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DAMAGE DETECTION AND LOCALIZATION OF A LOOSE JOINT THROUGH PATTERN CORRELATION OF MEASURED AND COMPUTED DYNAMIC PROPERTIES

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Abstract: This article presents a novel procedure for detecting and locating damage caused by a loose bolted joint in a modular plate structure. The primary aim of this work is to locate the loose joint with minimum measured points and without precise tune of computational model. The proposed method is based on correlating patterns of modal property changes using simulated and measured data. These patterns combine the relative shifts in natural frequencies and the norms of relative changes in mode shapes, derived from a pre-computed database of finite element method (FEM) simulations for various potential damage scenarios. The experimental validation demonstrates that the procedure can effectively and accurately locate the position of a loose joint using only five accelerometers, despite using an untuned FEM model for prediction.

KEYWORDS: structural health monitoring (SHM); damage detection; damage localization; loose joints; modal analysis; natural frequency; mode shapes; pattern correlation; finite element method (FEM)

1 Introduction

The integrity of mechanical joints is paramount for the safety, reliability, and performance of engineering structures. In practice, bolted connections are susceptible to loosening due to factors such as vibration, dynamic loading, and thermal cycles [1]. This degradation can lead to a catastrophic failure if undetected. Consequently, the development of robust Structural Health Monitoring (SHM) techniques for early detection and localization of loose joints is a critical area of research. Some of widely used approaches to ensure structural health monitoring are e.g. ultrasonic [1], thermographic vibration analysis [2] or vibration analysis based on modal parameter change or modal strain energy change [3]. These approaches allow a reduction in inspection effort related to structural health monitoring, especially at locations with limited accessibility for detecting potential damage explicitly.

Already, in 1979 Cawley and Adams published a method of non-destructive assessment of the integrity of structures using changes in natural frequencies to locate and quantify structural damage [4]. Many other methods of identification of structural damage have since been created, with a focus on analysis of changes in mode shapes (MS) or their derivatives [5, 6], or on natural frequency decreases in the context of related mode shapes [7–14].

A loose joint alters the system's dynamic characteristics, primarily resulting in a decrease in its natural frequencies (NFs) [14, 15]. From a diagnostics perspective, it is essential to not only detect the damage, indicated by a global decrease in NFs, but also to locate its precise position—i.e., identify which specific joint has failed. While detection is relatively straightforward, localization is more challenging, as it requires interpreting the often subtle and non-unique changes in mode shape patterns [16, 17].

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Existing methods often rely on detailed numerical models [18, 19] tuned to the exact experimental setup [20], or on dense sensor arrays to capture mode shapes with high spatial resolution [17]. These requirements can be prohibitively expensive and time-consuming for practical applications.

To overcome this, researchers have increasingly turned to mode shape data. The Modal Assurance Criterion (MAC) is a classic tool for comparing mode shapes [14]. Model updating techniques were used by [21, 22]. More advanced techniques involve operating on mode shapes directly, such as calculating mode shape curvatures [17, 23] or strain energy distributions [24], which are more sensitive to local stiffness changes. The modern approaches consider the data fusion to improve detection and localisation processes [24].

Specifically for bolted joints, which are critical points of failure [25], research has focused on their nonlinear dynamic behaviour [11, 26]. Titurus et al. [11] analysed nonlinear effects in bolted lap joints using impact hammer testing, highlighting the complexity of modelling such connections.

This paper demonstrates a novel localization technique that overcomes these limitations. We propose a method based on the correlation of modal property change patterns, applicable to structures like simplified modular jointed plates (overlapped sheets). The method utilizes both computed (from an untuned FEM model in ANSYS) and measured (from a physical test structure, processed in MATLAB) mode shape properties. The core idea is that the pattern of changes for a specific damage location is unique and can be identified even with a coarse model and few sensors.

The remainder of this paper is structured as follows: Section 2 describes the modular test structure and the computational FEM model. Section 3 analyses the sensitivity of dynamic properties to joint loosening. Section 4 details the proposed pattern correlation methodology. Experimental validation is presented in Section 5, followed by a discussion of results in Section 6 and conclusions in Section 7.

2 Tested Device Description

The test structure consists of a modular jointed plate assembly, chosen for its ability to simulate real-world structures with numerous connecting elements. The proposed modular plate, with overall dimensions of 960 mm x 720 mm, is constructed from the following modules (Fig. 1):

- **Part 1:** A plate measuring 240 mm x 240 mm, 5 mm thick, made of AISI 316 steel.
- **Part 2:** A plate measuring 240 mm x 120 mm, 5 mm thick, made of AISI 316 steel.
- **Part 3:** A connecting plate measuring 60 mm x 60 mm, 3 mm thick, made of AISI 316 steel. It contains 4 holes for M6 bolts.
- **Part 4:** A connecting plate measuring 60 mm x 30 mm, 3 mm thick, made of AISI 316 steel. It contains 2 holes for M6 bolts.

By assembling these modules, various configurations can be created. The connections are realized using Parts 3 and 4, hereafter called connecting plates. These plates are positioned on both sides of the structure to maintain symmetry and symmetric mass distribution. A pair of these bilateral connecting plates creates a structural connection node.

The primary focus was on a unified, open architecture that allows for the simulation of various system layouts, connection types, and damage scenarios by loosening bolts. Damage can be introduced in multiple ways: partial loosening (loss of preload) of a single bolt in one node, complete removal of a single bolt, loosening of multiple bolts within a single node, or simultaneous loosening of several connection nodes.

This work focuses exclusively on the complete loosening of a single connection node (one pair of connecting plates). Loosening the bolts in a node achieves zero preload at that location, releasing a group of plates. This reduces the local stiffness while the mass of the connecting plates is preserved. This approach represents a binary, two-state analogy similar to a switch: the fully tightened node is the 'On' state, and the completely loose node is the 'Off' state.

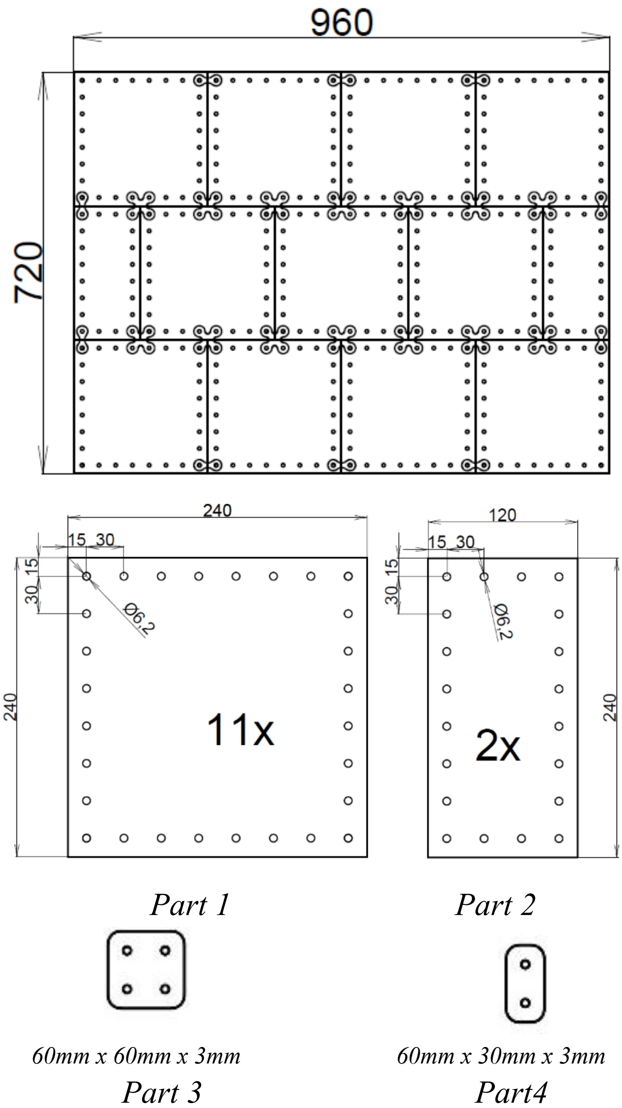

Fig. 1 Modular construction design

3 Computational FEM Model

A finite element (FEM) model was created prior to the physical construction of the modular plate. The model's task was to determine the dynamic properties of the system, primarily natural frequencies (NFs) and mode shapes (MSs), for various damage states. The model was created parametrically in ANSYS Mechanical APDL using the APDL language, replicating the geometric model's modularity.

The model was designed for speed and parametrization, not detailed accuracy. The goal was a coarse model that could quickly represent different states, capture the *trend* of changes, and provide an estimate of the damage vicinity—not the absolute values. Such a model is sufficient if it allows for damage location; a precise, tuned model would be required for subsequent detailed analysis. While not finely tuned, the model was designed to capture the fundamental dynamic behavior and trends of the physical system, a premise validated later in Section 5 through experimental correlation.

The FEM model consists of 2D shell elements representing the modular plates (Part 1 and Part 2). The nodes of these plates are not initially connected. Connection is achieved through the connecting plates (Fig. 2), whose boundary nodes are rigidly linked to the surrounding plate nodes. The connector model is simplified, representing the plate; the influence of bolts and holes is implicitly accounted for by adjusting the material properties. The thickness of the main modules (Parts 1 & 2) is 5 mm. The thickness at the connecting plate location was increased to 6.4 mm to account for the presence of bolts and base material.

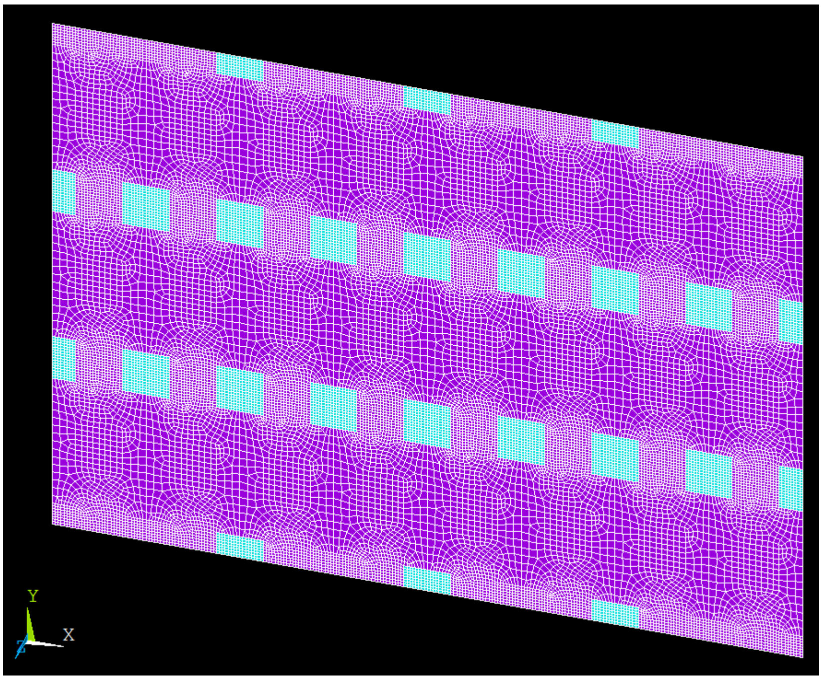

Fig. 2 FEM model of modular plate in Ansys Mechanical APDL,
blue areas represent connecting plates

The mesh used HEX elements (Solid 186). The material model was for homogeneous, isotropic AISI 316 stainless steel.

Damage simulation focused solely on the connection nodes. A tightened joint was simulated by rigidly connecting the nodes of adjacent plates within the connector domain. A loosened joint was modelled by releasing these connections, making the plate boundaries free; the stiffness of the connector plate was disregarded. The mass of the connector plates was retained in the model for all states. This local release of nodes results in a local reduction of stiffness (a change in the local stiffness matrix). The computational FEM model for simulating a loose joint is shown in Fig.2.

3.1 Sensitivity Analysis of Dynamic Properties via FEM

A modal analysis of the designed test structure was performed for the undamaged state and for nine damaged states, each corresponding to the loosening of a single connection node (positions P0-P8, see Fig. 3). The analysis focused on the first eight modes of the system.

Fig.4 illustrates the first four mode shapes for both the fully tightened structure and the structure loosened at position P2. The natural frequencies for the first six modes were extracted for the undamaged state and the state loosened at position P2, along with their absolute difference (Δf) and relative error (δf %) (Tab.1). The results show a consistent decrease in natural frequencies (Δf) upon loosening, with the relative change (δf) varying significantly across different modes (from 1.11% to 4.21%).

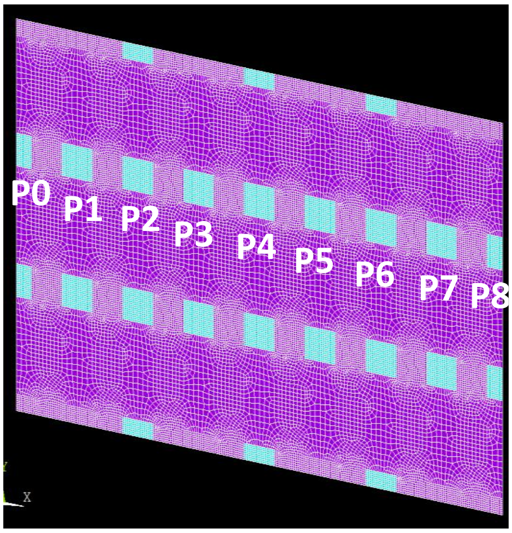

Fig. 3 Numbering of the connection points (P0-P8) considered for loosening

For further processing, modal displacements were extracted at five specific points (labelled A-E in Fig. 5), corresponding to planned sensor locations in the experiment. These points were chosen based on high modal displacement amplitudes across several modes of interest.

Tab.1 Natural frequency shift for loosening at position P2 (FEM Results).

MODE NO.	F (HZ) TIGHT	F (HZ) LOOSE	Δf (HZ)	δf %
1	23.37	22.85	0.52	2.22
2	23.99	23.60	0.61	2.54
3	49.75	48.60	1.15	2.31
4	53.25	52.66	0.59	1.11
5	64.18	61.48	2.70	4.21
6	70.95	68.19	2.86	4.03

3.2 Global and Local Mode Shape Changes

The analysis revealed two types of mode shape changes (Fig.6):

1. **Local Change:** Directly related to the loosening location; significant in displacement magnitude but difficult to measure in practice as the damage location is unknown *a priori*.
2. **Global Change:** A discernible alteration of the mode shape pattern in areas away from the immediate vicinity of the damage. Although smaller in magnitude, these global changes are measurable with a fixed sensor array and provide crucial information for localization.

Comparing the first mode shape of the tight and loosened (P2) structure reveals a global change: a shift in the axis of symmetry and a movement of the nodal lines (blue areas). The sensitivity of this global change to the damage location was exploited for localization.

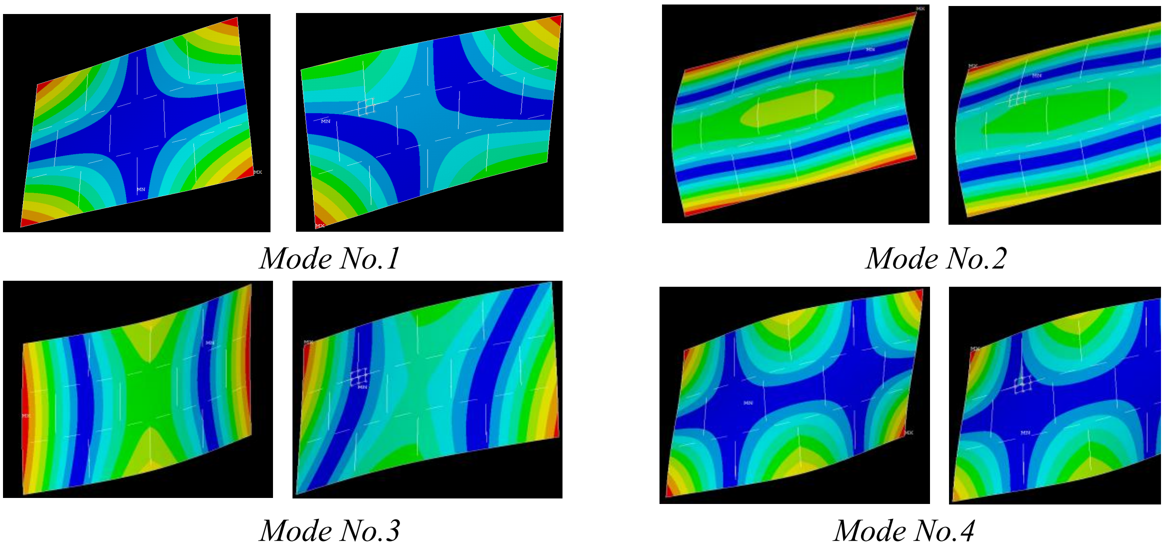

Fig. 4 Computed mode shapes of the original (left) and damaged (right, loosened at P2) structure from the FEM model.

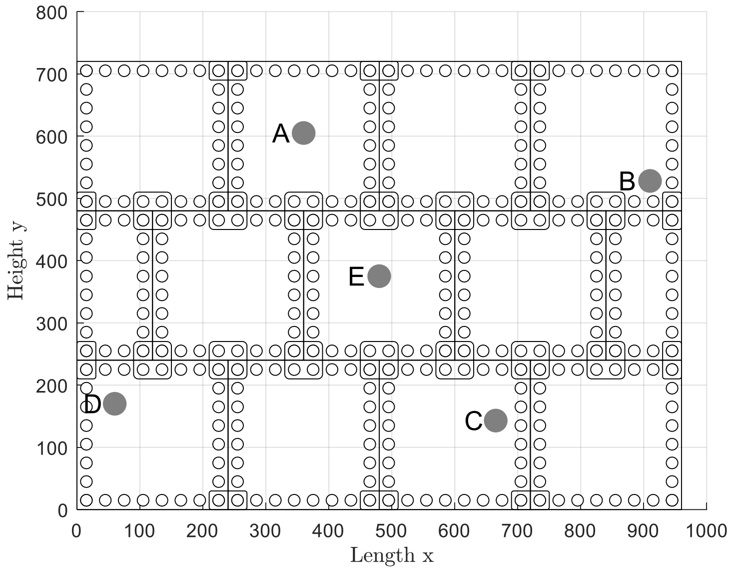

Fig. 5 Positions of measurement points A-E on modular plate

3.3 Influence of Loosening Location

The effect of damage location on the first mode shape is shown in Fig.7 for four different positions (P0, P1, P2, P4). The location of the loose joint significantly influences the resulting mode shape pattern due to the interplay between the damage location and the modal geometry.

Fig.8 presents the relative natural frequency change (1) and the absolute difference for the first mode, across all nine damage positions. The natural frequency change exhibits symmetry, as expected from the symmetric structure. However, the mode shape change pattern at sensors A-E does not, suggesting it carries more unique, location-specific information.

Critically, neither natural frequency changes nor mode shape changes (when used in conventional metrics like the Modal Assurance Criterion) alone provide unambiguous localization. The same frequency shift can occur for damage at different symmetric locations. This non-uniqueness necessitates a method that combines these parameters, leading to the proposed pattern correlation approach.

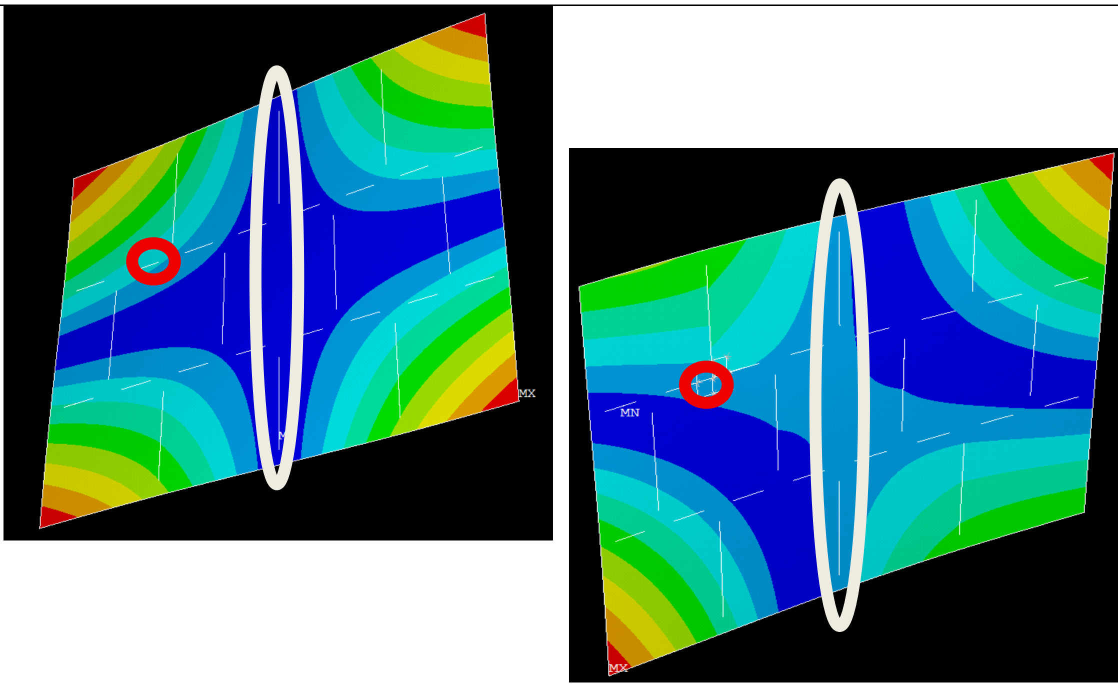

Fig. 6 Local (red highlight) and global (white highlight) changes in mode shapes between original and damaged (P2) structures

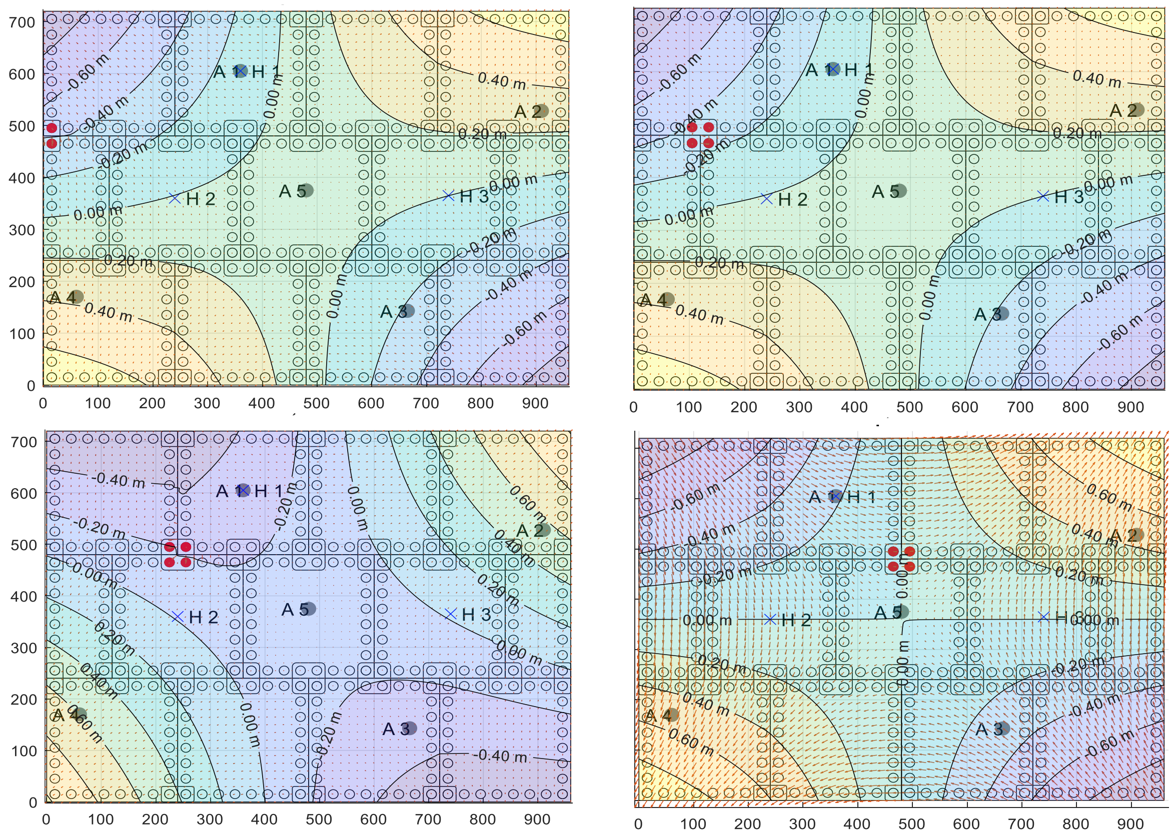

Fig. 7 Mode shapes of Mode 1 of the structure for four different loose joint positions (red points) P0, P1, P2, P4.

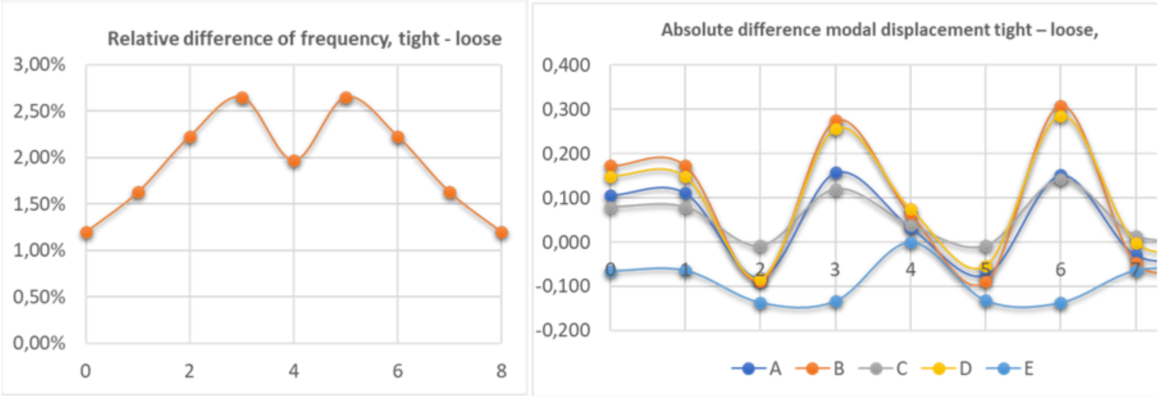

Fig. 8 The relative change of the natural frequency and the absolute difference of the mode shape change for the first mode

4 Proposed Pattern Correlation Methodology

The established limitations of standalone methods necessitate a robust approach. We propose a localization procedure based on the correlation of patterns formed by combined modal property changes. The fundamental premise is that the pattern of changes—simultaneously considering natural frequency shifts and mode shape deviations—for a specific loose joint location is unique. This pattern, derived from a pre-computed FEM database, can be correlated with a pattern obtained from experimental measurements to identify the most probable damage location. The methodology involves the following steps for each potential damage location.

In the first step, characteristic measures are obtained. For each mode i, two dimensionless measures are calculated:

A) Relative Natural Frequency Error:

$$\delta f_i = \frac{\left(f_i^{tight} - f_i^{loose}\right)}{f_i^{tight}}, \tag{1}$$

where f_i^{tight} and f_i^{loose} are the natural frequencies of the *i-th* mode for the undamaged and damaged states, respectively.

B) Norm of Relative Mode Shape Difference:

This is calculated at the *j* sensor locations (A, B, C, D, ...).

$$\delta v_i = \left\| \frac{\left(v_i^{tight} - v_i^{loose}\right)}{v_i^{tight}} \right\|, \tag{2}$$

where v_i is the vector of modal displacements for the *i-th* mode at the measured sensor points and $|| \;\; ||_2$denotes the L2-norm. The use of relative error normalizes the changes across modes with different absolute values.

The measures δf_i and δv_i are calculated for a set of modes (e.g., i=1 to N). Each mode contributes a point on a δv_i vs. δf_i plot. Connecting these points forms a unique pattern for each specific damage location (P0, P1, ... P8), as illustrated conceptually in Fig. 9. This creates a database of simulated patterns $(\delta v_{sim}, \delta f_{sim})$.

When damage is detected in the real structure (based on a global frequency drop), the same measures (δv_{exp}, δf_{exp}calculated from experimental measurements before and after the damage event, creating a measured pattern (Fig.10).

The final step is to compare the measured pattern against every pattern in the simulated database (Fig.11). The correlation is quantified using a distance metric.

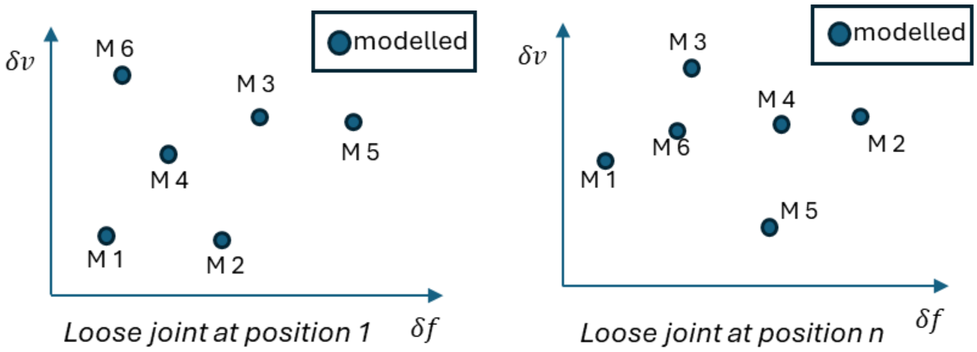

Fig. 9 Example δv vs. δf patterns for different simulated loose joint positions

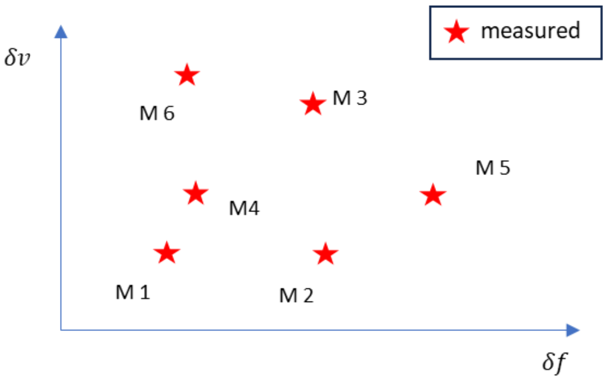

Fig. 10 Measured pattern of modes plotted as Norm of relative MS difference (δv) vs. relative NF difference (δf).

The Euclidean norm between the measured and simulated patterns was used as the correlation function:

$$\varepsilon_{\delta v} \;=\; \sum_i || \, \delta v_i^{\exp} - \delta v_i^{sim} \, ||_2 \,, \qquad (3)$$

where the sum is over the considered modes. The location corresponding to the **minimum** value of $\varepsilon_{\delta v}$ is identified as the most probable damage location. This minimum indicates the highest correlation between the predicted pattern for that location and the measured experimental data.

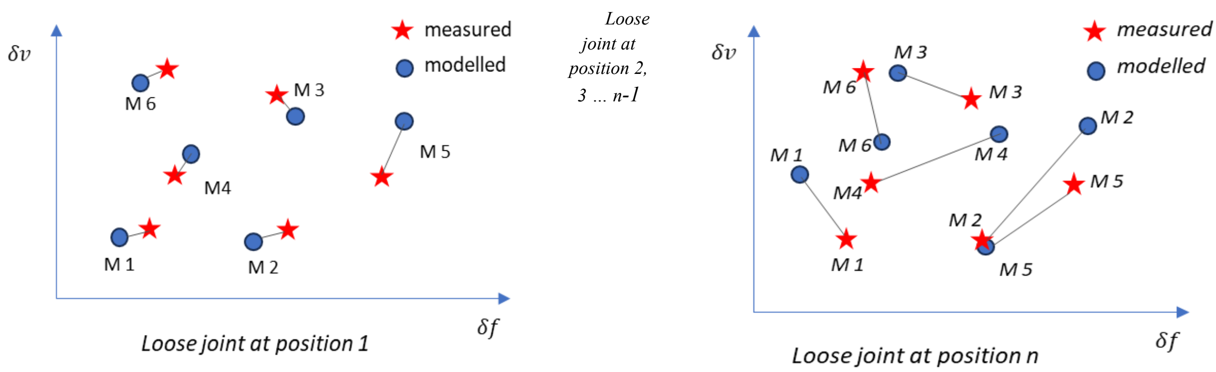

Fig.11 MS-s vs NF-s pattern for different position of loosed joint

5 Experimental Validation

To validate the proposed method, an experimental model of the modular plate was constructed (Fig. 12). The structure was suspended on elastic strings to simulate free-free boundary conditions. Five measurement points (A-E) (Fig.5) were instrumented with Bruel & Kjaer (B&K) B&K 4035 accelerometers. Data acquisition was performed using a B&K Pulse frontend system. Modal analysis was performed using impact hammer excitation (B&K hammer) at three different points to ensure excitation of the first eight modes.

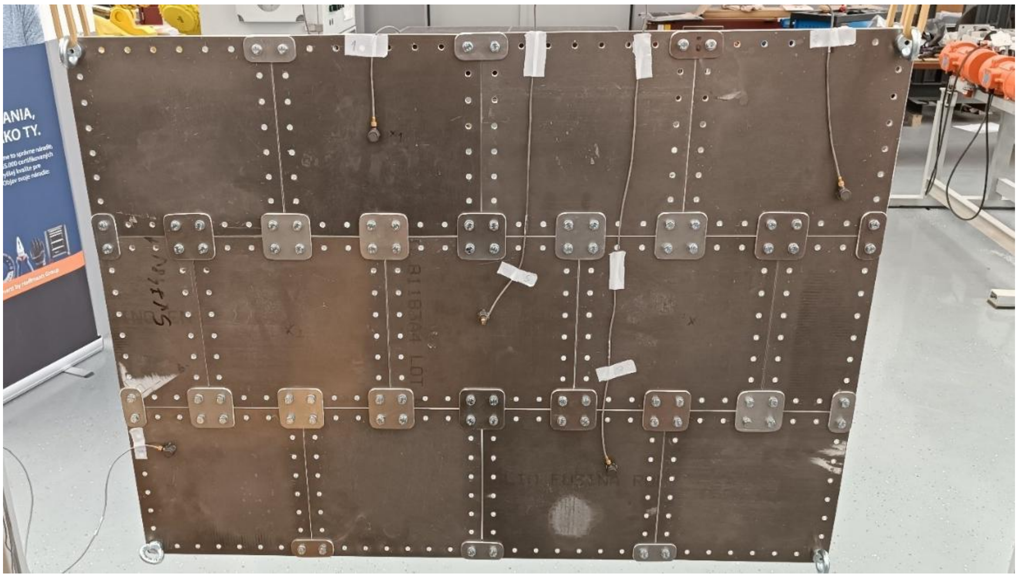

Fig. 12 Photograph of the measured device with positions of joints and sensors indicated.

All bolts were initially tightened to a specified preload using a torque wrench. A measurement of the undamaged ("tight") state was recorded. Subsequently, the joint at position P2 (as defined in Fig. 3) was completely loosened to create the damaged state, and the measurement was repeated.

A comparison of the relative frequency shifts between the numerical prediction and experimental data for loosening at P2 is presented in Tab.2. An increasing trend of frequency shift is observed, particularly for higher modes. This is expected and acceptable given the coarse, untuned nature of the FEM model, as the method relies on trend correlation rather than absolute accuracy.

Tab.2 Comparison of predicted (FEM) and experimental frequency shifts for loosening at P2

Mode No.	Numerical prediction $\boldsymbol{\delta f}$ %	Experimental data $\boldsymbol{\delta f}$ %
1	2.23	1.40
2	1.63	1.70
3	2.31	1.63
4	1.11	1.14
5	4.21	1.92
6	3.89	3.83
7	3.21	2.37
8	3.01	1.28

The Modal Assurance Criterion (MAC) was also calculated between the model and experiment for the first 8 modes (Tab.3). For the tight state and most modes in the loose state, the MAC values are above 90%, confirming that the untuned model sufficiently represents the dynamic behaviour of the actual structure for the purpose of this trend-based method.

Tab.3: MAC values (%) between the experimental and numerical models.

Mode No.	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
TIGHT (%)	93.09	99.03	83.80	96.84	97.60	87.94	98.17	94.12
LOOSE (%)	96.10	95.57	88.81	97.60	97.55	88.74	68.90	67.05

The proposed pattern correlation method was applied (Fig.13). The measured pattern for the experimentally loosened joint (P2) was compared against the database of all simulated patterns (P0-P8). The correlation norm $\varepsilon_{\delta v}$ (3) was calculated for each possible location.

The results (Fig. 14) show a unambiguous minimum in the correlation norm $\varepsilon_{\delta v}$ for the simulated damage at position **P2**. This indicates the highest correlation between the predicted pattern for P2 and the measured experimental pattern, successfully identifying the correct location of the loose joint. The method was also successfully validated for a damage scenario at position P6 with the same success.

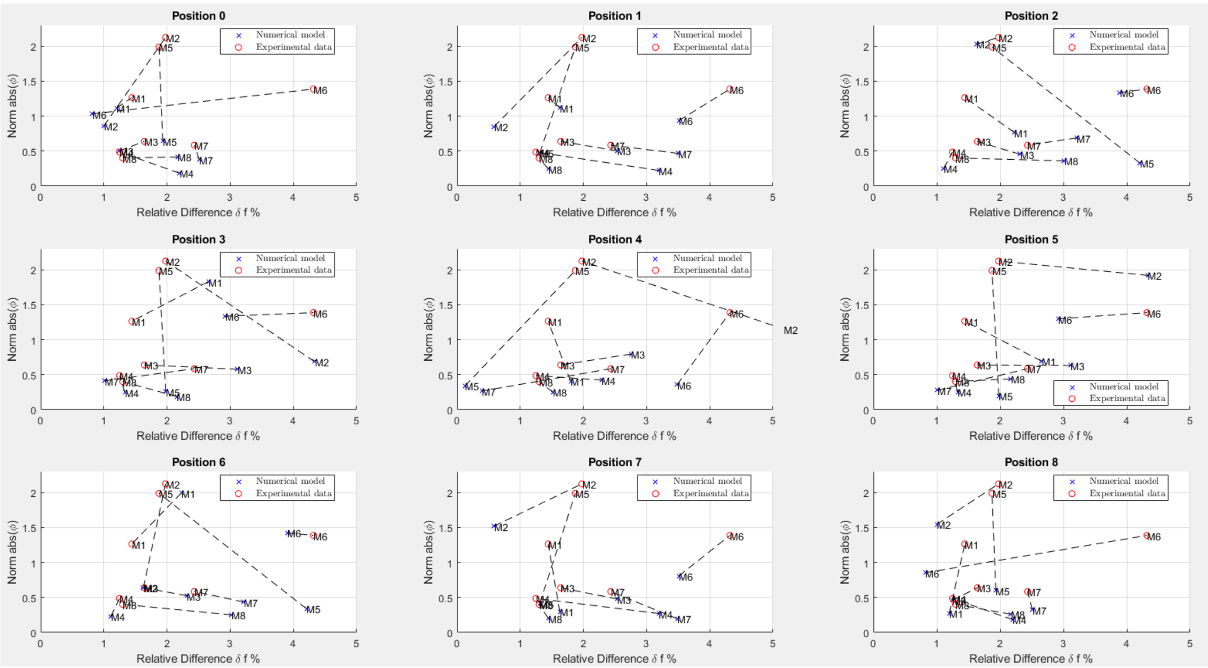

Fig.13 Chart of the correlation norm $\varepsilon_{\delta v}$ for all simulated damage positions vs. the experimental data (actual loose joint at P2)

6 Discussion

The presented localization method successfully identified the damage location based on predictions from an approximate, untuned FEM model. The only prerequisite was a general similarity in the dynamic properties between the model and the experiment. This allows for the creation of a model and a database of damage scenarios beforehand. Upon the occurrence of damage, the pattern from a new measurement can be compared to this database to locate the fault.

A significant advantage is the use of only five measurement points, reducing hardware costs and setup time compared to techniques requiring dense sensor arrays or laser vibrometry. The technique is relatively straightforward and avoids the need for complex inverse algorithms. The method was successfully validated for two different damage locations (P2 and P6).

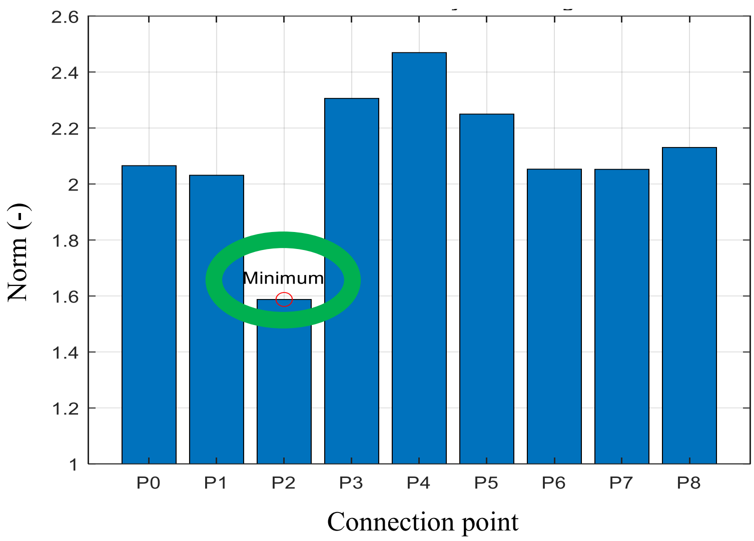

Fig.14 Bar graph of the correlation norm

Several limitations exist. The need for a pre-computed database of damage scenarios can be computationally demanding for structures with a very large number of potential damage locations. Future work could focus on intelligent sampling or machine learning to interpolate between simulated points and reduce the number of required simulations.

The presented results are for the binary states of "fully tight" and "fully loose." Investigating the method's sensitivity to partial loosening (loss of preload) is a crucial next step.

Furthermore, the optimal number and placement of sensors were not rigorously optimized and present an opportunity for future work. A systematic study on optimal sensor placement would enhance the method's robustness and potentially allow for further sensor reduction.

7 Conclusion

This paper focused on damage detection and localization of loose joints in modular structures. The primary objective was to develop a direct approach that reduces hardware costs by minimizing the number of sensors. A modular test structure was designed for this study, allowing for high variability in configuration and damage simulation.

The core contribution is a novel correlation principle for localization, based on correlating patterns composed of the relative error of natural frequencies and the norm of relative mode shape differences. Using results from modal analysis simulations for different damage locations is crucial for building the reference database.

The method was successfully validated through experimental measurements, correctly identifying the location of loosened joints.

Future work will focus on a sensitivity analysis for different measurement setups, reducing modelling errors through model tuning, and quantifying the level of damage (i.e., diagnosing partially loosened joints). Optimizing the number and placement of sensors will also be a key research direction.

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