Investigation of Enhanced Modal-Based Techniques for Structural Damage Detection, Localization, and Severity Estimation in Framed Structures

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree
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DECLARATION

I declare that this is my own work, and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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Signature of the Supervisors:

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Dr. H. G. H. Damruwan Date: 08/02/2026

Prof. C. S. Lewangamage Date: 08/02/2026

DEDICATION

To my loving parents and partner, whose unwavering encouragement, support, and motivation have guided me through every milestone of my life. This work is dedicated to you with deepest gratitude and love.

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ABSTRACT

Structural damage detection and estimation have become essential in ensuring the safety, functionality, and longevity of civil engineering structures, particularly framed systems that form the backbone of modern infrastructure. Traditional inspection techniques, although widely used, suffer from limitations such as subjectivity, accessibility challenges, and inefficiency when dealing with large-scale structures. This has driven the development of vibration- and modal-based methods, which utilize dynamic properties such as natural frequencies and mode shapes to identify and quantify structural damage. This research aims to enhance modal-based structural damage detection techniques for framed structures by integrating experimental and computational approaches. Scaled-down steel framed structures were tested on a shake table under both intact and damaged conditions to investigate the impact of damage on modal parameters. Complementary finite element (FE) models were developed and validated in ABAQUS, enabling a comprehensive parametric study of different damage scenarios. The study evaluated the Difference in Mode Shape Slope (DMSS), Difference in Mode Shape Curvature (DMSC), and Grey Relation Coefficient (GRC) methods for their effectiveness in detection, localization, and severity estimation of damages. Results demonstrated that both DMSS and DMSC methods are highly effective for single and multiple damage detection in simple beam structures, while DMSC showed superior reliability in complex framed structures. However, both methods exhibited sensitivity limitations near structural boundaries. The GRC-based approach successfully estimated damage severity in beams but showed reduced accuracy in higher damage cases and in complex frame models. Overall, the combined methodology highlights the potential of enhanced modal-based approaches for improving accuracy and reliability in structural damage detection. The findings contribute valuable insights into the practical application of modal-based techniques in structural health monitoring and provide a foundation for further research on refining severity estimation methods and extending these techniques to large-scale real-world structures.

Keywords: Structural Health Monitoring (SHM), Modal Analysis, Structural Damage Detection (SDD), Finite Element Modelling (FEM), Difference in Mode Shape Slope (DMSS), Difference in Mode Shape Curvature (DMSC), Grey Relation Coefficient (GRC)

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LIST OF ABBREVIATIONS

Abbreviation	Description
SHM	Structural Health Monitoring
SDD	Structural Damage Detection
DMSS	Difference in Mode Shape Slope
DMSC	Difference in Mode Shape Curvature
FEM	Finite Element Modelling
GRC	Grey Relation Coefficient

CHAPTER 1

INTRODUCTION

1.1 Background

Structural damage detection and estimation play a pivotal role in ensuring the safety, reliability, and longevity of civil infrastructure, particularly in framed structures such as residential buildings, high-rise towers, and other critical facilities [1]. Over the past decades, the increasing age of infrastructure has heightened the importance of developing efficient, accurate, and cost-effective methods for Structural Health Monitoring (SHM).

Traditionally, damage detection in civil structures has relied heavily on visual inspections and manual assessments. While such approaches have been widely adopted, they present several limitations that reduce their practicality for large-scale applications. First, the size and complexity of civil structures make routine inspections both labor-intensive and time-consuming. Second, the reliance on human judgment introduces subjectivity, requiring highly skilled and trained inspectors whose assessments may vary. Third, many structural components critical to load-bearing capacity—such as columns, beams, slabs, and foundations—are often concealed by non-structural elements like cladding, flooring, or false ceilings, making direct inspection difficult or even impossible. Collectively, these challenges highlight the limitations of traditional inspection methods and underscore the need for more advanced, automated, and objective approaches.

The success of vibration-based techniques in condition monitoring of mechanical systems has inspired their adoption in the SHM of civil infrastructure. Vibration-based Structural Damage Detection (SDD) methods rely on analyzing dynamic characteristics such as resonance frequencies, damping ratios, and mode shapes, which are inherently sensitive to changes in structural stiffness and mass distribution [2]. These techniques provide several advantages over conventional inspection approaches: they can be applied to inaccessible components, they are less labor-intensive, and they allow for continuous or periodic monitoring without interrupting service. Consequently, vibration-based methods have emerged as one of the most promising strategies in modern SHM.

Among vibration-based approaches, modal-based damage detection techniques have gained prominence. These methods utilize the modal parameters of a structure—specifically natural frequencies, mode shapes, and their derivatives—to detect, localize, and estimate the extent of damage. Natural frequency-based methods, although simple and computationally efficient, suffer from limitations in localizing damage since frequency shifts alone reflect global stiffness reduction rather than localized changes. To address this shortcoming, mode shape-based methods and their derivatives, such as the Difference in Mode Shape Slope (DMSS) and the Difference in Mode Shape Curvature (DMSC), have been developed. These indicators offer enhanced sensitivity to local stiffness changes, making them better suited for detecting and localizing damage in complex structures such as multi-storey framed buildings.

Civil infrastructure systems—including bridges, towers, pipelines, offshore platforms, and buildings—form the backbone of industrialized society. However, many of these structures are now approaching or surpassing their design lifespans. Aging, deterioration, fatigue, overloading, corrosion, and environmental exposure contribute to gradual weakening, which, if left undetected, can lead to catastrophic failures [3]. Structural damage may manifest as cracks, loose connections, broken welds, or reductions in stiffness and load-carrying capacity. As such, early detection and quantification of damage are essential for ensuring safety, maintaining serviceability, and reducing maintenance costs.

Building upon these foundations, the present research seeks to incorporate enhanced modal-based techniques for structural damage detection, localization, and severity estimation in framed structures. While existing modal-based approaches have demonstrated potential, challenges remain—particularly in detecting multiple damages, identifying damage near boundary regions, and estimating severity in complex frame systems. To address these gaps, this research integrates both experimental and computational approaches. Shake table experiments on a scaled seven-storey steel framed structure provide real-world insights into the influence of damage on modal parameters, while validated finite element models enable controlled parametric studies across a variety of damage scenarios. Furthermore, the study employs grey relation analysis in conjunction with curvature-based indicators to explore the quantification of damage severity.

By refining and expanding existing methodologies, this research aims to contribute novel insights to the field of structural engineering, with a specific focus on improving the accuracy and reliability of modal based SHM for framed structures. The findings are expected to advance both theoretical understanding and practical implementation, supporting the development of more robust and efficient systems for maintaining structural integrity and extending the service life of critical civil infrastructure.

1.2 Research Problem

Despite significant advances in vibration-based SDD, the reliable detection, localization, and quantification of damage in advanced framed structures remains a challenge. Frequency-based methods are sensitive but inadequate for accurate localization, while mode shape-based techniques such as DMSS and DMSC improve single damage localization but still required to explore their capabilities with multiple damages, boundary effects, and complex geometries. Moreover, methods for damage severity estimation often demand dense measurements, limiting their practical application. These gaps highlight the need for evaluating the capabilities of these modal-based approaches to deliver more accurate and reliable damage detection, localization, and severity estimation in framed structures through combined experimental and computational investigations.

1.3 Aim and Objectives

The aim of this research is to investigate enhanced modal-based techniques for structural damage detection, localization, and estimation in framed structures, utilizing both experimental and computational methods to improve the accuracy and reliability of structural health monitoring.

To achieve this aim, the study is guided by the following objectives:

- To critically study the principles of structural health monitoring and examine the limitations of existing damage detection, localization, and estimation methods, with a particular focus on modal-based techniques applied to framed structures.
- To experimentally investigate the influence of induced damages on modal parameters by conducting shake table tests on scaled-down steel frame models.
- To develop and validate detailed Finite Element (FE) models using ABAQUS software that replicate the experimental models, and to use them for simulating various damage scenarios.
- To evaluate the effectiveness of modal-based methods, particularly DMSS, DMSC, and grey relation coefficient analysis, for detecting, localizing, and estimating multiple damages in framed structures

1.4 Methodology

To achieve the aim and objectives of the research, a systematic methodology was adopted. First, an extensive literature review was conducted to examine previous studies in SHM, with emphasis on vibration-based damage detection, localization, and severity estimation techniques. This review also identified key limitations in existing approaches, particularly when applied to complex framed structures under varying load and boundary conditions.

Next, experimental investigations were carried out on scaled-down seven-storey steel framed structure using a shake table. Both intact and damaged scenarios were tested to capture variations in dynamic response and to extract modal parameters for damage assessment. The induced damages were carefully introduced in columns to study their impact on resonance frequencies and mode shapes.

In parallel, a detailed FE model of the experimental framed structure was developed using ABAQUS software. This model was validated against experimental results to ensure its accuracy in reproducing dynamic behavior. Once validated, the FE model was employed for an extensive parametric study, simulating various damage scenarios—including single, multiple, and joint damages—as well as irregularities in the structural configuration.

Finally, the effectiveness of DMSS and DMSC methods was evaluated for damage detection and localization, while the grey relation coefficient (GRC) based approach was applied for damage severity estimation. Comparative analyses were performed between experimental and computational results to establish the robustness, accuracy, and limitations of the proposed techniques.

1.5 Significance of the Research

The significance of this research lies in its contribution to advancing the field of SHM through the development and validation of enhanced modal-based techniques for structural damage detection, localization, and severity estimation in framed structures. Traditional methods of structural inspection are often labor-intensive, subjective, and limited in detecting internal or minor damages that may compromise long-term structural integrity. By integrating experimental investigations with FE modelling, this study provides a more reliable, quantitative, and scalable approach to damage assessment. The combined use of DMSS, DMSC, and GRC methods establishes a comprehensive framework for accurately identifying and quantifying structural damage. The outcomes of this research not only improve the precision and robustness of modal-based SHM techniques but also offer practical insights for engineers and researchers in assessing the health of civil structures, thereby contributing to safer, more resilient, and cost-effective infrastructure management.

1.6 Thesis Outline

This thesis is organized into seven chapters to systematically address the aim and objectives of the research.

Chapter 1 – Introduction

This chapter introduces the background of the study, defines the research problem, and outlines the aim and objectives. It also explains the adopted methodology and presents the overall structure of the thesis.

Chapter 2 – Literature Review

This chapter provides a detailed review of SHM techniques, with a special emphasis on modal-based damage detection, localization, and severity estimation methods. It also identifies the limitations of existing approaches and highlights the research gaps addressed in this study.

Chapter 3 – Experimental Study

This chapter describes the experimental program, including the shake table setup, preparation of scaled-down frame models, and data acquisition for both intact and damaged structural scenarios.

Chapter 4 – Finite Element Modelling

This chapter outlines the development of FE models using ABAQUS software and their validation against experimental results to ensure accuracy and reliability for further studies.

Chapter 5 – Parametric Study

This chapter discusses the parametric study carried out using validated FE models. Various damage scenarios are analysed to investigate their effects on modal parameters and assess the performance of damage detection and damage severity estimation methods.

Chapter 6 – Results and Discussion

This chapter presents and interprets the results, focusing on the effectiveness of DMSS, DMSC, and GRC methods for damage detection, localization, and severity estimation in framed structures.

Chapter 7 – Conclusion

This chapter concludes the thesis by summarizing the main findings, emphasizing the contributions of the research, and providing recommendations for future studies in structural damage detection and health monitoring.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

2.1.1 Structural Damages

Structural damage can be broadly defined as any weakening of a structure that adversely affects its performance [4]. Such damage often arises from deviations in geometric or material properties, leading to undesirable stresses, displacements, or vibrations [5]. Common forms of structural damage include cracks, loose bolts, broken welds, corrosion, and fatigue. Detecting and estimating these damages is critical for maintaining the safety and service life of civil structures, particularly in framed systems ranging from residential buildings to critical infrastructure [1].

In engineering practice, damage is an inherent phenomenon, predominantly driven by environmental and mechanical factors. Civil infrastructure is especially vulnerable to creep, corrosion, shrinkage, fatigue, and scour, which can accelerate deterioration over time [6]. Both short-term and long-term damages not only reduce the design life of structures but can also trigger catastrophic failures, leading to severe loss of life and property.

A striking example is the Morandi Bridge collapse in Genoa, Italy, on August 14, 2018 (Fig. 2.1). The cable-stayed bridge, designed by Riccardo Morandi in the 1960s, suffered from material degradation over decades of service. Investigations revealed that corrosion of steel cables embedded in prestressed concrete stays—aggravated by moisture and road salt—led to a significant loss of structural integrity, ultimately causing the collapse. This tragic event claimed 43 lives and caused widespread infrastructure damage [7].

Such incidents underscore the pressing need for early detection of structural damage and proactive maintenance strategies. This has driven the advancement of Structural Health Monitoring (SHM) techniques, which provide systematic approaches for assessing and managing the condition of civil infrastructure. The following section introduces the concept and evolution of SHM in this context.

Fig. 2.1: Morandi Bridge collapse [8]

2.1.2 Structural Health Monitoring (SHM)

Structural Health Monitoring (SHM) is an advanced methodology used to assess the integrity and safety of structures over time. It involves the continuous or periodic assessment of structural performance using a variety of sensors and data analysis techniques [9]. The importance of SHM has grown significantly due to aging infrastructure and the need for cost-effective maintenance strategies [10].

SHM plays a vital role in maintaining the safety and longevity of civil infrastructure, including buildings, bridges, and industrial facilities. Over time, structures degrade due to aging, environmental exposure, and extreme loading events, which can lead to damage and even catastrophic failure if not detected early. Both short-term and long-term damages accelerate structural deterioration and reduce service life, making monitoring an essential aspect of modern civil engineering [6].

The concept of SHM has evolved significantly, beginning with simple visual inspections and advancing into a wide range of sophisticated techniques for detecting, localizing, and quantifying structural damage [3]. Early identification of damage enables preventive maintenance, reduces repair costs, and enhances overall structural safety.

Various SHM techniques are available, ranging from traditional methods such as visual inspections and non-destructive testing (NDT) to more advanced approaches such as vibration-based monitoring. Among these, modal-based damage detection has gained considerable attention due to its ability to assess structural conditions through dynamic characteristics, including natural frequencies, mode shapes, and damping ratios [2], [11].

However, traditional SHM methods, including visual inspection and NDT, often require significant manual effort and can be subjective, time-consuming, and costly [12]. In contrast, vibration based SHM techniques utilize the dynamic response of structures, making them more efficient and capable of detecting damage even in concealed structural elements. Since damage alters the stiffness distribution of a structure, it produces measurable changes in modal parameters such as natural frequencies and mode shapes. These changes can be effectively leveraged to detect, localize, and estimate the severity of damage [13]. Given these advantages, vibration based SHM has emerged as a key foundation for structural damage detection, which will be discussed in detail in the following section.

2.1.3 Structural Damage Detection (SDD)

Structural Damage Detection (SDD) focuses on identifying, localizing, and quantifying the effects of damage in structures to ensure safety and serviceability. According to Farrar & Doebling [14], the effects of damage on structures can be broadly categorized into two situations:

- Linear damage situation: The structure remains linear elastic even after damage.
- Nonlinear damage situation: The initially linear-elastic structure exhibits nonlinear behavior after sustaining damage.

SDD methods have been classified into four levels by Rytter [15]:

- Level 1: Detection – determining whether damage is present.
- Level 2: Localization – identifying the geometric location of the damage.
- Level 3: Quantification – assessing the severity of the damage.
- Level 4: Prognosis – predicting the remaining service life of the structure.

More recently, Gharehbaghi et al. [16] have categorized damage identification into two broader groups: diagnosis and prognosis. These groups are further divided into five levels: identification, localization, classification, assessment, and lifetime prediction, which provide a comprehensive framework for structural damage evaluation.

The main components of a typical SDD system are illustrated in Fig. 2.2, which highlights the integration of monitoring, data processing, and decision-making processes in damage assessment.

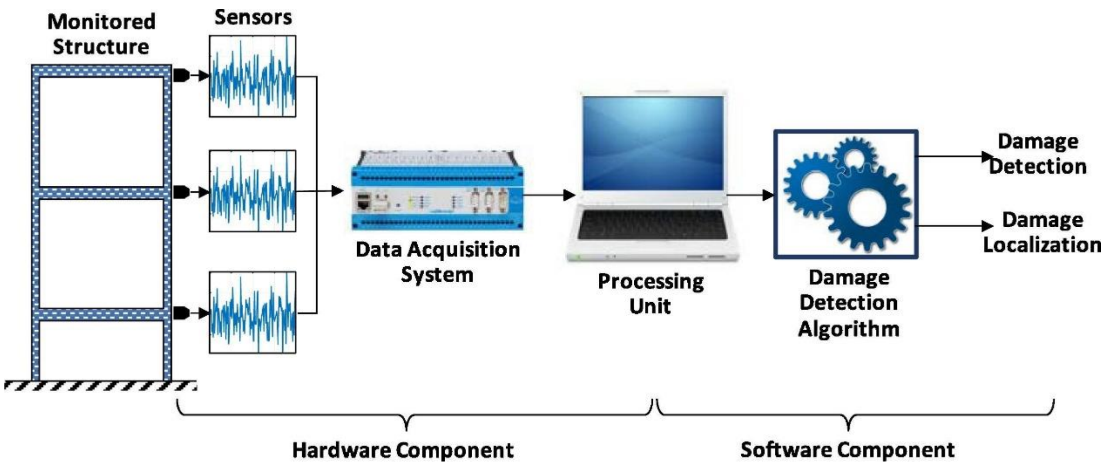


Fig. 2.2: Main components of SDD systems [3]

2.1.4 Structural Damage Detection (SDD) Methods

Over the past few decades, numerous techniques have been proposed and implemented for SDD. Early studies primarily focused on establishing relationships between natural frequency variations and structural damage through experimental and numerical methods. While natural frequency-based approaches provided initial insights, they showed limited sensitivity to localized damage and were significantly influenced by boundary conditions, environmental effects, and mass variations, thereby failing to deliver reliable spatial information about damage [2], [11], [17].

To overcome these limitations, researchers increasingly adopted modal analysis as a fundamental tool for evaluating the dynamic behavior of structures. Modal parameters—such as natural frequencies, mode shapes, and modal strain energy—have since become widely used indicators of structural integrity [18]. Based on these parameters, various modal-based methods have been developed, including:

- Frequency-based methods: Tracking shifts in natural frequencies caused by damage.
- Mode shape-based methods: Identifying changes in mode shapes to localize damage.
- Modal strain energy-based methods: Detecting reductions in element stiffness through energy distribution.

Despite their effectiveness, modal-based methods also face challenges such as sensitivity to environmental variations, measurement noise, and limited detection of minor damage [11]. To address these issues, recent research has combined experimental and computational approaches.

- Shaking table experiments have gained popularity due to their non-destructive nature, enabling controlled simulation of real-world dynamic loads and validation of SHM methods under damage scenarios.

- Finite Element (FE) modelling, supported by advanced software such as ABAQUS, plays a crucial role in simulating structural behavior and damage effects, as well as in validating experimental results [19].

By integrating these two approaches, researchers aim to improve the accuracy and reliability of modal based SDD techniques, thereby supporting better decision-making in structural maintenance and safety assessments.

This study builds on these foundations, focusing on the development and validation of enhanced modal-based damage detection, localization, and severity estimation methods for framed structures, using both experimental and computational approaches.

The classification of SDD methods is illustrated in Fig. 2.3, which outlines the different approaches developed over the years.

Since this research employs vibration-based damage detection techniques, the following section will provide a detailed discussion of vibration-based methods, their principles, and their applications in SHM.

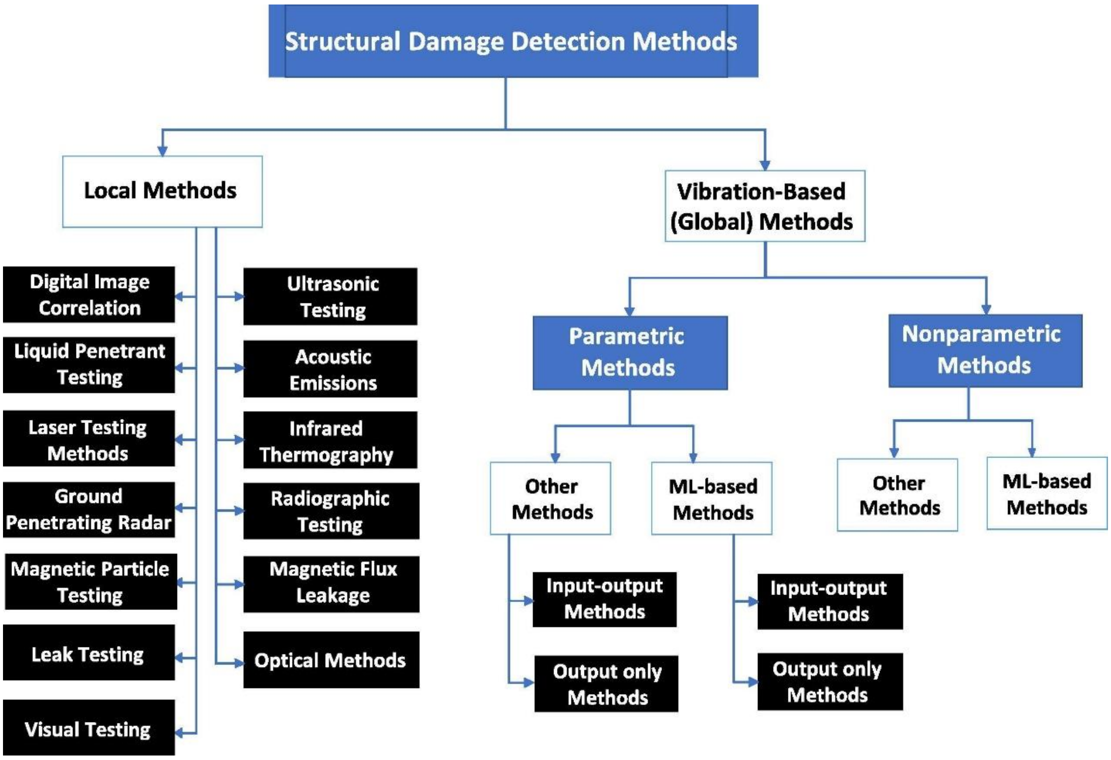


Fig. 2.3: Classification of SDD methods [3]

2.2 Vibration-Based Techniques

Vibration-based structural damage detection is an emerging field of research [20]. Vibration-based damage detection techniques are gaining popularity among researchers due to their non-destructive nature and potential to achieve a continuous structural health monitoring at a low cost [5]. Vibration-based methods have been developed and applied to detect structural damage in the civil, mechanical and aerospace engineering fields for many years [21]. Following Fig. 2.4 shows an overview of the vibration-based damage detection method.

Various techniques for structural damage detection involving modal parameters obtaining through vibration-based methods have widely been used over the past few decades. This is because the modal parameters of a structure can easily be obtained from forced, free or ambient vibration measurements [5]. In many of these techniques, mode shape curvature has been used for localization of damage. Modal-based damage detection techniques are further discussed in this research.

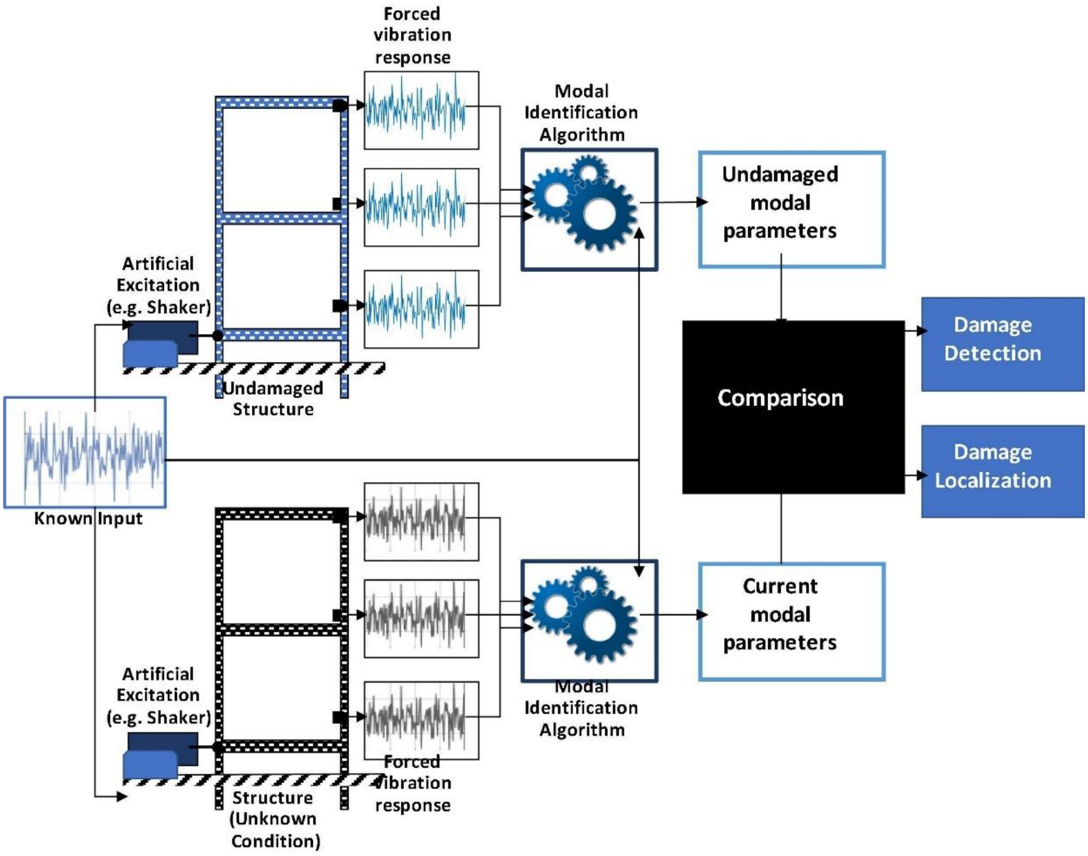


Fig. 2.4: A schematic of input–output parametric vibration-based damage detection methods [3]

2.2.1 Fundamentals of Modal Analysis and Mode Shapes

Modal analysis is defined as the study of the natural characteristics of a structure, which are essential in designing structural systems for vibration applications [22]. The dynamic behavior of a structure can be expressed as a combination of modes, where each mode is characterized by specific parameters such as natural frequency, damping ratio, and mode shape. These parameters are influenced by the geometry, material properties, and boundary conditions of the structure [23]. Experimental Modal Analysis (EMA) is utilized to identify these parameters based on measurements of the applied force and the resulting vibration response.

Modal analysis can be illustrated through a simple structural example shown in Fig. 2.5. A freely supported flat plate is subjected to a force that varies sinusoidally. The oscillation frequency of this force is gradually increased while maintaining a constant peak force.

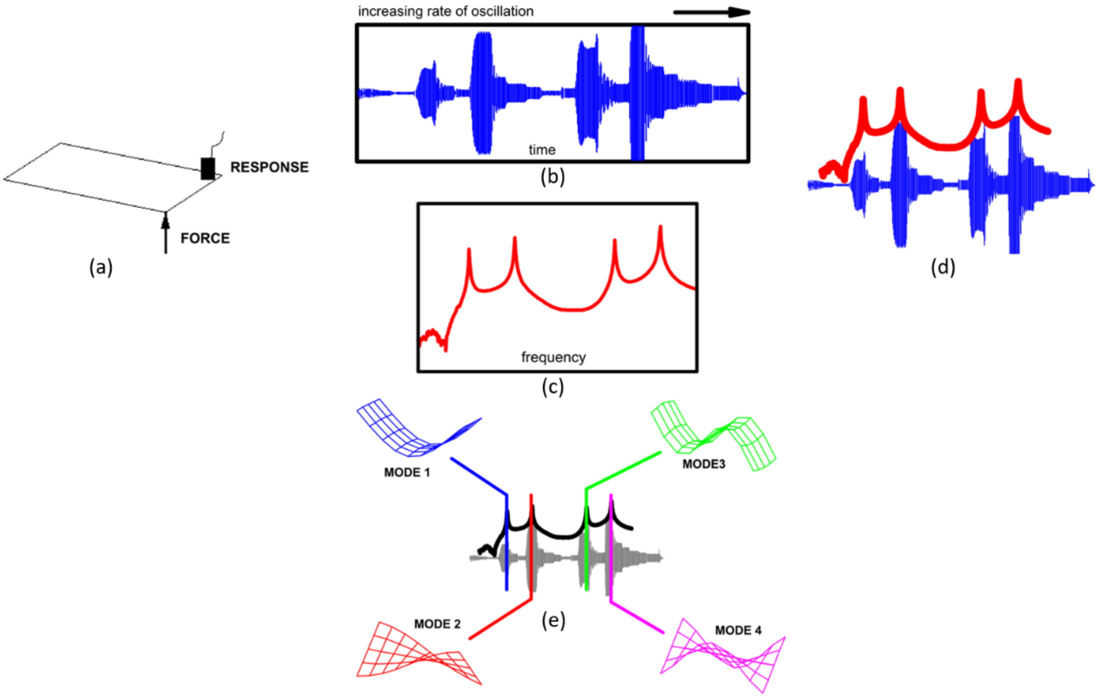


Fig. 2.5: Steps and presentation of the modal analysis process of a simple steel plate model (a) Simple plate excitation/response model, (b) Simple plate response, (c) Simple plate frequency response function, (d) Overlay of time and frequency response function, and (e) Simple plate sine dwell response [22]

The response of the plate is measured using an accelerometer placed at one of its corners (Fig. 2.5 (a)). As the input force oscillation frequency changes, variations in amplitude are observed in the accelerometer response. An increase in amplitude occurs as the applied force frequency approaches the natural frequency (or resonant frequency) of the system as shown in Fig. 2.5 (b), reaching a maximum when resonance is achieved.

This time-domain data provides valuable insights. However, when transformed into the frequency domain using the Fast Fourier Transform (FFT), a frequency response function can be computed. The peaks in this function correspond to the resonant frequencies of the system (Fig. 2.5 (c)). It can be observed that these peaks align with the points in the time response where maximum amplitude was recorded in response to the input excitation. By overlaying the time-domain and frequency-domain responses as shown in Fig. 2.5 (d), it becomes evident that the frequency at which the time-domain response reaches its maximum corresponds to the resonant frequency identified in the frequency response function. Consequently, either the time response or the frequency response function can be used to determine natural frequencies, with the latter offering a more straightforward evaluation.

At these natural frequencies, the deformation patterns of the structure take on distinct shapes depending on the excitation frequency. By distributing multiple accelerometers across the plate and measuring the amplitude response at different excitation frequencies, the deformation patterns corresponding to various natural frequencies can be identified. If excitation is applied at each natural frequency, distinct mode shapes are observed as shown in Fig. 2.5 (e). The first natural frequency results in a bending deformation pattern (Mode 1), the second natural frequency leads to the first twisting deformation pattern (Mode 2), and higher-order natural frequencies exhibit more complex bending and twisting deformation patterns (Mode 3), (Mode 4). These deformation patterns are referred to as the mode shapes of the structure.

Natural frequencies and mode shapes are intrinsic to all structures. These characteristics, which depend on the mass and stiffness of the structure, determine the locations of natural frequencies and corresponding mode shapes. Understanding these properties and their influence on structural vibrations allows for the optimization of structural design, ensuring improved performance and resilience under dynamic loading conditions.

2.2.2 How Structural Damage Affects Modal Parameters

Structural damage alters a structure's stiffness distribution, leading to detectable changes in its natural frequencies, mode shapes, and damping ratios [2]. Monitoring these changes allows engineers to detect and localize damage effectively [11]. According to Pandey et al. [24], any kind of damage in a structure leads to alterations in the eigen parameters by reducing the stiffness (EI), causing a decrease in natural frequencies. Stiffness of a section can be defined as the multiplication of the Elastic modulus (E) of the section and the second moment of the cross-sectional area (I) of the section. Similarly, mode shapes of structure experience local distortions in damaged regions, and damping ratios may increase due to energy dissipation in cracked or fractured areas.

Following Fig. 2.6 illustrates the stiffness reduction of a steel column section due to a formation of a crack and due to a material degradation. In the Fig. 2.6 (a), the crack has reduced the I of the section while keeping the E of the section as a constant. In the Fig. 2.6 (b), the corroded section has reduced the E of the section while keeping the I of the section as a constant. Either way the stiffness (EI) of the section is reduced. This provides the fundamental connection between the structural damages and modal parameters of a structure.

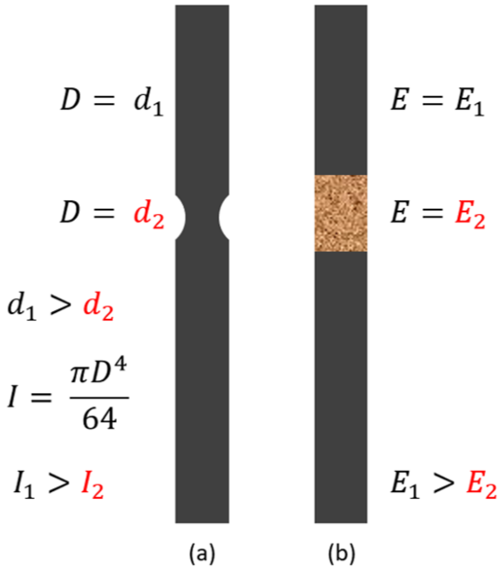


Fig. 2.6: Stiffness reduction of a steel column section due to the reduction of (a) second moment of the cross-sectional area (I), and (b) Elastic modulus (E)

2.2.3 Natural Frequency-Based Methods

Natural frequency variations are among the earliest and most widely used indicators of structural damage. The presence of damage reduces the stiffness of a structure, leading to observable shifts in its natural frequencies. Since resonance can amplify structural vibrations and potentially cause failure, analyzing natural frequencies is critical in cracked or damaged structures. When the frequency of an applied load coincides with a natural frequency, the structure experiences resonance, resulting in large amplitudes that may lead to catastrophic collapse. Therefore, identifying resonant frequencies is essential for preventing failure under periodic loading [25].

Natural frequency-based methods are relatively simple and effective because frequencies can be measured with high accuracy, even from a limited number of measurement points, and are less affected by experimental noise [11]. These advantages make them attractive for practical monitoring. However, their major limitation lies in the inability to localize damage, as different damage scenarios may produce similar frequency shifts. For instance, cracks of varying lengths at different locations can cause nearly identical reductions in natural frequencies, making it difficult to distinguish between damage cases [24]. Due to these limitations, researchers have shifted towards mode shape–based methods, which provide richer spatial information and are more sensitive to local damage, thereby offering improved capabilities for damage localization compared to natural frequency-based approaches.

2.2.4 Mode Shape-Based Methods

Mode shape–based methods have gained significant attention in structural damage detection and localization, as they are generally more sensitive to structural changes than natural frequency–based approaches [5]. Unlike frequency shifts, which often provide only global information, mode shapes can capture local distortions in the structural response caused by damage, thereby offering greater potential for localization [24].

According to Fan & Qiao [11], mode shapes contain inherent local information, making them suitable for detecting multiple damage locations. Moreover, mode shapes are less influenced by environmental factors such as temperature compared to natural frequencies [14]. In practice, this method requires comparing the mode shapes of an intact (undamaged) and a damaged structure. The baseline mode shapes for the intact condition may be obtained experimentally, or, when experimental data are unavailable, through accurate finite element (FE) modelling [11].

Over the years, several mode shape–based approaches have been developed and successfully applied for damage detection in beam and frame structures [5], [21], [24], [26]. However, many studies have reported that fundamental mode shapes are often less sensitive to localized damage [20]. To overcome this limitation, researchers have proposed the use of mode shape derivatives—namely, the first derivative (Mode-Shape Slope, MSS) and the second derivative (Mode-Shape Curvature, MSC)—as more precise and reliable damage indicators [27].

Mode-Shape Slope (MSS) method proposed by Zhu et al. [21] has defined it through the following equation (2.1).

$$\varphi'_{ij} = \frac{\varphi_{ij} - \varphi_{i(j-1)}}{h_j} \tag{2.1}$$

Where, φ'_{ij} is the mode shape slope of the j th story in the i th mode, and h_j is the height of the j th storey. Here φ_{ij} is the j th component of the i th mode shape, φ_i.

Mode-Shape Curvature (MSC) method proposed by Pandey et al. [24] is related to the flexural stiffness of beam cross-section. Curvature at a point can be calculated by (2.2).

$$V'' = M/(EI) \tag{2.2}$$

Where, V'' is the curvature at the section, M is the bending moment at the section, E is the Elastic modulus, and I is the second moment of the cross-sectional area.

Therefore, to calculate the slopes and curvatures of the mode shapes, following equations can be derived by using the first order and second-order of the central difference method [20]. MSS and MSC is provided by the first order (φ'_{ij}) and second order (φ''_{ij}) derivatives (2.3 – 2.4).

$$\varphi'_{ij} = \frac{\varphi_{i(j+1)} - \varphi_{i(j-1)}}{2h_j} \tag{2.3}$$

$$\varphi''_{ij} = \frac{\varphi_{i(j+1)} - 2\varphi_{ij} + \varphi_{i(j-1)}}{h_j^2} \tag{2.4}$$

However, at boundaries of the structure where the fixed and free ends are located, the above equations do not have all the required values. Therefore, at the fixed end, the forward difference method and at the free end, the backward difference method can be used. The expressions for the forward and backward difference methods are shown in (2.5 – 2.8).

$$\varphi'_{ij}|_{forward} = \frac{\varphi_{i(j+1)}-\varphi_{ij}}{h_j} \tag{2.5}$$

$$\varphi''_{ij}|_{forward} = \frac{\varphi_{i(j+2)}-2\varphi_{i(j+1)}+\varphi_{ij}}{h_j^2} \tag{2.6}$$

$$\varphi'_{ij}|_{backward} = \frac{\varphi_{i(j)}-\varphi_{i(j-1)}}{h_j} \tag{2.7}$$

$$\varphi''_{ij}|_{backward} = \frac{\varphi_{ij}-2\varphi_{i(j-1)}+\varphi_{i(j-2)}}{h_j^2} \tag{2.8}$$

Hence, using backward, forward, and central difference method the first and second derivatives of the any mode shape of a structure can be calculated. In this study, MSS and MSC methods are utilized for the parametric study.

2.2.5 Other Modal-Based Methods

The modal flexibility-based method can be found as another method which has been proposed as an approach for detecting structural damage based on changes in modal flexibility. Initially introduced by Pandey & Biswas [28], this method evaluates structural changes by analyzing variations in flexibility matrices derived from modal parameters. Further advancements in this approach were made by Z. Zhang & Aktan [29], who examined modal flexibility and its derivative, the uniform load surface (ULS). The ULS serves as a weighted average of mode shapes, making it less sensitive to noise when compared to direct mode shape analysis. To enhance damage localization and quantification, Wu and Law applied ULS curvature analysis to plate structures [30], [31]. Their findings demonstrated that ULS curvature effectively identifies local damage, even in scenarios where measurements are truncated, incomplete, or affected by noise. Additionally, Wang & Qiao [32] modified the gapped smoothing method (GSM), initially introduced by Ratcliffe [33], to detect delamination in composite beams. By employing a simplified gapped smoothing (SGS) technique that utilizes a fourth-order polynomial, the ULS curve of a damaged beam was accurately fitted. The squared difference between the polynomial and ULS curves was then computed to develop a reliable damage index, further refining the accuracy of structural damage detection methodologies.

Furthermore, Ren & Roeck [4] introduced the Singular Value Decomposition (SVD) method as an approach for structural damage identification based on frequency and mode shape changes. Their methodology utilizes eigenvalue equations that characterize the dynamic behavior of structures to establish element damage equations. Various solution techniques were explored and compared, with findings indicating that the SVD-R method, which is based on singular value decomposition, demonstrated the highest effectiveness in damage identification. The proposed method was initially validated using numerical simulations on both a simple beam and a continuous beam, each subjected to multiple simulated damage scenarios. Further experimental validation was conducted through laboratory testing on a reinforced concrete beam, confirming the robustness and accuracy of the SVD-based approach in identifying structural damage [34].

2.3 Previous Approaches in Modal-Based Damage Detection

2.3.1 Shake Table Testing

Shake table testing is a widely adopted experimental approach for investigating the dynamic behavior of structures under controlled loading conditions. By simulating real-world ground motions, shake table experiments enable the evaluation of structural response characteristics and the effects of damage under dynamic excitation. Owing to their non-destructive testing (NDT) nature, shake table tests have been extensively used in modal-based structural damage detection studies. With the availability of shake tables covering a wide range of capacities and frequency bands, researchers are able to perform investigations on both scaled models and full-scale structures, providing valuable insight into damage-sensitive dynamic parameters.

Zhu et al. [21] conducted an experimental study to evaluate modal-based damage detection techniques using a reduced-scale three-storey steel framed structure tested on a uniaxial shake table. The model, with overall dimensions of 0.85 m × 0.5 m × 1.45 m, consisted of high-strength steel columns with rectangular cross-sections (9.5 mm × 75 mm) and rigid steel floor plates of 25 mm thickness. To realistically simulate floor mass, additional steel blocks of 135 kg were placed on each storey. The structure was subjected to white-noise ground excitation, and accelerometers were installed at each floor level to record the dynamic responses. Structural damage was introduced by reducing the cross-sectional dimensions of selected columns, thereby simulating stiffness degradation. The test configuration is shown in the following Fig. 2.7.

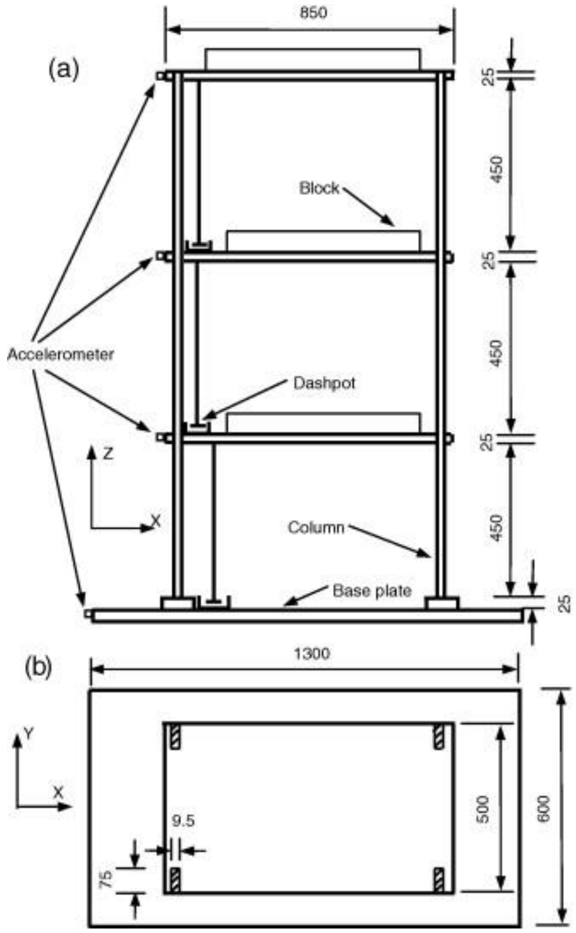


Fig. 2.7: Configuration of the three-storey steel framed structure (a) side elevation and (b) plan view [21]

The experimental results demonstrated that changes in mode shape slopes were highly sensitive to localized stiffness reductions, enabling effective damage localization within the framed structure. The study confirmed that the mode shape slope method could successfully identify damaged storeys under controlled experimental conditions, even when global changes in natural frequencies were relatively small. These findings highlighted the potential of modal-based indicators, particularly mode shape derivatives, for damage detection in framed structures subjected to dynamic loading.

However, the study primarily focused on the detection and localization of single damage scenarios and did not extend the investigation to damage severity estimation or multiple damage cases. In addition, the influence of damage location along the structural height and the associated limitations in sensitivity near boundary regions were not systematically examined. Furthermore, the experimental work was not complemented by validated numerical models that could facilitate parametric studies for a wider range of damage scenarios.

Another experimental investigation was conducted by Roy [20] to evaluate mode-shape-based structural damage detection techniques using a six-storey scaled-down steel frame structure subjected to shake table excitation. The model had plan dimensions of 0.21 m × 0.21 m with a storey height of 0.13 m. Square shaped steel sections with dimensions of 8 mm × 8 mm were used for the columns, while two different beam sections (6 mm × 6 mm and 30 mm × 6 mm) were adopted to represent varying stiffness characteristics. Additional mass blocks were attached to the beams at each floor level to simulate realistic inertial effects. The experimental configuration is illustrated in Fig. 2.8.

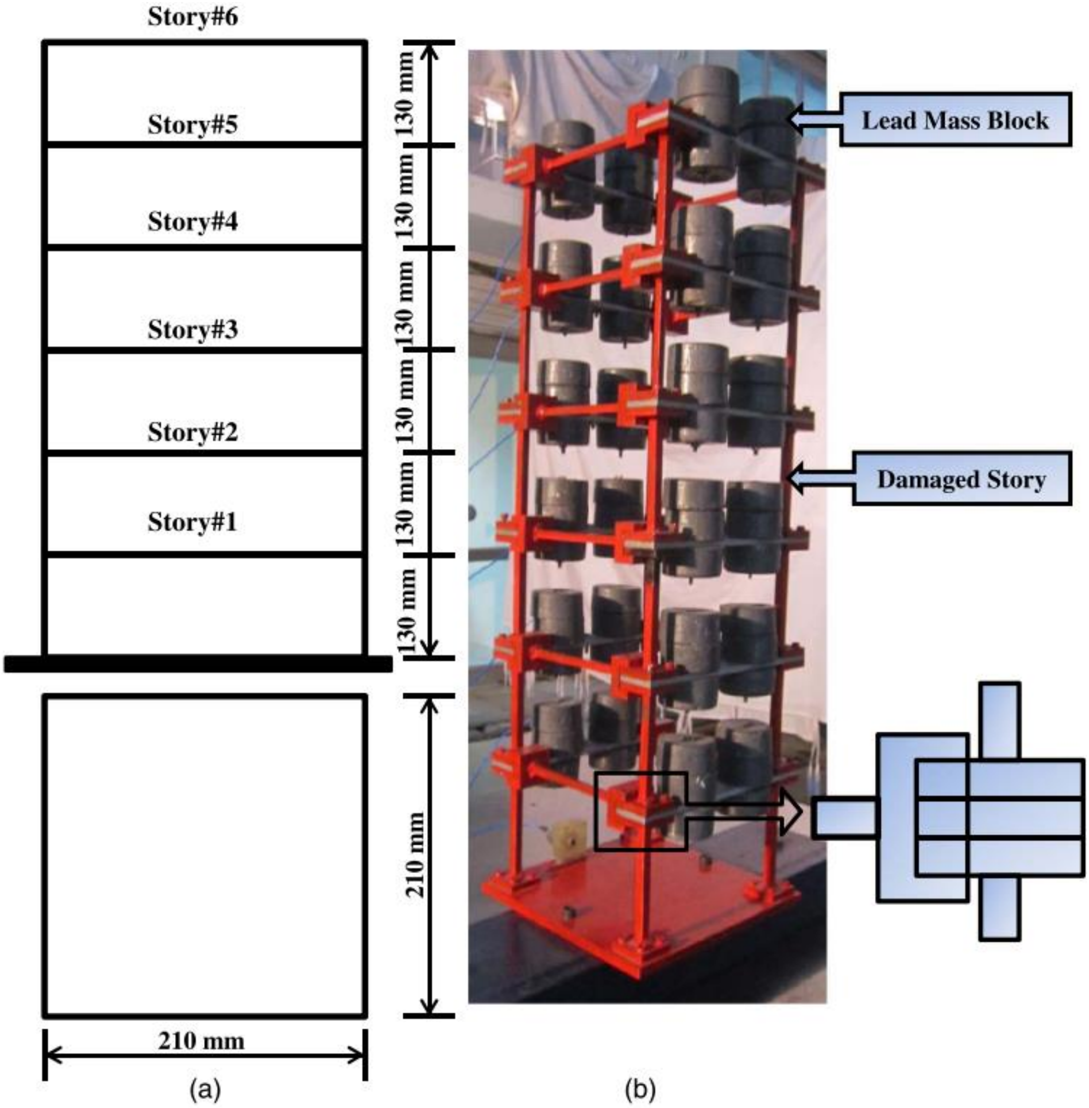


Fig. 2.8: Experimental model used by Roy [20] (a) schematic elevation and plan view and (b) prototype

The structure was rigidly connected to a uniaxial shake table through a bolted base plate, and accelerometers were installed at each floor to record the dynamic response in the direction of excitation. Controlled dynamic loading was applied through the shake table to excite the structural modes, and damage scenarios were introduced by modifying the stiffness of selected structural elements.

The experimental results demonstrated that both the mode-shape slope and mode-shape curvature methods were capable of identifying the presence and location of structural damage within the frame. In particular, the DMSC method exhibited higher sensitivity to localized stiffness reductions compared to the DMSS method, especially for damage occurring at intermediate storeys. The study concluded that higher-order mode shape derivatives provide improved damage localization capability in framed structures under dynamic excitation, while also highlighting the influence of measurement resolution and noise on the accuracy of the damage indicators.

Bogahawaththa et al. [35] conducted an experimental investigation using the same shake table facility employed in the present study to evaluate modal-based damage detection techniques. The experimental specimen consisted of a six-storey framed structure, as illustrated in Fig. 2.9. Steel threaded bars were used as columns, while plywood plates served as slab panels at each storey level. The base plate, with dimensions of 195 mm × 195 mm, was welded to four steel columns and rigidly bolted to the shake table using four nuts. The floor-to-floor height was maintained at 160 mm, and the column diameter was 6.6 mm.

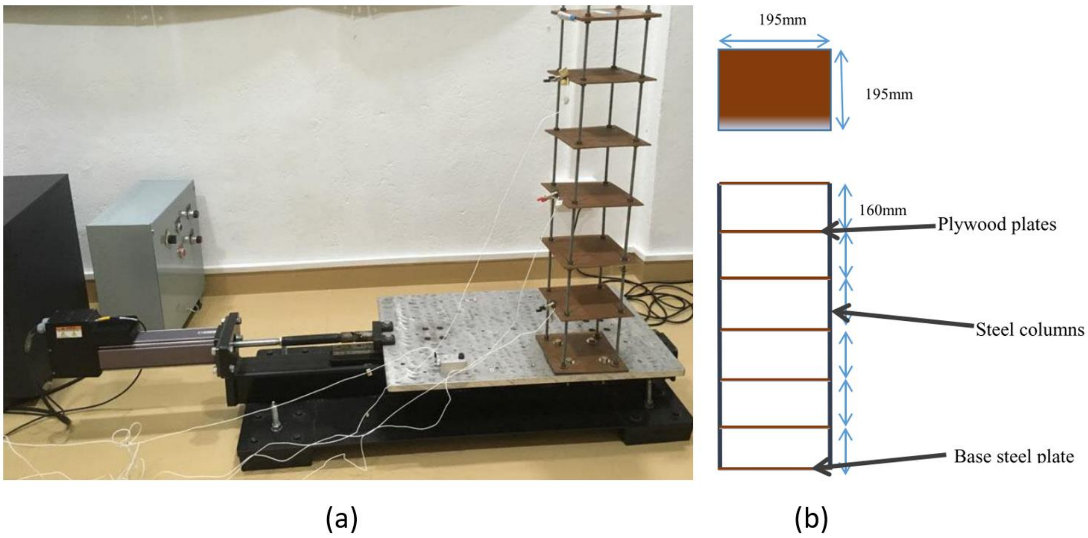


Fig. 2.9: (a) Shake table test setup and (b) dimension of the tested structure [35]

Structural damage was introduced by removing the plywood slab panel at the third storey level, thereby simulating a localized stiffness and mass reduction. Damage detection and localization were carried out using the DMSS and DMSC methods. The results demonstrated that both methods were capable of successfully detecting and localizing the introduced damage for this single damage scenario.

However, the study was limited to a symmetric structural configuration with a symmetric damage case. As a result, the applicability of the proposed methods to irregular structures, non-symmetric damage patterns, and boundary-sensitive damage scenarios was not investigated. Furthermore, the study focused solely on damage detection and localization, without addressing damage severity estimation or the identification of multiple damage scenarios in framed structures, which restricts its applicability to practical structural health monitoring problems.

De Silva et al. [36] performed an experimental study using the same shake table and steel framed structure configuration adopted in the present research, as shown in Fig. 2.10. The seven-storey steel frame model consisted of steel beams and circular steel columns with monolithically connected beams at each floor level. Rigid beam–column connections were ensured using four 6 mm bolts, nuts, and spring washers at each joint, while the steel base plate was rigidly fixed to the shake table deck. These design measures minimized unintended damage accumulation and reduced potential nonlinear effects during testing.

The modular nature of the experimental model allowed the columns and beams to be dismantled and replaced, enabling variations in column diameter and the number of storeys (from one to seven) while maintaining rigid connections. In the undamaged configuration, circular steel columns with a diameter of 16 mm were used. To simulate damage, three sets of reduced-diameter columns (12 mm, 10 mm, and 6 mm) were fabricated and installed at selected storey levels.

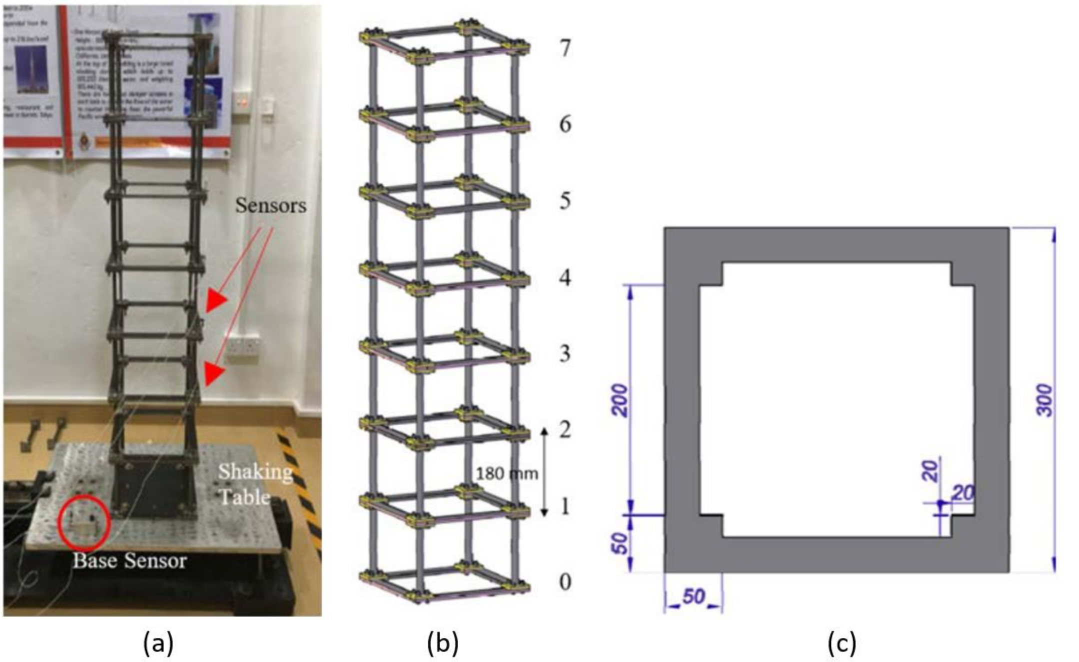


Fig. 2.10: (a) Steel framed structure mounted on the shake table with sensor arrangement, (b) schematic diagram of the structure, and (c) dimensions of the steel beam arrangement [36]

Damage detection and localization were investigated using the DMSS and DMSC methods through a parametric study in which the damage location was varied across different storeys, extending the scope beyond the single-damage case considered by Bogahawaththa et al. [35]. The results showed that both methods were generally effective in localizing damage; however, reduced accuracy was observed when damage was located near the fixed base or free end of the structure. Similar to earlier studies, the investigation did not successfully address multiple damage scenarios or damage severity estimation, limiting its usefulness for comprehensive structural health monitoring applications.

From the reviewed shake table studies by Zhu et al. [21], Roy [20], Bogahawaththa et al. [35], and De Silva et al. [36], it is evident that modal-based damage detection techniques—particularly those relying on mode-shape derivatives such as DMSS and

DMSC—are effective for identifying and localizing structural damage under controlled experimental conditions. These studies collectively demonstrate the capability of shake table testing as a reliable non-destructive approach for validating damage detection methodologies in framed structures.

However, several critical research gaps remain. Most existing studies focus primarily on single damage scenarios and symmetric structural configurations, with limited consideration of irregular structures, non-symmetric damage patterns, or boundary-sensitive damage locations, where modal-based indicators tend to lose accuracy. Moreover, while damage detection and localization have been extensively explored, quantitative damage severity estimation has received significantly less attention, despite its importance for decision-making in SHM. Additionally, the performance of modal-based methods under multiple damage scenarios has not been adequately investigated. These limitations highlight the need for enhanced damage detection frameworks capable of reliably localizing and quantifying damage severity in complex framed structures, motivating the present study's focus on improved modal-based indicators and severity estimation techniques validated through both experimental and numerical investigations.

2.3.2 Finite Element (FE) Modelling

Finite Element (FE) modelling plays a critical role in Structural Health Monitoring (SHM) by simulating structural behavior under various conditions [19]. Many researchers have adapted FEM to test damage detection techniques and conduct parametric studies during the past years. Those previous approaches for model-based damage detection are reviewed in this section.

Ren & Roeck [4] developed a two-dimensional FE model to verify a modal-based damage detection technique using a simply supported beam and a continuous beam. Their study incorporated the Moore–Penrose pseudoinverse method and the non-negative least-squares (NNLS) method, initially introduced by Lawson & Hanson [37]. Additionally, a regularization algorithm based on the singular value decomposition (SVD) of the system matrix, as proposed by the authors, was briefly presented.

The effectiveness of the proposed method was validated through multiple simulated damage scenarios. The simply supported beam was discretized into fifteen equal beam elements, while the continuous beam model consisted of two simply supported beams. Various damage scenarios were introduced by reducing the stiffness of selected beam elements. The FE modelling and simulations were conducted using the ANSYS FEM package, while numerical results were processed using MATLAB routines. Modal frequencies and mode shapes for both undamaged and damaged models were extracted from ANSYS simulations. An advantage of this approach is that modal nodal forces can be directly extracted from any FEM package, enhancing its applicability. The authors suggested that this damage identification technique could be extended to other structural types, broadening its potential for SHM applications.

A similar kind of a study was conducted by Vestroni & Capecchi [38], to identify the damage location and the damage severity of a beam element. Modal-frequencies were obtained by using a FE model, prepared using a computer code called IDEFEM.

Dawari & Vesmawala [39] conducted a comprehensive study on crack damage detection in reinforced concrete (RC) beams using the Modal-Flexibility Method and the Modal-Curvature Method. To analyze the effectiveness of these methods, a three-dimensional (3D) FE model of an intact RC beam was developed in ANSYS as shown in Fig. 2.11. To evaluate the applicability of the proposed algorithms, eigenvalue analyses were performed on FE models of the RC beam. The corresponding eigenvectors were extracted for different damage cases. Crack damage was simulated using the discontinuing element model method. The study demonstrated that these methods effectively detected the presence of damage and accurately localized single and multiple damage scenarios in beams.

Simulated damage scenarios were investigated at two specific locations along the beam span: L/4 and L/2, where L represents the total beam length. For each damage case, modal analysis was conducted, yielding three natural frequencies and corresponding flexural mode shapes for the damaged beam. Changes in modal flexibility and differences in modal curvature between the damaged and intact states were computed using a MATLAB code developed specifically for this study. The input modal data for the MATLAB analysis was obtained from FE simulations. Both the curvature difference and modal flexibility change methods proved effective in identifying and localizing structural damage for beams.

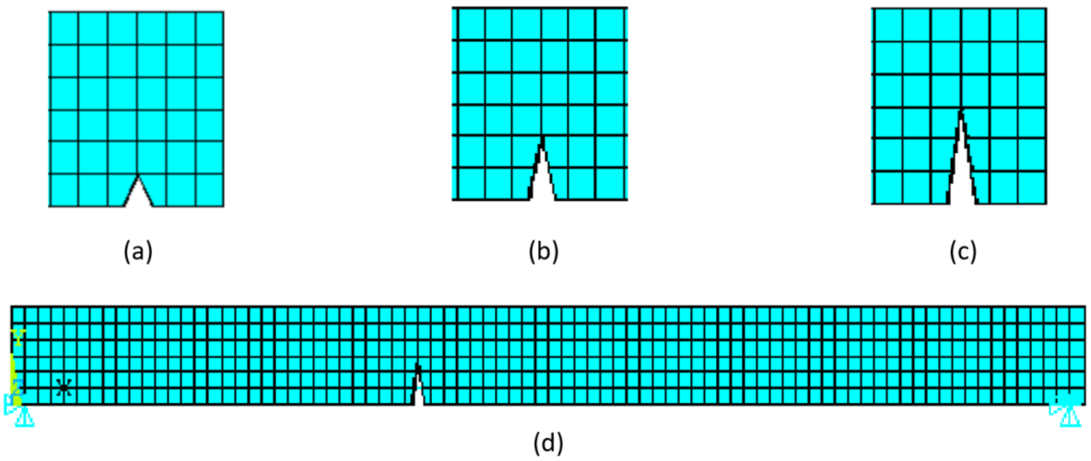


Fig. 2.11: (a) Light damage, (b) medium damage, (c) severe damage, and (d) the front elevation of a typical cracked beam [39]

Li and Yang [40] proposed an enhanced damage localization method known as the Modal Strain Energy Decomposition Method. This approach was developed to improve the identification of structural damage in 3D frame structures. To validate the method, a FE model of a simple 3D five-story frame structure was developed and analysed. The proposed method introduces two distinct damage indicators—an axial damage indicator and a transverse damage indicator—designed to assess individual members of the frame structure. In the study, damage scenarios were simulated by reducing the Elastic modulus of selected columns and beams to evaluate the effectiveness of the method. While this approach demonstrated high accuracy in locating damage within 3D frame structures, its effectiveness in estimating the severity of damage was limited. The authors suggested the development of an efficient algorithm to improve damage severity estimation.

2.3.3 ABAQUS for Damage Detection

The use of the ABAQUS FEM package for vibration-based structural damage detection has been prevalent for several decades. Ray et al. [41] conducted a study to assess the effectiveness of ABAQUS in detecting structural damage by analyzing a cantilevered steel plate structure. The research involved both an experimental study and a validation study using a FE model.

Three types of stiffness damage scenarios were considered in the study: slots, seams, and surface cracks. To excite higher-order vibration modes, a disturbance impact force was applied at the center of the cantilevered plate's free end in the transverse direction. The corresponding dynamic response, including nodal displacement and velocity, was recorded at six sensor points on the model. The study demonstrated that ABAQUS simulations provide an effective means to model and analyze complex damage scenarios that are difficult to evaluate through experimental methods. Furthermore, the results confirmed that ABAQUS FEM offers a powerful approach for examining the dynamic behavior of damaged structures, making it a valuable tool in vibration-based damage detection research.

Following the work of Ray et al. [41], Fan and Qiao [11] further investigated vibration-based structural damage detection using the ABAQUS finite element package through a detailed numerical study on beam structures. In their research, eigenvalue analysis was performed to extract natural frequencies and mode shapes for both intact and damaged beam models. Structural damage was simulated by introducing localized reductions in the elastic modulus at predefined locations along the beam, thereby representing stiffness degradation.

The beam was discretized using three-node quadratic beam elements, which enabled accurate capture of bending behavior and higher-order vibration modes. Mode shape data were extracted at multiple nodal locations along the beam length to facilitate the computation of mode-shape-based damage indicators. A comprehensive parametric study was conducted by varying damage locations and damage severities to examine the sensitivity of modal parameters to different damage scenarios.

The numerical results revealed that damage-induced stiffness reductions produced localized anomalies in the mode shapes and their spatial derivatives, allowing accurate identification of damage locations. The study demonstrated that mode-shape-based indicators exhibited greater sensitivity to damage localization than changes in natural frequencies, particularly for small and moderate damage levels.

Based on these findings, Fan and Qiao [11] concluded that ABAQUS-based finite element modelling is a reliable and effective tool for validating modal-based damage detection techniques under controlled numerical conditions. Their work highlighted the potential of mode-shape derivatives for damage localization in beam-type structures and emphasized the importance of careful mode selection when applying vibration-based damage detection methods.

Another modal-based numerical investigation was carried out by Mia et al. [25] on a cracked cantilever beam using the ABAQUS finite element package. Unlike stiffness-reduction-based damage modelling, the study represented damage explicitly by introducing an open-edge V-shaped crack perpendicular to the beam axis. The beam was analysed under free undamped vibration to evaluate the influence of crack location and crack depth on its natural frequencies through eigenvalue analysis. Due to the complexity introduced by the crack, local meshing with wedge elements was specifically applied in the crack region. The cracked cantilevered beam is shown in the following Fig. 2.12.

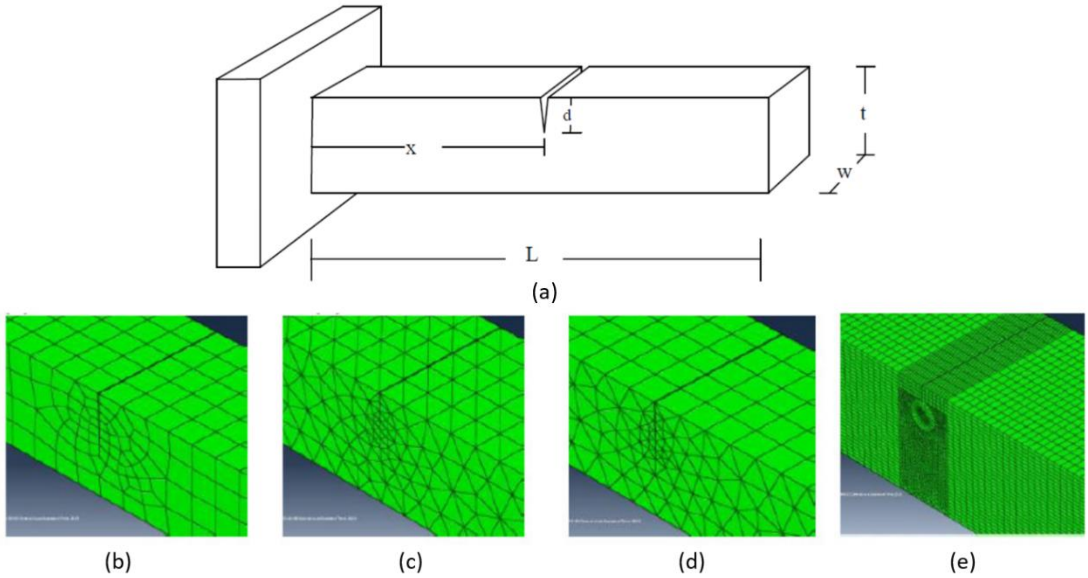


Fig. 2.12: (a) Cracked cantilever beam, (b) close-up at crack location with all hexahedral elements, (c) close-up at crack location with all tetrahedral elements, (d) close-up at crack location with all wedge elements, and (e) close-up at crack location with local meshing [25]

A key contribution of this study was the examination of different meshing strategies near the crack region. The authors demonstrated that local mesh refinement is essential for accurately capturing the dynamic response of cracked structures. In particular, the combined use of hexahedral and wedge elements in the crack vicinity produced the most accurate reduction in natural frequencies, showing close agreement with theoretical expectations for discontinuous structures. In contrast, uniform meshing without localized refinement resulted in reduced accuracy.

The numerical results confirmed that natural frequencies decrease with increasing crack depth and that the sensitivity of frequency changes diminishes as the crack moves away from the fixed end of the beam. The study also showed that crack opening size has a relatively minor influence on modal frequencies compared to crack depth and location, especially for small openings. Overall, Mia et al. [25] concluded that ABAQUS is well suited for simulating cracked beam structures, provided that appropriate local meshing techniques are employed. Their findings emphasize that accurate modal-based damage detection using finite element models strongly depends on mesh refinement strategies, particularly when representing localized damage such as cracks.

Vafaie and Salajegheh [42] conducted a vibration-based damage identification study on steel plate structures using finite element modal analysis. In their work, ABAQUS was employed to generate mode shapes of a fully fixed rectangular plate, with damage simulated through a reduction in elastic modulus. The resulting mode shape contours of both intact and damaged states were treated as image data for further analysis. The visual outputs for the damaged and undamaged models are shown in the following Fig. 2.13.

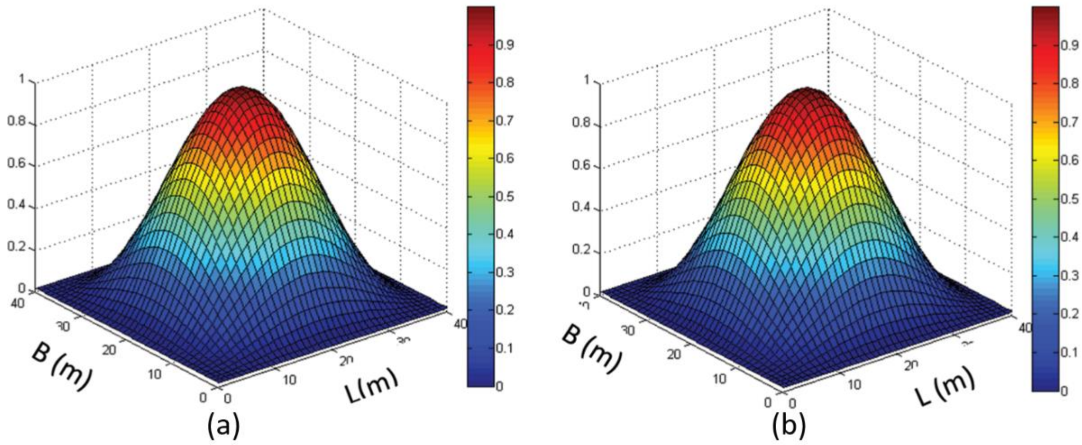


Fig. 2.13: Fundamental mode shape of the plate: (a) without damage and (b) with damage [42]

The study primarily focused on comparing the effectiveness of wavelet transform (WT) and contourlet transform (CT) techniques for damage localization. The numerical results showed that two-dimensional wavelet transforms are effective in detecting localized discontinuities, particularly point-type damage. However, WT was found to be limited in representing smooth, curved crack geometries due to the isotropic nature of its basis functions. In contrast, the contourlet transform, which employs elongated and directionally sensitive basis elements, demonstrated superior performance in identifying curved damage patterns. The authors concluded that CT provides a more robust and accurate representation of crack geometry in plate structures compared to WT, particularly for damage with smooth contours. Overall, this study highlights the potential of combining modal analysis with advanced image-processing techniques for damage localization in plate-like structures, while emphasizing the limitations of conventional wavelet-based approaches in capturing complex crack geometries.

C. Zhang et al. [43] investigated a novel vibration-based damage detection method using a general vibration model identification (GVMI) approach. Their study focused on an aluminum lightweight honeycomb sandwich cantilever beam, a material widely used in civil, aeronautical, and aerospace industries due to its high strength-to-weight ratio, enhanced bending stiffness, and good damage tolerance. A FE model was developed using 3D solid elements in the ABAQUS software to simulate structural behavior. The authors highlighted the effectiveness of their proposed method in detecting damage within complex structural systems while also demonstrating the capability of ABAQUS for modelling such materials.

The reviewed ABAQUS-based studies demonstrate the strong capability of finite element modal analysis for simulating structural damage and evaluating vibration-based damage detection techniques. Previous research has successfully modelled various damage types, including stiffness reduction, cracks, slots, seams, and curved defects, and has shown that modal parameters such as natural frequencies and mode shapes are sensitive to damage location and severity. Several studies further highlighted the importance of appropriate meshing strategies and advanced post-processing techniques to improve damage localization accuracy, particularly for complex geometries and materials.

However, most existing numerical investigations are largely confined to simple structural components such as beams and plates, with limited extension to framed structural systems that better represent real civil engineering applications. In addition, damage modelling is often restricted to single damage scenarios, while multiple damage cases and joint-level damage—which are common in real structures—remain insufficiently explored. Although some studies addressed damage localization effectively, systematic damage severity estimation using modal-based indicators has received comparatively less attention, particularly for framed structures. Furthermore, the combined influence of boundary conditions, structural irregularities, and damage location on the reliability of modal-based damage detection methods has not been comprehensively investigated.

These limitations highlight the need for a more holistic numerical framework that extends modal-based damage detection, localization, and severity estimation techniques to framed structures under various damage scenarios, while accounting for boundary effects and structural irregularities. The present research is therefore motivated to address these gaps by conducting an extensive parametric study using validated ABAQUS finite element models, with particular emphasis on framed structural systems.

2.4 Limitations and Research Gap

Over the past decades, numerous approaches have been proposed to enhance the detection and localization of structural damages in beams, plates, and frame structures. For example, Bajaba & Alnefaie [44] introduced a technique that couples modal analysis with wavelet transforms for identifying single and multiple damages in cantilevered beams. Similarly, Shih et al. [45] employed modal flexibility and modal strain energy methods, based on vibration characteristics, for damage assessment in beams and plates using dynamic computer simulations. Ručevskis et al. [46] also focused on multiple damage detection in aluminum beams containing mill-cut damages to validate their proposed modal-based technique. Extending this concept to plates, Xiang & Liang [47] applied a 2-D wavelet transform to mode shapes of simply supported plates and demonstrated its effectiveness in multiple damage detection even under imprecise frequency measurements. More recently, Altunışık et al. [48] localized multiple cracks in steel cantilever beams using modal curvature and flexibility methods, confirming the applicability of modal derivatives in complex damage scenarios.

Beyond purely modal-based techniques, alternative strategies have emerged. (S. Li et al. [49] proposed a Fully Convolutional Network (FCN) to detect diverse types of concrete damages, while Sha et al. [50] introduced Relative Natural Frequency Change (RNFC) curves for local damage characterization in beam-type structures. The Mode Shape Damage Index (MSDI) method was further validated by Duvnjak et al. [51] for plate-like structures, showing capability to detect, localize, and even estimate severity of single or multiple damages. Advancements in image-based diagnostics have also been explored: Rinaldi et al. [52] applied Hybrid Lagrangian Particle Tracking (HLPT) and Digital Image Correlation (DIC) techniques to a small-scale steel frame, detecting damages induced by removing bracing elements. Similarly, Angeletti et al. [53] applied data-driven Long Short-Term Memory (LSTM) networks for detecting debris-induced damages in solar panel arrays using finite element simulations.

Despite these advancements, traditional mode shape derivative methods remain fundamental. Pandey et al. [24] validated the DMSC method for a single damage scenario in a simple beam structure through numerical and finite element studies. Zhu et al. [21] validated the DMSS method for single damage in a steel frame, integrating numerical, FEM, and experimental results. Similarly, Roy [20] assessed both DMSS and DMSC for single damage scenarios in framed structures. However, while these studies confirmed the reliability of DMSS and DMSC in single damage cases, they explicitly suggested—but did not investigate—their effectiveness in multiple damage detection and localization, particularly in complex framed structures.

Therefore, to address this critical gap, the present study investigates the application of DMSS and DMSC methods for multiple damage detection, localization, and severity estimation. The research integrates both experimental shake table tests on a scaled steel frame and computational modelling using FE methods, thereby advancing the applicability of modal-based techniques for real-world structural health monitoring of framed systems.

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Introduction

Experimental investigations were conducted at the Structural Dynamics and Health Monitoring Laboratory of the Department of Civil Engineering, University of Moratuwa, to evaluate the vibrational response of a scaled-down steel frame structure. The objective of the study was to analyze the effects of resonance frequency changes on modal parameters under controlled excitation. The test specimen was mounted on the laboratory shake table, which was used to apply dynamic loading representative of structural vibrations. The resulting response was measured and analysed to provide experimental validation for the modal-based damage detection techniques employed in this research.

3.2 Steel Framed Structure

The experimental specimen, illustrated in Fig. 3.1, is a modular steel frame structure designed to replicate the behavior of multi-storey buildings. The model consists of steel columns (rods) and beams (plates) and can be configured up to seven storeys. Each storey level incorporates monolithically connected beams with a width of 300 mm and a depth of 6.35 mm, fabricated from steel plates. The geometric scale of the model is 1:20. Beam-to-column connections were made rigid using four 6 mm bolts and nuts at each joint, while the entire frame was secured to the shake table deck through a rigid steel base plate. The storey height was maintained at 180 mm. In its undamaged state, the structure used circular steel columns with a diameter of 16 mm.

To simulate damage, three sets of reduced-diameter columns (12 mm, 10 mm, and 6 mm) were fabricated, corresponding to stiffness reductions of approximately 68%, 85%, and 98%, respectively. These reduced-diameter columns could be installed at any storey level, allowing flexibility in simulating different damage scenarios. Furthermore, each beam was slotted to accommodate 1 kg steel blocks as external masses, which could be rigidly attached to introduce irregularities in the structural configuration.

The steel framed structure adopted in this study was intentionally selected to provide a controlled, repeatable, and well-defined experimental platform for investigating modal-based structural damage detection techniques. Steel offers material homogeneity, predictable linear elastic behavior, and stable dynamic properties, which are essential for isolating the influence of stiffness degradation on modal parameters such as mode shapes, slopes, and curvatures. Since the primary objective of this research is methodological evaluation rather than replication of a specific full-scale building system, the steel frame serves as a representative model of multi-storey framed structures under dynamic loading. While the model does not capture material nonlinearities associated with reinforced concrete or composite systems, the fundamental mass–stiffness–boundary relationships governing structural vibration remain valid. Consequently, the results are most applicable to framed structures exhibiting predominantly linear dynamic behavior, and the use of a steel substructure ensures reliable interpretation of damage detection and severity estimation outcomes while providing a sound basis for future extension to more complex structural systems. Moreover, steel substructures are widely employed in experimental structural health monitoring studies due to their ease of fabrication, modularity, and compatibility with shake table testing, allowing systematic introduction of controlled damage scenarios at predefined locations.

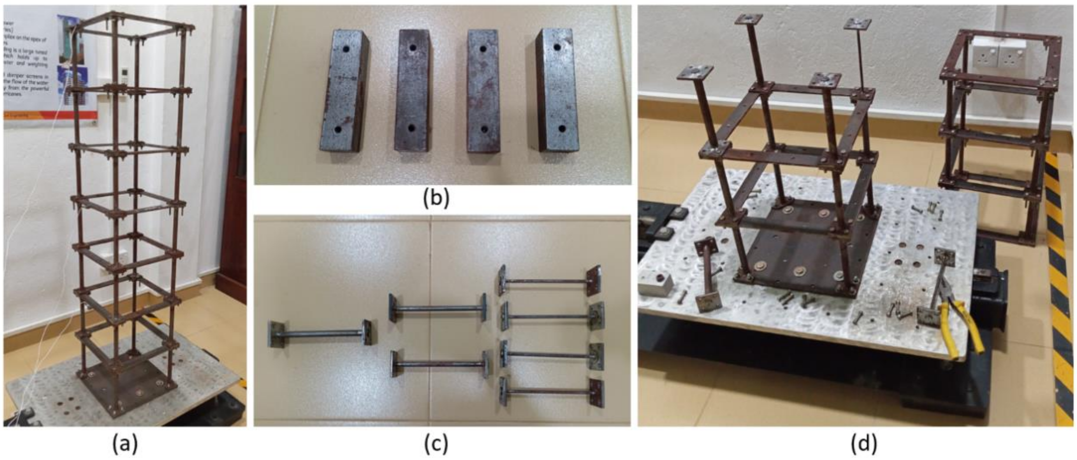


Fig. 3.1: (a) Steel framed structure, (b) additional weight blocks, (c) columns with 12mm, 8mm, and 6mm diameters, and (d) detached famed structure while assembling

3.3 Shake Table

Shake tables are widely used to simulate ground motions and to study the dynamic response of structures under controlled vibration excitations. By placing structural models on these tables, engineers can investigate vibration characteristics, resonance behavior, and earthquake-induced responses [54].

All experiments in this study were conducted using an ANCO R-200 family shake table available at the Structural Dynamic and Health Monitoring Laboratory. The R-200 series is designed for fundamental investigations in vibration, structural dynamics, and earthquake engineering [55]. The available system is a single-degree-of-freedom (1-DOF) horizontal shake table, equipped with a 50 cm × 75 cm deck with a tapped-hole grid. It provides a peak acceleration of up to 1.5 g, a maximum load capacity of 80 kg, and an operating frequency range from 0 Hz to 20 Hz. The table allows a maximum displacement of ±12 cm and a peak velocity of 50 cm/s. With a maximum force capacity of 1.2 kN, it can also be configured as a large-structure vibrator and even simulate passenger ride experiences through an attached chair [56]. For the present study, the steel frame specimen was securely mounted on the deck using screws as shown in Fig. 3.2.

The R-200 shake table can be operated with two digital controllers: FOX TROT, an open-loop controller without data acquisition capabilities, and DANCE, a PC-based closed-loop controller that uses feedback from a table accelerometer. The DANCE system offers enhanced fidelity by performing equalization using the accelerometer feedback, while also enabling the recording and display of time histories, Fast Fourier Transforms (FFT), and response spectra for up to 8 or 16 transducer channels [57].

Fig. 3.2: Shake table test setup and steel framed structure mounted on top of the shake table

For this study, the DANCE controller shown in Fig. 3.3 was selected due to its superior data acquisition and closed-loop control capabilities. The SINE Sweep Module was employed to identify resonance frequencies by gradually varying input frequency and amplitude over a defined range. This module generates sine waves or beat sequences in real time, automatically adjusting excitation based on acceleration feedback from the shake table or mounted specimen.

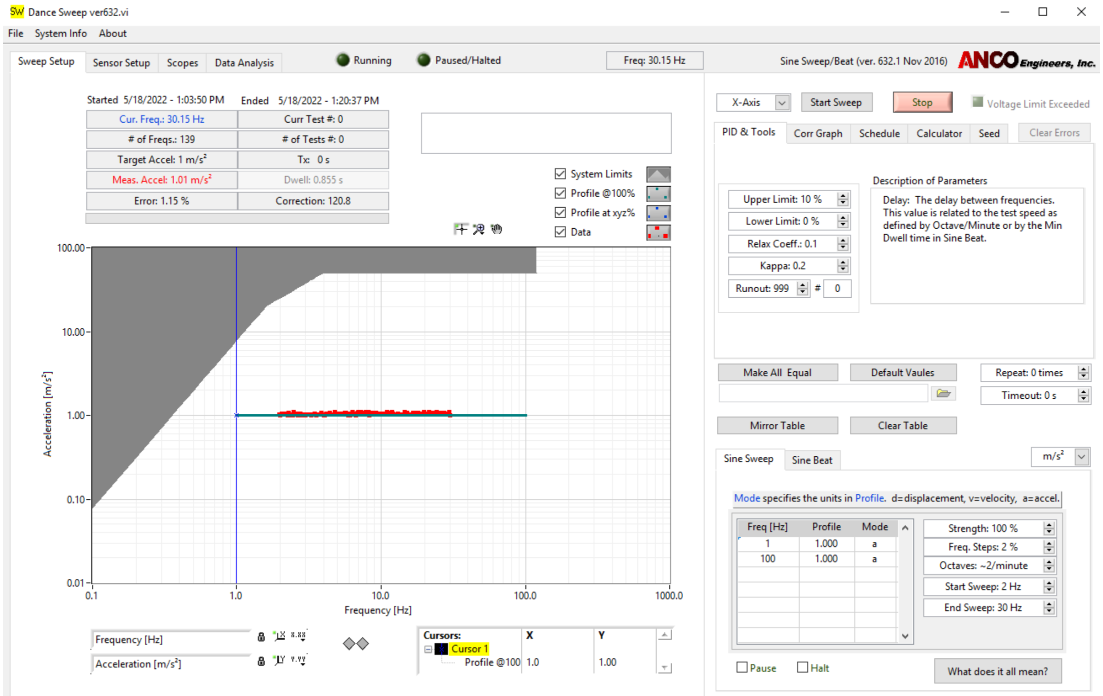


Fig. 3.3: DANCE controller SINE Sweep test interface

Instrumentation included four analog accelerometers with a sensitivity of 1 V/g and a sampling interval of 0.001 s. One accelerometer was fixed to the table deck, while the other three were attached to the steel frame structure along the shaking direction to capture its dynamic response as shown in Fig. 3.4. The recorded data were processed using the DANCE controller interface, enabling accurate observation of resonance frequencies and vibrational behavior of the test model.

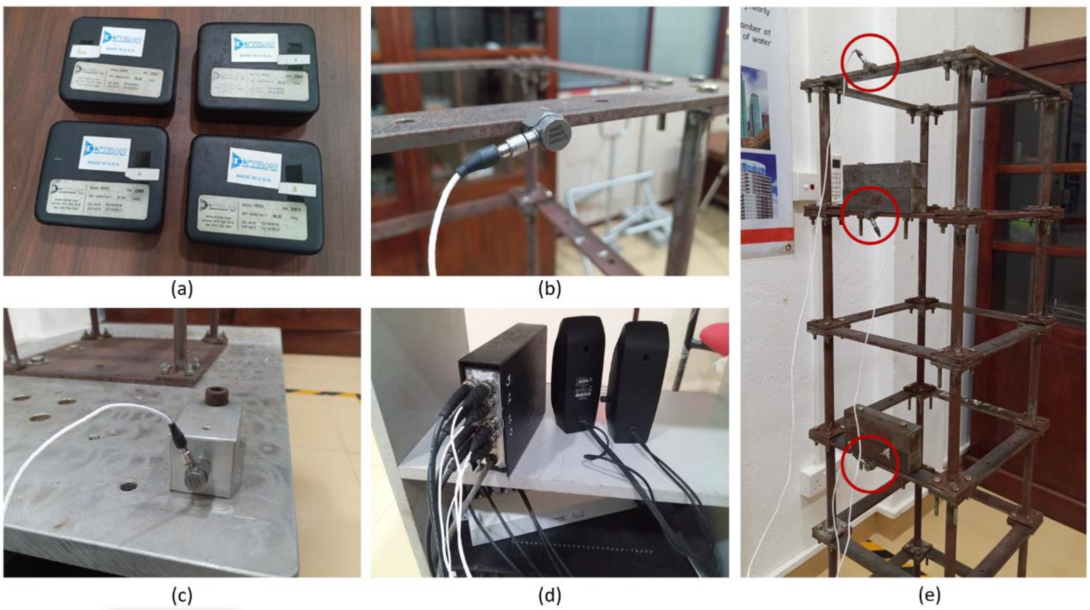


Fig. 3.4: (a) Four accelerometers, (b) attachment to the top of the structure, (c) attachment to the shake table deck, (d) connection device to the computer, and (e) attachment to the middle of the structure

3.4 Experiments and Results

Experimental investigations were carried out on the intact, damaged, and damaged–irregular configurations of the steel frame structure in order to determine the resonance frequencies under controlled dynamic excitation.

3.4.1 Intact Structure

The intact structure consisted of a 7-story steel frame structure with circular columns of 16 mm diameter, representing the undamaged condition of the specimen. The experimental test setup is shown in Fig. 3.5.

Fig. 3.5: Undamaged structure prepared for the experiment on top of the shake table

The frequency sweep test was performed using the DANCE digital controller and SINE Sweep Module. The excitation frequency was varied continuously from 0 Hz to 20 Hz, while acceleration responses were recorded using the mounted accelerometers. The Dance Sweep Software automatically generated acceleration–frequency plots (Fig. 3.6), from which the resonance frequency was identified as the peak response.

The results indicated that the intact steel frame exhibited a fundamental resonance frequency of 13.12 Hz. This value serves as the baseline reference for subsequent comparisons with damaged and irregular structural configurations.

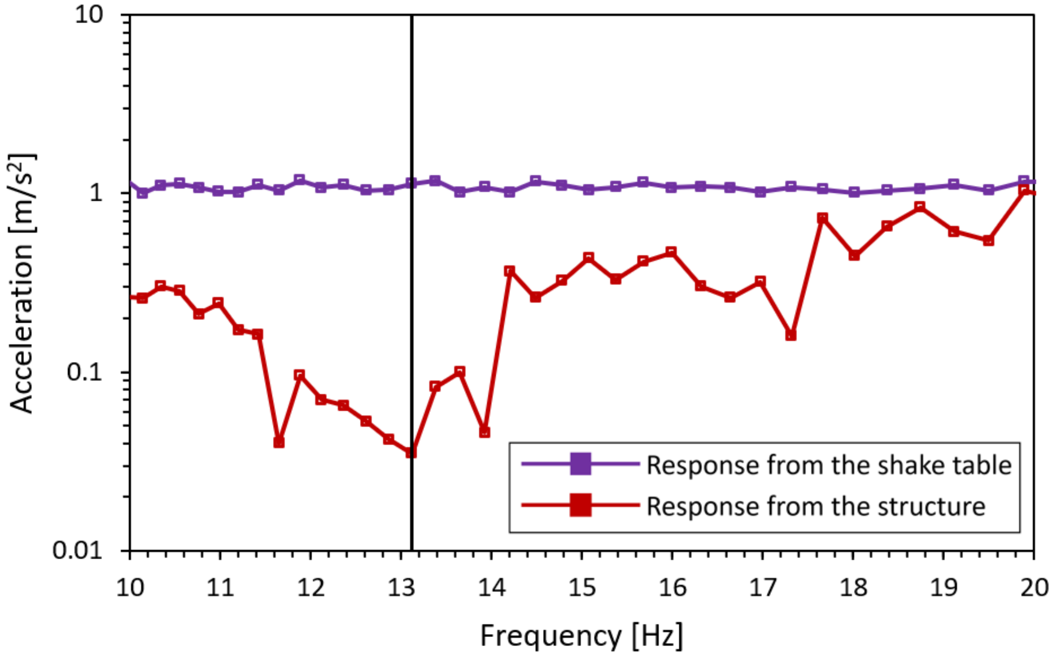


Fig. 3.6: Acceleration Vs. Frequency graph of the intact structure

3.4.2 Damaged Structure

To simulate structural damage, two 16 mm diameter columns between the 3rd and 4th stories were replaced with 6 mm diameter columns, as illustrated in Fig. 3.7. The reduction in column diameter effectively decreased the stiffness of the structure, thereby replicating a severe damage scenario.

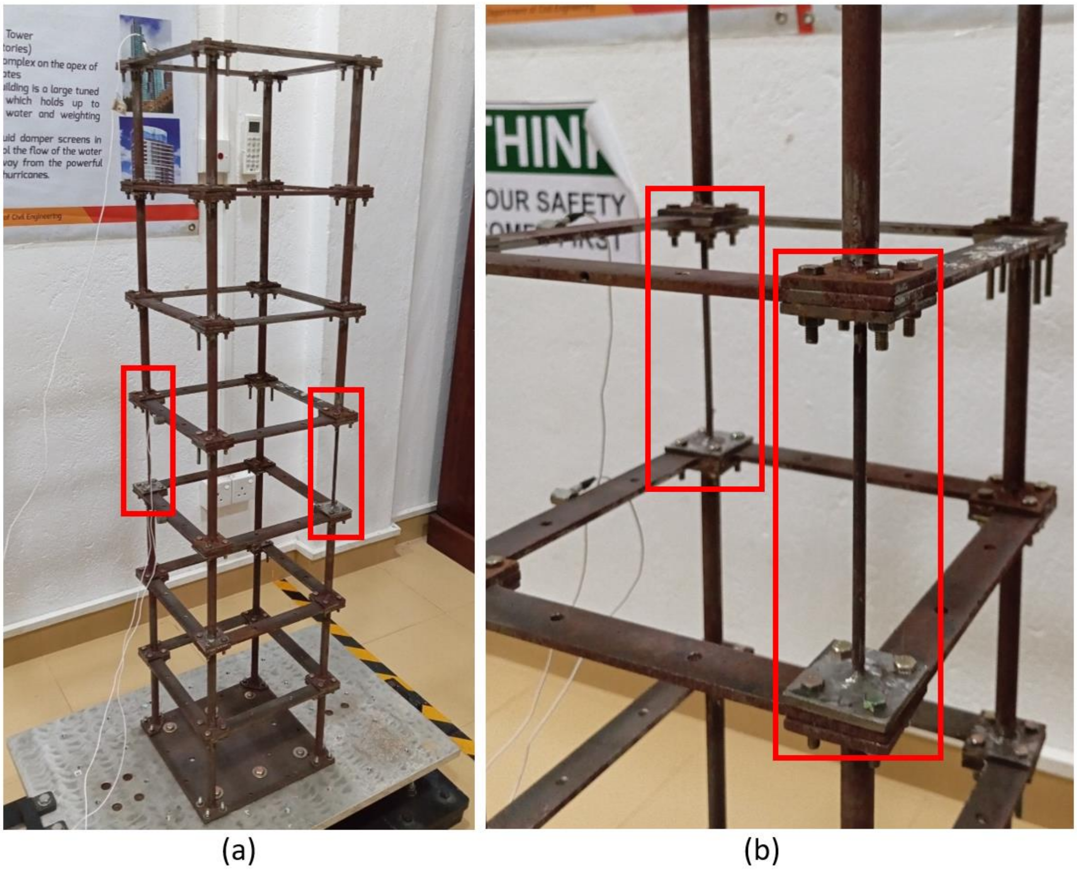


Fig. 3.7: (a) Damaged model prepared for the experiment on top of the shake table and (b) closeup view of the damaged section (damaged columns are highlighted in red color)

Similar to the intact case, a frequency sweep test was carried out over the 0–20 Hz range using the DANCE controller. The corresponding acceleration–frequency response is presented in Fig. 3.8.

From the results, the resonance frequency of the damaged structure was identified as 12.86 Hz, indicating a clear reduction compared to the intact structure (13.12 Hz). This frequency shift reflects the stiffness loss due to the introduced damage.

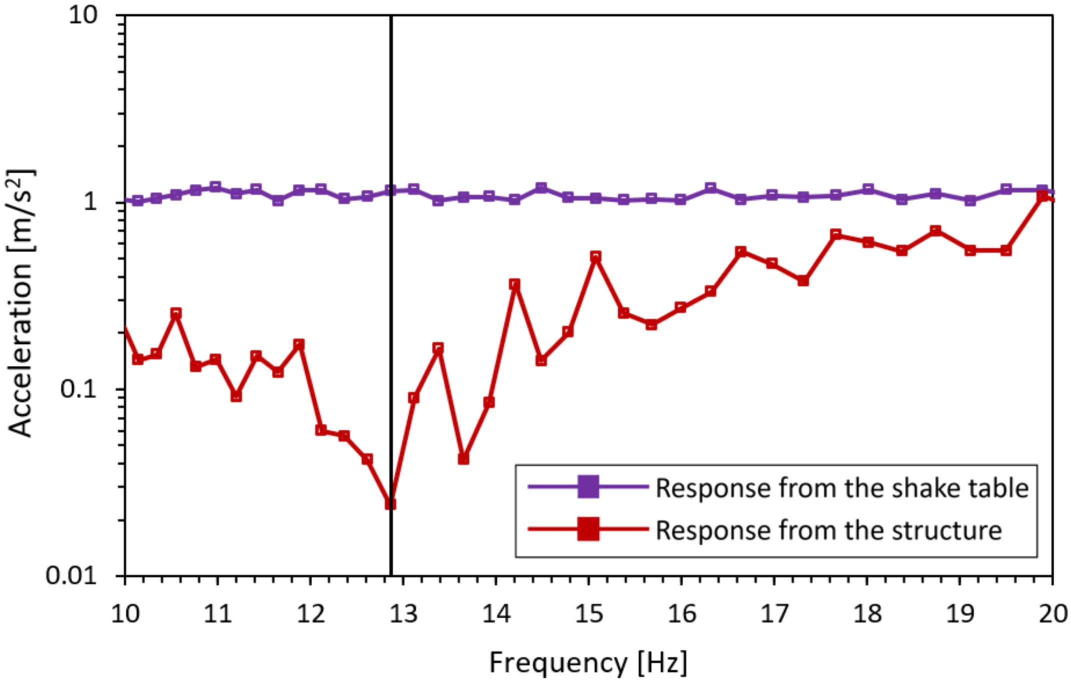
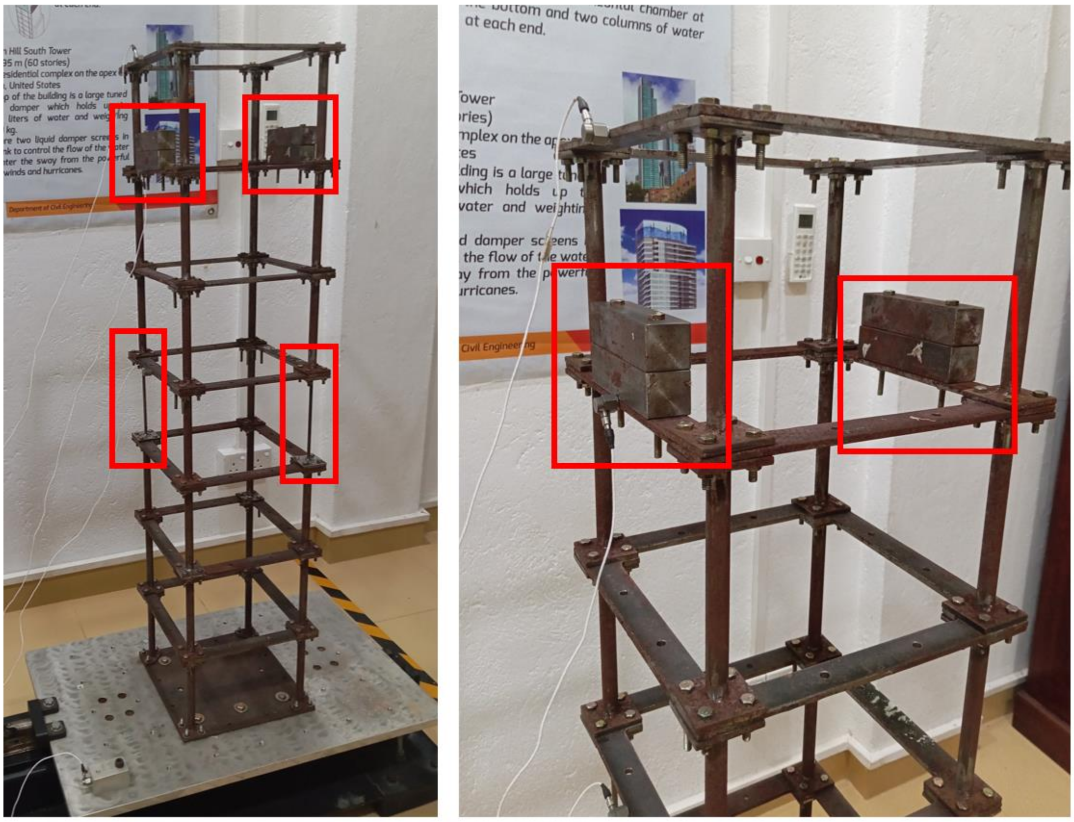


Fig. 3.8: Acceleration Vs. Frequency graph of the damaged structure

3.4.3 Damaged-Irregular Structure

To replicate structural irregularity, four 1 kg steel blocks were attached to the 6th story of the structure using nuts and bolts, as shown in Fig. 3.9. The damaged-irregular configuration was therefore created by combining the column damage (two 6 mm columns replacing 16 mm columns between the 3rd and 4th stories) with the added external masses.



(a) (b)

Fig. 3.9: (a) Damaged irregular model prepared for the experiment on top of the shake table and (b) closeup view of the external mass-added section (damaged columns and external masses are highlighted in red color)

The frequency sweep test was again performed over the 0–20 Hz range, and the corresponding acceleration–frequency response is illustrated in Fig. 3.10.

From the experimental results, the resonance frequency of the damaged-irregular structure was recorded as 11.62 Hz, showing a further reduction compared to both the intact structure (13.12 Hz) and the damaged structure (12.86 Hz). This trend confirms the cumulative effect of stiffness reduction and mass irregularity on the dynamic behavior of the frame.

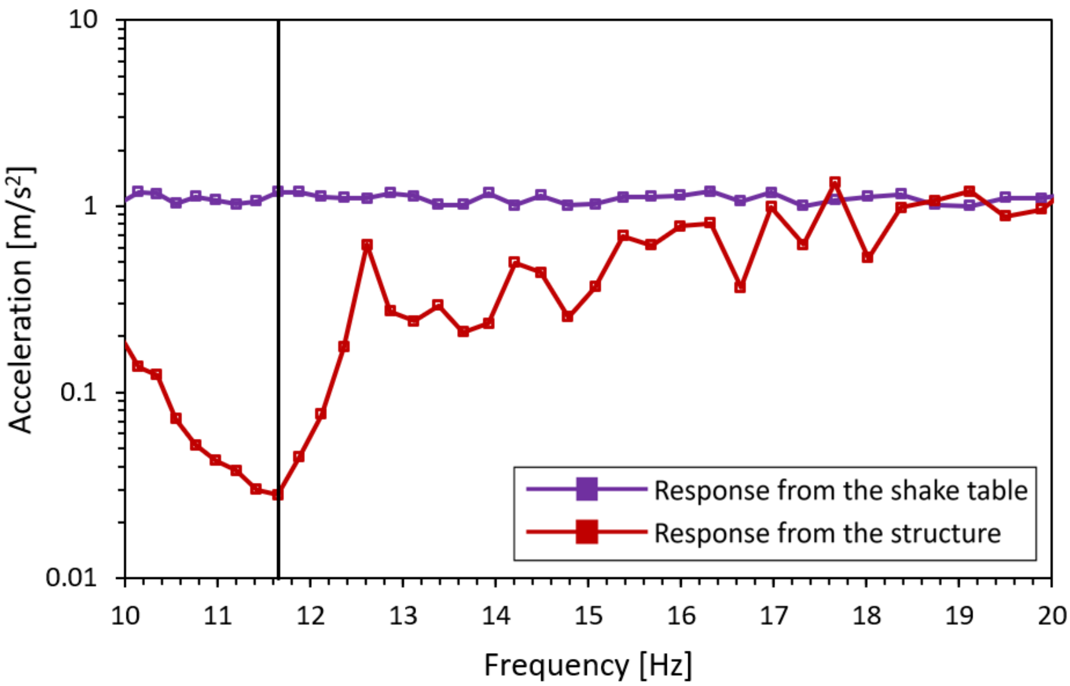


Fig. 3.10: Acceleration Vs. Frequency graph of the damaged-irregular structure

3.5 Chapter Summary

This chapter presented the experimental program conducted to investigate the dynamic response of a scaled-down steel framed structure under intact, damaged, and damaged–irregular conditions using the ANCO R-200 shake table at the Structural Dynamics and Health Monitoring Laboratory of the University of Moratuwa. The experiments aimed to examine the influence of stiffness reduction and mass irregularity on the modal parameters, particularly resonance frequency. Results showed a progressive decrease in the fundamental frequency from 13.12 Hz in the intact model to 12.86 Hz in the damaged model, and further to 11.62 Hz in the damaged–irregular configuration as shown in Fig. 3.11, confirming that both stiffness loss and mass variation significantly affect the dynamic behavior. These experimental findings provided essential validation data for the numerical modelling and parametric analyses presented in the following chapters, serving as a critical foundation for assessing the effectiveness of the proposed modal-based damage detection, localization, and estimation methods.

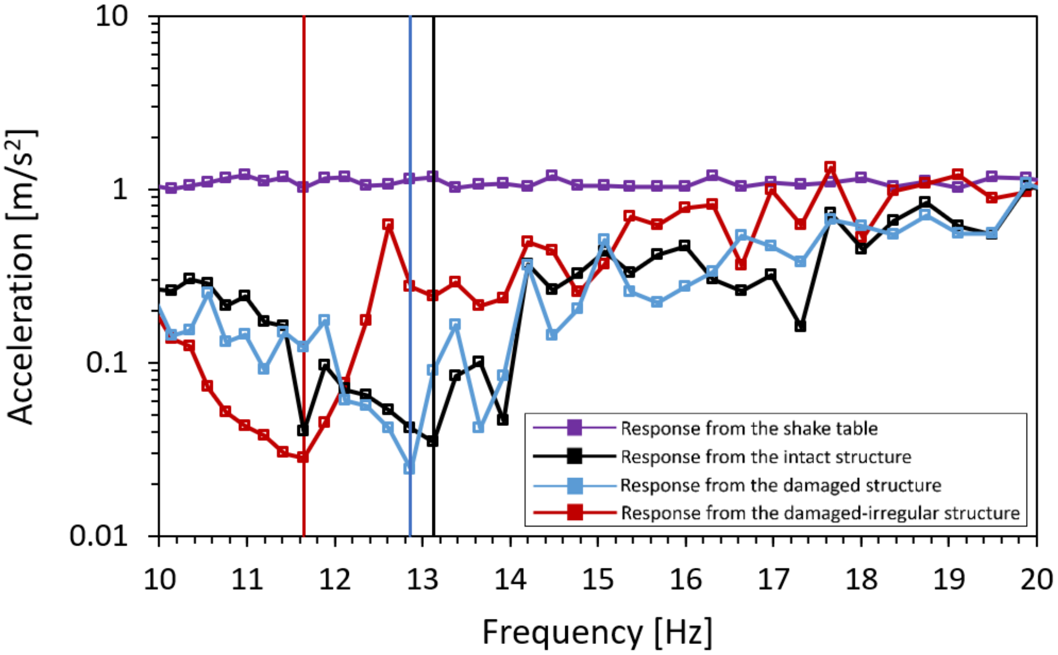


Fig. 3.11: Combined acceleration Vs. Frequency graph for intact, damaged, and damaged-irregular structures

CHAPTER 4

FINITE ELEMENT MODELLING

4.1 Introduction

Finite element (FE) modelling was performed using the commercial software package ABAQUS CAE 6.14-5. Models representing the intact, damaged, and damaged-irregular conditions were developed within the Standard/Explicit module. These models were designed to replicate the same structural elements and dimensions as those used in the scaled prototype tested during the laboratory experiment, ensuring consistency between the numerical and experimental analyses.

4.2 Elements Design and Mesh

All components, including the base plate, beam plates, columns, and bolts were individually modelled in the 'part' module using the exact dimensions as the prototype. The overall modelling process in ABAQUS follows a sequential order of modules, as illustrated in Fig. 4.1, progressing from initial modelling to simulation and post-processing. Individual parts including the base plate, beam plates, and columns are shown in Fig. 4.2.

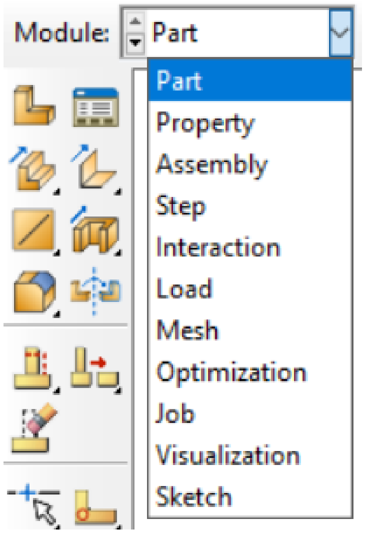


Fig. 4.1: Modelling sequential order of modules in ABAQUS

After preparing the elements, the same material properties as those of the prototype were defined as included in Table 1 and assigned in the 'Property' module. S355 steel was used for the base plate, columns, and beam plate, while high-strength materials were selected for the bolts.

TABLE 4.1: MATERIAL PROPERTIES OF THE FEM ELEMENTS

Element	Density (kg/m^3)	Elastic Modulus (MPa)	Poisson Ratio	F_y (MPa)	F_u (MPa)
Base Plate, Beam Plate, Columns	7,850	200,000	0.3	355	470
Bolts	7,850	200,000	0.3	640	800

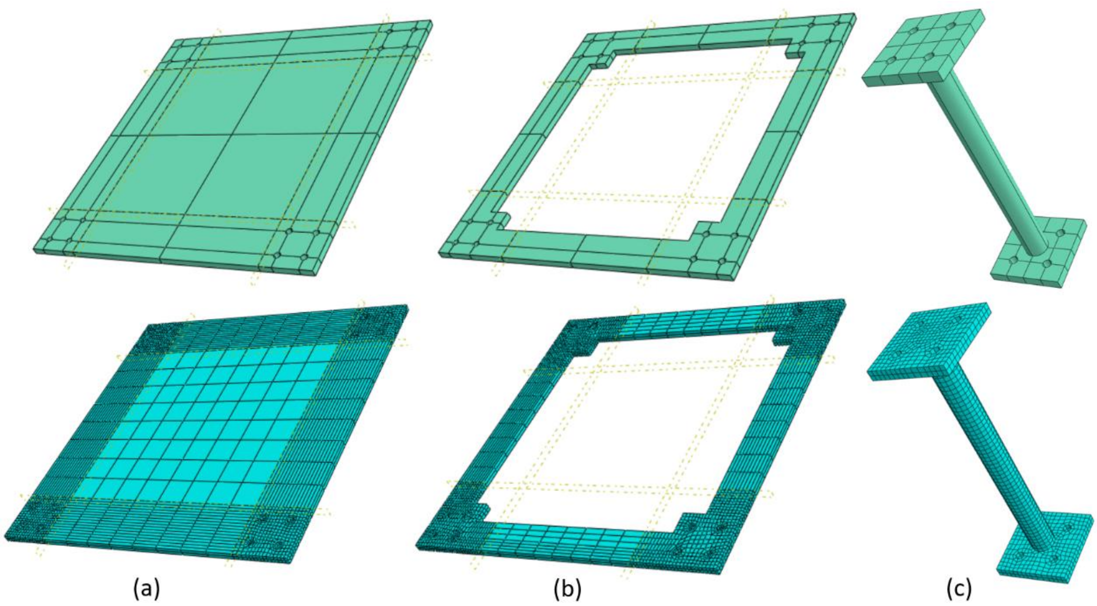


Fig. 4.2: (a) Base plate, (b) beam plate, and (c) column before and after meshing

Bolt design was carried out following the guidelines provided by Crolo et al. [58]. A dumbbell-shaped solid model was employed to represent both the shank and the nut of the high-strength bolts, ensuring realistic stiffness representation while maintaining numerical stability. In the finite element model, the bolt diameter was assumed to be identical to the corresponding bolt-hole diameter. This modelling choice was intentionally adopted to eliminate artificial clearances and potential numerical instabilities associated with contact opening and closing, which are not critical for modal analysis and could otherwise obscure the global dynamic characteristics of the structure. Since the primary objective of this study was to capture changes in modal parameters rather than local joint deformation or slip behavior, this assumption was considered appropriate and widely accepted in vibration-based damage detection studies.

Three distinct bolt configurations were modeled: a long bolt with a nut for intermediate connections, a short bolt with a nut for the top connection, and a short bolt without a nut for the bottom connection to the base plate, as shown in Fig. 4.3. All components were assembled in the 'Assembly' module, and a 'linear perturbation' procedure was employed in the ‘Step’ module to extract natural frequencies through modal analysis. Accordingly, the FE model assumes linear elastic material behavior, perfectly rigid bolt–plate contact without slippage, and uniform frictional behavior across all joints. These assumptions are consistent with the experimental setup, where bolts were tightly fastened to minimize slip, and with the scope of the study, which focuses on global modal response rather than nonlinear joint behavior.

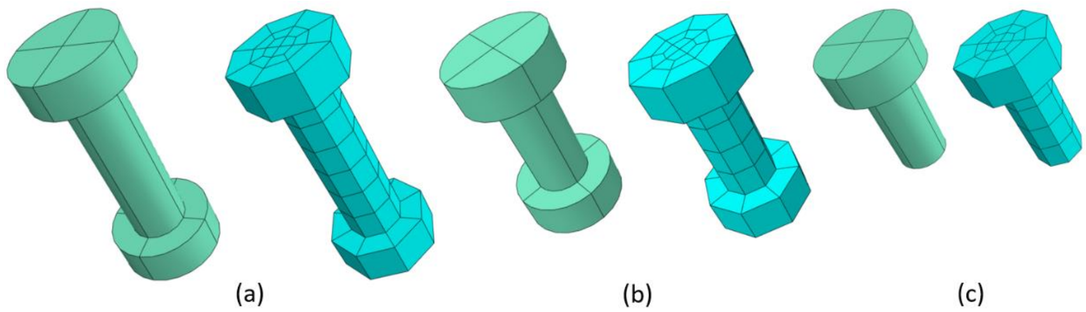


Fig. 4.3: (a) Long bolt with a nut, (b) Short bolt with a nut, and (c) Short bolt without a nut before and after meshing for intermediate, top, and bottom connections

Contact interactions were defined in the ‘Interaction’ module, with each beam–column joint comprising four bolts connecting columns on both sides of the central beam plate. A uniform friction coefficient of 0.3 was applied to all contact interfaces between columns, and beam plates shown in Fig. 4.4, based on experimental findings reported by Liu et al. [59] for steel–steel contact under similar surface and loading conditions. The use of a constant friction coefficient across all joints ensures modeling consistency and reduces parametric uncertainty, while remaining representative of realistic joint behavior. Although variations in friction and potential bolt slippage may influence higher-order or nonlinear dynamic responses, their effects on the lower-order modal parameters considered in this study are expected to be minimal. Therefore, the adopted assumptions provide a balanced compromise between physical realism, numerical robustness, and computational efficiency.

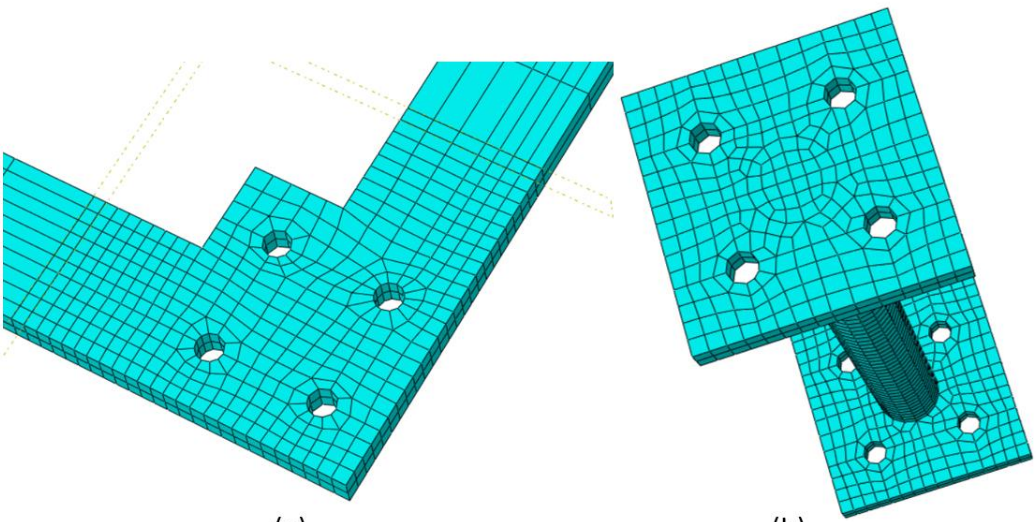
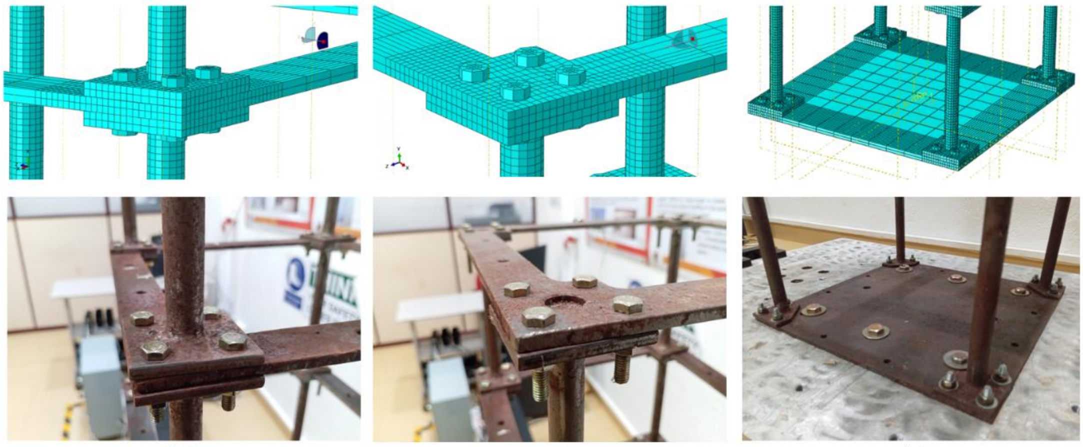


Fig. 4.4: Contact surfaces of (a) beam plate, and (b) column

Boundary conditions were established in the 'Load' module, where a fixed boundary condition was applied to the bottom of the base plate to replicate its fixed connection with the shake table deck.

Mesh generation was performed in the ‘Mesh’ module with careful consideration of both numerical accuracy and computational efficiency. Instead of applying a uniform mesh to the entire structure, each structural component was meshed individually using element sizes appropriate to its geometry and expected stress distribution, following best practices recommended by Okereke [60]. This part-wise meshing strategy allowed local refinement in critical regions while avoiding unnecessary mesh density elsewhere. Hexahedral elements were employed with a minimum cell size of approximately 3 mm, and mesh density was further controlled by subdividing elements into multiple sections, with increased refinement applied near beam–column connections where higher stress gradients and modal curvature are expected.

A formal mesh sensitivity (convergence) analysis was not conducted, as the adopted meshing strategy already incorporated localized refinement in critical regions and coarser meshes in low-gradient zones, ensuring stable modal characteristics without excessive computational cost. The adequacy of the selected mesh was further supported by the absence of distorted elements, reasonable simulation times, and the close visual and geometric correspondence between the finite element model and the experimental prototype, as shown in Fig. 4.5 and Fig. 4.6. Based on these considerations, the selected mesh configuration was deemed sufficient to accurately capture the dynamic behavior required for the modal-based analyses conducted in this study.



(a) (b) (c)

Fig. 4.5: FEM visual comparison of (a) intermediate connection, (b) top connection, and (c) bottom connection with the prototype

After meshing the model, FE simulations were performed using the 'Job' module. This module functions as the interface for submitting, monitoring, and controlling analysis jobs, ensuring efficient simulation management throughout the process.

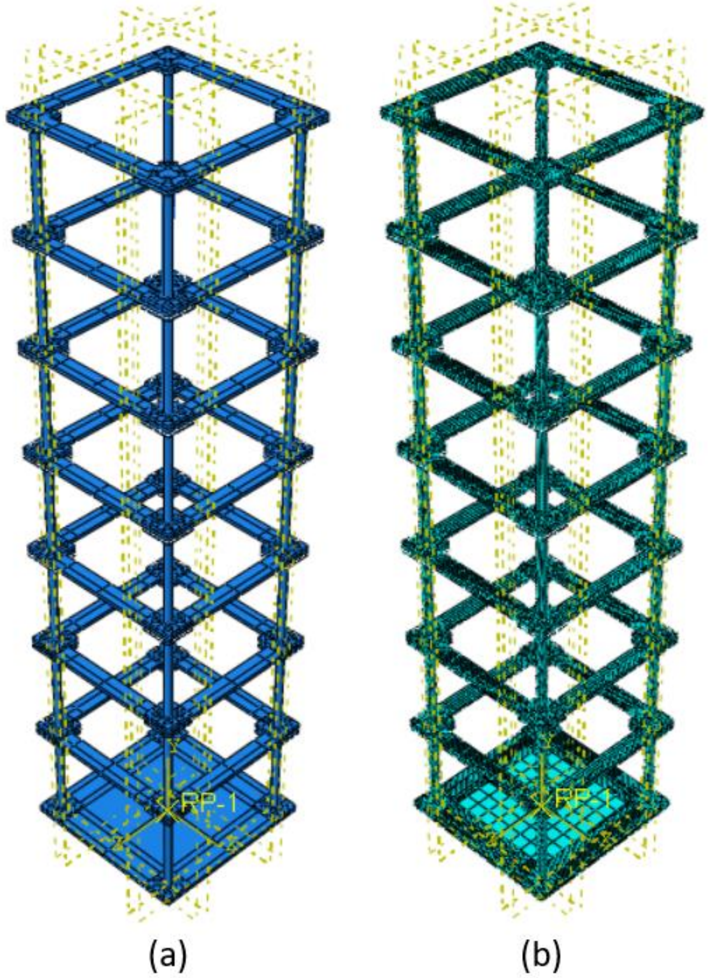


Fig. 4.6: Complete FEM (a) before mesh, and (b) after mesh

4.3 Simulations and Validation

To validate the experimental results, three numerical models were developed and simulated in ABAQUS. The resonance frequencies obtained from the simulations were compared with those recorded during the shake table experiments. The same 7-story steel frame structure (intact, damaged, and damaged–irregular configurations) used in the experiments was modelled, and modal analysis was performed to extract the resonance frequencies.

4.3.1 Intact Model

The intact 7-story steel frame structure with 16 mm diameter columns was modelled in ABAQUS, as shown in Fig. 4.7. The resonance frequency obtained from the simulation was 13.126 Hz, which was in close agreement with the experimental value of 13.12 Hz.

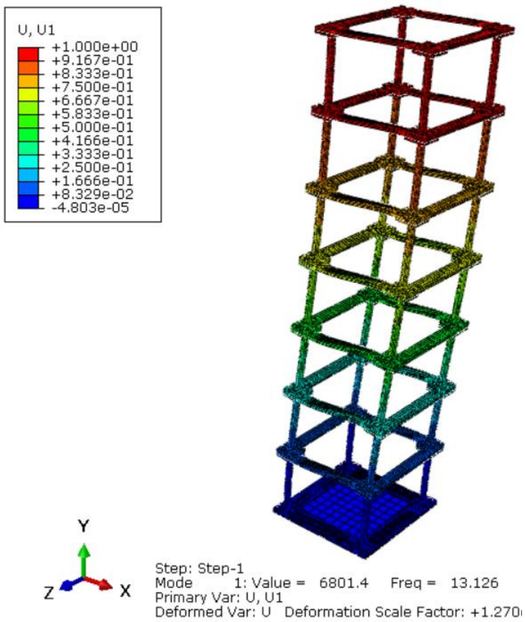


Fig. 4.7: Intact FEM developed using ABAQUS

4.3.2 Damaged Model

The damaged structure, in which two columns between the 3rd and 4th stories were replaced with 6 mm diameter columns, was modelled as shown in Fig. 4.8. The simulated resonance frequency was 12.912 Hz, compared to the experimental value of 12.86 Hz.

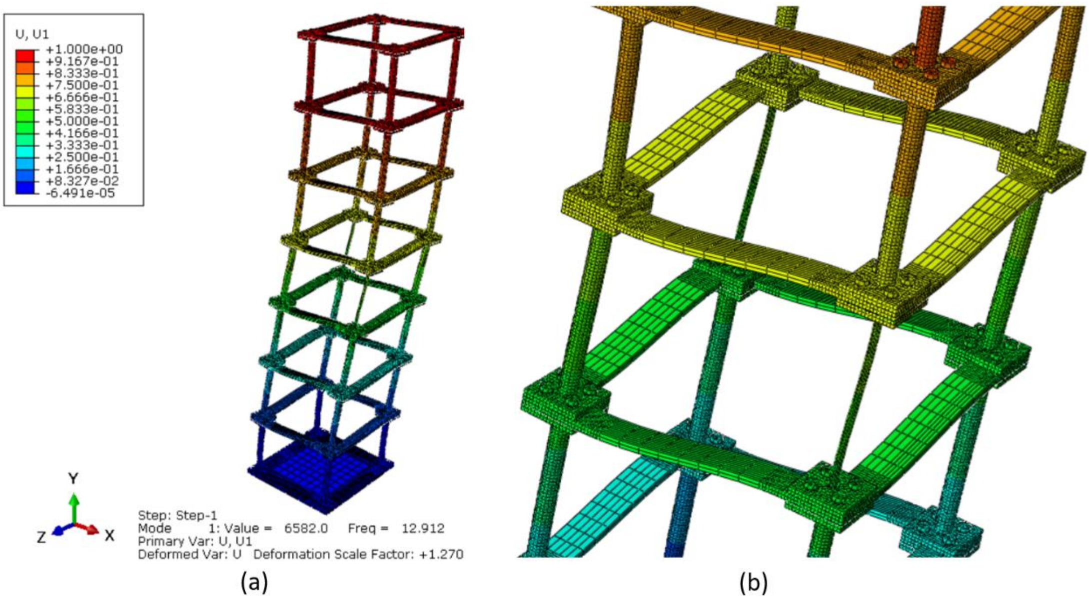


Fig. 4.8: (a) Damaged FEM developed using ABAQUS and (b) closeup view of the damaged section

4.3.3 Damaged-Irregular Model

For the damaged–irregular structure, the damaged configuration was combined with four 1 kg steel blocks attached to the 6th story, as illustrated in Fig. 4.9. The simulation yielded a resonance frequency of 11.506 Hz, while the experimental value was 11.62 Hz.

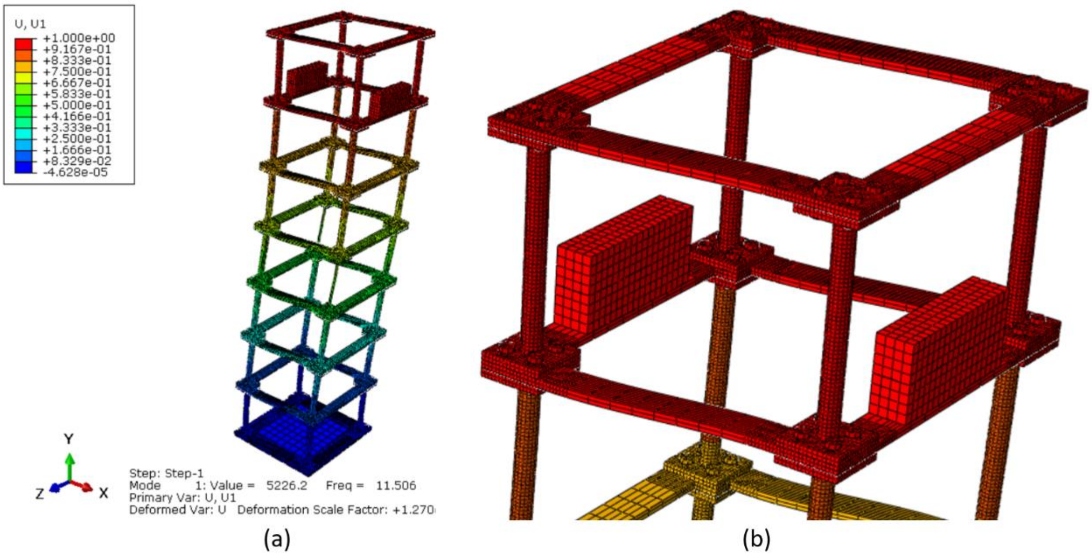


Fig. 4.9: Damaged-Irregular FEM developed using ABAQUS and (b) closeup view of the weighted (irregular) section

4.3.4 Comparison of Experimental and FEM Results

The natural frequencies obtained from both the shake table experiments and FEM simulations are summarized in Table 4.2. The results indicate excellent agreement, confirming the accuracy and reliability of the developed ABAQUS models for further analysis.

TABLE 4.2: RESONANCE FREQUENCY COMPARISON

Model	Resonance Frequencies (Hz)		
	Shake Table	FEM	% Difference
Intact	13.12	13.126	0.05
Damaged	12.86	12.912	0.4
Damaged-Irregular	11.62	11.506	0.9

4.4 Chapter Summary

This chapter detailed the FE modelling and simulation procedures conducted using ABAQUS CAE 6.14-5 to replicate the experimental steel frame structure under intact, damaged, and damaged–irregular conditions. Each structural component was modelled with precise geometric dimensions and material properties consistent with the laboratory prototype. Appropriate boundary conditions, contact interactions, and meshing strategies were applied to ensure both accuracy and computational efficiency. Modal analyses were carried out to determine the natural frequencies, and the results were validated against the experimental data. The comparison showed excellent agreement, with percentage differences below 1%, confirming that the developed FE models accurately represented the physical behavior of the tested structures. These validated models provide a reliable foundation for the subsequent parametric study on damage detection, localization, and severity estimation presented in the next chapter.

CHAPTER 5

PARAMETRIC STUDY

5.1 Introduction

This chapter presents a comprehensive parametric study conducted to evaluate and enhance modal-based structural damage detection, localization, and severity estimation techniques for framed structures. The study builds upon both experimental and validated finite element (FE) models developed in the previous chapters. Initially, the mode shape slope (MSS) and mode shape curvature (MSC) methods were verified using a simple cantilever beam model to ensure their reliability and numerical accuracy. Subsequently, these methods were applied to more complex structural configurations, including regular and irregular framed models, to examine their performance under various single and multiple damage scenarios. Additional investigations were carried out to assess the capability of the methods in detecting joint-related damage. Finally, a damage severity estimation approach, based on the grey relation coefficient and mode shape curvature, was implemented to quantify the extent of structural deterioration. The outcomes of this parametric analysis form a key part of validating the proposed methodology for reliable modal-based damage assessment in framed structures.

5.2 Initial Method Verification

Mode shape slope (MSS) method by Zhu et al. [21] and Mode-shape curvature (MSC) method by Pandey et al. [24] were further validated using a simple two-dimensional FE model of a cantilever beam. The initial models were developed using the ABAQUS FEM package. The beam had a square cross-section of 12.7 mm × 12.7 mm and was divided into 20 elements, each with a length of 25.4 mm, resulting in a total beam length of 508 mm, consistent with the model used in the original study by Pandey et al. [24]. The division scheme was aligned with the approach adopted by the reference study, enabling direct comparison and consistent verification of the method. The material properties of steel were used: density of 7850 kg/m³, Elastic modulus (E) of 200 GPa, and Poisson's ratio of 0.3.

Four FE models were developed: one intact cantilever beam model and three damaged models, each containing a single damage at element 5, 8, or 13, respectively as shown in the following Fig. 5.1 (a). Damage was simulated by reducing the Elastic modulus of the damaged element by 50%. Modal analysis was carried out for each model, and the natural frequencies and nodal displacements of the first five mode shapes were extracted.

The changes in resonance frequencies for each damage scenario were compared in the following Table 5.1, and further analysis was performed using numerical differentiation techniques (backward, forward, and central difference) to compute the

Difference in Mode Shape Slope (DMSS) and Difference in Mode Shape Curvature (DMSC) for the first mode shape. These values were normalized with respect to their maximum value (set to unity) for consistent comparison and plotted to check the damage detection capability for the above single damage scenarios.

TABLE 5.1: COMPARISON OF RESONANCE FREQUENCIES OF THE FIRST FIVE MODE SHAPES FOR THE THREE SINGLE DAMAGE SCENARIOS AT ELEMENT 5, 8 AND 13

Mode	Intact Model	Damage Location					
		Element 5		Element 8		Element 13	
	Frequency	Hz	%	Hz	%	Hz	%
1	40.10	38.32	4.47	39.16	2.35	39.94	0.42
2	250.61	250.42	0.08	244	2.63	240.56	4.01
3	698.42	682.52	2.28	679.87	2.66	675.39	3.30
4	1359.4	1312.5	3.45	1354.1	0.39	1354.7	0.35
5	2228	2191.7	1.63	2143.9	3.77	2145.9	3.68

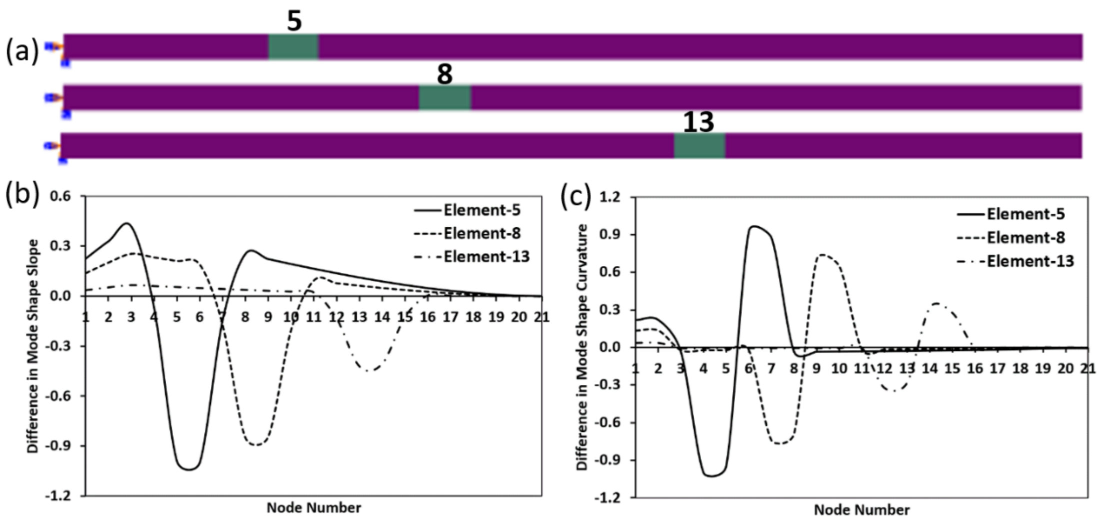


Fig. 5.1: (a) Beam with 3-single damage scenarios, (b) DMSS, and (c) DMSC plots

According to previous research [20] and [21] for finite degree-of-freedom systems, normalized DMSS plots reach a minimum or maximum at the location of damage. As illustrated in Fig. 5.1 (b), the model with a single damage at element 5 shows a minimum DMSS value between nodes 5 and 6, indicating stiffness degradation at that location. Similarly, models with damages at elements 8 and 13 show minimum DMSS values between nodes 8–9 and 13–14, respectively, demonstrating the capability of the DMSS method to accurately localize damage.

It is also observed that the magnitude of DMSS variation is highest for damage at element 5 and progressively decreases as the damage location shifts toward elements 8 and 13. This trend reflects a reduction in damage sensitivity as the damage approaches the free end of the beam. The observed behavior can be attributed to the lower modal strain energy and reduced mode shape curvature near the free boundary, which inherently limits the detectability of stiffness degradation in these regions.

As indicated in the previous research [20] and [24] DMSC plots typically show steep slope changes on either side of the damage, and the curve becomes sharply inclined at the damage location. As illustrated in Fig. 5.1 (c), the model with damage at element 5 shows a steep DMSC slope between nodes 5 and 6. Similarly, steep slopes are observed between nodes 8–9 and 13–14 for the other two damaged models.

The findings confirm that both DMSS and DMSC are effective in localizing damage in single-damage scenarios for simple structures. However, higher vibration modes were not considered in this study due to their limited practical contribution to reliable damage detection in the investigated structural system. Lower-order modes dominate the global dynamic response of framed structures under typical excitation and exhibit higher modal participation, making them more robust and consistently identifiable in both experimental and numerical analyses. In contrast, higher modes are more sensitive to measurement noise, modelling uncertainties, and local numerical differentiation errors, particularly when slope-based and curvature-based indicators such as DMSS and DMSC are employed. Previous studies have shown that the effectiveness of these indicators tends to deteriorate for higher modes due to increased spatial oscillations and reduced signal-to-noise ratios, leading to less stable damage localization results [20]. Furthermore, focusing on the first few modes improves computational efficiency while aligning with realistic monitoring conditions, where higher modes are often difficult to excite and accurately capture. Therefore, the exclusion of higher vibration modes represents a justified and practical simplification that does not compromise the validity of the damage detection outcomes for the objectives of this research.

5.3 Single Damage Detection

Parametric study was conducted on the framed structure considering single and multiple damage scenarios. Different cases were investigated by changing the damage locations on the structure to find out the damage detection capabilities of DMSS and DMSC methods.

5.3.1 Regular Framed Model

The regular frame models were first analysed to evaluate single damage detection performance. The intact configuration is shown in Fig. 5.2 (a), while the damaged configuration is shown in Fig. 5.2 (b). Damage was introduced by replacing two 16 mm diameter columns between the 3rd and 4th storeys with two 6 mm diameter columns. The first mode shapes at each storey level were extracted for both intact and damaged models. Subsequently, the DMSS and DMSC values were calculated, and the corresponding normalized plots were generated to assess damage detection capability.

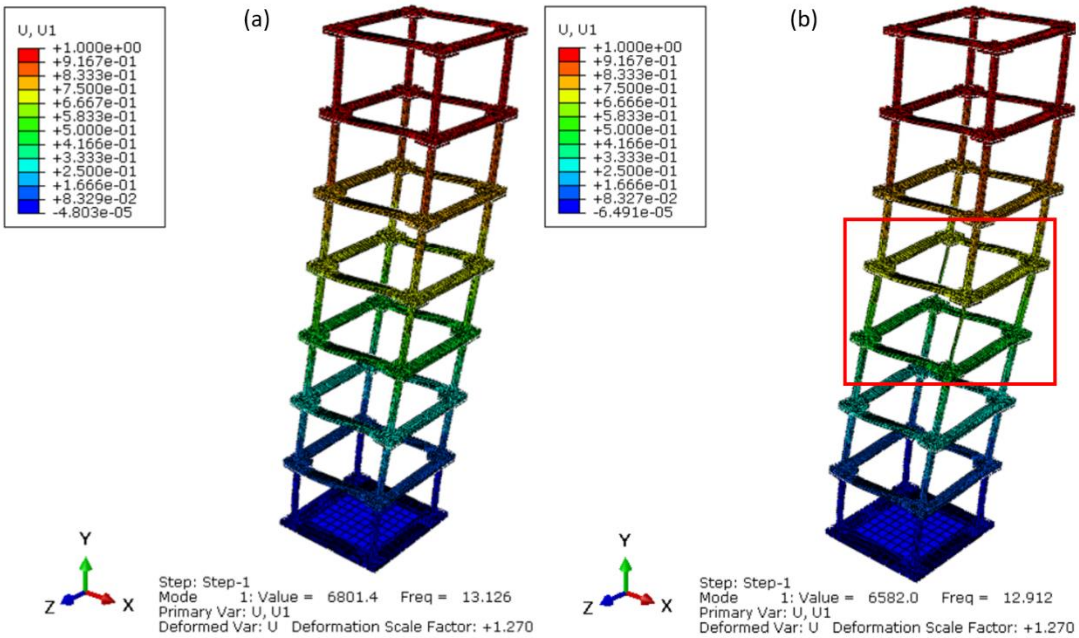


Fig. 5.2: (a) Intact FE Model and (b) Damaged FE Model with the damage between 3rd – 4th storeys

5.3.2 Irregular Framed Model

The irregular frame models were then analysed under similar conditions. The intact configuration is shown in Fig. 5.3 (a), and the damaged configuration in Fig. 5.3 (b). In this case also, damage was introduced by replacing two 16 mm diameter columns between the 3rd and 4th storeys with two 6 mm diameter columns, while irregularity was incorporated by attaching external mass blocks as shown in the model. The first mode shapes were extracted at each storey level for both intact and damaged conditions. Using these mode shapes, the DMSS and DMSC values were calculated, and normalized plots were developed to investigate the accuracy of damage detection in irregular structures.

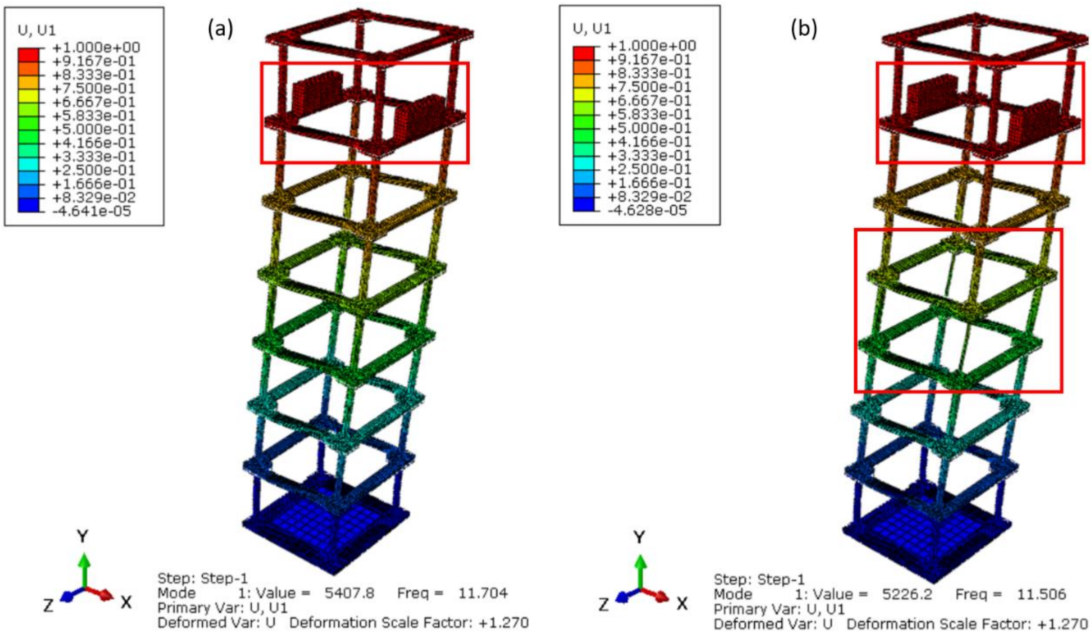


Fig. 5.3: (a) Intact-Irregular FEM and (b) Damaged-Irregular FEM with the damage between 3rd – 4th storeys

5.4 Multiple Damage Detection

5.4.1 Beam Model

The cantilever beam FE model was further analysed to investigate the capability of mode shape slope (DMSS) and mode shape curvature (DMSC) methods in detecting multiple damage scenarios. Two additional models were developed for this purpose as shown in Fig. 5.4:

- Two-damage scenario: Damages were introduced simultaneously at element 5 and element 13.
- Three-damage scenario: Damages were introduced simultaneously at element 5, element 12, and element 17.

As with the single-damage models, damage in each element was simulated by reducing its Elastic modulus (E) by 50%. After developing the models, modal analysis was conducted, and the natural frequency and nodal displacements corresponding to the first mode shape were extracted.

Fig. 5.4: Beam FEM with multiple damage scenarios (a) damage at element number 5 and 13, (b) damage at element number 5,12, and 17

5.4.2 Regular Framed Model

For the regular frame model, two damages were introduced at different storey levels by replacing one 16 mm diameter column at each storey with two 6 mm diameter columns. The following damage cases were considered:

- Case 1: Damages between the 3rd–4th and 5th–6th storeys, located on the same edge of the model (Fig. 5.5 (a)).
- Case 2: Damages between the 3rd–4th and 5th–6th storeys, located on opposite edges of the model (Fig. 5.5 (b)).
- Case 3: Damages between the 1st–2nd and 5th–6th storeys, located on the same edge of the model (Fig. 5.6 (a)).
- Case 4: Damages between the 0–1st and 6th–7th storeys, located on the same edge of the model, near the fixed and free ends (Fig. 5.6 (b)).

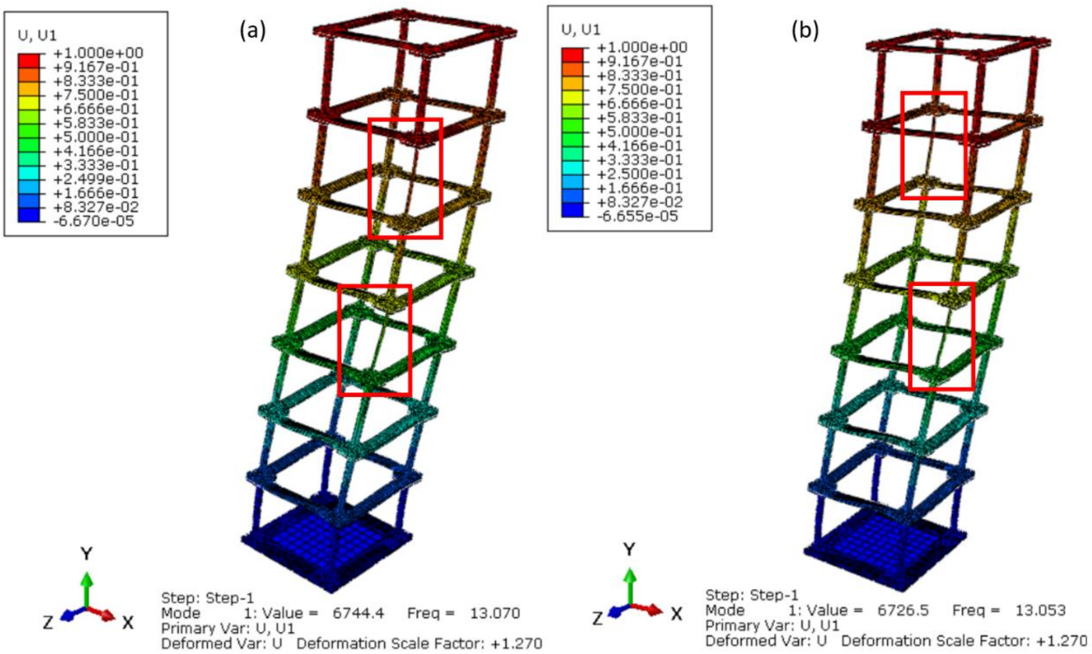


Fig. 5.5: Multiple damage scenario with damage between 3rd – 4th and 5th – 6th storeys (a) at the same edge and (b) at the opposite edges

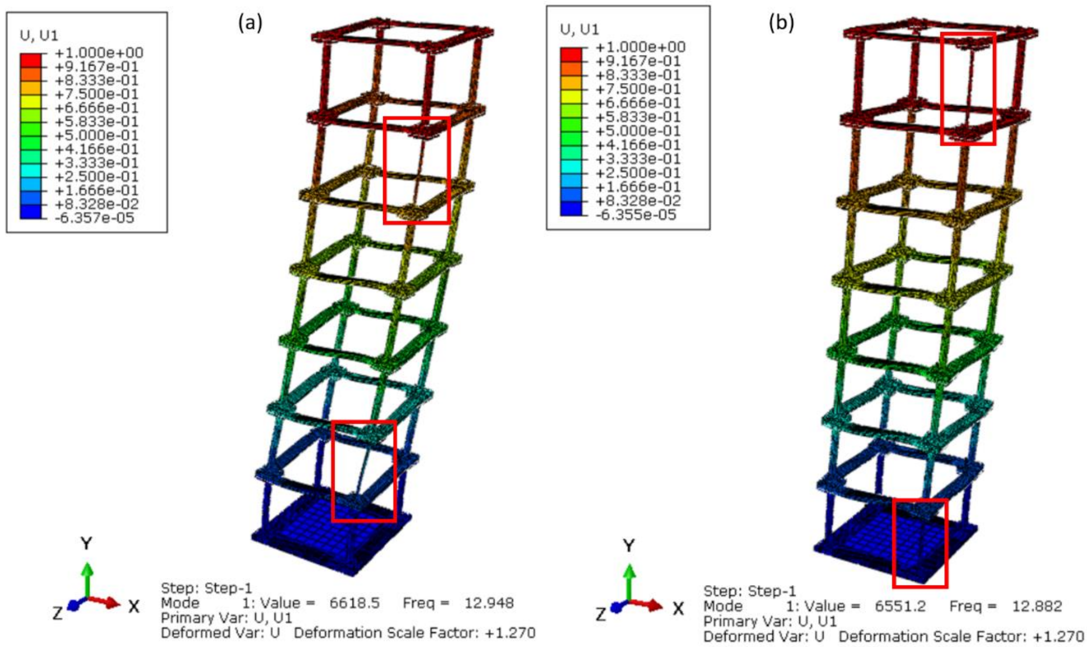


Fig. 5.6: Multiple damage scenario with damage between (a) 1st – 2nd and 5th – 6th storeys and (b) ground – 1st storeys and 6th – 7th storeys

5.4.3 Irregular Framed Model

For the irregular frame model, the same procedure was followed: two damages were introduced at separate storeys by replacing one 16 mm diameter column at each storey with two 6 mm diameter columns. In addition, irregularity was incorporated by attaching external mass blocks, as shown in the model. The following cases were analysed:

- Case 1: Damages between the 3rd–4th and 5th–6th storeys, located on the same edge of the model (Fig. 5.7 (a)).
- Case 2: Damages between the 3rd–4th and 5th–6th storeys, located on opposite edges of the model (Fig. 5.7 (b)).
- Case 3: Damages between the 0–1st and 6th–7th storeys, located on the same edge of the model (Fig. 5.7 (c)).

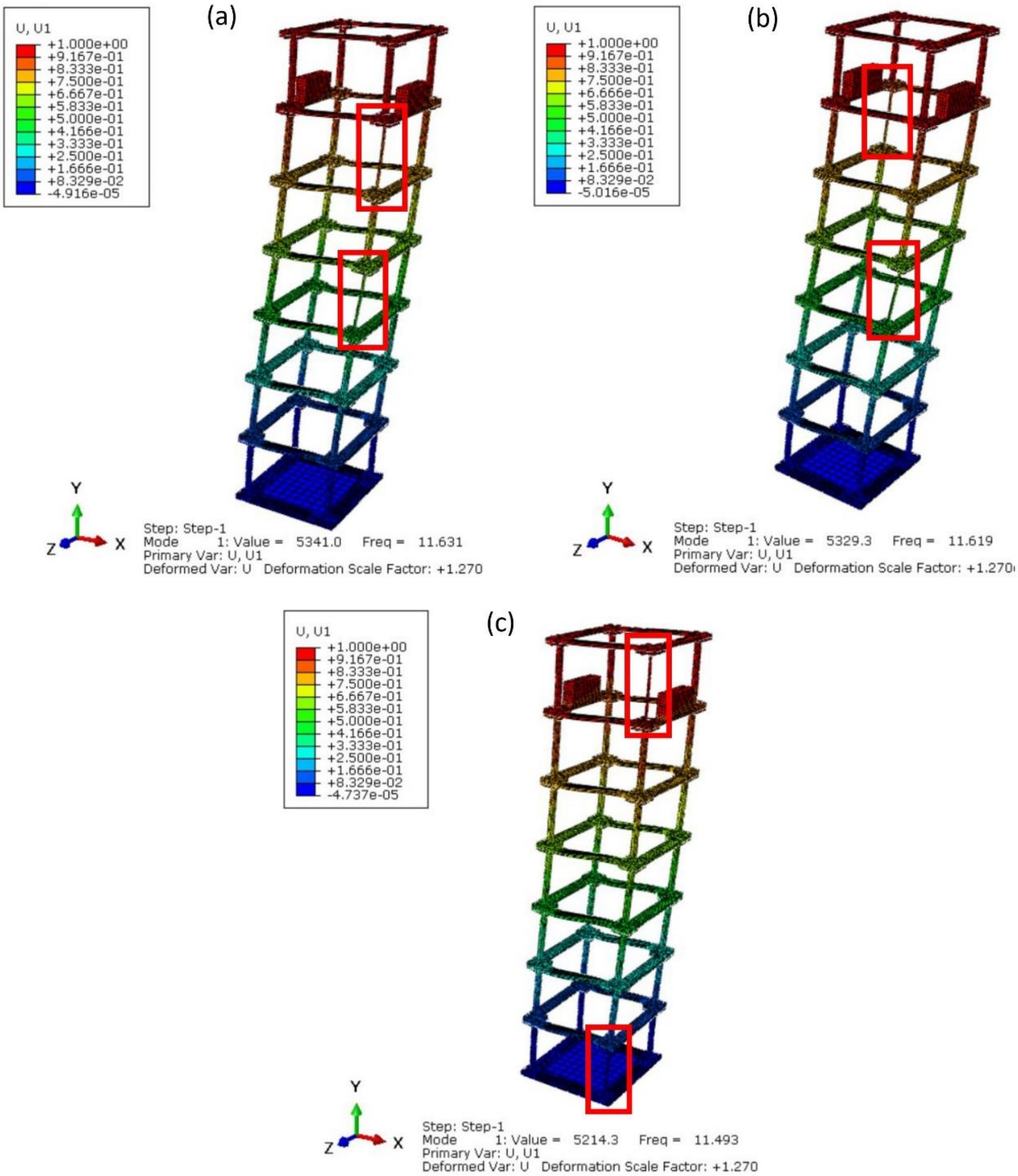


Fig. 5.7: Multiple damage scenario of the Damaged – Irregular modal with damage between (a) 3rd – 4th and 5th – 6th storeys at the same edge, (b) 3rd – 4th and 5th – 6th storeys at the opposite edges, and (c) damages between ground – 1st storeys and 6th – 7th storeys at the same edge

5.5 Damage Detection at Joints

In this case, joint damage was analysed to evaluate the effectiveness of the proposed methods. The damage was introduced at the 4th storey joint by removing the bolts of the connection, as illustrated in Fig. 5.8. The first mode shapes at each storey level were extracted for both the intact and damaged conditions. Using these mode shapes, the DMSS and DMSC values were calculated, and normalized plots were developed to assess the accuracy of damage detection at the joins of the structure.

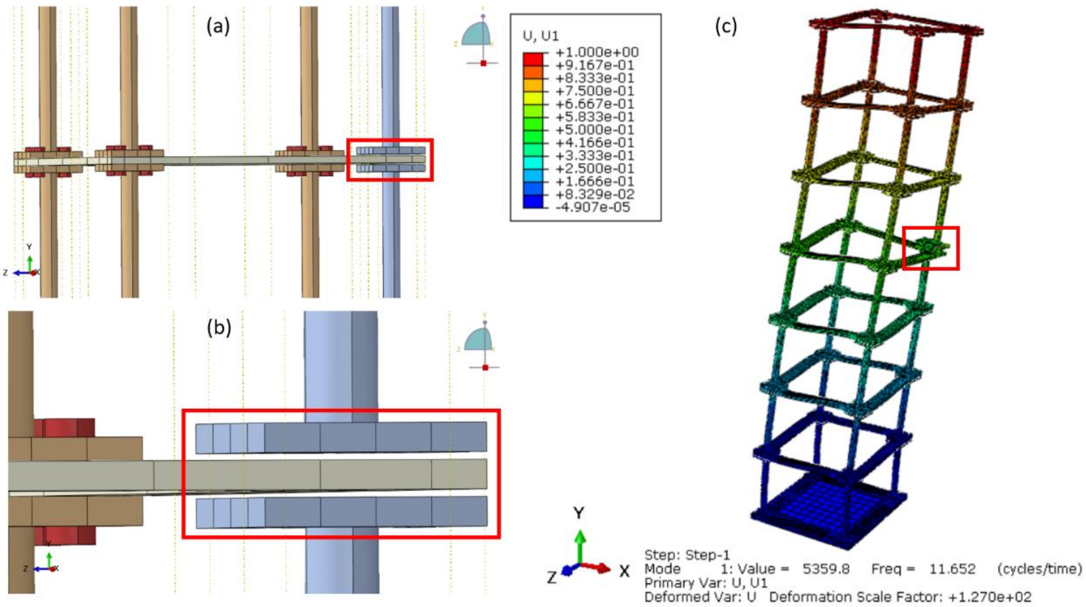


Fig. 5.8: (a) Damage introduced at a joint of 4th storey, (b) closeup view, and (c) analysed structure

5.6 Damage Severity Estimation

In this research, a structural damage severity estimation procedure based on the grey relation coefficient and the mode shape curvature is adopted, as proposed by (Grandić & Grandić [61]. This method relies on mode shapes obtained through modal analysis and applies an arithmetic operation (Fig. 5.9) to quantify the severity of damage in beam structures. Building on this approach, the present study extends its application to the framed structure analysed in previous sections, focusing on estimating damage severity under different damage scenarios through numerical simulations.

5.6.1 Theory

The mode shape curvature $\varphi''(x_i)$ of a structure can be calculated using the second derivative of central finite difference as shown in the below equation (5.1):

Here, $\varphi''(x_i)$ is the mode shape curvature of the i th storey of the structure.

$$\varphi''(x_i) = \frac{\varphi(x_{i+1}) - 2.\varphi(x_i) + \varphi(x_{i-1})}{(x_i - x_{i-1}).(x_{i+1} - x_i)} \tag{5.1}$$

According to the previous equation, the curvature for damaged state can be written as follows (5.2):

$$\varphi''^{*}(x_i) = \frac{\varphi^{*}(x_{i+1}) - 2.\varphi^{*}(x_i) + \varphi^{*}(x_{i-1})}{(x_i - x_{i-1}).(x_{i+1} - x_i)} \tag{5.2}$$

If damage is represented as reduction in bending stiffness as shown in (5.3),

$$EI = (1 - \delta)EI \tag{5.3}$$

The decrease in bending stiffness $\delta(x_i)$ inside the storey i, can be express as (5.4):

$$\delta(x_i) = 1 - \frac{\varphi''(x_i)}{\varphi''^*(x_i)} \tag{5.4}$$

5.6.2 Grey Relation Coefficient

The grey relation coefficient $\zeta(x_i)$ is employed to identify points of significant difference between the curvature of a damaged structure and its corresponding intact structure [62]. This coefficient provides a quantitative measure of similarity, where lower values indicate higher deviations caused by damage. $\zeta(x_i)$ is calculated by using the equation (5.5) and $R(x_i)$ value is calculated by using the equation (5.6) as follows:

$$\zeta(x_i) = \frac{\min R + 0.5 \max R}{R(x_i) + 0.5 \max R} \tag{5.5}$$

Where;

$$R(x_i) = \left| \varphi''(x_i) - \varphi''^*(x_i) \right| \tag{5.6}$$

Generally,

- $\zeta(x_i) > 0.9$ indicates that the reference point and the test point are related completely.
- $0.8 < \zeta(x_i) < 0.9$ indicates the good relation of the two points.
- $0.6 < \zeta(x_i) < 0.8$ indicates that the two points are relative or irrespective possibly.
- $\zeta(x_i) < 0.6$ represents that the two points are almost irrelative.

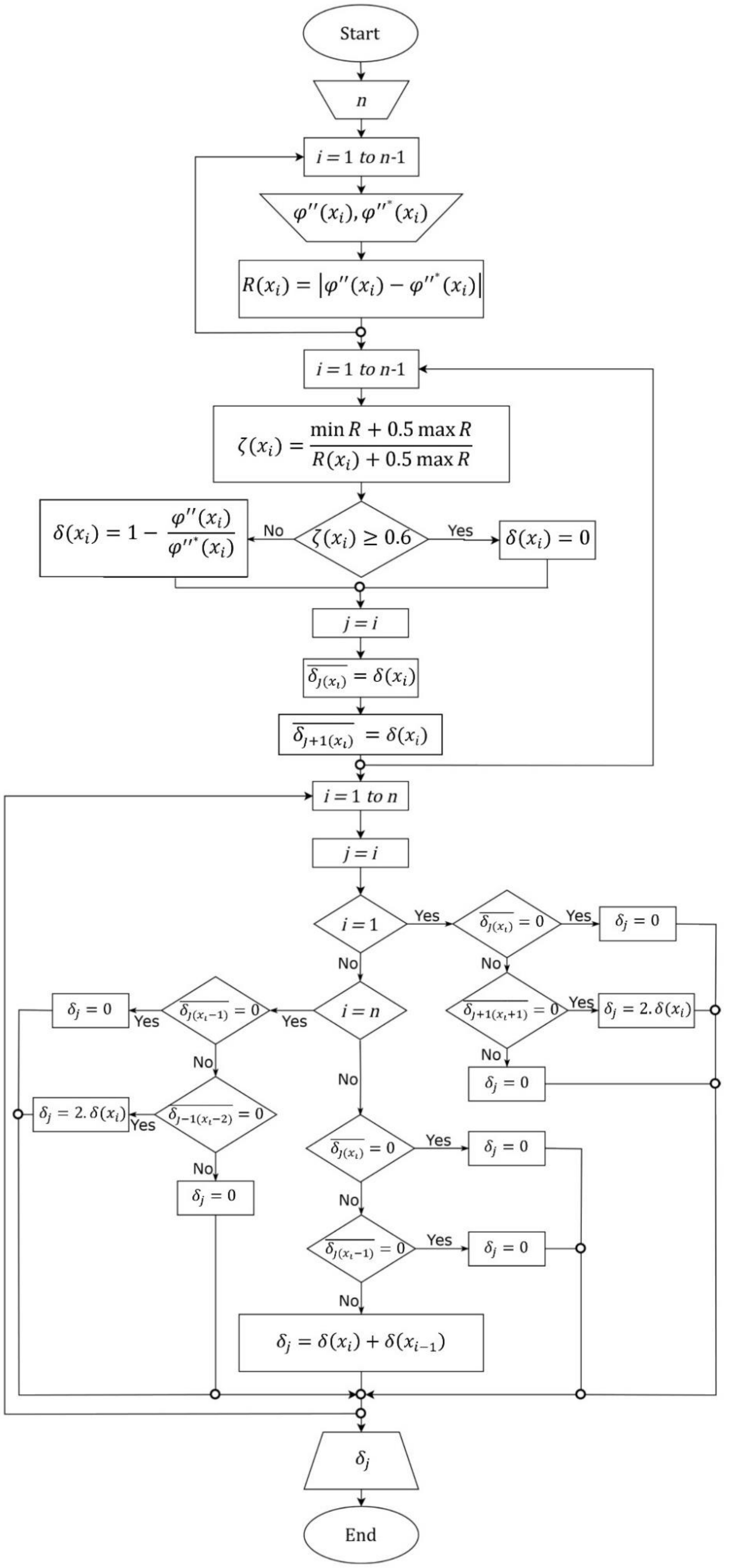


Fig. 5.9: Arithmetic operation proposed by Grandic et al. [61] for the damage severity estimation

5.6.3 Beam Model

For the validation study, intact and damaged beam models (Fig. 5.10) were initially analysed to estimate damage severity before extending the method to frame structures. Damage was introduced in the 5th, 10th, 13th, and 18th elements by reducing the elastic modulus, thereby simulating different levels of stiffness loss. The variation of elastic modulus and the corresponding damage intensity are presented in Table 5.2.

Fig. 5.10: Beam FEM with the damage at element number 5, 10, 13, and 18

TABLE 5.2: DAMAGE INTENSITY VARIATION IN THE BEAM MODEL

Case	Damage Intensity (%)	Elastic Modulus (MPa)	Resonance Frequency (Hz)
0	0	200,000	40.107
1	10	180,000	39.895
2	25	150,000	39.482
3	50	100,000	38.315
4	75	50,000	35.349

5.6.4 Framed Model

Following the beam model analysis, intact and damaged frame models (Fig. 5.11) were examined to estimate damage severity. In this case, damage was introduced between the 3rd and 4th storeys by replacing two 16 mm columns in the longitudinal direction with columns of 6 mm, 8 mm, 10 mm, 12 mm, and 14 mm diameters, as shown in Fig. 5.12. This variation in column diameter corresponds to different levels of stiffness reduction, and thus damage intensity, as summarized in Table 5. The first mode shapes at each storey level were extracted for all damaged models to perform the severity estimation.

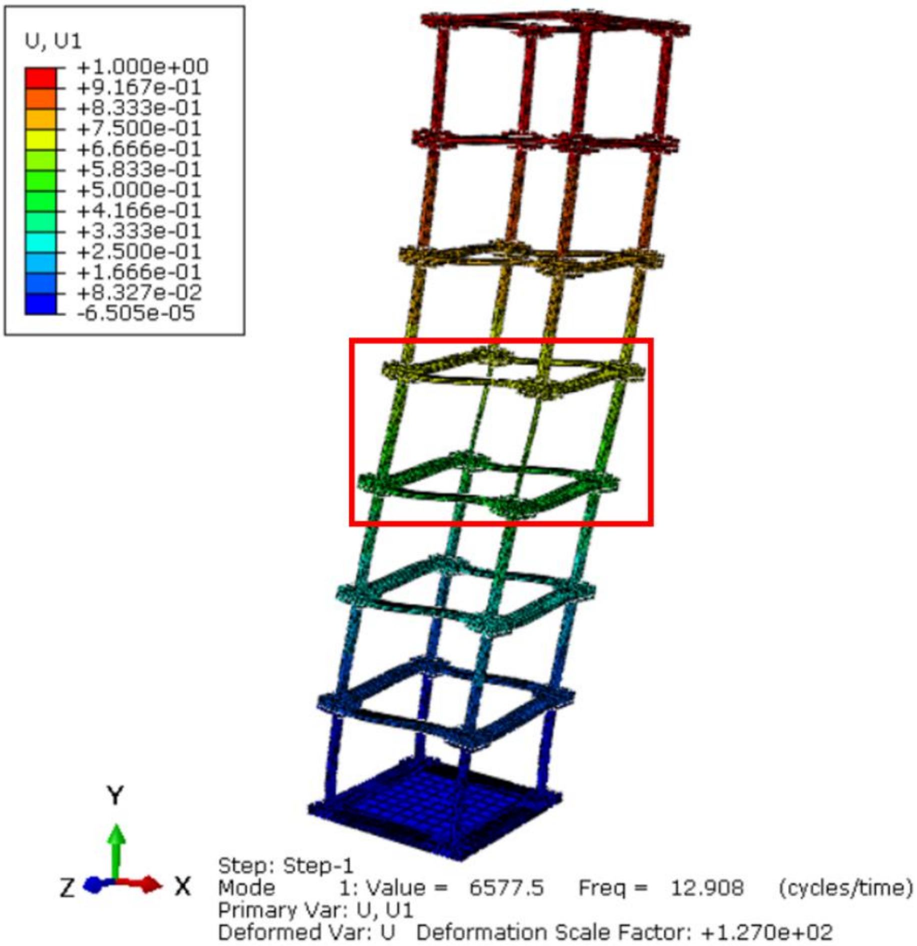


Fig. 5.11: Frame model used for the damage severity estimation with the damage between 3rd – 4th storeys

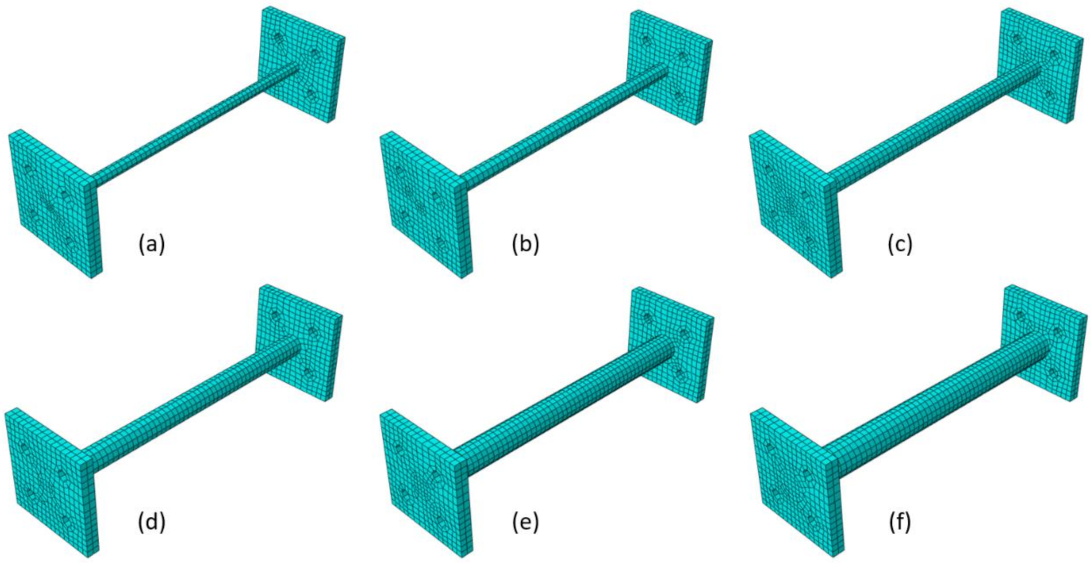


Fig. 5.12: Columns used for varying the damage intensity (a) 6 mm, (b) 8 mm, (c) 10 mm, (d) 12 mm, (e) 14 mm, and (f) 16 mm

TABLE 5.3: DAMAGE INTENSITY VARIATION WITH COLUMN DIAMETERS IN THE FRAMED MODEL

Column Diameter (mm)	Damage Intensity (%)	Resonance Frequency (Hz)
6	98	12.908
8	94	12.943
10	85	13.008
12	68	13.064
14	41	13.108
16	0	13.126

5.7 Chapter Summary

This chapter presented a series of parametric studies conducted to examine the applicability and robustness of modal-based techniques for structural damage detection, localization, and severity estimation. The analysis began with the verification of the mode shape slope (MSS) and mode shape curvature (MSC) methods using a cantilever beam model to ensure methodological reliability. These methods were then applied to FE models of regular and irregular framed structures under various single and multiple damage conditions to assess their performance in more complex systems. Additional simulations were carried out to study joint-level damage scenarios, followed by an extended numerical analysis to estimate damage severity using a grey relation coefficient and mode shape curvature-based approach. Overall, the chapter outlined the complete framework of numerical investigations employed to evaluate and refine the proposed modal-based damage assessment techniques.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Introduction

This chapter presents the results and discussion of the experimental and numerical investigations carried out to evaluate the effectiveness of enhanced modal-based techniques for structural damage detection, localization, and severity estimation in framed structures. The analyses are based on mode shape slope and curvature indices derived from both single and multiple damage scenarios in regular and irregular frame models, as well as in simple beam models for validation. The chapter also examines the performance of these indicators under different damage configurations, including joint damages, to assess their sensitivity and reliability in identifying stiffness reductions. Additionally, the chapter explores the application of a grey relation coefficient (GRC)–based method for quantifying damage severity, providing a comparative perspective on its applicability to simple and complex structural systems. The collective results contribute to a comprehensive understanding of the capabilities and limitations of modal-based approaches in structural health monitoring, establishing a foundation for further refinement and future applications in real-world structures.

6.2 Single Damage Detection

This section presents the results of single damage detection in both regular and irregular framed models. The aim was to evaluate the performance of the Difference in Mode Shape Slope (DMSS) and the Difference in Mode Shape Curvature (DMSC) indices in detecting and localizing damage. Results are discussed comparatively to highlight the similarities and differences in detection capability between the two models.

6.2.1 Regular Framed Model

DMSS and DMSC values were calculated using forward, backward, and central difference methods based on the mode shapes extracted from the FEM simulations. Fig. 6.1 (a) shows the variation of normalized DMSS values with storey number for the regular framed model with damage introduced between the 3rd and 4th storeys. A distinct minimum DMSS value was observed exactly at the damaged location, confirming the ability of DMSS to detect stiffness reduction. The pronounced dip in DMSS illustrates its effectiveness in pinpointing localized changes in modal behavior caused by reduced column stiffness.

Similarly, the corresponding DMSC distribution, illustrated in Fig. 6.1 (b), presents a steep slope variation between the 3rd and 4th storeys. This sharp gradient in the DMSC curve reinforces the accuracy of damage localization, as curvature-based indicators are particularly sensitive to localized structural changes. The local amplification in slope confirms that even subtle stiffness losses produce significant curvature responses in mode shapes, making DMSC an effective complementary metric to DMSS.

Overall, for the regular framed structure, both DMSS and DMSC successfully identified the damage position with high sensitivity.

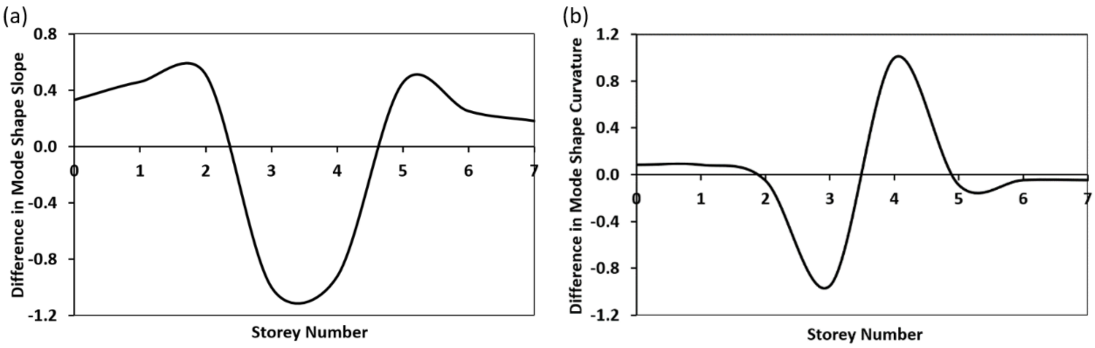


Fig. 6.1: (a) DMSS and (b) DMSC plots of the single damage scenario in regular framed modal

6.2.2 Irregular Framed Model

The results for the irregular framed model are presented in Fig. 6.2. As in the regular case, a minimum DMSS value was clearly detected between the 3rd and 4th storeys, corresponding to the location of damage. Likewise, the DMSC distribution exhibited a steep slope between the same levels, again validating the effectiveness of curvature-based detection for identifying stiffness reduction.

Interestingly, the overall shapes of the DMSS and DMSC curves in the irregular frame were found to be almost identical to those of the regular model. This suggests that the introduction of irregularity, through additional mass blocks at higher storeys, did not significantly alter the ability of the DMSS and DMSC methods to detect and localize damage. The indices remained robust against the geometric and mass-related irregularities of the system.

This finding highlights a significant advantage: DMSS and DMSC indicators are not only effective in detecting damage in idealized regular structures but also maintain their reliability in irregular structural systems, which more closely resemble real-world civil infrastructure. This robustness against irregularity is an important step toward their practical application in complex structures where irregularity is common due to architectural or functional constraints.

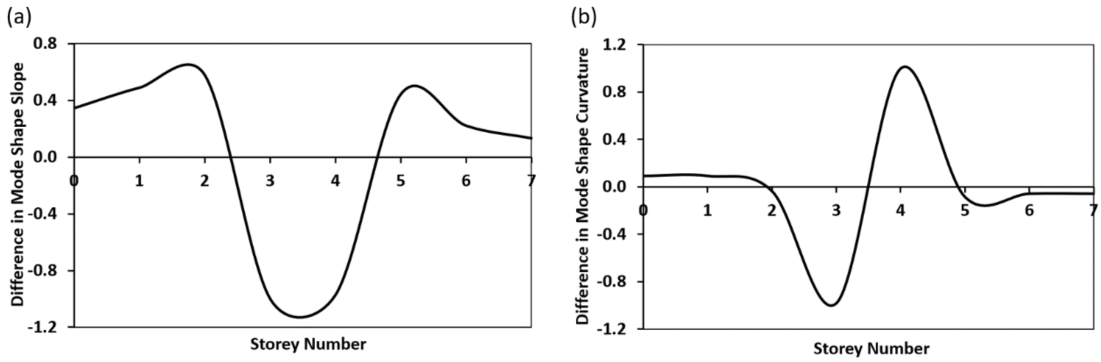


Fig. 6.2: (a) DMSS and (b) DMSC plots of the single damage scenario in irregular framed modal

6.3 Multiple Damage Detection

This section presents the results of multiple damage detection in beams as well as in both regular and irregular framed models. The objective was to evaluate the performance of the DMSS and the DMSC indices for detecting and localizing multiple damages. Results are discussed comparatively to highlight the similarities and differences in detection capability across the models.

6.3.1 Beam Model

DMSS and DMSC plots of the beam models with multiple damage scenarios are shown in Fig. 6.3. Two cases were analysed: one model with two damages introduced at elements 5 and 13, and another model with three damages at elements 5, 12, and 17. As in the previous analyses, the DMSS and DMSC values were normalized to their maximum values (unity) to facilitate interpretation.

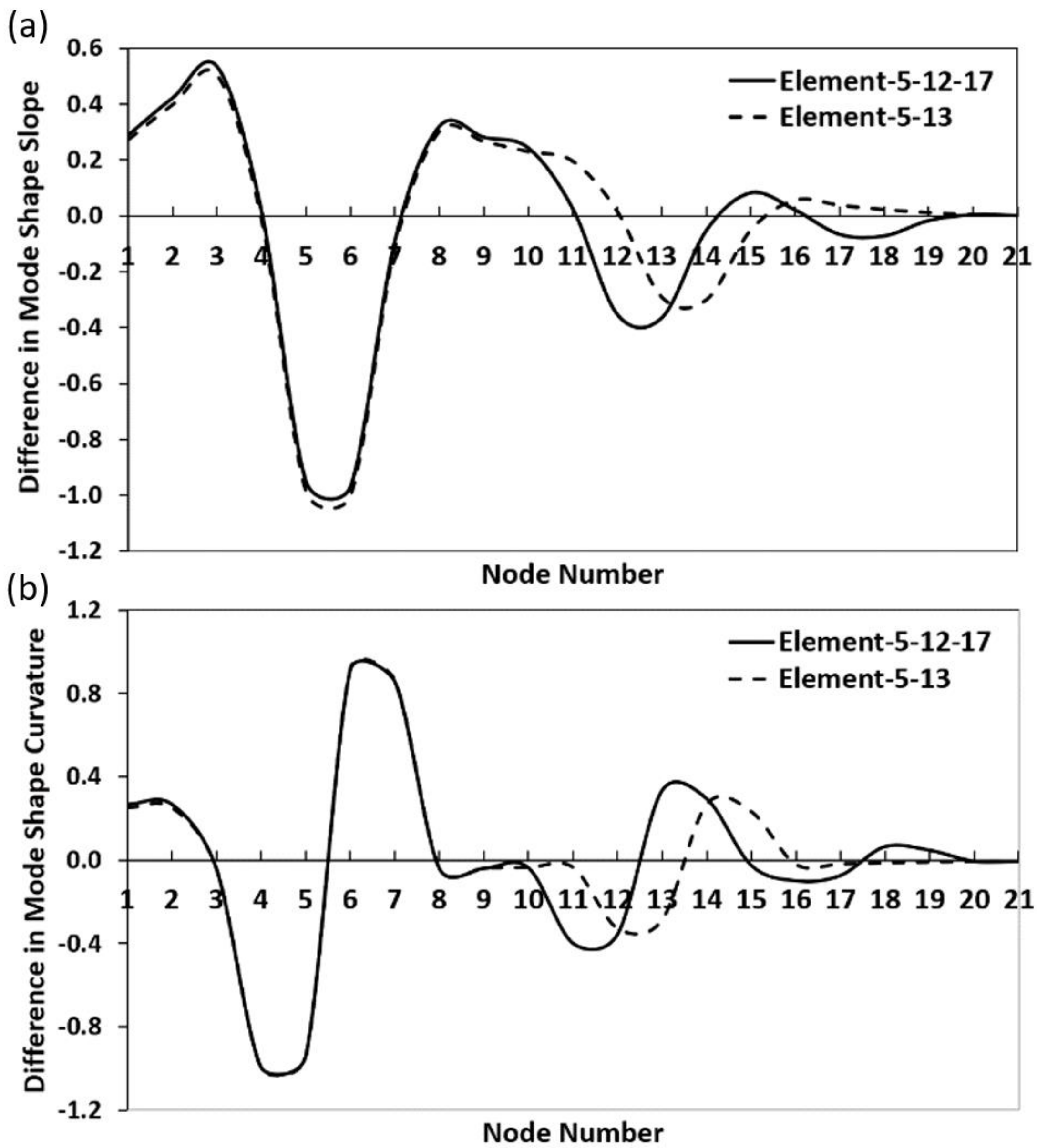


Fig. 6.3: (a) DMSS and (b) DMSC plots of the beam model for the multiple damage scenario

For the two-damage scenario, Fig. 6.3 (a) shows clear DMSS minima between nodes 5–6 and 13–14, indicating stiffness degradation at elements 5 and 13. Similarly, for the three-damage scenario, DMSS minima were observed between nodes 5–6, 12–13, and 17–18, correctly identifying damage at all three locations.

The DMSC curves presented in Fig. 6.3 (b) reinforce these findings. For the two-damage scenario, steep slope variations were observed between nodes 5–6 and 13–14, while for the three-damage scenario, slopes appeared between nodes 5–6, 12–13 and 17–18. These results further validate the ability of DMSC to detect multiple localized damages in simple beam structures.

It is noteworthy that in both DMSS and DMSC plots, the amplitude of the indicators decreases toward the free end of the beam for both scenarios. This trend can be attributed to the lower modal energy and reduced mode shape curvature near the free boundary, which inherently limits damage detectability in these regions.

6.3.2 Regular Framed Model

For the regular frame model, multiple damages were introduced at two different storey levels by replacing one 16 mm diameter column at each storey with 6 mm diameter columns. Four distinct damage cases were analysed to assess the effectiveness of DMSS and DMSC indices in detecting and localizing multiple damages.

In Case 1, damages were introduced between the 3rd–4th and 5th–6th storeys, located on the same edge of the frame. As shown in Fig. 6.4 (a), the DMSS plot exhibited a peak near the 2nd storey but failed to identify either damage location. In contrast, the DMSC distribution in Fig. 6.4 (b) clearly presented steep slope variations between the 3rd–4th and 5th–6th storeys, successfully capturing both damage positions.

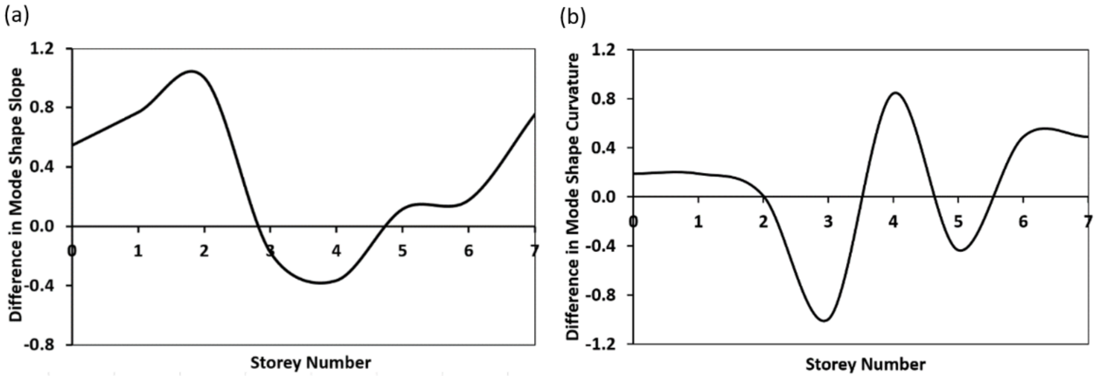


Fig. 6.4: (a) DMSS and (b) DMSC plots of the case with damages between the 3rd–4th and 5th–6th storeys, located on the same edge of the regular model

In Case 2, the same storeys were damaged but on opposite edges of the model. Again, the DMSS curve (Fig. 6.5 (a)) showed a misleading maximum near the 2nd storey, offering no useful detection. Conversely, the DMSC plot (Fig. 6.5 (b)) highlighted sharp gradients at the damaged storeys, confirming that the method was effective even when the damages were spatially separated on opposite sides of the frame.

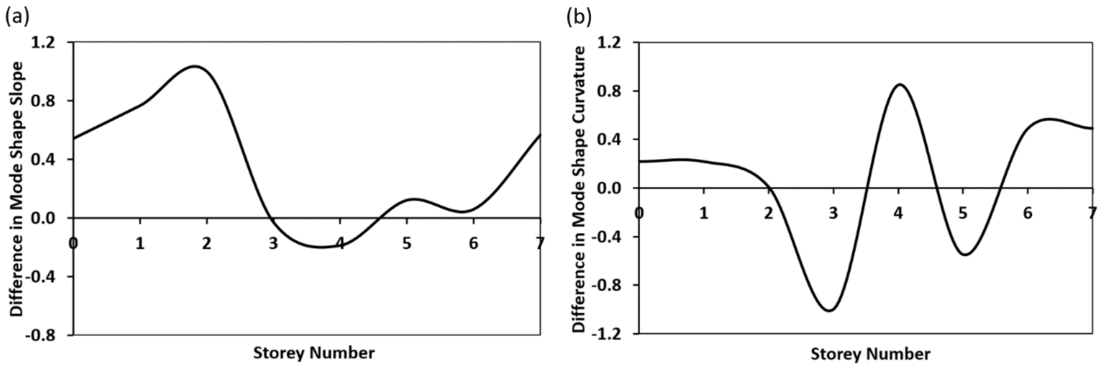


Fig. 6.5: (a) DMSS and (b) DMSC plots of the case with damages between the 3rd–4th and 5th–6th storeys, located on the opposite edges of the regular model

In Case 3, damages were introduced between the 1st–2nd and 5th–6th storeys on the same edge of the structure. The DMSS distribution (Fig. 6.6 (a)) again failed to detect the damages, showing a spurious maximum near the 3rd storey. However, the DMSC plot (Fig. 6.6 (b)) exhibited sharp gradient at both the 1st–2nd and 5th–6th levels, correctly identifying the damage.

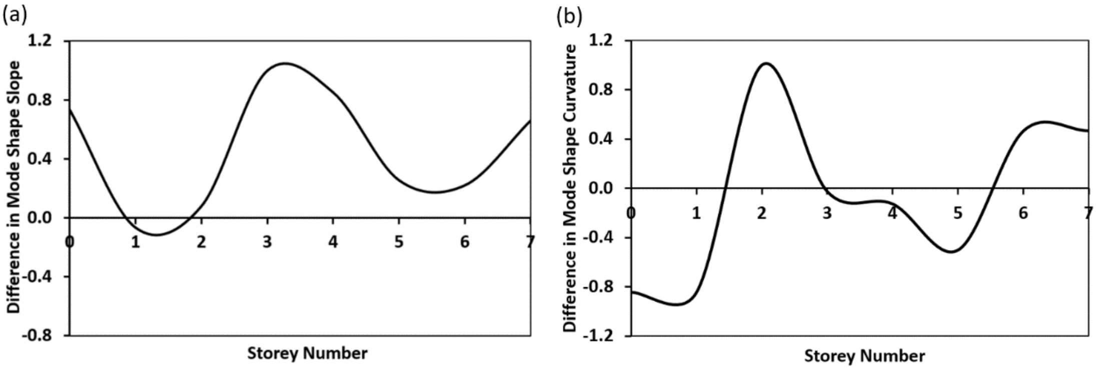


Fig. 6.6: (a) DMSS and (b) DMSC plots of the case with damages between the 1st–2nd and 5th–6th storeys, located on the same edge of the regular model

In Case 4, damages were applied near the structural boundaries — between the 0–1st and 6th–7th storeys, close to the fixed and free ends. In this scenario, the DMSS curve (Fig. 6.7 (a)) failed to localize any damage, while the DMSC curve (Fig. 6.7 (b)) presented only minor slope variations near mid-height of the structure, missing both damage positions.

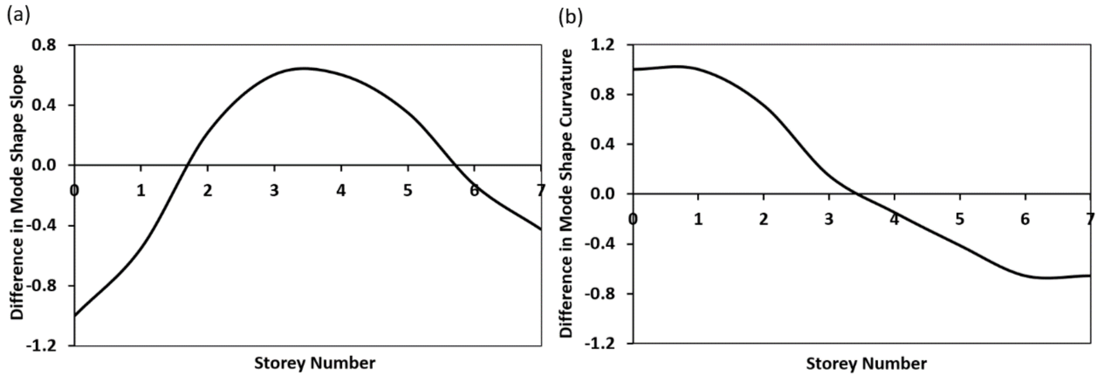


Fig. 6.7: (a) DMSS and (b) DMSC plots of the case with damages between the 0–1st and 6th–7th storeys, located on the same edge but near the fixed end and free end of the regular model

Overall, the results reveal a clear trend: the DMSS method consistently failed to detect multiple damages across all scenarios in regular frames. The DMSC method, however, demonstrated robust performance in three of the four cases, accurately identifying damages except when they were located near the fixed and free boundaries. This limitation can be attributed to reduced modal energy and low curvature sensitivity near the supports, which restricts the ability of curvature-based indices to highlight stiffness reductions in those regions.

When damage occurs in columns located on opposite sides of the structure, an asymmetric stiffness distribution may develop, leading to torsional effects due to a shift between the center of mass and the center of rigidity. This torsional coupling can influence the global dynamic response by altering modal characteristics, particularly mode shapes and natural frequencies associated with lateral vibration. In the present study, torsional effects were implicitly captured through the three-dimensional modeling and largely remained limited when damage was symmetric or confined to a single column line, resulting in a response dominated by bending modes. However, under asymmetric damage conditions, increased torsional sensitivity may reduce the effectiveness of modal-based indicators that primarily rely on translational mode shapes. Since the experimental excitation and sensor arrangement were aligned with the principal direction of motion and the analysis focused on lower-order global modes, higher-order torsional modes were not explicitly examined.

6.3.3 Irregular Framed Model

The irregular frame model, modified by attaching additional mass blocks at the 6^{th} storey, was analysed under the same multiple damage scenarios. The results for this case are presented in Fig. 6.8, Fig. 6.9, and Fig. 6.10.

Similar to the regular frame, the DMSS method (Fig. 6.8 (a), Fig. 6.9 (a), and Fig. 6.10 (a)) failed to detect damages in all scenarios. The distributions showed misleading peaks at intermediate storeys, offering no reliable localization of the introduced damages.

On the other hand, the DMSC method successfully captured the damage in most scenarios. In Cases 1 and 2, where damages were introduced between the 3^{rd}–4^{th} and 5^{th}–6^{th} storeys on the same and opposite edges, respectively, the DMSC plots (Fig. 6.8 (b) and 6.9 (b)) exhibited steep slope variations at the correct damage locations. These results highlight the strong sensitivity of curvature-based indices to stiffness reduction, even in geometrically irregular systems.

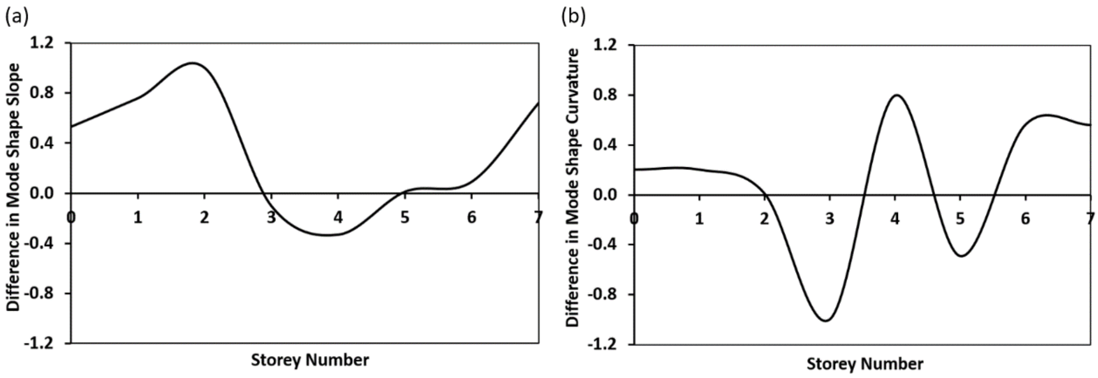


Fig. 6.8: (a) DMSS and (b) DMSC plots of the case with damages between the 3^{rd}–4^{th} and 5^{th}–6^{th} storeys, located on the same edge of the irregular model

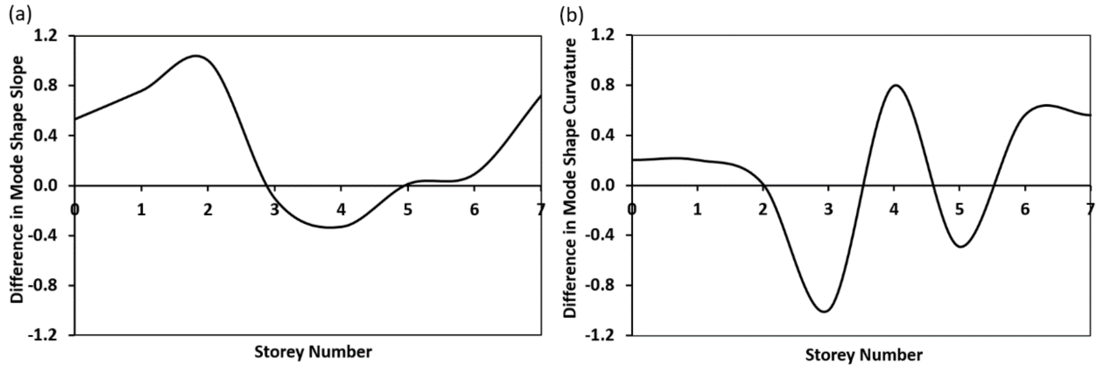


Fig. 6.9: (a) DMSS and (b) DMSC plots of the case with damages between the 3rd–4th and 5th–6th storeys, located on the opposite edges of the irregular model

However, in Case 3, where damages were introduced near the fixed and free ends (0–1st and 6th–7th storeys), the DMSC method (Fig. 6.10 (b)) failed to identify the damage. This mirrors the findings in the regular frame model, reaffirming that damages close to boundaries remain challenging to detect using curvature-based approaches due to low modal curvature and weak dynamic response at these zones.

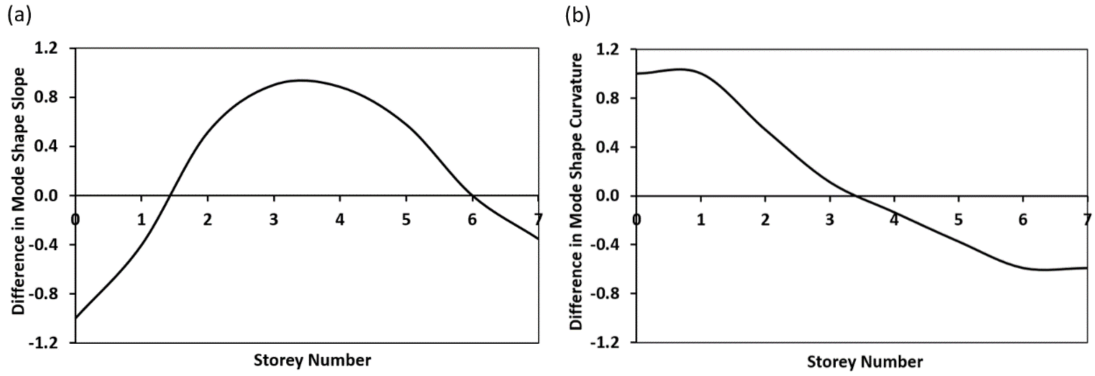


Fig. 6.10: (a) DMSS and (b) DMSC plots of the case with damages between the 0–1st and 6th–7th storeys, located on the same edge but near the fixed end and free end of the irregular model

Interestingly, a comparison of the DMSS and DMSC results between regular and irregular frames shows that the introduction of irregularity did not significantly affect the overall shape or behavior of the indices. The curves remained almost identical across both models, suggesting that the additional mass blocks did not alter the detection capability of either method. This indicates that DMSS and DMSC are robust against geometric and mass-related irregularities, though their limitations near supports persist regardless of frame regularity.

6.4 Damage Detection at Joints

The results for the framed model with joint damage scenario is presented in Fig. 6.11. As shown in Fig. 6.11 (a), the DMSS plot exhibited a peak near the 2nd storey but failed to correctly identify the actual joint damage location. Similarly, the DMSC distribution in Fig. 6.11 (b) showed a slope variation near the 2nd storey, but once again, the observed response did not correspond to the true position of the damage.

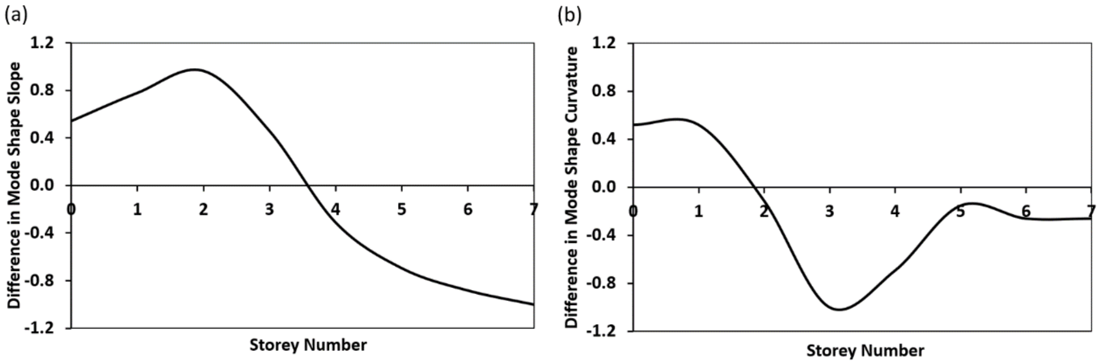


Fig. 6.11: (a) DMSS and (b) DMSC plots of the case with a damage at a joint of the 4th storey

These results clearly indicate that neither DMSS nor DMSC methods were effective in detecting joint damages in framed structures. Unlike column or beam element damages along the span, where stiffness reduction induces noticeable changes in mode shapes and curvature distributions, joint damages tend to manifest more subtly in the global vibration response. The localized stiffness loss at joints is often masked by the surrounding redundancy of the frame system, leading to insignificant variations in mode shape slopes and curvatures. Another contributing factor is that joints are highly constrained regions, where modal displacements and curvatures are inherently small. As a result, the sensitivity of displacement curvature–based indicators is significantly reduced in these zones.

6.5 Summary and Limitations of DMSS and DMSC Methods

Table 6.1 presents a consolidated summary of the performance of the Difference in Mode Shape Slope (DMSS) and Difference in Mode Shape Curvature (DMSC) methods across all single and multiple damage detection scenarios. The results provide clear insights into the relative strengths and weaknesses of both indices.

TABLE 6.1: SUMMARY OF THE RESULTS FROM THE DAMAGE DETECTION

	Scenario	**Damage Location**	**Resonance Frequency (Hz)**	**DMSS**	**DMSC**
Regular Model	S-1	3rd-4th	12.912	✅	✅
	M-1	3rd-4th, 5th-6th – Same Edge	13.070	❌	✅

	M-2	2^{nd}-3^{rd}, 5^{th}-6^{th} – Same Edge	12.948	❌	✅
	M-3	3^{rd}-4^{th}, 5^{th}-6^{th} – Opposite Edges	13.053	❌	✅
	M-4	0-1^{st}, 6^{th}-7^{th} – Same Edge	12.882	❌	❌
	J-1	3^{rd}	11.652	❌	❌
Irregular Model	S-1	3^{rd}-4^{th}	11.506	✅	✅
	M-1	3^{rd}-4^{th}, 5^{th}-6^{th} – Same Edge	11.631	❌	✅
	M-2	3^{rd}-4^{th}, 5^{th}-6^{th} – Opposite Edges	11.619	❌	✅
	M-3	0-1^{st}, 6^{th}-7^{th} – Same Edge	11.493	❌	❌

* S – Single Damage; M – Multiple Damage; J – Joint Damage

Overall, the findings indicate that:

- Both DMSS and DMSC methods are effective for detecting and localizing single and multiple damages in simple beam structures, showing consistent agreement with the introduced damage positions.
- For framed structures, the DMSS method is only reliable in single damage scenarios. It consistently failed to detect multiple damages, highlighting its limited robustness in more complex systems.
- The DMSC method demonstrated superior performance, successfully detecting both single and multiple damages in framed structures, except for cases where damages were located near the fixed ends, free ends or at the joints.
- Both methods were insensitive to damages near structural boundaries, such as the fixed base and free end, suggesting reduced modal sensitivity at these regions.
- Structural irregularity (mass blocks added at higher stories) did not significantly affect detection accuracy, as the outcomes for regular and irregular frames were nearly identical.
- Similarly, vertical axis variation in multiple damage scenarios (same vs. opposite edges) did not influence detection results.

These observations collectively highlight that while both methods are useful tools for modal-based damage detection, DMSC is more reliable than DMSS in complex structural systems, especially for multiple damage cases.

6.5.1 Limitations of the Methods

DMSS

- Effective for single and multiple damage detection and localization in simple beam structures.
- Only reliable for single damage detection in framed structures.
- Consistently failed to locate damages near fixed and free ends, limiting its applicability in boundary regions.

DMSC

- Effective for single and multiple damage detection and localization in simple beam structures.
- Reliable for detecting both single and multiple damages in complex framed structures.
- Similarly, failed to accurately detect damages near fixed and free ends, indicating a shared limitation with DMSS.

6.6 Damage Severity Estimation

This section presents the damage severity estimation of the beam and framed models using the structural damage severity estimation procedure based on the grey relation coefficient and mode shape curvature. Mode shapes were first obtained through modal analysis, and then the arithmetic operation outlined in Fig. 5.9 was applied to quantify the severity of damage in the models.

6.6.1 Beam Model

The intact and damaged beam models used in the validation study were initially analysed for damage severity estimation before extending the procedure to frame models. Damage was introduced in the 5th, 10th, 13th, and 18th elements of the beam by varying (reducing) the elastic modulus to simulate four severity levels: 10%, 25%, 50%, and 75% reductions.

Fig. 6.12 presents the DMSS and DMSC plots for the four levels of damage severity when the damage was at 5th element of the beam model. In Fig. 6.12 (a), the minimum DMSS values were observed for the 75% damage case, while the least pronounced differences were recorded at 25% severity. Similarly, Fig. 6.12 (b) shows that the steepest slope in the DMSC curve corresponded to the 75% damage, whereas the least steep slope was observed for the 25% damage case.

These results demonstrate that both DMSS and DMSC indices are sensitive to variations in damage severity, with their magnitudes increasing consistently as the damage level intensifies.

Overall, the findings confirm that mode shape–based indicators not only localize damage but can also provide a reliable measure of its intensity. However, while DMSS and DMSC provide sensitivity to changes in stiffness, they do not directly quantify the percentage of severity. For this reason, the study further focused on applying the grey relation coefficient (GRC) method to estimate the actual severity levels in the beam model.

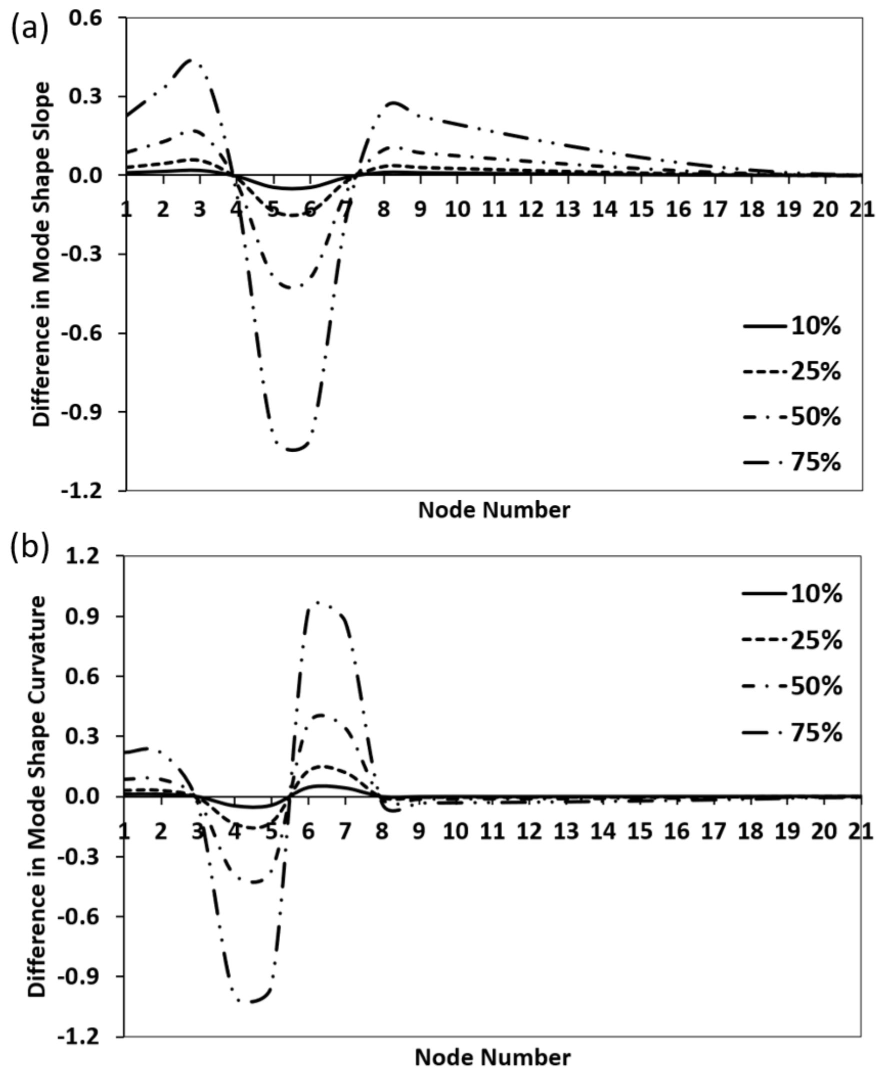


Fig. 6.12: (a) DMSS and (b) DMSC plots of the beam model with different damage intensities when the damage is at 5th element

With this observation, the analysis was extended to directly estimate damage severity in the beam element using the Grey Relation Coefficient (GRC) approach. Figure 6.13 presents the severity estimation results for four damage levels—10%, 25%, 50%, and 75% stiffness reductions—introduced at four different beam locations (5th, 10th, 13th, and 18th elements). In each case, the estimated damage severity (blue bars) is compared with the actual introduced damage (orange bars).

- 10% Damage (Fig. 6.13 (a)): The estimated severity showed a slight underestimation when damage was introduced at the 5th element, while very close agreement with the actual value was observed for the 10th and 13th elements. A minor overestimation occurred when the damage was located at the 18th element. These results demonstrate that the method is sufficiently sensitive to detect small stiffness reductions, although minor deviations may occur at low damage levels. Furthermore, a clear trend was observed in which the estimated severity gradually shifted from underestimation to overestimation as the damage location moved from the fixed end toward the free end of the beam.
- 25% Damage (Fig. 6.13 (b)): A similar pattern was observed. Slight underestimation occurred when damage was introduced at the 5th element; however, excellent agreement between the estimated and actual severities was achieved overall. The transition from underestimation near the fixed end to slight overestimation toward the free end remained consistent with the 10% damage scenario, highlighting the robustness and reliability of the GRC method for moderate damage levels.
- 50% Damage (Fig. 6.13 (c)): The estimated severity slightly overestimated the actual damage for the first damage scenario but remained reasonably close to the true value. However, for damage introduced at the 10th, 13th, and 18th elements, the estimated severities were noticeably higher than the actual damage level. This indicates a decreasing sensitivity of the method to both damage severity and location as stiffness degradation becomes more pronounced.
- 75% Damage (Fig. 6.13 (d)): The method significantly overestimated the damage severity, with estimated values reaching approximately 96% compared to the actual 75% in the first damage scenario. This overestimation became more pronounced as the damage location shifted toward the free end of the beam. Such behavior suggests a loss of proportional accuracy at high damage levels, likely due to nonlinear structural effects and the amplified sensitivity of mode shape curvature under large stiffness reductions, where the assumptions of linear modal analysis are less valid.

From these findings, two key observations can be made:

1. Accuracy at Low-to-Moderate Severity: For damage severities up to 50%, the GRC method produced estimates that closely matched the actual damage, demonstrating its suitability and reliability for early-stage and moderate damage detection in practical structural health monitoring applications.
2. Reduced Reliability at High Severity: At higher damage severity (75%), the method exhibited a clear tendency to overestimate damage, indicating reduced reliability under severe stiffness degradation. This limitation is likely

associated with nonlinear structural behavior and limitations inherent in linear modal-based approaches.

Overall, the findings confirm that the Grey Relation Coefficient method is an effective and reliable tool for damage severity estimation, particularly for early detection and moderate damage scenarios. Although its accuracy decreases at very high damage levels, this limitation is less critical in real-world applications, where intervention is typically expected before damage progresses to severe stages.

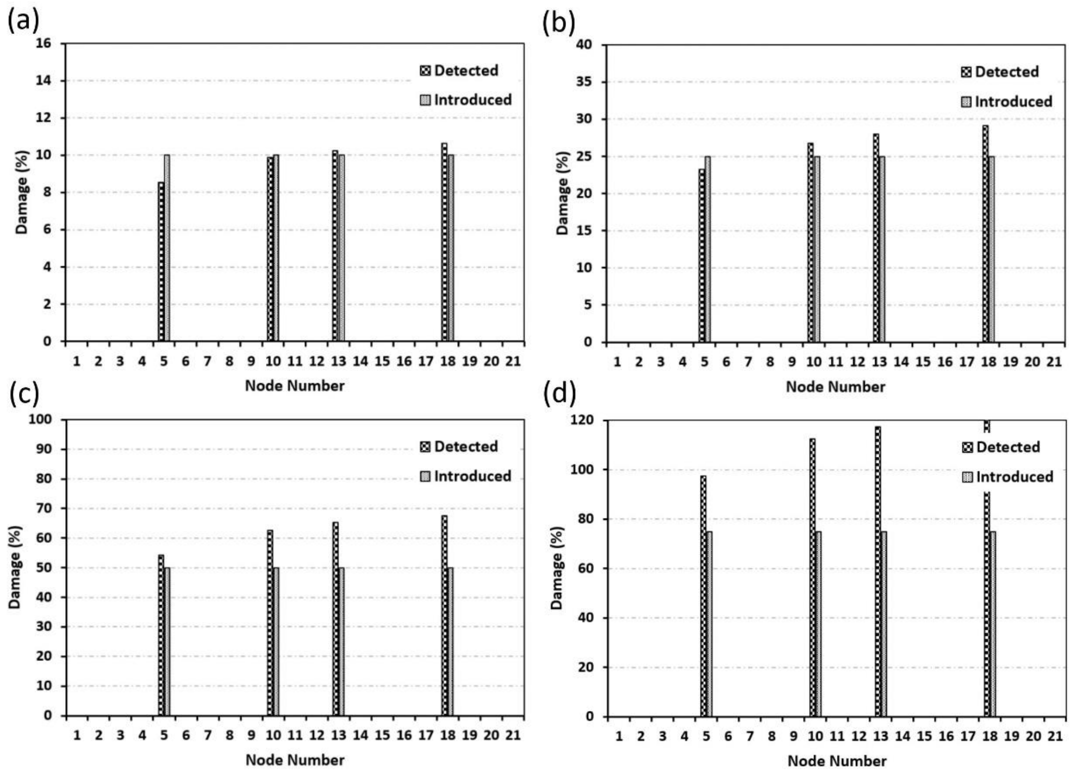


Fig. 6.13: Damage severity estimation of the beam structure for the (a) 10%, (b) 25%, (c) 50%, and (d) 75% scenarios using the arithmetic operation

6.6.2 Framed Model

The intact and damaged framed models used in the validation study were next analysed for damage severity estimation. Damage was introduced between the 3rd and 4th storeys by varying (reducing) the column diameter to simulate five severity levels: 6 mm, 8 mm, 10 mm, 12 mm, and 14 mm, as summarized in Table 5.3.

Fig. 6.14 presents the DMSS and DMSC plots for the five damage severity cases. In Fig. 6.14 (a), the minimum DMSS values were observed for the 6 mm column damage case, while the least pronounced differences were recorded for the 14 mm column case. Similarly, Fig. 6.14 (b) shows that the steepest slope in the DMSC curve corresponded to the 6 mm column damage, whereas the 14 mm column damage produced the smallest curvature variation. These results confirm that, consistent with the beam model, both DMSS and DMSC indices are sensitive to variations in damage severity, with their magnitudes increasing as the level of stiffness reduction intensifies.

However, as with the beam model, DMSS and DMSC alone cannot directly quantify the percentage of damage severity. Therefore, the grey relation coefficient (GRC) method was applied to estimate the actual severity levels in the framed model.

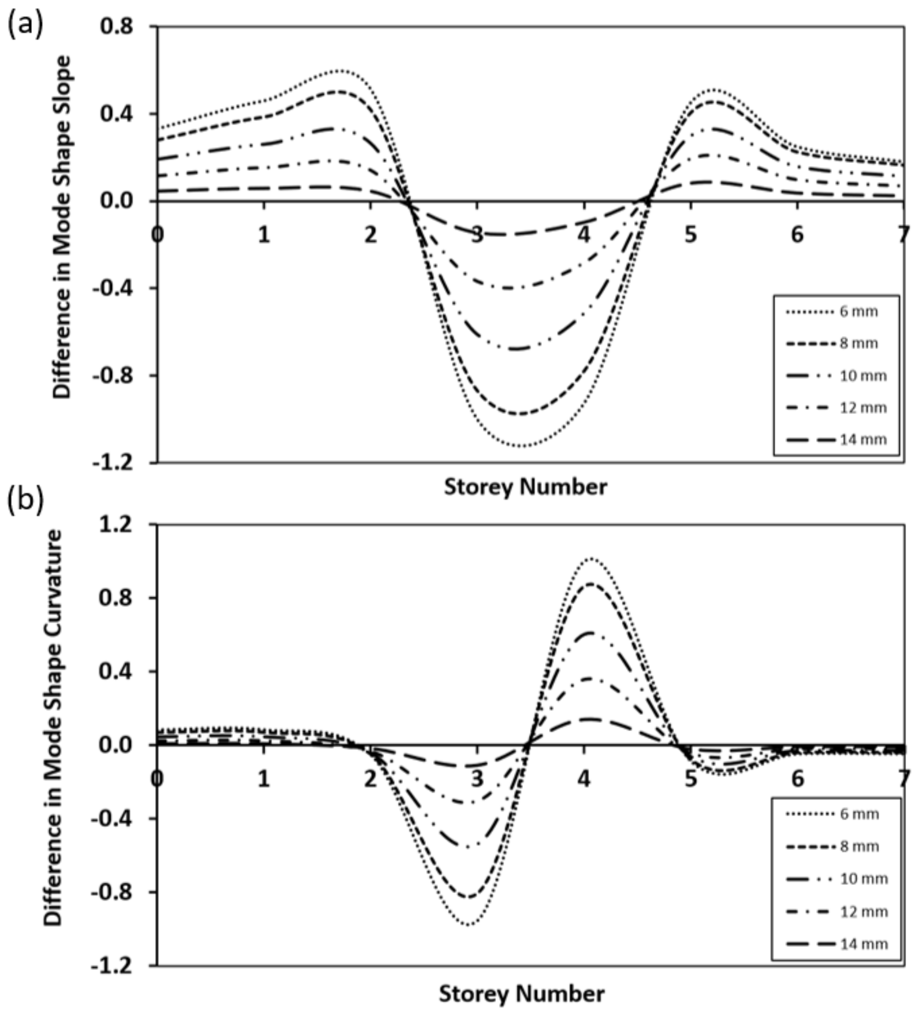


Fig. 6.14: (a) DMSS and (b) DMSC plots of the frame model with different damage intensities between 3rd and 4th storeys

Fig. 6.15 presents the GRC-based estimation results, where the introduced damage (orange bars) is compared against the estimated damage (blue bars) for the five column diameter cases:

- 6 mm column (Fig. 6.15 (a)): The estimated severity was lower than the actual value but remained close to the target. This suggests that the method is able to capture higher levels of stiffness reduction in frame structures, though with some underestimation.
- 8 mm column (Fig. 6.15 (b)): The estimated severity was significantly underestimated, at less than half of the actual damage. This indicates a limitation of the method in capturing intermediate damage levels, where the modal response differences may not be sufficiently amplified.

- 10 mm, 12 mm, and 14 mm columns (Fig. 6.15(c–e)): For these cases, the GRC values exceeded 0.6, resulting in the estimation of damage severity as 0%. This outcome demonstrates that the method failed to recognize low-to-moderate damage intensities in the frame model.

These findings highlight an important distinction between beam and frame applications. While the GRC method showed strong performance in the beam model—accurately estimating damage up to 50% severity and only overestimating at the highest level—its application to framed structures revealed significant limitations. In particular, the method struggled to quantify damage severity at low-to-moderate levels, where structural redundancy and the distribution of stiffness among multiple members reduce the sensitivity of modal parameters to estimate changes.

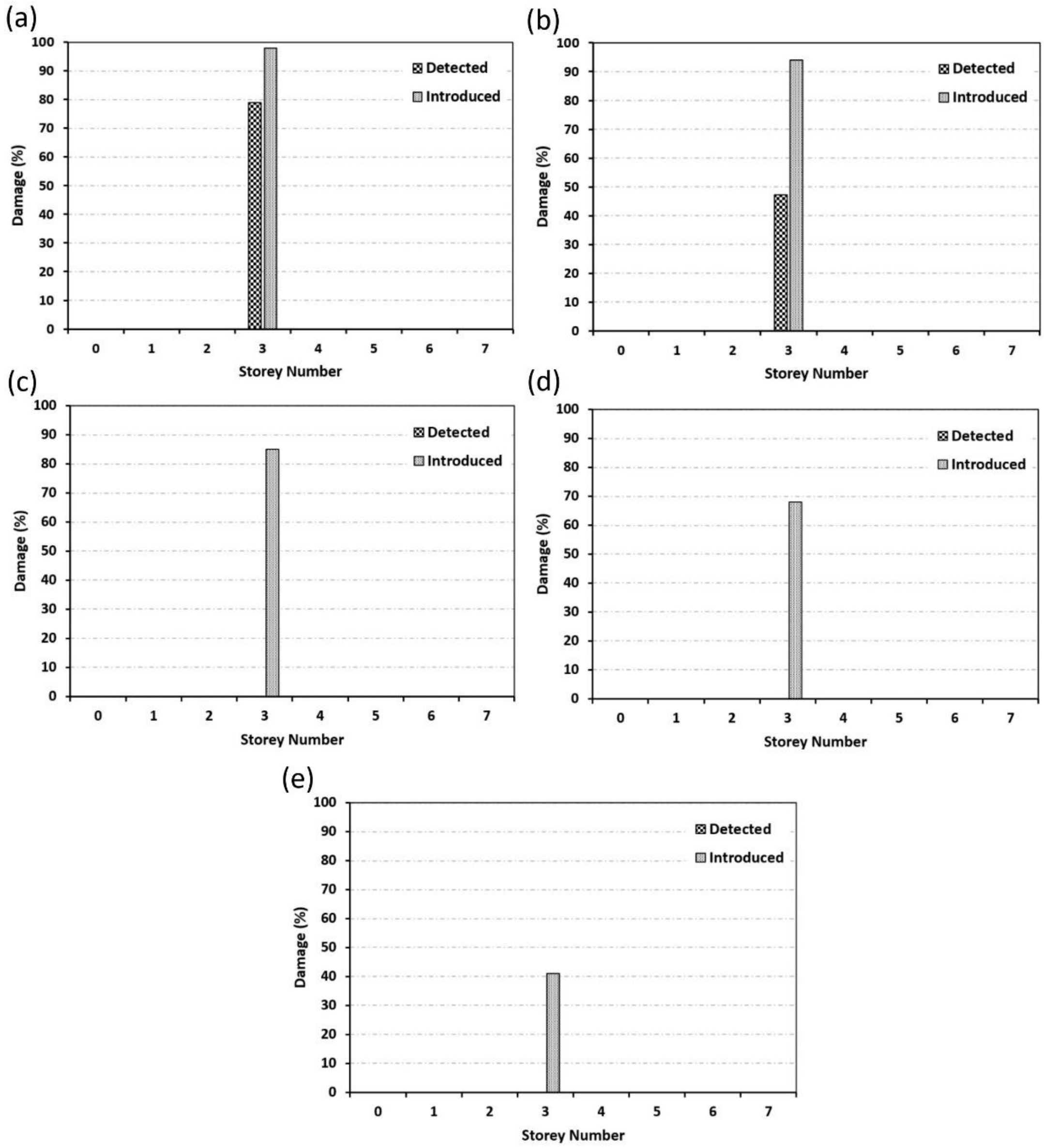


Fig. 6.15: Damage severity estimation of the framed structure for the (a) 6 mm, (b) 8 mm, (c) 10 mm, (d) 12 mm, and (e) 14 mm scenarios using the arithmetic operation

6.6.3 Summary of the Damage Severity Estimation Method

Overall, the results suggest that while the GRC method remains promising for simple structures such as beams, its accuracy decreases when applied to more complex framed structures. This reduced effectiveness may be attributed to:

1. Modal energy distribution in frames, where localized stiffness reductions are less dominant compared to the global system behavior.
2. Interaction between multiple members, which masks the localized damage effects in the global mode shapes.
3. Thresholding in GRC interpretation, where high similarity values (>0.6) cause moderate damage to be misclassified as undamaged.

In summary, the GRC-based approach provided partial success in estimating damage severity for the framed model, being reasonably effective only at higher levels of stiffness reduction (6 mm case). However, for intermediate and low damage scenarios, the method underestimated or completely failed to detect severity. This underlines the need for refinements or hybrid approaches—such as combining GRC with additional modal or frequency-based features—to improve robustness when applied to complex frame systems.

6.7 Chapter Summary

This chapter presented and discussed the results obtained from experimental and numerical analyses aimed at evaluating modal-based damage detection, localization, and severity estimation techniques. The Difference in Mode Shape Slope (DMSS) and Difference in Mode Shape Curvature (DMSC) indices were applied to a range of single and multiple damage scenarios in both regular and irregular framed structures, as well as in beam models used for validation. The comparison of the two indicators revealed their relative strengths and limitations, particularly in identifying damages near boundary regions and joint locations. Furthermore, the chapter examined the applicability of the grey relation coefficient (GRC)–based method for damage severity estimation, highlighting its accuracy in simple structural systems and its reduced reliability in complex framed structures due to distributed stiffness effects. Overall, the chapter provided a detailed interpretation of the modal-based analyses performed, demonstrating the potential and challenges of DMSS, DMSC, and GRC techniques in enhancing SHM frameworks for framed systems.

CHAPTER 7

CONCLUSION

7.1 Overview

The primary aim of this research was to investigate enhanced modal-based techniques for structural damage detection, localization, and estimation in framed structures, utilizing both experimental and computational methods to improve the accuracy and reliability of structural health monitoring (SHM). To achieve this aim, four key objectives were pursued: (i) a review of SHM principles and the limitations of existing modal-based damage detection techniques; (ii) the experimental investigation of the effects of induced damages on modal parameters using shake table tests; (iii) the development and validation of finite element (FE) models to conduct parametric studies across different damage scenarios; and (iv) the evaluation of the effectiveness of modal-based methods for multiple damage detection, localization, and severity estimation in framed structures. This chapter synthesizes the main findings, contributions, limitations, and implications of the study while also providing recommendations for future research directions.

7.2 Summary of Experimental and Numerical Findings

The research began by conducting a detailed experimental study on a scaled seven-storey steel framed structure using shake table testing. Damages were introduced by reducing column diameters and irregularities were simulated by attaching additional masses. The results consistently showed that resonance frequencies decreased with both damage and irregularity, confirming the fundamental principle that modal parameters are highly sensitive to stiffness reduction in structural systems. These findings not only validated the feasibility of modal-based approaches but also provided an empirical foundation for subsequent numerical modelling.

FE models developed in ABAQUS were then employed to replicate the intact, damaged, and damaged–irregular structural scenarios. The numerical predictions were found to be in close agreement with the experimental resonance frequencies, thereby confirming the reliability of the FE models. Once validated, these models were used for a series of parametric studies to investigate various single, multiple, and joint damage scenarios in beams and framed structures. This combination of experimental and computational approaches directly addressed the second and third objectives of the research by systematically establishing a framework for testing and validating modal-based damage detection methods.

7.3 Performance of DMSS and DMSC Methods

The evaluation of modal-based damage detection techniques centered on the Difference in Mode Shape Slope (DMSS) and the Difference in Mode Shape Curvature (DMSC), both of which were applied to beam and frame structures under different damage scenarios.

In the case of simple beam models, both DMSS and DMSC demonstrated high sensitivity and accuracy for identifying single and multiple damages. The methods reliably pinpointed the locations of stiffness reductions, although their accuracy decreased near free ends, indicating boundary-related sensitivity issues.

For framed structures, the performance diverged. DMSS was able to identify single damage scenarios but consistently failed to detect multiple damages. By contrast, DMSC proved more robust, successfully detecting both single and multiple damages in framed structures. Importantly, the presence of irregularities introduced by additional masses did not significantly impair the performance of either method, suggesting a degree of robustness to vertical mass variations. However, both methods failed to detect damages introduced near the fixed ends, free ends, or at the joints of framed structures, highlighting a critical limitation when applied to connection-sensitive systems.

Through these investigations, the study addressed the fourth objective of the research, demonstrating that while DMSS has limited applicability in complex systems, DMSC offers greater promise for multiple damage detection and localization in framed structures.

7.4 Damage Severity Estimation

Beyond damage detection and localization, this study explored the estimation of damage severity using a Grey Relation Coefficient (GRC)-based approach, combined with mode shape curvature differences.

In beam models, the GRC-based method produced encouraging results. For lower levels of damage (10% and 25%), the estimated severities closely matched the actual values, while for intermediate damage (50%), the method slightly overpredicted but remained accurate. At higher levels (75%), the method significantly overestimated severity, yet still captured the general trend of increasing damage. This indicates that the method is well-suited for moderate damage levels in simple structural systems but requires refinement to handle more severe cases.

In framed models, however, the performance was less consistent. For severe damages (6 mm diameter columns), the method underestimated severity but still indicated a significant level of damage. For moderate and lower damage levels (8 mm, 10 mm, 12 mm, and 14 mm columns), the method failed to provide reliable estimates, with several cases being misclassified as zero damage. This suggests that while the GRC approach is effective for beams, its extension to complex framed structures requires further development, particularly for detecting subtle reductions in stiffness across distributed structural elements.

7.5 Research Contributions

This study makes several significant contributions to the field of SHM. Firstly, it demonstrated the successful integration of shake table experiments with FE modelling, providing a validated framework for testing and extending modal-based methods. Secondly, it offered a comparative evaluation of DMSS and DMSC methods across beams and framed structures, clearly defining their relative strengths and weaknesses. Thirdly, it evaluated a GRC-based severity estimation approach, offering new insights into its applicability and limitations across different structural configurations. Collectively, these contributions extend the understanding of modal based SHM techniques, particularly in the context of complex framed structures, and provide a foundation for future methodological advancements.

7.6 Limitations of the Study

Despite its contributions, this study has several limitations. The DMSS and DMSC methods exhibited boundary sensitivity, consistently failing to detect damages near fixed and free ends of structures. Neither method proved effective in detecting joint damages, highlighting their limitations when applied to connection-dominated systems. The GRC-based severity estimation method performed well for beam models but lacked accuracy in complex framed structures, particularly at lower damage levels. Additionally, the experimental study was limited to a scaled laboratory model, which, while useful for validation, may not capture the full range of complexities present in full-scale real-world structures.

7.7 Final Remarks

In conclusion, this research has successfully achieved its stated aim of investigating enhanced modal-based techniques for structural damage detection, localization, and estimation in framed structures. Through experimental validation, FE modelling, and comparative analysis, it has been shown that while DMSS and DMSC are capable of providing valuable diagnostic information, their performance is strongly influenced by structural complexity, boundary conditions, and the type of damage introduced. The GRC-based approach offers promise for severity estimation, particularly in simple systems, but requires further refinement for practical application in framed structures. Overall, the findings of this study contribute to advancing the field of SHM and provide a foundation for future research aimed at developing more accurate, robust, and scalable damage detection techniques for real-world applications.

7.8 Recommendations for Future Research

Future research should focus on addressing these limitations in several ways. First, developing enhanced boundary-sensitive methods or hybrid indicators may help overcome detection failures near supports. Second, integrating modal-based methods with localized sensing techniques, such as strain gauges or digital image correlation, could improve joint damage detection. Third, refining the GRC approach for framed structures, potentially through the incorporation of multiple modal parameters or coupling with machine learning techniques, could enhance severity estimation accuracy. Fourth, extending this research to full-scale or field applications would provide valuable insights into scalability and environmental effects on detection performance. Finally, integrating traditional modal analysis with advanced data-driven approaches, such as deep learning models, may offer real-time, robust monitoring solutions for complex structural systems.

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