Modal Identification of Damage in the Dowling Hall Pedestrian Footbridge

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Abstract. The methods that stand out in damage identification are those rooted in vibration response analysis, known as Vibration-based Damage Identification (VBD). This arises from the direct influence of deterioration on the global and local dynamic responses of structural elements, leading to alterations in dynamic parameters. Modal indices, such as modal curvature (MC) and modal strain energy (MSE), were evaluated for the Dowling Hall pedestrian walkway using a finite element model that extracted three-dimensional vibration modes. Additionally, a newly introduced index known as the resultant vector, which incorporates three-dimensional modal coordinates, was also examined and compared with the other indices. The results showed that there is a strong correlation between the location of the actual damage and the location predicted by the indices. The study further investigates the influence of damage magnitude on the accuracy of the indices and analyzes how damages impact adjacent beams. The objective is to minimize ambiguities in determining damage locations and to provide guidance for inspection and structural integrity monitoring programs. In conclusion, the methods of MC and MSE presented more satisfactory results in identifying the introduced damages, whereas the resultant vector method exhibited certain inconsistencies. The study also observed minimal variations when applying damages of different intensities, indicating heightened sensitivity primarily in lower intensities.

Keywords: Damage detection; Structural dynamics; Modal Curvature; Modal Strain Energy; Finite Element Model.

1 Introduction

Structural Health Monitoring (SHM) is a comprehensive and crucial research field in engineering, with diverse applications. Technological advancements and the development of increasingly precise sensors have facilitated the utilization of monitoring data to assess structural condition and propel studies conducted for structural health maintenance, as demonstrated in the work by Cha et al. [1]. Structures such as bridges and pedestrian bridges are exposed to various factors that can compromise their functionality and integrity. These factors include varied environmental conditions, gaps in continuous maintenance, as well as unforeseen loads and inadequate construction practices that also contribute to degradation.

The implementation of indicators in structural monitoring systems allows for early damage detection, preventing accidents. Non-destructive methods hold growing significance, enabling the monitoring and inspection of civil structures in service, especially those with special characteristics, such as works of art.

Methods based on the analysis of structural dynamic behavior have proven effective in damage detection. Deterioration of structural elements results in changes in the physical properties of the building, impacting its overall dynamic response.

Technological development has enabled the use of computational tools, including the Finite Element Method (FEM), for numerical analysis of structures. These tools allow the investigation of structural behavior through simulations that replicate various conditions. FEM enables the identification of dynamic parameters derived from simulations.

These methods aim to detect changes in the modal properties of the structure, such as natural frequencies, modal damping, and vibration modes. Modal damage indices have been studied in relation to the diagnostic levels proposed by Rytter [2]: detection, localization, severity quantification, and estimation of remaining useful life. Numerous techniques for evaluating structural damage through vibration analysis have been put forth in existing literature. Comprehensive assessments and reviews regarding damage identification using vibration-based approaches have been offered by Doebling el al. [3].

The present study analyzed the dynamic behavior of the Dowling Hall pedestrian walkway at Tufts University, Massachusetts, USA and evaluated the effectiveness of damage detection indices selected from the literature. The pedestrian bridge features a continuous monitoring system based on vibrations and a comprehensive database. A finite element model was developed and used to examine the circumstances affecting the accuracy of indices in locating damages, considering the position and severity of the damage.

2 Finite Element Model of Dowling Hall Footbridge

To analyze the dynamic behavior of the pedestrian bridge, it is essential to obtain the vibration modes and corresponding natural frequencies of each mode. Based on the information from Dowling Hall, a model was created using the ABAQUS software, developed by Simulia Dassault Systèmes, using the finite element method.

The Dowling Hall footbridge has a length of 44 m, divided into two spans of 22 m, and a width of approximately 3.9 m. It connects two parts of the campus and is supported by columns located on the west side, in the middle, and on the east side. The walkway structure consists of A992 steel HSS (Hollow Structural Sections) profiles and a reinforced concrete deck, as per the study by Moaveni et al. [4] and Bowman [5].

For the modeling of the steel structure, B31 beam elements were employed to represent the HSS profiles with an elastic modulus of $2.0\text{x}10^8$ kN/m², a density of 7849 kg/m³ and Poisson´s coefficient of 0.3. The upper and lower flanges of the frame adopt TS10x6x5/16 and TS10x6x3/8 sections, respectively. The horizontal flanges correspond to TS10x4x5/16 profiles, while the diagonal and vertical profiles are TS8x6x5/16, except at the support positions, where the vertical elements use the TS8x6x1/2 section. In reference to the 10 cm reinforced concrete deck, S4R shell elements were employed, considering a density of 2403 kg/m³ and an elastic modulus of $1.4\text{x}10^7$ kN/m² as documented in the literature [4-5]. The adopted shell element size was 0.55 m, obtained after a convergence analysis. Boundary conditions were modeled as rigid supports. Consequently, one side of the bridge was fixed akin to a hinge, thereby constraining all rotational and translational movements. For the other two support regions (at 22 meters and the opposing end), secondary supports were simulated, allowing rotational degrees of freedom at the walkway's connection points with the columns. In Figure 1, it is possible to observe a view of the Dowling Hall footbridge structure and the finite element model constructed in Abaqus, based on the information provided within this section.


(a)

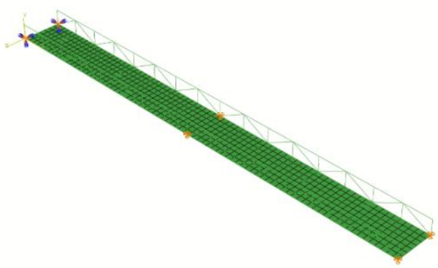
(b)

Figure 1. View of the Dowling Hall Pedestrian Footbridge (a) and the FE Model created in Abaqus (b)

3 Methods for Detecting Damage in Footbridges

Several indices reported in the literature that are based on the results of modal analysis are presented in this section. The selected indices are based on natural frequencies and vibration modes, including their derivations:

modal curvature and modal strain energy. The Resultant Vector index proposed by Gonçalves [6] is also investigated in the context of this study.

3.1 Modal Curvature (MC) Index

Originally proposed by Pandey et al. [7-8], the modal curvature index emerged as a novel parameter based on the curvature of vibration modes, serving as a damage index in structures. Fundamentally, the modal curvature method proposes damage detection in structures based on a local reduction in the flexural stiffness of the beam through the utilization of vibration modes. Modal Curvature is computed using the modal coordinate value of node i from the finite element model and its neighboring nodes $i-1$ and $i+1$, spaced at an equal distance of h. In other words, modal curvature is calculated relying on the central finite difference approximation.

Therefore, to determine the index commonly referred to in literature as the Curvature Damage Factor (CDF), ($\Delta\varphi''$), it suffices to define the absolute variation between the curvature of a damaged structure (φ''*) and that in intact conditions (φ''), taking into consideration the "n" analyzed vibration modes, as per equation (3.1). It should be noted that the intact condition refers to a current scenario in which previous damage to the structure is unknown. Here, this state is defined hypothetically after the structure has been built.

$$\Delta\varphi'' = |\, \varphi''^{*} - \varphi'' \,| \tag{3.1}$$

3.2 Resultant Vector (RV) Index

The index associated with the magnitude of the Resultant Vector was introduced by Gonçalves [6] to account for variations in the three-dimensional behavior of vibration modes during the damage detection process. Unlike other conventional methods, the damage index of the resultant vector is based on the three-dimensional analysis of vibration modes related to torsion and vertical and lateral bending (X, Y, and Z). Thus, in order to determine a singular index that incorporates three-dimensional variations, it suffices to find the resultant vector (RV) which takes into consideration the modal displacements in the three axes, and then the modulus of the difference between the damaged and intact structure, a process demonstrated in equations (3.2) and (3.3) below.

$$VR'_{i,j} = \sqrt{\varphi_{x,i,j}^2 + \varphi_{y,i,j}^2 + \varphi_{z,i,j}^2} \tag{3.2}$$

$$\Delta VR'_{i,j} = \left| VR'^{*}_{i,j} - VR'_{i,j} \right| \tag{3.3}$$

The symbol $VR'_{i,j}$ refers to the value of the Resultant Vector associated with vibration mode j at node i in the finite element model of the structure. The symbol $\varphi_{x,i,j}$ denotes the mass-normalized vibration mode related to modal coordinate x, and similarly for the vibration modes associated with coordinates y and z. The notation $\Delta VR'_{i,j}$ indicates the difference in $VR'_{i,j}$ between the damaged condition of the structure (indicated by a superscript asterisk) and the intact structure.

3.3 Modal Strain Energy (MSE) Index

Initially proposed by Stubbs et al. [9-10], the current method employs the change in Modal Strain Energy (MSE) within a subregion of the structure as a sensitive parameter for the presence of damage. The method relies on analyzing the variation of modal strain energy caused by reductions in element stiffness. In general, the methodology employed for this article was calculated based on modal curvature, thus, it considers only the modal strain energy associated with flexure in the longitudinal direction. Thus, the method considers the following parameters below:

$$\beta_{ij} = [(\varphi_{ij}{*}\,'')^2 + \textstyle\sum(\varphi_{ij}{*}\,'')^2] * [\textstyle\sum(\varphi''_{ij})]/[(\varphi_{ij}\,'')^2 + \textstyle\sum(\varphi_{ij}\,'')^2] * [\textstyle\sum(\varphi''{*}_{ij})] \tag{3.4}$$

$$Z_i = (\beta_i - \bar{\beta}_i)/\sigma_\beta \tag{3.5}$$

Where in the equation (3.4), i is the mode number, j is the element number, φ_{ij} is the modal curvature, and the symbol * indicates the term referring to the damaged structure. In the equation (3.5), β_i is normalized, where $\bar{\beta}_i$ and σ_β are, respectively, the mean and standard deviation values of β_i, thus forming the damage indicator (Z).

4 Evaluation of Damage Indices

To evaluate the effectiveness of the aforementioned damage indices, damages were introduced at various points on the footbridge, varying in severity levels. With the purpose of assessing the detection methods' capability and understanding the influence of boundary conditions, damages were introduced in three distinct elements of one of the footbridge's girders, one at a time.

Labelled D1 (1st damage case), D2 (2nd damage case), and D3 (3rd damage case), these damages were applied at specific locations: D1 was positioned near the rigid support on the western end; D2 was applied in the central region of the first span (between 0 and 22 meters); D3 was introduced in an intermediate region between the center of the span and the support located on the eastern side (between 22 and 44 meters). The graphical representation of the elements subjected to damages is illustrated in Figure 2. To examine the methods' response at different damage levels, damages of 5%, 10%, and 20% were applied. These damages were represented by corresponding reductions in the thickness of the girder elements, according to the applied percentage of damage.

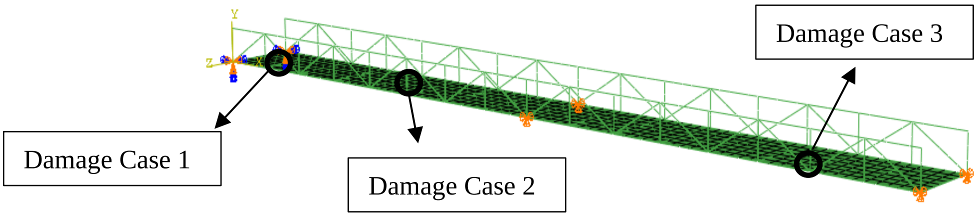

Figure 2. Positions of Elements Subjected to Damages

5 Finite Element Model Results and Damage Detection

5.1 Vibration Modes of Dowling Hall Pedestrian Bridge

From the developed finite element model, the first five vibration modes of Dowling Hall footbridge were obtained, as shown in the Figure 3, which also includes the natural frequencies for each mode. In the figure, labeled (a) through (e), representing vibration modes 1 to 5, respectively. These results have been validated with existing data provided in the literature. Thus, it can be observed that modes 1, 2, and 5 correspond to bending modes, while modes 3 and 4 are torsional modes.

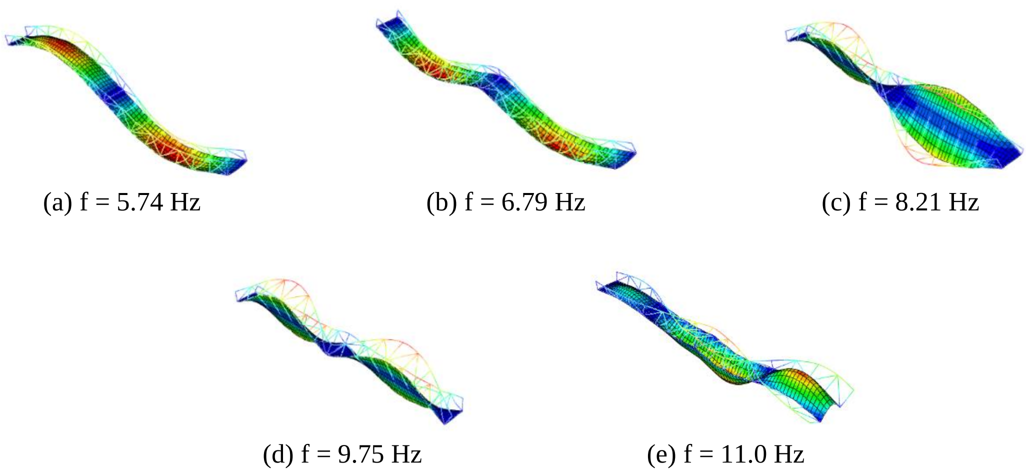

Figure 3. First 5 Vibration Modes of Dowling Hall footbridge

5.2 Response of Damage Indices

For all the analyzed indices, subsequent graphs illustrate the damaged girder, with each bar representing the index results for nodes along the horizontal axis. Nodes belonging to the element with simulated damage are highlighted. It will be presented only damage cases 1 and 2, as damage case 3 displayed behavior similar to case 2. Moreover, the outcomes for damage intensities of 20% and 10% exhibited analogous behavior. Consequently, the graphs will solely encompass outcomes for 5% and 10%.

The results of the Modal Curvature (MC) method for damage detection are presented in Figures 4 and 5 para o Caso 2. The application of the MC method demonstrated effectiveness in identifying the presence of damage and highlighting the affected region. However, it is important to mention a certain imprecision in detecting the damaged element in the case of damage D1. In this scenario, damage was also inaccurately observed in the adjacent elements of the actual element where damage was introduced. One possible explanation for this phenomenon is the proximity of the damaged element to the rigid support. Furthermore, by analyzing the impact of each vibration mode, the developed graphs accurately located the damages within the affected region. An improved method response was also observed when subjected to more severe damages.

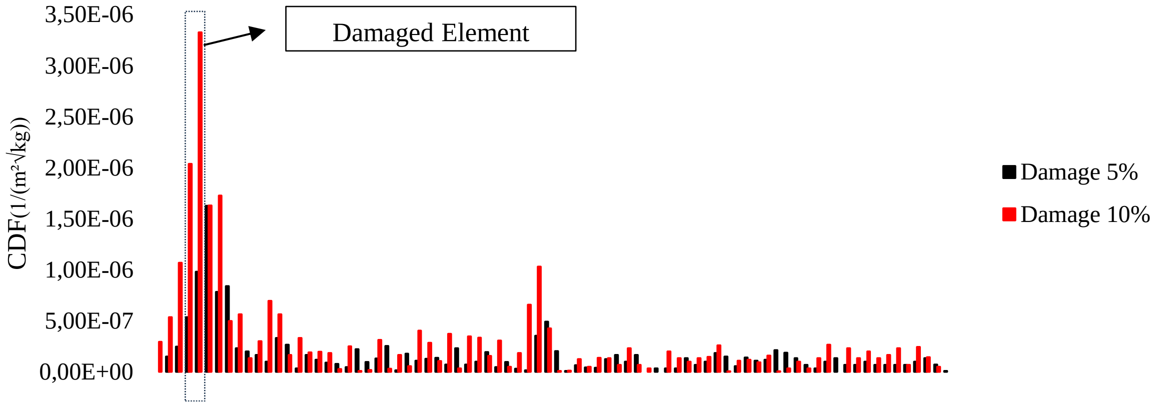

Figure 4. Comparison of MC in Case 1 Damage for Damage Intensities of 5% and 10%.

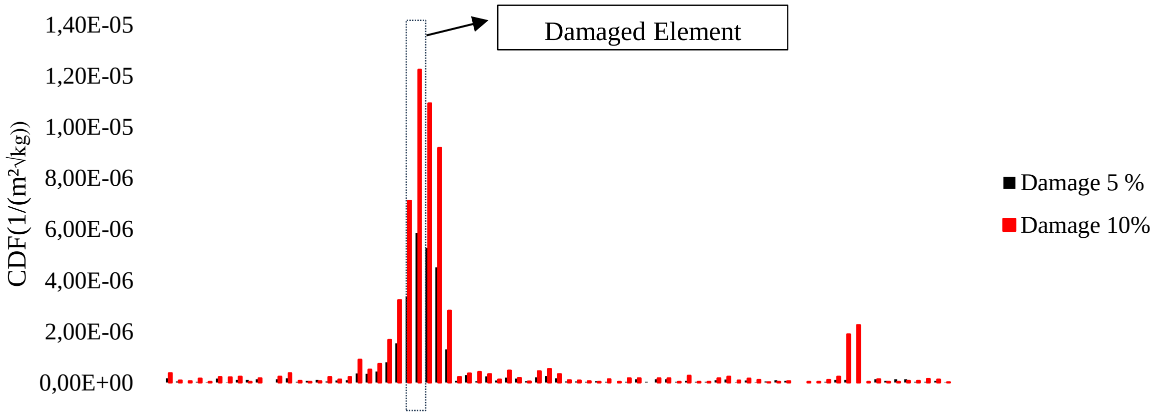

Figure 5. Comparison of MC in Case 2 Damage for Damage Intensities of 5% and 10%.

The results obtained from the implementation of the Residual Vector (RV) method for damage detection are presented in Figures 6 and 7. The RV method identified the presence of damages in the region of interest through the highest peaks, although it demonstrated high sensitivity to interference. This sensitivity is manifested by observable perturbations along the analyzed beam in all damage scenarios, particularly in the case of damage D1. This phenomenon arises because the RV method is based on the scalar difference between the resultant vectors of modal displacement, without accounting for the directions of these vectors in the final index response.

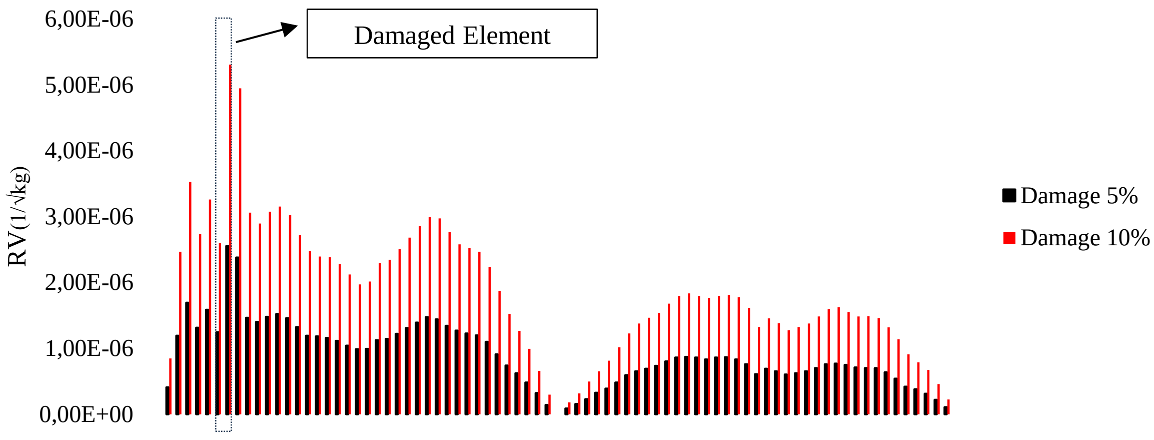

Figure 6. Comparison of RV in Case 1 Damage for Damage Intensities of 5% and 10%.

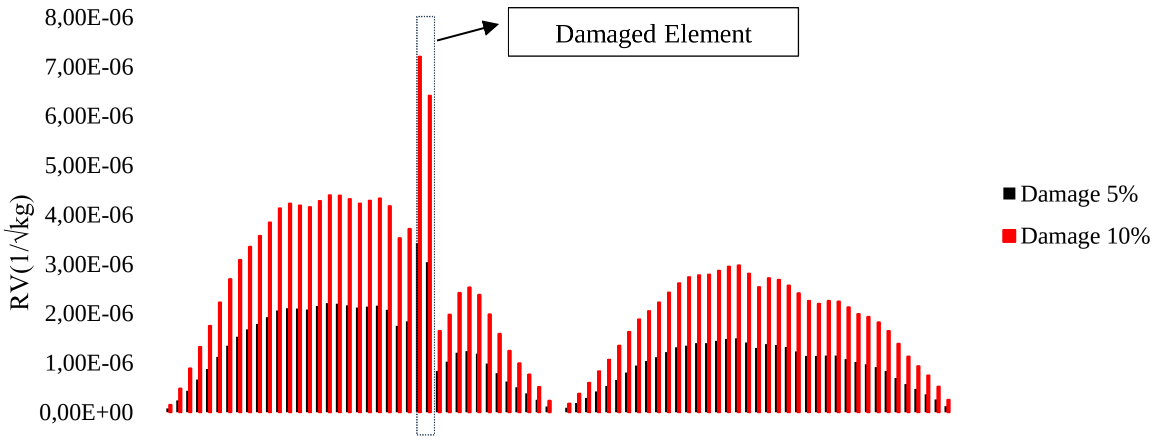

Figure 7. Comparison of RV in Case 2 Damage for Damage Intensities of 5% and 10%.

Modal Strain Energy (MSE), derived from modal curvature, also proved effective in detecting and locating damages in the structure, as illustrated in Figures 8 and 9. The maximum value of the MSE index accurately identifies the affected region and the damaged element in the model. However, an influence from the subsequent element to the damaged one on the index response is noticeable, occurring in all damage scenarios. This effect is manifested through peaks in the nodes adjacent to the damaged element. This influence occurs because MSE utilizes information from modal coordinates of neighboring nodes to calculate the index. Similarly to the MC method, individual mode analysis also succeeded in detecting the damaged region.

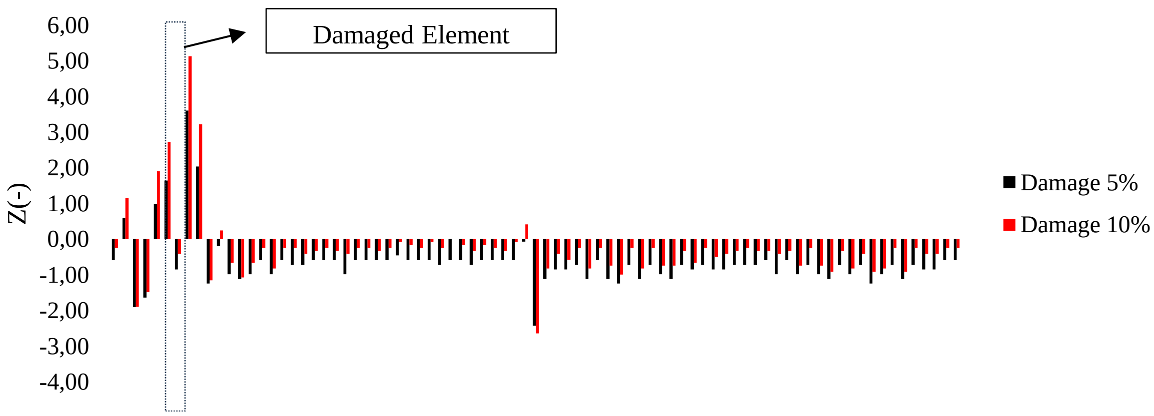

Figure 8. Comparison of MSE in Case 1 Damage for Damage Intensities of 5% and 10%.

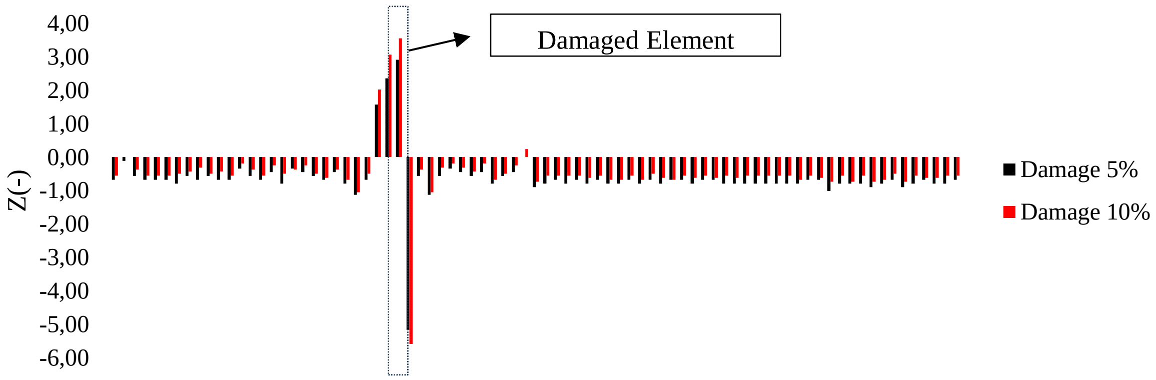

Figure 9. Comparison of MSE in Case 2 Damage for Damage Intensities of 5% and 10%.

6 Conclusions

This study presented a numerical assessment of the effectiveness of modal indices widely discussed in the literature: modal curvature, modal strain energy, and the index proposed by Gonçalves [2], referred to as the resultant vector, for damage detection in a footbridge with three-dimensional vibration modes. From the obtained results, it can be stated that these methods have demonstrated effectiveness in identifying the presence of damage, irrespective of the severity level. However, the results also indicated that these methods might be influenced when the damage is located closer to the support region.

Across all evaluated indices, it is noteworthy that the first damage scenario (D1) exhibited results with a higher level of false-positive damage in adjacent elements due to the stiffer behavior of this portion of the structure. Considering that these indices are directly derived from modal displacements, the low flexibility of modes in these segments affects the precision in accurately identifying damages in this region.

Among the examined indices, the analysis revealed that Modal Strain Energy (MSE) outperformed in terms of precision in detecting damage cases. Modal Curvature (MC) successfully identified the presence and damaged region, albeit with less accuracy in pinpointing the damaged element. Conversely, the outcomes for Resultant Vector (RV) exhibited inadequate performance. Despite accurately indicating the damaged region, the RV method's graphs displayed excessive sensitivity, uncovering methodological issues. The MSE approach achieved greater precision in detecting the damaged element, as evidenced by graphs with lower levels of false-positive damages.

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