SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

MATLAB Implementation of Response Surface Methodology for Structural Damage Identification Using Frequency Response Function Curvature

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ARTICLE INFO

Article history:
Received 27 November 2025
Received in revised form 20 February 2026
Accepted 15 April 2026
Available online 16 June 2026

Keywords:
Structural damage identification; FRF curvature; response surface methodology; model updating

ABSTRACT

Structural health monitoring and damage identification are critical for maintaining the integrity and safety of engineering structures. Traditional methods often struggle with accurately identifying damage, particularly in complex structures. This study addresses this challenge by developing a MATLAB-based framework that employs Response Surface Methodology (RSM) and Frequency Response Function (FRF) curvature for model updating in structural damage identification. The methodology involves several key stages: initial finite element (FE) model development, DOE to strategically select parameters, computation of FRF curvature to capture structural responses, construction of primary and secondary response surface models, and an iterative model updating process. The simply supported beam model, with its practical and representative nature, serves as the numerical example. The model's accuracy is validated through comparison with established studies, confirming the low percentage errors in natural frequencies. The response surface models exhibit a strong fit and predictive accuracy, as indicated by high R^2 values. The study successfully achieves its objective, showing that the RSM-based model updating approach, utilizing FRF curvature, can effectively identify structural damage. In conclusion, this study successfully develops and implements an RSM-based framework for structural damage identification using FRF curvature as the response feature. The findings highlight the method's effectiveness and underscore the need for future research to refine algorithms and validate the approach across a broader range of structural systems, including those exhibiting nonlinear behaviour.

1. Introduction

Structural health monitoring (SHM) plays an important role in modern engineering practices, ensuring the safety, reliability, and longevity of civil infrastructure [1]. Traditional methods for detecting structural damage often rely on visual inspections or simplified analytical models, which may overlook subtle or localized forms of deterioration. To address these shortcomings, advanced

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https://doi.org/10.37934/araset.60.5.414432

methodologies leveraging numerical simulations and experimental data have emerged as powerful tools for accurate damage identification and characterization [2-5]. Among these advanced methods, global approaches, particularly those analyzing structural vibrations, have shown significant promise. These methods assess the entire structure by examining vibration parameters, such as frequency response functions (FRF) and mode shapes, to detect alterations in structural properties.

Finite element (FE) model updating is a widely used global method that refines an FE model to align numerical simulations with experimental data [6-8]. This technique involves refining an FE model to rectify discrepancies between numerical and experimental data. The FE model updating can be executed using either a direct or iterative method. The direct method, also referred to as the non-iterative method, involves modifying the system matrix [9]. This method offers computational advantages and produces accurate results. However, it has limited applicability due to the lack of physical interpretation of changes in structural characteristics [3]. On the contrary, the iterative method overcomes the limitations of the direct method, but requires the creation of a sensitivity matrix for all update parameters, which leads to lengthy calculations [6].

This research is motivated by the limitations of the classical FE model updating-based damage identification method, which suffers from convergence issues and high computational costs. To address these challenges, we explore the Response Surface Methodology (RSM), which combines mathematical and statistical approaches. While traditional RSM-based methods rely on natural frequencies and mode shapes, they are susceptible to false damage detection due to modeling and measurement errors [10-13]. FRF, which exhibit lower measurement errors, have not been extensively utilized in RSM due to their broad frequency range [12, 14]. The curvature of FRF, as demonstrated by Sampaio, Maia [15], offers enhanced sensitivity to structural changes but remains underexplored in this context [16-18].

Our study aims to fill this gap by proposing a novel algorithm for structural damage identification using RSM-based model updating with FRF curvature as the response parameter. We present a MATLAB implementation of this methodology, integrating modal analysis data with numerical simulations to refine structural models. By leveraging FRF curvature, our approach enhances sensitivity to changes in structural properties, enabling precise localization and quantification of damage.

The objective of this study is to develop and implement a MATLAB-based framework for RSM-based model updating using FRF curvature, providing a reliable and efficient tool for damage detection in engineering structures. Accurate identification and characterization of structural damage are essential for optimizing maintenance strategies, extending infrastructure lifespan, and ensuring public safety. By leveraging RSM and FRF curvature, this research aims to provide engineers with a robust tool for detecting and assessing damage, ultimately enhancing the safety and reliability of civil infrastructure.

2. Methodology

The research methodology employed in this study has been meticulously designed to align seamlessly with the research objective, as illustrated in Figure 1. **Stage 1:** The initial phase focuses on developing the RSM approach using FRF curvature for structural damage identification. This stage begins with identifying design variables and structural responses for constructing the FE model. Selecting parameters with the most significant impact on the analyzed structure is crucial for obtaining accurate results. To ensure precision, a screening process is conducted to eliminate insignificant parameters. Using the ANOVA approach, each parameter's effect on the overall model variance is evaluated through the F-test results. In this study, Young's modulus (E) is chosen as the design variable, while FRF curvature serves as the response. Subsequently, the initial FE model is developed, utilizing the initial Young's modulus value (E_i) as the basis for further analysis.

Stage 2: A series of processes unfold to construct the primary RS model. Firstly, FRF data of the intact and damaged structure is generated through experimental modal analysis, employing impact hammer testing to capture the dynamic response. Subsequently, FRF curvature values are calculated by using Eq. (1) for both experimental and FE analyses, precisely determined at 96% of the peak of the first FRF resonance as proposed by Mondal, Mondal [19]:

$$H''(\omega)_{i,j} = \frac{H(\omega)_{i-1,j} - 2H(\omega)_{i,j} + H(\omega)_{i+1,j}}{h^2} \tag{1}$$

where $H''(\omega)_{i,j}$ denotes the FRF curvature for any frequency, $H(\omega)_{i,j}$ represents the receptance FRF measured at location i for a force input at location j, and h denotes a constant representing distance between the measurement points. The FRF curvature calculation involves measuring the receptance FRF at each node across the structure. The construction of the primary RS model then commences, utilizing the calculated FRF curvature data obtained from the FE model. Since the FRF curvature is selected as the response and Young's modulus of each element is chosen as the design variable, the RS model is simplified as Eq. (2) below:

$$H''(\omega)_{i,j} = \beta_0 + \sum_{i=1}^{k} \beta_i E_i + \sum \sum_{i<j=2}^{k} \beta_{ij} E_i E_j + \sum_{i=1}^{k} \beta_{ii} E_i^2 + \varepsilon \tag{2}$$

where k represents the element, $\beta_0, \beta_i, \beta_{ij}, \beta_{ii}$ are the regression coefficients, and E for Young's modulus. Concurrently, the E_i in the FE model undergoes a model updating process to derive the intact Young's modulus value (E'_i).

Unlike the standard model updating procedure that necessitates continuous adjustments to structural parameters for each iteration, the proposed method operates on the cost-effective RS model, significantly reducing the time required for the iterative process. MATLAB®'s "`fgoalattain`" function, designed for multiobjective optimization, plays a key role in the updating process. The objective function used in this study is formulated as in Eq. (3) and (4):

$$\min_{x,\gamma} \begin{cases} F(x) - \omega\gamma \leq goal \\ lb \leq x \leq ub \end{cases} \tag{3}$$

$$F(x) = abs\left(\frac{H"_{RSM} - H"_{exp}}{H"_{exp}}\right) \tag{4}$$

where $H^{"}_{RSM}$ is the FRF curvature predicted by the RSM, while $H^{"}_{exp}$ corresponds to the FRF curvature acquired through experiment. The weight vector, denoted by ω, is employed to regulate the goal attainment factor, and γ represents the dummy variable. lb stands for the lower boundary, and ub is the upper boundary. In numerical analysis, the value of $H^{"}_{exp}$ is obtained from the FE model of the damaged structure. The optimization process involves updating the parameter x, which signifies the initial value of Young's modulus, E_i, until convergence or satisfaction of the termination criterion. Finally, the FRF curvature values obtained from the model updating process are compared with the corresponding values derived from the experimental modal analysis of the intact structure. This comparative analysis serves as a critical step in verifying the primary RS model's capability to accurately represent the structural response of the intact structure, thereby ensuring the reliability and robustness of the primary RS model in subsequent stages.

Stage 3: A meticulous series of processes unfold to construct the secondary RS model. The construction of the secondary RS model relies on utilizing the E'_i obtained from the updated primary RS model. This value serves as a fundamental parameter in the secondary RS model. Importantly, the FRF curvature values for the damaged structure obtained from the experimental data are subsequently employed to update the secondary RS model. The results obtained from the updated secondary RS model yield the Young's modulus values for the damaged structure (E_d).

Stage 4: The pivotal stage of the research methodology is dedicated to damage identification. Here, a meticulous process unfolds to identify damage within the structural elements. E_d values, obtained through the updating of the secondary RS model, are systematically compared with the corresponding E'_i values. By meticulously assessing the deviation between these values, the stiffness reduction factor (SRF) is calculated, as defined in Eq. (5) below:

$$SRF = 1 - \frac{E_d}{E'_i} \tag{5}$$

The SRF acts as a quantitative indicator, conveying the extent to which the stiffness of the damaged elements has been reduced. This reduction is expressed on a scale where 1 signifies a complete 100% reduction in stiffness, while 0 denotes no reduction, signifying an intact, undamaged state.

The process of RSM for model updating using FRF curvature is depicted in Figure 2. The procedure begins with the implementation of Design of Experiments (DOE) by using Design Expert software to strategically select the key parameters for the model. Following this, the FRF curvature is calculated to capture the structural response at a specific frequency range. These calculated FRF curvature values are then used to construct the response surface (RS) model, which describes the relationship between the chosen design variables and the corresponding FRF curvature response. To ensure the accuracy and reliability of the RS model, it is subjected to criteria testing, which confirms that the model accurately represents the system's behaviour. Finally, an iterative process of refining the RS model through updating procedures is carried out. This iteration continues until the model converges or meets predefined termination criteria.

2.1 Algorithm for FRF Extraction

The FRF serves as a fundamental tool for characterizing the dynamic behavior of structures. In this study, the Structural Dynamics Toolbox (SDT) within MATLAB is utilized for efficient computation and analysis of FRFs. The algorithm for extracting the FRF involves the following steps:

i. Initialization:
    - Read the Young's modulus values from an input file.

ii. Setup parameters:
    - Define the number of elements, nodes, and frequency points.
    - Initialize a matrix to store the FRF values for each node and each Young's modulus row.

iii. Iterate over each row of Young's modulus values:
    - For each row:
        1) Setup FE mesh:

- Initialize the FE mesh.
- Add nodes with their coordinates.
- Add structure elements connecting the nodes.

2) Material and beam properties:
   - Define the material properties for each element using the converted Young's modulus values.
   - Define the beam properties (cross-sectional area, moments of inertia, etc.).
3) Boundary conditions:
   - Set boundary conditions for the structure (fixed, pinned, and roller constraints).
4) Eigenvalue analysis:
   - Set the eigenvalue solver options and compute the eigenmodes.
   - Extract and process the frequency values to determine the target frequency range for FRF computation.
5) Compute FRF for each node:
   - Initialize a matrix to store the FRF values for each frequency and node.
   - Loop over each frequency point:
     - Set point load at a specific node and compute the FRF.
     - Repeat for all nodes to obtain FRF values.
   - Store the computed FRF values.

iv. Output Results:
   - Save the FRF results of the computed FRF values for each frequency and node to an output file.

2.2 Algorithm for FRF Curvature Calculation

FRF curvature enhances sensitivity to changes in structural properties, thereby aiding in the detection of localized damage. The algorithm for calculating FRF curvature involves the following steps:

i. Initialization:
   - Read the FRF values from the input file.
   - Determine the number of rows in the FRF dataset.
   - Initialize matrices to store the FRF and the corresponding FRF curvature values for each row of data.

ii. Iteration over each FRF row:
   - Extract the current row of FRF values from the dataset.
   - Initialize a matrix to store the curvature values for each node within the current row.

iii. Computation of curvature for each node:
   - Apply the central difference formula to compute the FRF curvature for intermediate nodes.

- Implement specific handling for edge cases, i.e., the first and last nodes, due to their unique positioning and lack of adjacent nodes on one side.
- Store the computed curvature values for each node in the initialized matrix.

iv. Visualization of curvature:
- Plot the FRF curvature values for each row to visualize the changes and trends across nodes.

v. Saving results:
- Open the output file for writing the computed data.
- Write the curvature values for each row to the file in a structured format.
- Close the output file to finalize the data storage process.

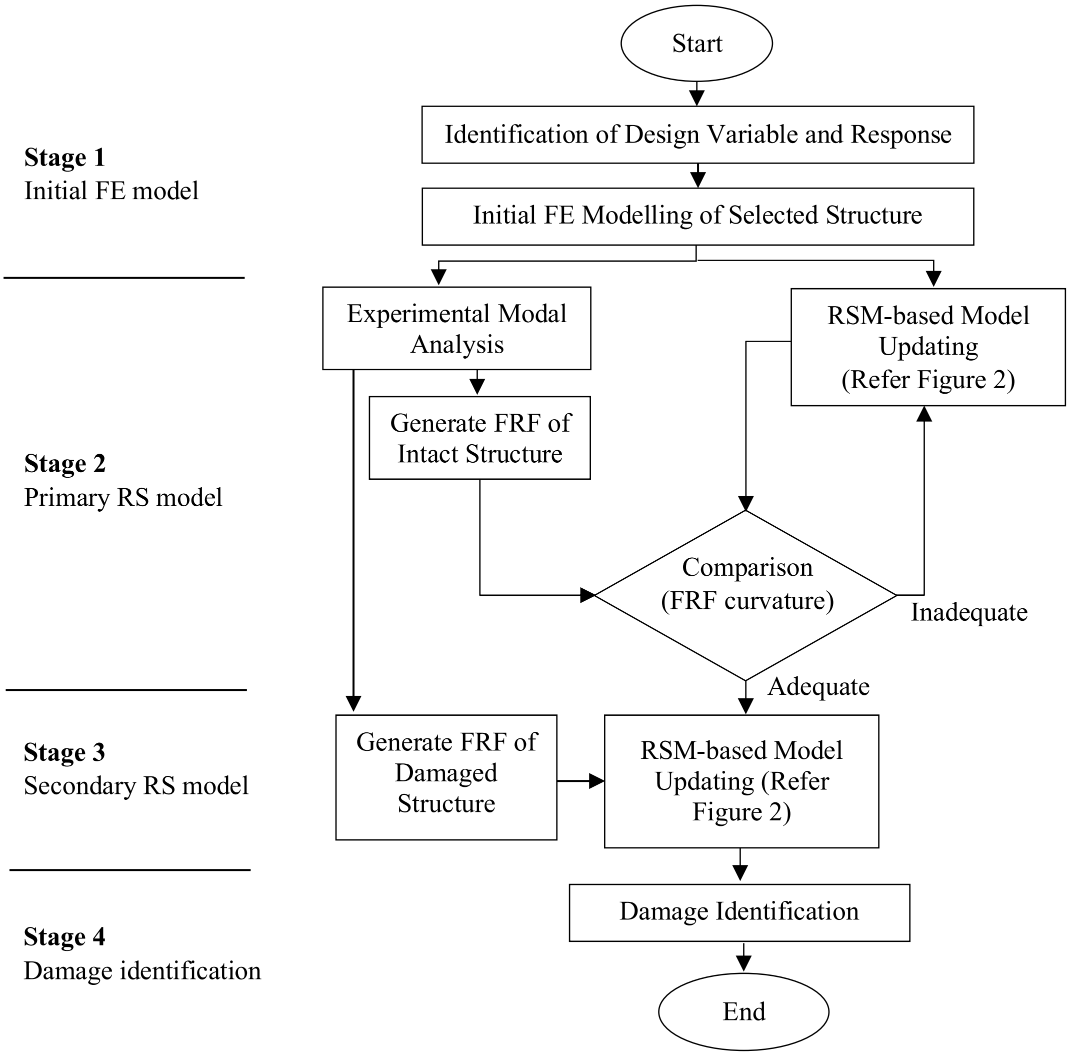


Fig. 1. Flowchart of methodology of the study

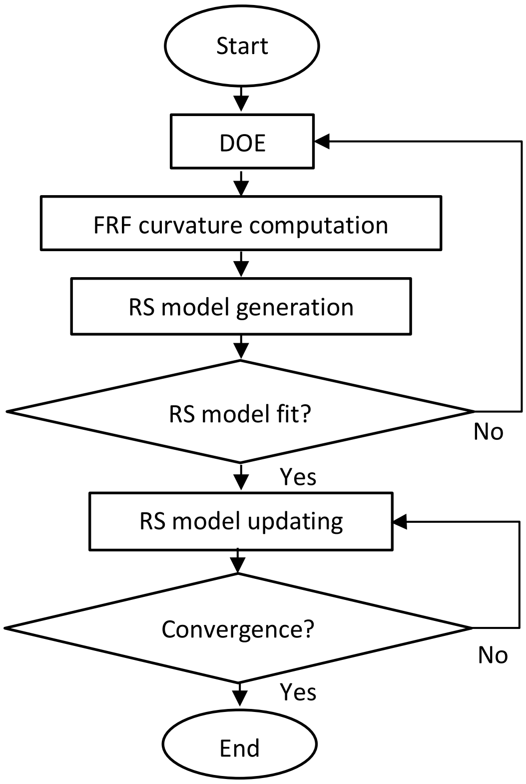


Fig. 2. RSM-based model updating using FRF curvature.

2.3 Algorithm for Optimization Objective Function

The objective function serves as a crucial metric for evaluating the discrepancy between simulated and experimental data, guiding the model updating process. The algorithm for constructing the objective function incorporates the following steps:

i. Load experimental data and objective function tolerances.
    - Load the data required for the objective function from a .mat file.
ii. Define experimental data (`FRFC_exp`).
    - Define the experimental FRF curvature (FRFC) data.
iii. Define response surface model polynomial equation (`FRFC_rs`)
    - Use a predefined equation involving the variables 'x' to calculate the FRFC response surface model data.
iv. Calculate objective function values.
    - For each element in the FRFC, compute the absolute value of the relative difference between the experimental data and the response surface model data.
v. Return objective function values.
    - Return the calculated objective function values.

2.4 Algorithm for Model Updating

Model updating aims to refine numerical models using experimental data to improve accuracy in predicting structural behavior. The algorithm for model updating involves the following steps:

i. Initialization and setup
   - Define the initial guess for the variables (`E0` and `x0`).

ii. Define boundaries
   - Set the lower (`lb`) and upper (`ub`) bounds for the variables.

iii. Define optimization parameters
   - Set the goal, weight, and other optimization parameters (`'A'`, `'b'`, `'Aeq'`, `'beq'`, `'nonlcon'`).

iv. Set optimization options
   - Configure the optimization settings (e.g., tolerance, display options).

v. Run optimization
   - Use the `'fgoalattain'` function to perform the optimization with the defined objective function.

vi. Save results to a text file

This structured methodology outlines the sequential procedures involved in FRF extraction using the SDT, FRF curvature analysis, formulation of the objective function, and iterative model updating using MATLAB-based numerical simulations and experimental data. These steps collectively form the basis of the proposed framework for structural damage identification and model refinement.

2.5 Summary of key steps

This pseudocode outline provides a comprehensive framework for understanding the computational process involved in FRF generation, FRF curvature calculation, and response surface model updating for structural damage identification.

i. FRF extraction

```
Initialize:
    Define the structure and material properties
    Apply boundary conditions and external forces
    Set up the frequency range for analysis

For each frequency in the defined range:
    Calculate the structural response using FE Method (FEM)
    Extract the FRF at each node

Store the FRF data:
    Save the FRF data to an output file
```

ii. FRF curvature calculation

```
Initialize:
    Read FRF values from the input file
    Determine the number of rows in FRF values
    Initialize matrices for storing FRF and FRF curvature values for
      each row

For each row in FRF values:
    Extract the current row of FRF values
    Initialize a matrix to store curvature values for each node
    For each node:
       If node is the first node:
```

```
        Calculate curvature using:(0 - 2 * FRF_value + next
             FRF_value)/(spacing^2)
        Else if node is the last node:
        Calculate curvature using: (previous FRF_value - 2 * FRF_value
             + 0)/(spacing^2)
        Else:
        Calculate curvature using central difference formula:
        (previous FRF_value - 2 * FRF_value + next FRF_value)/
             (spacing^2)
        Store the calculated curvature value for the node
      Store the curvature values for the current row
      Plot the FRF curvature for the current row

  Save the results to an output file:
      For each row of curvature values:
          Write the row index and curvature values to the file
```

iii. Response Surface Model Updating: Primary Response Surface Model Construction

```
  Generate FRF data through experimental modal analysis:
      Conduct impact hammer testing to capture dynamic response
      Calculate FRF curvature values for experimental and FE analyses at
        specified frequency

  Construct the primary response surface model:
      Use calculated FRF curvature data from FE model
      Update initial Young's modulus in FE model to derive intact Young's
        modulus

  Validate the primary response surface model:
      Compare FRF curvature values from model updating with experimental
        data
      Verify accuracy of primary RS model in representing intact
        structural response
```

iv. Response Surface Model Updating: Secondary Response Surface Model Construction

```
  Construct the secondary response surface model:
      Use updated intact Young's modulus value to construct secondary RS
        model
      Update secondary RS model using FRF curvature values for damaged
        structure obtained from experimental data
      Derive Young's modulus values for damaged structure

  Compare Young's modulus values for intact and damaged structures:
      Calculate stiffness reduction factor (SRF) using the formula:
          SRF = 1 - (E_d / E'_i)
      Assess the deviation between updated Young's modulus values
```

3. Numerical analysis

This study relies on a singular numerical analysis, focusing specifically on a simply supported beam. This focused approach allows for a comprehensive exploration of the chosen criteria's impact and effectiveness in the context of structural damage identification. Additionally, the choice of a beam as the numerical model provides a practical and representative case, offering insights that can be extrapolated to broader applications in structural health monitoring and damage identification.

The simply supported beam is adopted from study conducted by Ren and Chen [20] and Umar, Bakhary [10]. The length and cross-section of the beam are 6m and 0.2m x 0.25m, respectively. The elastic modulus, density and Poisson's ratio are 32GPa, 2500kg/m^3, and 0.2, respectively. The beam is equally divided into 15 elements and 16 nodes as shown in Figure 3. The Structural Dynamic Toolbox® (SDTools), implemented within the MATLAB® environment, is employed for modeling both intact and damaged geometry of each beam.

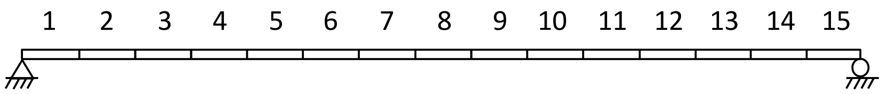


Fig. 3. Illustration of the structural model used in numerical analysis.

To verify the accuracy of the implemented MATLAB's code for adopted model, a comparison as shown in **Error! Reference source not found.** and **Error! Reference source not found.** are made between the frequencies obtained and those reported by Ren and Chen [20] and Umar, Bakhary [10]. The low percentage errors suggest that the natural frequencies from the study closely align with those from the previous studies, validating the accuracy of the numerical model used in this research. To assess the damage identification performance, three damage cases are generated by reducing the value of Young's modulus. Table 3 provides details for each simulated damage cases. Cases 1 and 2 involved a single damage point, symmetrically positioned near the boundary condition. Meanwhile, Case 3 represented multiple damage scenarios.

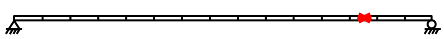
Table 1: Validation of natural frequencies obtained in this study against established literature

Natural frequency	Ren and Chen [20]	Umar, Bakhary [10]	Numerical model
Mode 1	8.99 Hz	9.01 Hz	9.009 Hz
Mode 2	35.95 Hz	35.99 Hz	35.986 Hz
Mode 3	80.63 Hz	80.79 Hz	80.781 Hz

Table 2: Analysis of error percentages relative to previous studies, indicating minimal deviations and affirming the accuracy of the MATLAB's code implemented.

Natural frequency	Error to Ren and Chen [20]	Error to Umar, Bakhary [10]
Mode 1	0.21 %	0.01 %
Mode 2	0.10 %	0.01 %
Mode 3	0.19 %	0.01 %

Table 3: Damage cases

Damage case	Damage location	Young's modulus value at damage element
1	Element 3 	19.2 GPa
2	Element 13 	19.2 GPa
3	Element 1 Element 8 Element 15 	19.2 GPa 22.4 GPa 19.2 GPa

The Box-Behnken DOE (BBD) layout was generated using Design Expert software. For BBD, the lower and upper boundaries were established at 19.2 GPa and 32 GPa, respectively, with 6 center points, resulting in a total of 246 runs. The lower and upper boundaries were selected based on the material properties of the beam and the range of potential damage scenarios. The computation of FRF curvature was carried out at 96% of the first peak of FRF resonance. Young's modulus values for each element were designated as RSM design variables, with the FRF curvatures at nodes 1 to 16 serving as the response. Simulations were executed with 1N impact force applied at node 9 for all damage cases. The FRF for each node was computed using SDTools. Notably, scholars had highlighted difficulties in identifying symmetric damage location [21]. Figure 4 reveals that the natural frequencies for symmetrical damage location are remarkably similar. Meanwhile, Figure 5 illustrates the FRF for intact and multiple damage Case 3. Figure 6 displays the FRF curvature for both intact and damaged cases at 96% of the first resonance value.

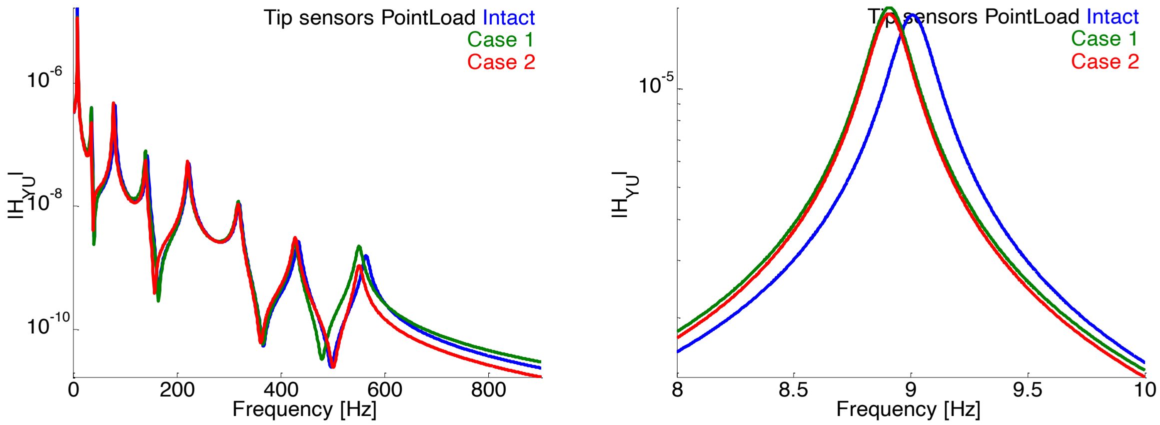


Fig. 4. Comparison of natural frequencies in symmetric damage scenarios, highlighting the challenge of distinguishing damage locations with similar frequency responses

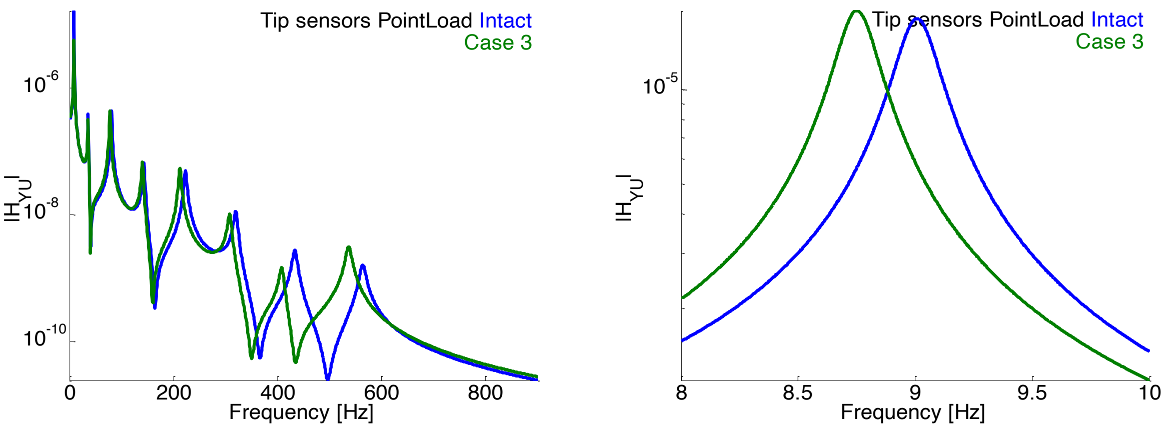


Fig. 5. FRF analysis showcasing multiple damage scenarios, indicating varied structural responses to distributed damages across the beam.

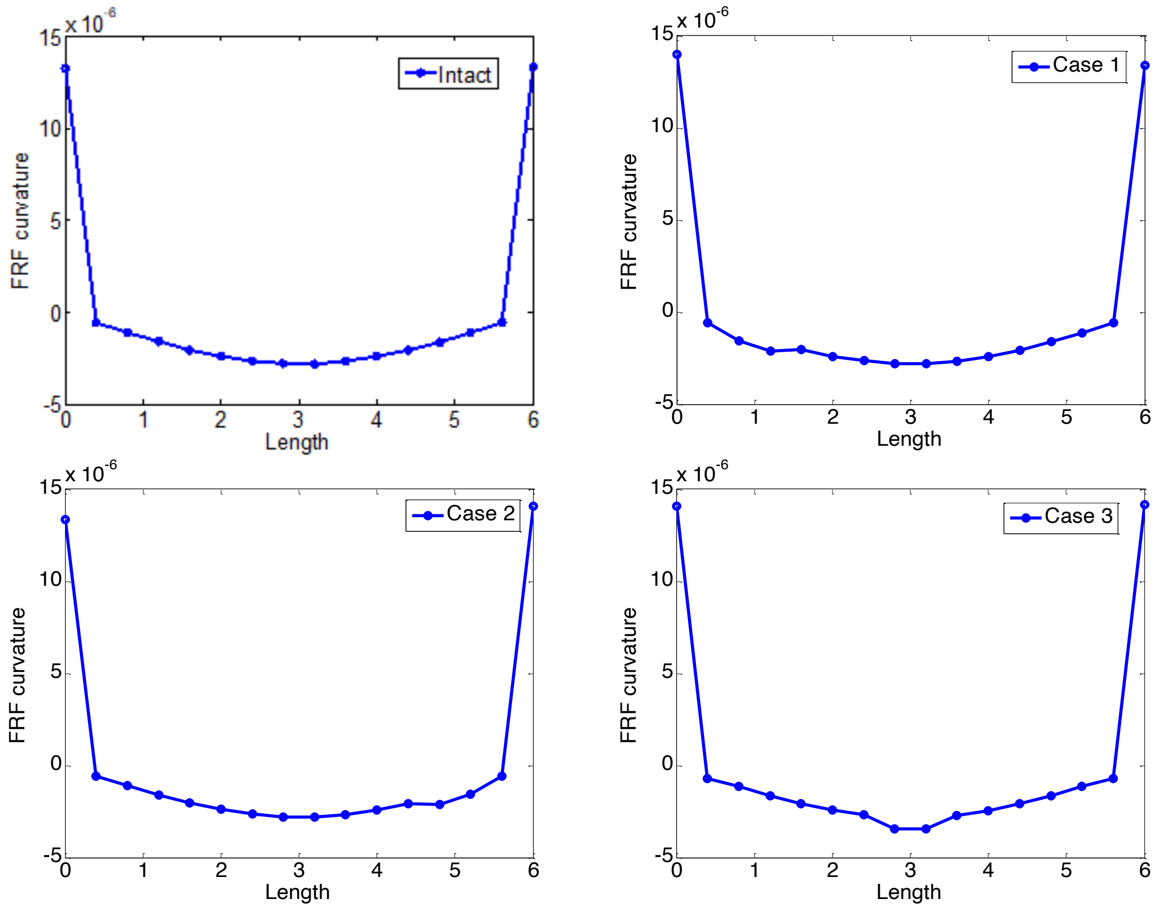


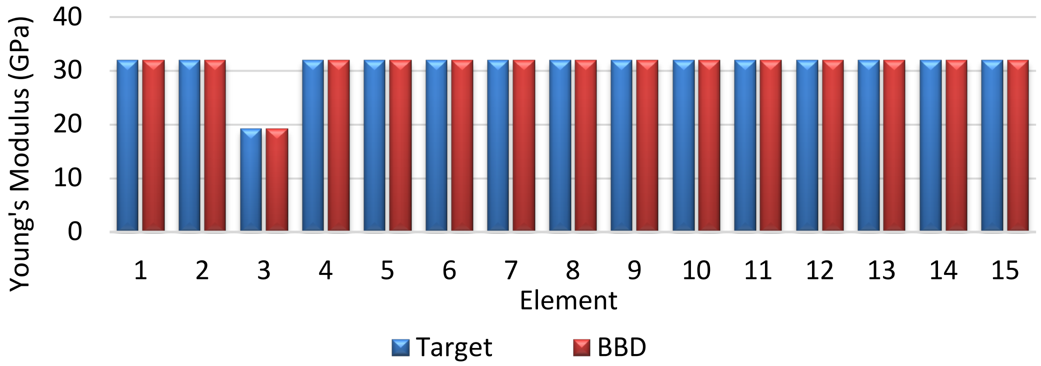
Fig. 6. Quantitative comparison of FRF curvatures, crucial for identifying and quantifying structural changes

Table 4 presents a comprehensive evaluation of the RS model criteria for BBD. The R^2 values for BBD consistently being 1 indicate a strong fit of the data to the RS models. R^2_{pred} evaluates the model's predictive accuracy, while R^2_{adj} measures the model's ability to explain variation about the mean. The minimal difference of less than 0.2 between these values underscores the significance of all parameters in this study. Remarkably, the BBD model scored a perfect 1.0000 across all three criteria, indicating exceptional fit, accurate prediction, and a high level of explained variation. This rigorous evaluation confirms the strong predictive accuracy and fitness of the RS models for capturing the relationship between design variables and FRF curvature responses.

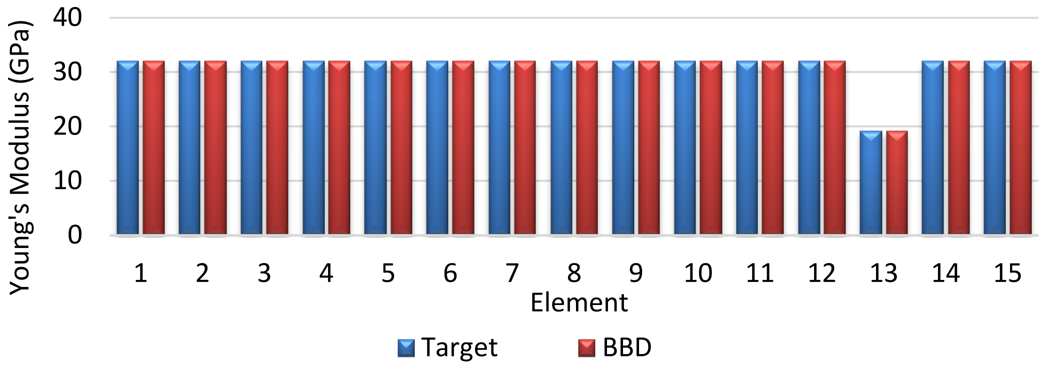
The FE model was substituted with a quadratic RS model constructed from BBD. Once the RS model was validated, its design variables were updated to ensure that the responses matched those of the actual structure. The '`fgoalattain`' function, facilitated the updating process, with the lower bound was fixed at 19.2 GPa, the upper bound at 32 GPa and the weighting factor, ω, was set to 0. The termination criterion is based on the convergence of the response surface model, which is determined by the minimal change in the objective function between iterations. Figure 7 depicts Young's modulus values obtained by primary RS models post-updating (E_d). Figure 7(a) and (b) illustrates the results for a damaged case located at the symmetrical location. Meanwhile, Figure 7(c) presents the results for a case with multiple damaged locations. The updated design variables, E_d, were compared to those in their intact state, enabling the computation of the SRF. The SRF results for damage Case 1 through Case 3 are visually represented in Figure 8. In Figure 8, it is evident that the proposed method accurately calculates the SRF for all damage cases.

Table 4: RS model criteria

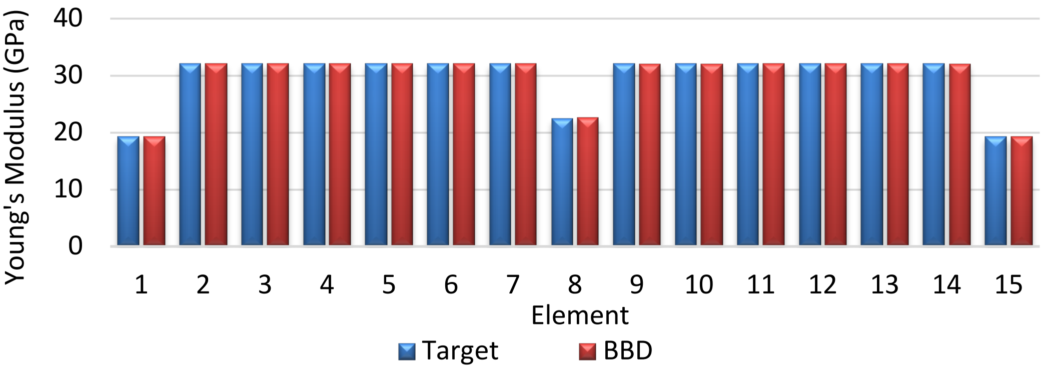
Response	Criteria	BBD
FRF curvature node 1	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 2	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 3	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 4	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 5	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 6	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 7	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 8	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 9	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 10	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 11	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 12	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 13	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 14	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 15	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000
FRF curvature node 16	R^2 R^2_{adj} R^2_{pred}	1.0000 1.0000 1.0000



(a) Case 1

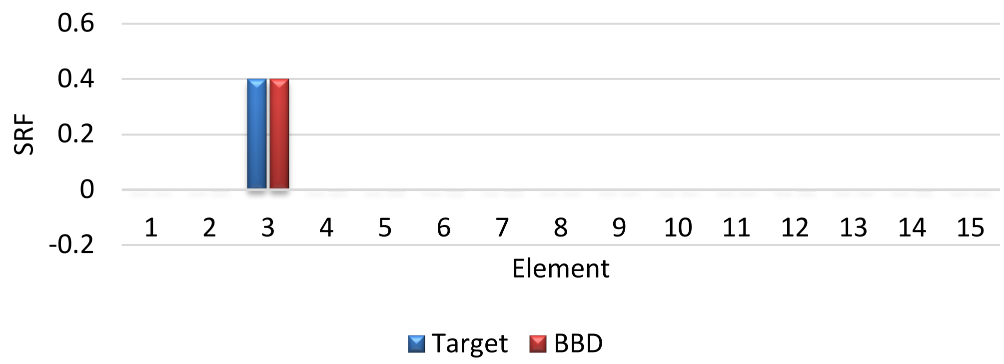


(b) Case 2

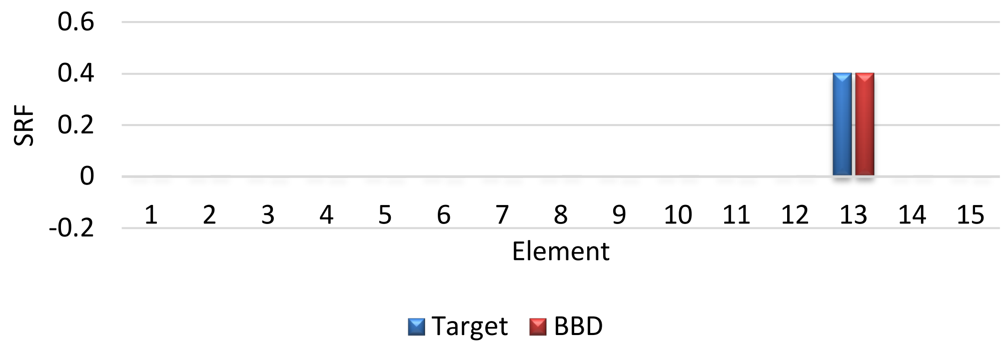


(c) Case 3

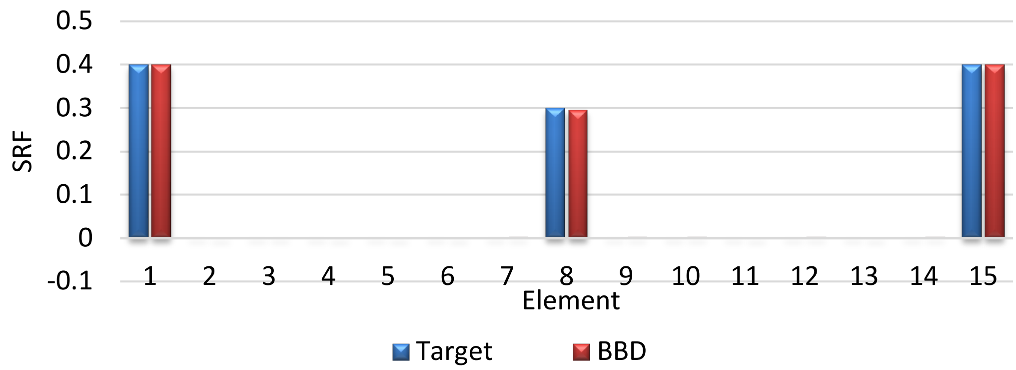
Fig. 7. Updated Young's modulus values post-model updating, demonstrating the RSM approach's accuracy in predicting and localizing structural damage.



(a) Case 1



(b) Case 2



(c) Case 3

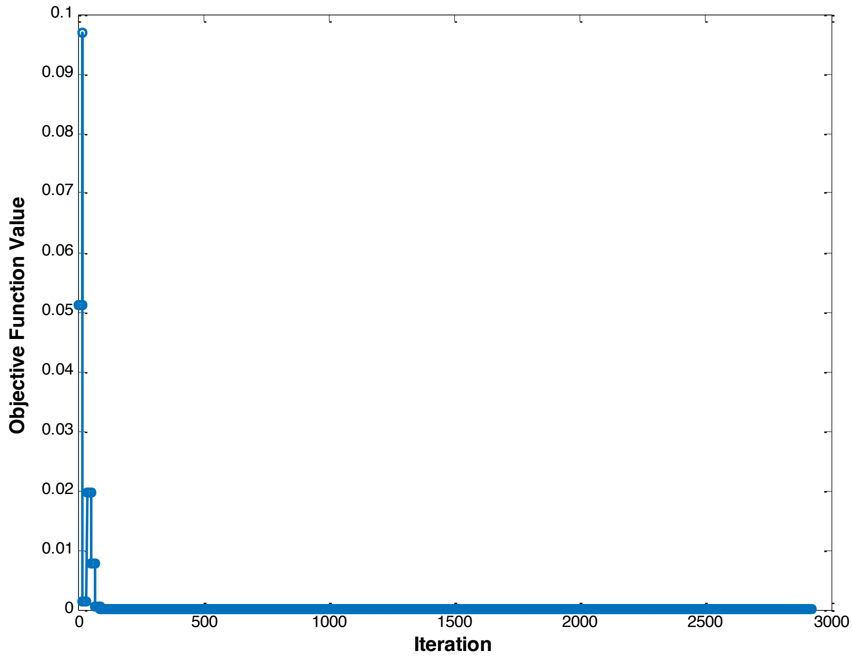
Fig. 8. Visualization of SRFs across different damage scenarios, providing a clear assessment of structural stiffness changes due to identified damages.

Figure 9 illustrates the convergence plots for Cases 1, 2, and 3 in the model updating process. For Case 1, convergence was achieved after 97 iterations and 3017 function evaluations. At the point of convergence, the line search step length was 0.125, with a step size of 0.0019, indicating finely tuned adjustments to the model parameters. The absence of first-order optimality indicates that a local optimum was attained without further gradient refinement. Additionally, the constraint violation was minimized to 0.0074, demonstrating close adherence to the imposed constraints.

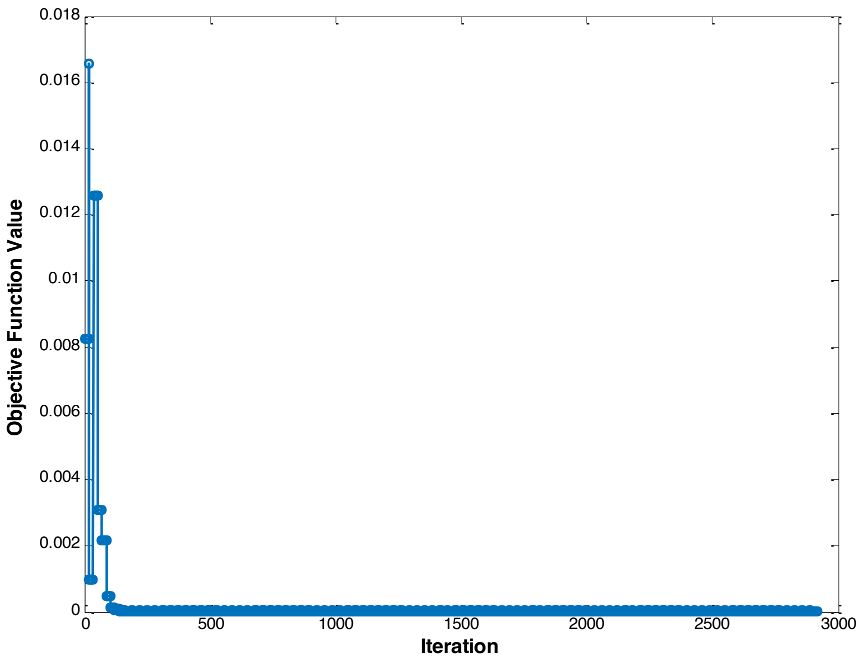
In Case 2, the model updated through 98 iterations and 3013 function evaluations. At convergence, the line search step length was extremely small at 1.2207e-04, and the step size was 1.9211e-06, indicating highly precise adjustments to the model parameters. Again, the absence of first-order optimality suggests a local optimum was reached without additional gradient refinement.

The constraint violation was reduced to 0.0064, reflecting close adherence to the specified constraints.

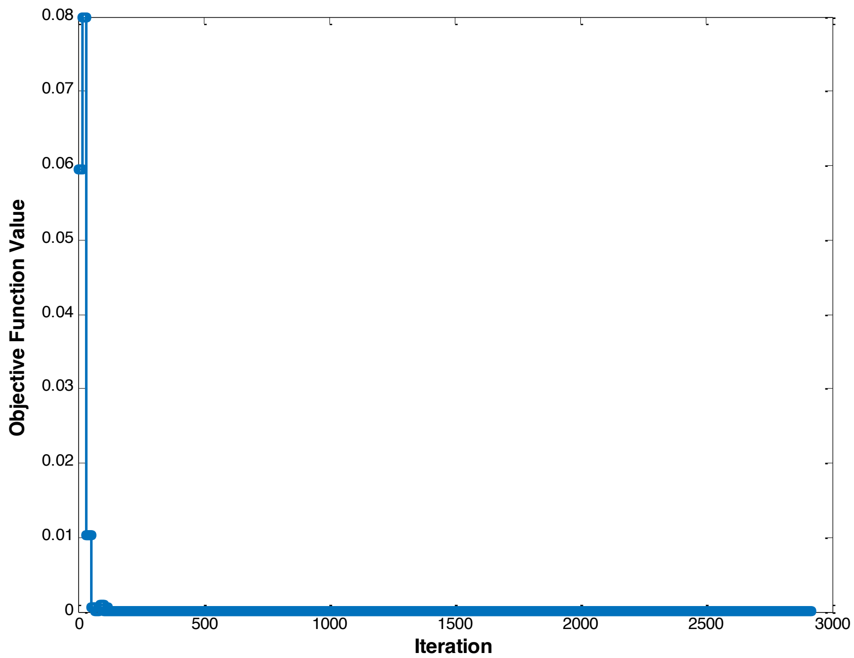
For Case 3, convergence was reached after 97 iterations and 3013 function evaluations. The line search step length at convergence was -6.1035e-05, and the step size was 1.4797e-07, indicating extremely fine-tuned parameter adjustments. The absence of first-order optimality suggests that a local optimum was found without needing further gradient refinements. The constraint violation was minimized to 0.0024, indicating that the solution closely met the imposed constraints.



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 9. Convergence plot for model updating

4. Conclusion and recommendations

This paper develops and implement a MATLAB-based framework for RSM-based model updating using FRF curvature in structural damage identification through the following stages: initial finite element model development, primary response surface model construction, secondary response surface model creation, and structural damage identification. The process commences with DOE to strategically select key parameters, followed by the computation of FRF curvature to capture structural responses within a specified frequency range. These curvature values serve as the basis for constructing response surface models, expressing the relationship between design variables and FRF curvature responses. Criteria testing is conducted on the RS model to ensure its fitness and accuracy, representing the underlying behaviour of the system. Finally, an iterative process refines the RS model through updating procedures until convergence or predetermined termination criteria are satisfied. Notably, the model updating process unfolds in two distinct stages: initially at the primary RS model, followed by refinement at the secondary RS model.

This research successfully achieves its objective to develop a MATLAB-based framework for RSM-based model updating approach utilizing FRF curvature as the response for structural damage identification. The calculation of FRF curvature, entailing the measurement of receptance FRF at each node across the structure, has been meticulously executed. Notably, the structural response, captured by FRF curvature, has been determined at 96% of the first FRF resonance. The results of this study underscore the practical utility of the extracted FRF curvature, particularly in the context of RSM-based model updating for structural damage identification. Furthermore, the findings demonstrate the effectiveness of the developed RSM-based model updating approach.

The unique contributions of this study lie in the integration of FRF curvature with RSM, significantly enhancing the accuracy of damage detection. This framework offers practical applications for real-world structures, providing a reliable method for early damage identification and maintenance planning. However, further investigation into the application of FRF curvature as a response feature, including refinement of algorithms and validation across a broader range of structural systems, including those exhibiting nonlinear behaviour, is expected for future research. Specific future directions include exploring different types of structures, applying the method to field data, and integrating advanced computational techniques.

In conclusion, while this study validates the framework against established models, ensuring its accuracy and reliability, acknowledging any assumptions made and potential sources of error will help refine future iterations. This research sets the stage for subsequent studies to build upon and expand the capabilities of RSM-based model updating in structural health monitoring.

Acknowledgement

The research was funded the Ministry of Higher Education under the Fundamental Research Grant Scheme (FRGS), UTM, FRGS/1/2022/TK0/UTM/02/41 and supported by Universiti Teknologi Malaysia (UTM). The first author was funded by the Ministry of Higher Education of Malaysia under Hadiah Latihan Persekutuan (HLP).

References

[1] Nordila Ahmad, Elwin Yu You Kuan, Siti Khadijah Che Osmi, Jestin Jelani, Zuliziana Suif, Edy Tonnizam Mohamad, Badronnisa Yusuf, and Thamer Ahmed Mohammed. "Analysis of Bridge Performance Exposed to Earthquake and Flood Induced-Scour for Very Dense Sand: Derivation of Fragility Curves." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 63, no. 3 (2025): 216-229. https://doi.org/10.37934/araset.63.3.216229

[2] Rongrong HouYong Xia. "Review on the new development of vibration-based damage identification for civil engineering structures: 2010–2019." *Journal of Sound and Vibration* 491 (2021): https://doi.org/10.1016/j.jsv.2020.115741

[3] N. F. Alkayem, M. Cao, Y. Zhang, M. Bayat, and Z. Su. "Structural damage detection using finite element model updating with evolutionary algorithms: a survey." *Neural Comput Appl* 30, no. 2 (2018): 389-411. https://doi.org/10.1007/s00521-017-3284-1

[4] Nizar Faisal Alkayem, Maosen Cao, and Minvydas Ragulskis. "Damage Diagnosis in 3D Structures Using a Novel Hybrid Multiobjective Optimization and FE Model Updating Framework." *Complexity* 2018 (2018): 1-13. https://doi.org/10.1155/2018/3541676

[5] Yonghui An, Eleni Chatzi, Sung-Han Sim, Simon Laflamme, Bartlomiej Blachowski, and Jinping Ou. "Recent progress and future trends on damage identification methods for bridge structures." *Structural Control and Health Monitoring* 26, no. 10 (2019): e2416. https://doi.org/10.1002/stc.2416

[6] John E. Mottershead, Michael Link, and Michael I. Friswell. "The sensitivity method in finite element model updating: A tutorial." *Mechanical Systems and Signal Processing* 25, no. 7 (2011): 2275-2296. https://doi.org/10.1016/j.ymssp.2010.10.012

[7] Nur Raihana Sukri, Husain Nurulakmar Abu, Nordin Syarifah Zyurina, and Sani Mohd Shahrir Mohd. "Structural Damage Identification Using Model Updating Approach: A Review." *Journal of Advanced Research in Applied Mechanics* 84, no. 1 (2021): 1-12.

[8] Suzana Ereiz, Ivan Duvnjak, and Javier Fernando Jiménez-Alonso. *Review of finite element model updating methods for structural applications*. in *Structures*. 2022. Elsevier. https://doi.org/10.5592/CO/ZT.2021.04

[9] Ashok Kumar Bagha, Prashant Gupta, and Varun Panwar. "Finite element model updating of a composite material beam using direct updating method." *Materials Today: Proceedings* 27 (2020): 1947-1950. https://doi.org/10.1016/j.matpr.2019.09.024

[10] Sarehati Umar, Norhisham Bakhary, and A. R. Z. Abidin. "Response surface methodology for damage detection using frequency and mode shape." *Measurement* 115 (2018): 258-268. https://doi.org/10.1016/j.measurement.2017.10.047

[11] Emre Alpaslan, Kemal Hacıefendioğlu, Gökhan Demir, and Fahri Birinci. "Response surface-based finite-element model updating of a historic masonry minaret for operational modal analysis." *The Structural Design of Tall and Special Buildings* 29, no. 9 (2020): https://doi.org/10.1002/tal.1733

[12] Tanmoy Mukhopadhyay, Tushar Kanti Dey, Rajib Chowdhury, and Anupam Chakrabarti. "Structural Damage Identification Using Response Surface-Based Multi-objective Optimization: A Comparative Study." *Arabian Journal for Science and Engineering* 40, no. 4 (2015): 1027-1044. https://doi.org/10.1007/s13369-015-1591-3

[13] Emre AlpaslanZeki Karaca. "Response surface-based model updating to detect damage on reduced-scale masonry arch bridge." *Structural Engineering and Mechanics, An Int'l Journal* 79, no. 1 (2021): 9-22.

[14] Xiuming Yang, Xinglin Guo, Huajiang Ouyang, and Dongsheng Li. "A Kriging Model Based Finite Element Model Updating Method for Damage Detection." *Applied Sciences* 7, no. 10 (2017): https://doi.org/10.3390/app7101039

[15] RPC Sampaio, NMM Maia, and JMM Silva. "Damage detection using the frequency-response-function curvature method." *Journal of sound and vibration* 226, no. 5 (1999): 1029-1042. https://doi.org/10.1006/jsvi.1999.2340

[16] MC Porcu, DM Patteri, S Melis, and F Aymerich. "Effectiveness of the FRF curvature technique for structural health monitoring." *Construction and Building Materials* 226 (2019): 173-187. https://doi.org/10.1016/j.conbuildmat.2019.07.123

[17] A. Nayyar, U. Baneen, S. A. Z. Naqvi, and M. Ahsan. "Detection and localization of multiple small damages in beam." *Advances in Mechanical Engineering* 13, no. 1 (2021): https://doi.org/10.1177/1687814020987329

[18] K. A. KumarD. M. Reddy. *Application of frequency response curvature method for damage detection in beam and plate like structures*. in *International Conference on Advances in Materials and Manufacturing Applications (IConAMMA)*. 2016. Bangalore, INDIA. https://doi.org/10.1088/1757-899X/149/1/012160

[19] Subhajit Mondal, Bidyut Mondal, Anila Bhutia, and Sushanta Chakraborty, *Damage detection in beams using frequency response function curvatures near resonating frequencies*, in *Advances in Structural Engineering*. 2015, Springer. p. 1563-1573. https://doi.org/10.1007/978-81-322-2193-7_119

[20] Wei-Xin RenHua-Bing Chen. "Finite element model updating in structural dynamics by using the response surface method." *Engineering Structures* 32, no. 8 (2010): 2455-2465. https://doi.org/10.1016/j.engstruct.2010.04.019

[21] Yangyang RenYi Ye. *Damage Identification Based on the Loaded Frequency Changes and Deep Learning for Bridge*. in *Journal of Physics: Conference Series*. 2021. IOP Publishing.