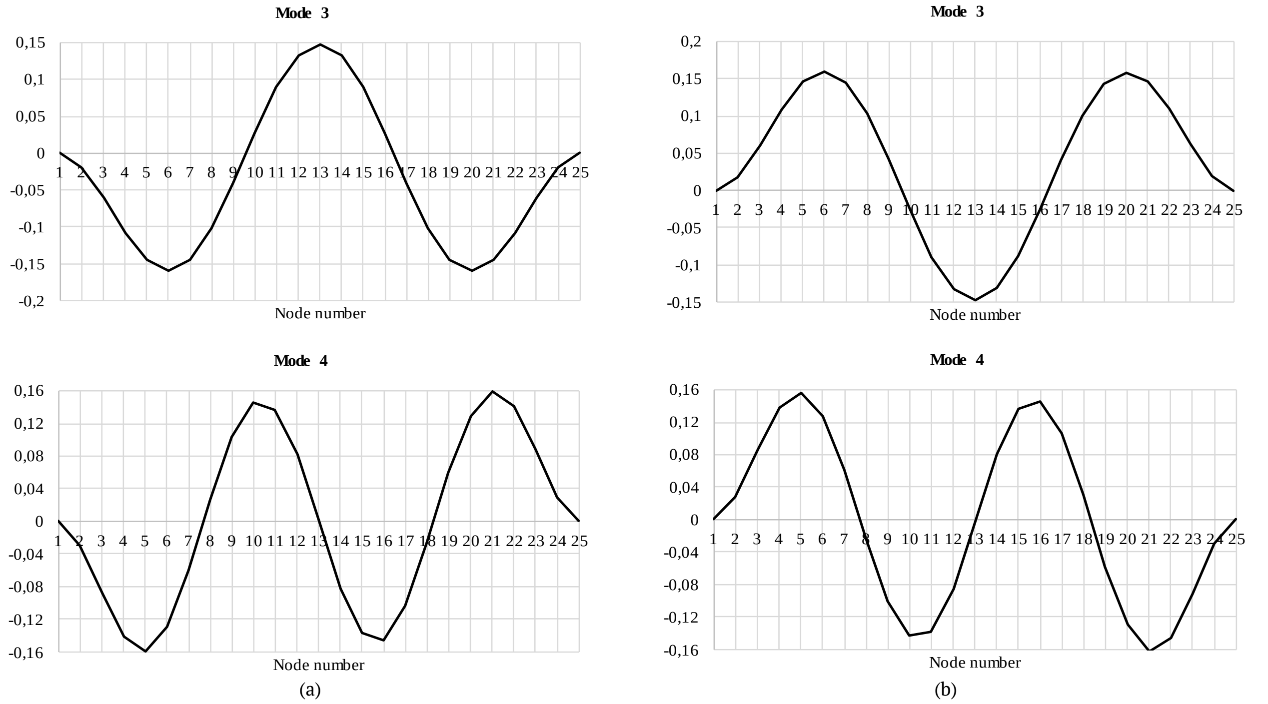


Figure 16. Displacement mode shapes in the fixed-end beam models (Discretization II) (a) intact and (b) damaged, with a 15 and 20% reduction of flexural rigidity.

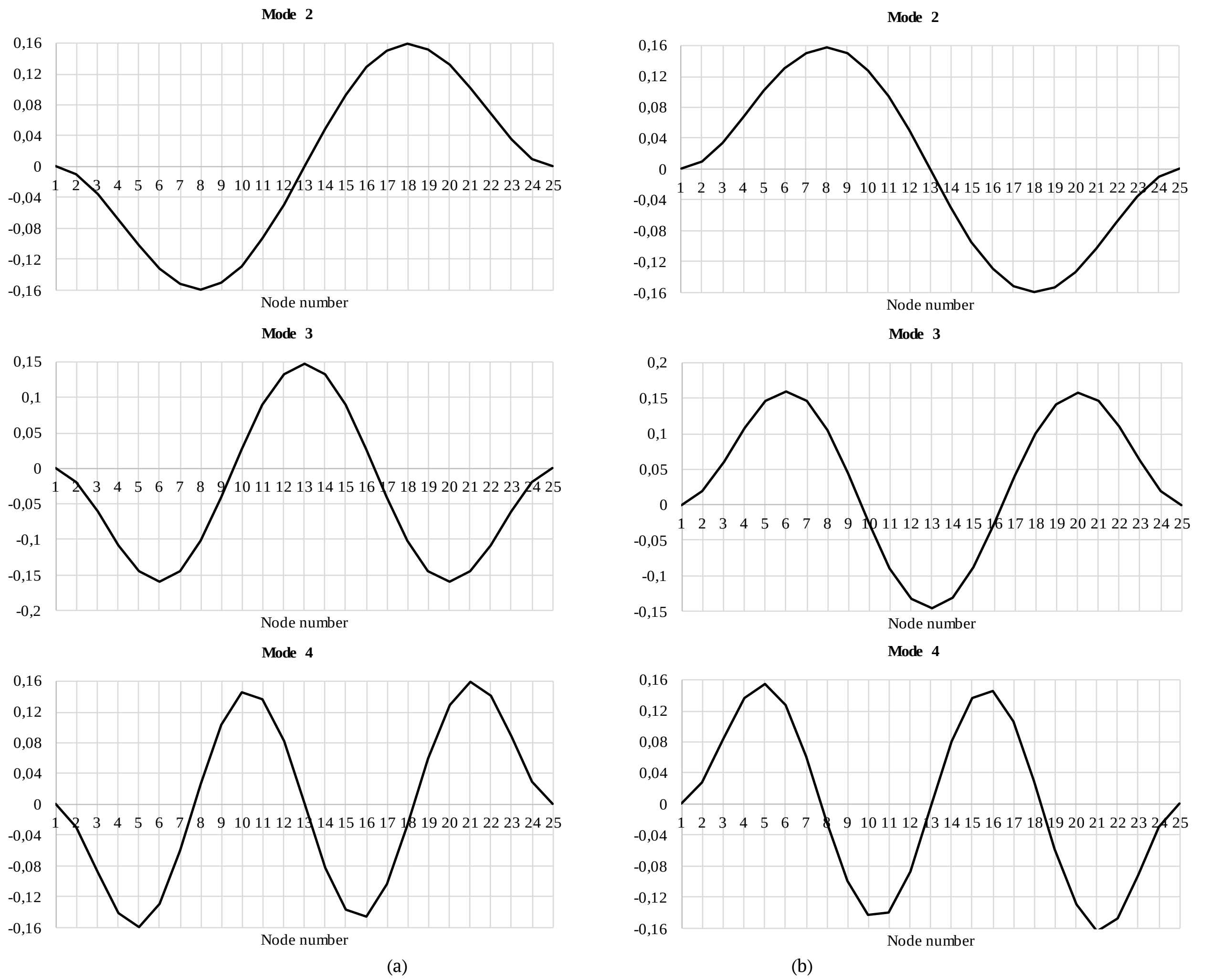


Figure 17. Displacement mode shapes in the fixed-end beam models (Discretization II) (a) intact and (b) damaged, with a 20 and 20% reduction of flexural rigidity.

Figure 18 shows a qualitative comparison of the results obtained by the methods in the cases and scenarios discussed in this section. The attribution of the classification "*Identifies the damage (single or multiple) with clarity*" present in that Chart, was established by assuming that the undamaged elements had an index value (MSDBI and MSDBIM) below 50% of that presented by the element with damage. In the Chart, the method obtained by the modification proposed by the authors was highlighted with gray filling in the identification cell.

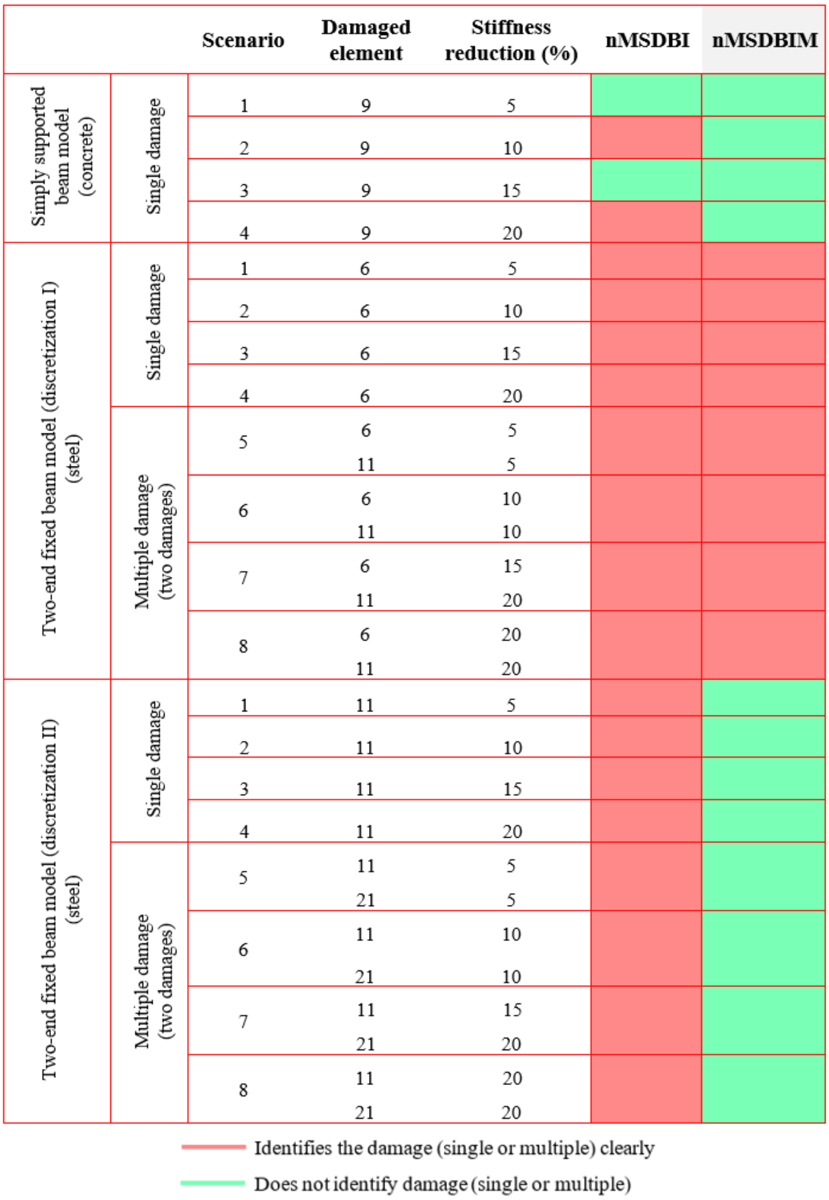


Figure 18. Qualitative comparison of the results obtained.

Conclusion

This paper proposes a modified method to detect and locate structural damage. Different damage scenarios were studied to verify the effectiveness of the proposed method in numerical models of simply supported (concrete) and fixed-end (steel) beams. The proposed modified method MSDBIM performed better than the traditional method MSDBI. After analyzing the results, we found that:

- The modified MSDBIM method identifies the single damage in the concrete beam models, while the traditional MSDBI method, for certain damage intensities, attributes damage to undamaged regions, making it impossible to identify the damaged elements correctly.
- No method could detect single or multiple damages when analyzing the steel beam models (Discretization I). However, the modified method correctly detected the region containing the element with damage in the case of single damage.

- The results in the steel beam models (Discretization II) improve with the models' increased mesh refinement. In this condition, the modified method is a good indicator of single and multiple damages, while the traditional method does not provide results compatible with a good indication of single or multiple damages.
- The modified method identifies the damage of models of the simply supported beam in the same region as the one introduced by Carvalho (2015), showing the efficiency of the damage investigation through the proposed modified method.
- The joint analysis of the results for the first five vertical mode shapes, as proposed by the modified method, allows concluding that the damaged element can be identified with a certain degree of safety, since in the individual analysis, a certain mode can identify the incorrect location or may not present the highest index value on the damaged element.

The proposed modified method is more efficient than the traditional one because, in certain modes of the damaged structure, the displacement mode shape configuration presents mirroring compared to the configuration observed in the undamaged structure. In these situations, the traditional algorithm cannot adequately indicate the damage. The number of mirrored modes is not related only to the damage intensity. The structure material, the number of mirrored modes, and the order in which the mirroring occurred affect the results provided by the traditional method.

Acknowledgments

The authors would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior Brasil (CAPES) for the scholarship and the Laboratory of Scientific Computing and Visualization (LCCV) of the Federal University of Alagoas (UFAL) for making the software available.

References

Allemang, R. J., & Brown, D. L. (1982). A Correlation coefficient for modal vector analysis. *Proceedings of the 1st International Modal Analysis Conference (IMAC I).* Orlando, Florida, USA. p. 110-116.

Kim, J. T., & Stubbs, N. (2003). Crack detection in beam-type structures using frequency data. *Journal of Sound and Vibration*, 259(1), 145-160. DOI: https://doi.org/10.1006/jsvi.2002.5132

Lieven, N., & Ewins, D. J. (1988). Spatial correlation of mode shapes, the Coordinate Modal Assurance Criterion (COMAC). *Proceedings of the 6th International Modal Analysis Conference*.

Moradipour, P., Chan, T. H. T., & Gallage, C. (2015). An improved modal strain energy method for structural damage detection, 2D simulation. *Structural Engineering and Mechanics, 54*(1), 105-119. DOI: http://dx.doi.org/10.12989/sem.2015.54.1.105

Pandey, A.K., Biswas, M., & Samman, M. (1991). Damage detection from changes in curvature mode shape. *Journal of Sound and Vibration, 145*(2), 321-332. DOI: https://doi.org/10.1016/0022-460X(91)90595-B.

Pandey, A. K., & and Biswas, M. (1994). Damage detection in structures using changes in flexibility. *Journal of Sound and Vibration, 169*(1), 3-17. DOI: https://doi.org/10.1006/jsvi.1994.1002

Ratcliffe, C. P. (1997). Damage detection using a modified laplacian operator on mode shape data. *Journal of Sound and Vibration, 204*(3), 505-517. DOI: https://doi.org/10.1006/jsvi.1997.0961

Roy, K. (2017). Structural Damage Identification Using Mode Shape Slope and Curvature. *Journal of Engineering Mechanics, 143*(9), 1-12. DOI: https://doi.org/10.1061/(ASCE)EM.1943-7889.0001305.

Samman, M. M., & Biswas, M. (1994-a). Vibration testing for nondestructive evaluation of bridges I: Theory. *Journal of Structural Engineering, 120*(1), 269-289. DOI: https://doi.org/10.1061/(ASCE)0733-9445(1994)120:1(269)

Samman, M. M., & Biswas, M. (1994-b). Vibration testing for nondestructive evaluation of bridges II: Results. *Journal of Structural Engineering*, 120(1), 290-306. DOI: https://doi.org/10.1061/(ASCE)0733-9445(1994)120:1(290)

Shi, Z. Y., & Law, S. S. (1998). Structural damage localization from modal strain energy change. *Journal of Sound and Vibration, 218*(5), 825-844. DOI: https://doi.org/10.1006/jsvi.1998.1878

Shi, Z. Y., Law, S. S. & Zhang, L. M. (2000). Structural damage detection from modal strain energy change, *Journal of Engineering Mechanics, 126*(12), 1216-1223. DOI: https://doi.org/10.1061/(ASCE)0733-9399(2000)126:12(1216)

Wang, S. Q., & Li, H. J. (2012). Assessment of structural damage using natural frequency changes. *Acta Mechanica Sinica, 28*(1), 118-127. DOI: https://doi.org/10.1007/s10409-012-0017-7

Wu, S., Zhou, J., Rui, S, & Fei, Q. (2017). Reformulation of elemental modal strain energy method based on strain modes for structural damage detection. *Advances in Structural Engineering, 20*(6), 896–905. DOI: https://doi.org/10.1177/1369433216665626

Yazdanpanah, O., Seyedpoor, S. M., & Bengar, H. A. (2015). A new damage detection indicator for beams based on mode shape data. *Structural Engineering and Mechanics, 53*(4), 725–744. DOI: http://dx.doi.org/10.12989/sem.2015.53.4.725