

EVALUATION OF DYNAMIC RESPONSE OF STEEL FRAME MOUNTED ON A SHAKE TABLE USING DIGITAL IMAGE CORRELATION TECHNIQUE

A PROJECT REPORT

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OF

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Submitted by

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I, Barjesh Kainth, Roll No's – 2K24/STE/22. students of M.Tech (Structural engineering), hereby declare that the project Dissertation titled “The DYNAMIC RESPONSE OF STEEL FRAME MOUNTED ON SHAKE TABLE USING DIGITAL IMAGE CORRELATION TECHNIQUE ” which is submitted by us to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of degree of Bachelor of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled “THE DYNAMIC RESPONSE OF STEEL FRAME MOUNTED ON SHAKE TABLE USING DIGITAL IMAGE CORRELATION TECHNIQUE ” which is submitted by Barjesh Kainth, Roll No’s – 2K24/STE / 22, Department of Civil Engineering ,Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the Master of Technology degree is a record of the project work carried out by the students under my To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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Abstract

Accurate assessment of structural dynamic response under seismic excitation is critical for the continuous evaluation and resilient design of infrastructure. This study presents a comprehensive experimental investigation into the dynamic behavior of a scaled three-storey steel frame model subjected to horizontal shake table testing across varying excitation frequencies. To capture the structural response, a dual-measurement approach was employed, contrasting traditional contact-based sensing with advanced optical techniques. Accelerometers were installed at each floor level to record structural acceleration data, which was subsequently processed using vibration analysis and Fast Fourier Transform (FFT) algorithms to derive peak frequency responses and dynamic displacements. Concurrently, Digital Image Correlation (DIC), a high-resolution non-contact measurement method, was utilized to evaluate the spatial deformation characteristics of the frame. By tracking full-field surface displacements during excitation, the DIC method successfully extracted the structural mode shapes and inter-storey drift ratios without adding localized mass or altering the frame's inherent dynamic properties. The comparative analysis evaluates the precision, practical implementation, and data-richness of DIC against conventional accelerometer-derived metrics. Ultimately, this research highlights the efficacy of non-contact optical sensing methodologies in advancing structural health monitoring and provides a robust framework for capturing highly detailed kinematic data in structural assessments.

Contents

Candidate's Declaration	i
Certificate	ii
Acknowledgement	iii
Abstract	iv
Content	vi
List of Figures	vii
1 Introduction	viii
1.1 Background and Motivation	viii
1.2 System Identification Using Digital Image Correlation	viii
1.3 Floor Amplification by Non-Contact Methods	ix
1.4 Research Objectives	ix
1.5 Scope of Work	ix
2 LITERATURE REVIEW	2
3 METHODOLOGY	5
3.1 Overview of Experimental Program	5
3.2 Test Specimen and Setup	5
3.3 Instrumentation Plan	5
3.3.1 Conventional Sensing (Accelerometers)	5
3.3.2 Non-Contact Sensing (Digital Image Correlation)	5
3.4 Experimental Protocol	6
3.5 Data Processing and Analysis	6
3.5.1 Accelerometer Signal Processing	6
3.5.2 DIC Post-Processing	6
3.6 Extraction of Dynamic Characteristics	6
3.7 Three-Storey Steel Frame Model	7
3.7.1 Experimental Scale Models	7
3.7.2 Weight of Frame	7
3.8 Horizontal Shake Table System	7
3.9 MEMS Accelerometers Instruments	8
3.10 DIC System Setup and Speckle Preparation	8
3.10.1 2D DIC (Single Camera Setup)	9
3.10.2 Speckle Preparation	9
3.11 Camera Positioning and Rigid Isolation	10

3.11.1	High-Intensity Lighting	11
3.11.2	System Calibration	11
3.11.3	Data Acquisition Synchronization	11
3.11.4	Selecting the Right Frame Rate (FPS)	11
3.12	Theoretical Structural Foundations	12
3.12.1	Digital Image Correlation (DIC) Theoretical Framework	12
3.12.2	Floor Amplification Mechanics	13
4	RESULTS and DISCUSSION	14
4.1	Frequency Sweep Test Results	14
4.2	Floor-by-Floor Acceleration Analysis	15
4.2.1	First Floor Response	15
4.2.2	Second Floor Response	15
4.2.3	Third Floor (Roof) Response	15
4.3	DIC Results — Non-Contact System Identification	15
4.3.1	Full-Field Displacement Measurements	15
4.3.2	Mode Shape and Storey Drift from DIC	16
5	CONCLUSION	37
5.1	Conclusions	37
5.2	Recommendations for Future Work	38

List of Figures

3.1	3 Storey steel frame	7
3.2	3 Storey steel frame	7
3.3	Horizontal Shake Table	8
3.4		9
3.5	Accelerometer	9
3.6	Speckles	10
3.7	Digital Image Correlation (DIC) Visualizer	13
4.1	Displacement Mode Shapes and Corresponding Storey Drifts at 3Hz. . . .	16
4.2	Normalized Displacement Mode Shapes and Corresponding Storey Drifts at 3Hz.	16
4.3	Normalized Displacement Mode Shapes and Corresponding Storey Drifts at 3.5Hz.	18
4.4	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (4_output).	19
4.5	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (4.5_output).	20
4.6	Normalized Displacement Mode Shapes and Corresponding Storey Drifts at 5.0Hz.	22
4.7	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (5.5_output).	23
4.8	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (6_output).	25
4.9	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (6.5_output).	26
4.10	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (7_output).	27
4.11	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (8.5_output).	29
4.12	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (9_output).	30
4.13	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (10_output).	32
4.14	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (10.5_output).	33
4.15	Normalized Displacement Mode Shapes and Corresponding Storey Drifts (11_output).	35

Chapter 1

Introduction

1.1 Background and Motivation

The accurate evaluation of a structure's dynamic response is a fundamental pillar of modern seismic engineering. As infrastructure becomes more complex, the ability to precisely measure parameters such as displacement, mode shapes, and story drift during seismic events is critical for assessing structural integrity and validating design codes. Traditionally, dynamic response evaluation during shake table testing relies on contact sensors, primarily accelerometers and non contact Methods (Digital correlation technique). While these instruments are highly reliable, they present inherent limitations: they are susceptible to low-frequency noise, require complex wiring networks, add artificial mass to lightweight scaled models, and, most importantly, only provide discrete point measurements. To find displacement, acceleration time-history data must undergo double integration, a mathematical process notoriously prone to baseline drift and error accumulation. These limitations motivate the adoption of advanced non-contact optical techniques. Digital Image Correlation (DIC) has emerged as a powerful, non-destructive evaluation tool capable of capturing full-field, high-resolution displacement data. By tracking a random speckle pattern applied to the structure's surface during dynamic excitation, DIC eliminates the physical constraints of contact sensors. The primary motivation of this research is to bridge the gap between traditional point-sensing methods and modern full-field optical measurements, demonstrating the efficacy of DIC in capturing complex structural behaviors under dynamic loads.

1.2 System Identification Using Digital Image Correlation

System identification involves extracting the dynamic characteristics of a structure—such as its natural frequencies, damping ratios, and mode shapes—from experimental data. In traditional setups, structural acceleration data is recorded and processed via signal processing techniques, such as applying a Fast Fourier Transform (FFT) to derive peak acceleration versus frequency results. In contrast, DIC natively tracks spatial coordinates across the entire region of interest over time, calculating direct displacement rather than relying on integration. By utilizing high-speed cameras to capture consecutive images of the deforming three-story steel frame, the DIC algorithm correlates subsets of pixels between the reference (undeformed) and target (deformed) images. This allows for the precise, simultaneous extraction of lateral displacements at every story level. Conse-

quently, the structure's mode shapes and inter-story drifts can be visualized and quantified directly from the optical data, offering a more comprehensive spatial understanding of the frame's dynamic properties than discrete accelerometer arrays can provide.

1.3 Floor Amplification by Non-Contact Methods

Floor amplification—the phenomenon where acceleration and displacement demands generally increase with the height of a multi-story building—is a critical factor in the design of structural components and non-structural elements. Accurately profiling this amplification along the height of a frame is challenging with traditional sensors, as they interpolate behavior between discrete floor nodes. Non-contact methods like DIC excel in this domain. By capturing the continuous displacement field along the entire height of the columns and beam-column joints, DIC provides an uninterrupted gradient of floor amplification. This allows for a highly granular analysis of how dynamic energy propagates through the three-story steel frame from the shake table base to the roof, capturing localized drifts and rotation effects that might be missed by isolated accelerometers.

1.4 Research Objectives

The primary aim of this thesis is to evaluate the dynamic response of a scaled three-story steel frame using both traditional contact sensors and advanced optical methods. The specific objectives are:

- To conduct dynamic shake table testing on a three-story steel frame under horizontal excitations across various frequencies.
- To measure structural accelerations using traditional contact sensors and process the data in the frequency domain to establish baseline displacement and acceleration profiles.
- To implement Digital Image Correlation (DIC) as a non-contact method for directly extracting full-field displacement data during the dynamic excitation.
- To determine and analyze the mode shapes, inter-story drift ratios, and continuous floor amplification factors utilizing the DIC method.
- To systematically compare the performance, accuracy, and operational limitations of the DIC method against the accelerometer-derived data.

1.5 Scope of Work

The scope of this research is confined to the experimental testing and analytical evaluation of a rigid three-story steel frame model subjected to uni-directional horizontal base excitation on a shake table. The experimental phase involves applying a high-contrast speckle pattern to the frame, calibrating the DIC camera system, and deploying an array of accelerometers. The testing protocol will subject the frame to harmonic loading at varying frequencies to capture steady-state and resonant behaviors. The analytical phase encompasses the post-processing of optical images using DIC software to track target subsets,

alongside the signal processing of accelerometer data. The study focuses strictly on the elastic and early inelastic dynamic response of the frame, culminating in a comparative analysis of system identification parameters obtained from both methodologies.

Thesis Organization This thesis is structured into six chapters, outlined as follows:

- Chapter 1: Introduction outlines the background, motivation, objectives, and scope of the research.
- Chapter 2: Literature Review synthesizes existing research on shake table testing, traditional system identification methods, and the application of DIC in structural engineering.
- Chapter 3: Experimental Setup and Methodology details the design of the three-story steel frame, shake table specifications, accelerometer placement, and the optical setup required for DIC.
- Chapter 4: Data Processing and Analysis explains the mathematical and computational procedures used to extract displacement from acceleration data (e.g., filtering and integration) and the spatial tracking algorithms utilized by the DIC software.
- Chapter 5: Results and Discussion presents a comprehensive comparison of the dynamic responses, specifically focusing on mode shapes, story drift, and floor amplification derived from both methods.
- Chapter 6: Conclusion and Future Scope summarizes the key findings of the comparative study and suggests potential avenues for future research in non-contact structural health monitoring.

Chapter 2

LITERATURE REVIEW

Islam, S. M. Z., Sarker, Md. T. H., & Islam, M. (2025)

The seismic vulnerability of high-rise steel structures featuring vertical geometric irregularities, such as setbacks, remains a critical engineering challenge. Setbacks inherently disrupt the uniform distribution of mass and stiffness, amplifying inter-story drifts and localizing stress during dynamic excitation. Islam et al. (2025) demonstrated through small-scale uniaxial shake table testing that setback steel frames exhibit significantly higher top-story displacements and natural frequencies compared to uniform, regular frames. Consequently, irregular frames are particularly vulnerable to high-frequency seismic waves. To mitigate these amplified seismic demands, advanced structural protection technologies are increasingly integrated. Although passive base isolation, such as Lead Rubber Bearings (LRB), is recognized for decoupling structures from ground motion, its application in vertically irregular frames necessitates careful evaluation. Future experimental comparative studies—specifically assessing rigid multistory frames with and without LRB base isolation under varying frequency shake-table excitations—are vital. Such empirical research is crucial for advancing analytical evaluation methods and refining regional regulatory frameworks, such as the Indian Standard IS 1893, to ensure resilient seismic design.

Pappalardo, C. M., & Guida, D. (2018)

Juang, J. N., Phan, M., Horta, L. G., & Longman, R. W. (1993)

This literature review examines the study by Pappalardo and Guida, which advances experimental modal analysis and system identification methodologies for structural engineering. The authors address the challenge of developing accurate dynamical models strictly from time-domain input-output measurements, utilizing a two-story shear building frame as their primary case study. Methodologically, the study successfully integrates the Observer/Kalman Filter Identification Method (OKID) with the Eigensystem Realization Algorithm (ERA) to extract system Markov parameters, yielding a precise first-order state-space model. A significant theoretical contribution of the research is the subsequent derivation of a realistic second-order mechanical model directly from these state-space representations, which is further enhanced by a least-square approach for estimating proportional damping coefficients. Furthermore, the authors practically apply the identified mechanical model to the optimal design of an actively controlled inertial-based vibration absorber. By implementing a Linear Quadratic Gaussian (LQG) control strategy via a motorized physical pendulum, the authors demonstrate substantial reductions in structural vibrations, successfully validating their proposed time-domain identification and control framework.

Niezrecki, C., Baqersad, J., & Sabato, A. (2019)

Niezrecki et al. present a comprehensive review of Digital Image Correlation (DIC) and photogrammetry for Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM). Traditional sensors, such as accelerometers, are often limited by discrete measurement points and cumbersome wiring requirements. In contrast, 3D-DIC and 3D point tracking (3DPT) provide non-contact, full-field extraction of structural displacements and strain fields. This optical approach is highly effective for dynamic structural applications, including the capture of structural acceleration data during simulated shaking table tests. By recording time-domain displacements and applying signal processing to transform data into the frequency domain, DIC systems accurately identify natural frequencies, mode shapes, and complex vibration characteristics. The study highlights DIC's scalability, demonstrating that advancements in target-less tracking and high-speed image processing are rapidly establishing optical techniques as robust, high-resolution alternatives for advanced structural and vibration analysis.

Hann et al. (2009) present a computationally efficient algorithm for real-time Structural Health Monitoring (SHM) of nonlinear shear-type buildings during seismic events. Their approach addresses limitations in traditional vibration-based methods by directly tracking time-varying stiffness and permanent deformation. The algorithm uniquely relies on high-resolution acceleration data combined with low-frequency displacement measurements, motivated by modern GPS tracking capabilities. By reformulating the differential equations of a Bouc-Wen hysteresis model into an integral-based format, the authors transformed a highly nonlinear optimization process into a rapid, standard piecewise linear least squares problem. The methodology was rigorously validated using both simulated responses and laboratory measurements from a one-fifth scale four-story nonlinear steel frame structure subjected to the El-Centro earthquake record. The results demonstrate that the algorithm accurately identifies permanent residual displacement and structural stiffness, providing critical metrics for rapid safety evaluations and the development of probabilistic fragility functions.

This literature review examines the systematic study by **Mousa et al. (2023)**, which evaluates the application of Digital Image Correlation (DIC) techniques in laboratory structural testing. The paper comprehensively synthesizes the evolution and current state-of-the-art of DIC as a non-contact, full-field optical measurement tool for assessing structural displacements, strains, and fracture mechanics. The authors highlight DIC's significant advantages over traditional discrete sensors, such as strain gauges and LVDTs, emphasizing its high spatial resolution and versatility in capturing complex 2D and 3D deformation behaviors. Furthermore, the review critically discusses the integration of DIC with other Non-Destructive Testing (NDT) methods, alongside prevailing challenges like optimal speckle patterning, calibration complexities, and computational processing demands. By systematically categorizing recent advancements and identifying existing knowledge gaps, the authors provide a foundational framework for future research aimed at optimizing optical measurement techniques in structural engineering.

Digital Image Correlation was introduced by **Peters and Ranson (1982)** and rapidly advanced by **Sutton et al. (1983, 2009)**. The technique matches image subsets between reference and deformed images using normalized cross-correlation, achieving sub-pixel displacement accuracy. Stereo DIC extends this to 3D displacement measurement

by triangulating matched subsets from two calibrated cameras.

Sutton, Orteu, and Schreier (2009) provide the comprehensive reference for DIC methodology, including speckle optimization (3–5 pixel speckles), subset size selection (25–61 pixels), calibration procedures, and uncertainty quantification. Pan et al. (2009) systematically studied DIC errors as a function of subset size, noise, and speckle quality, establishing guidelines for sub-0.01 pixel displacement uncertainty.

Helfrick et al. (2011) first demonstrated extraction of operating deflection shapes from DIC on a vibrating plate, achieving agreement with accelerometer results within 3% — the landmark result establishing DIC for structural dynamics. Ngeljaratan and Sutton (2020) applied stereo DIC to a full-scale steel frame under seismic excitation, reporting displacement accuracy within ± 0.3 mm at 500 fps and frequency deviations below 1.5% from accelerometer data — the most directly comparable precedent to this thesis.

Poozesh et al. (2016) demonstrated DIC-based mode shape extraction on a wind turbine blade with MAC values exceeding 0.95 for the first three modes, confirming DIC as a standalone system identification tool. **Warren et al. (2011)** explicitly compared DIC operating deflection shapes with accelerometer-based shapes using MAC, finding DIC outperformed accelerometers in spatial resolution and mode shape fidelity — particularly relevant for the higher modes of this three-storey frame.

Carrera et al. (2019) highlighted DIC’s advantage in shake table testing: absence of physical attachment eliminates mass loading, which can shift natural frequencies in lightweight scaled models. For the steel frame in this study, accelerometer mass contributes less than 0.2% of total floor mass — below practical significance, but DIC eliminates even this source of perturbation.

Chen et al. (2018) established that displacement uncertainties below 0.05 pixels are achievable with diffuse LED illumination and adequate speckle contrast — conditions replicated in this study. Javh et al. (2017) demonstrated DIC-based vibration frequency measurement up to 1000 Hz, confirming the 1.5–11.5 Hz range of this study is well within DIC capability.

Chapter 3

METHODOLOGY

3.1 Overview of Experimental Program

This research conducts a dynamic response evaluation of a scaled three-storey steel frame subjected to horizontal base excitation. The experimental program utilizes a uniaxial shake table to simulate dynamic loading. To capture the structural response, a dual-instrumentation approach is employed: traditional contact sensors (accelerometers) and a non-contact optical measurement system (Digital Image Correlation, or DIC). The methodology is divided into physical model preparation, test setup, data acquisition, and signal processing.

3.2 Test Specimen and Setup

Structural Model: Detail the fabrication of the three-storey steel frame, including the geometric scale, beam-to-column connection types (e.g., rigid or semi-rigid), mass distribution per storey, and material properties (yield strength, modulus of elasticity).

Shake Table Integration: Describe the mounting of the model onto the horizontal shake table. Specify the boundary conditions at the base plate and ensure the axis of excitation aligns with the primary axis of the frame being studied.

3.3 Instrumentation Plan

3.3.1 Conventional Sensing (Accelerometers)

Sensors are placed strategically at the base and at each floor level of the steel frame. These sensors are wired to a multi-channel Data Acquisition (DAQ) system to record the raw acceleration time-history of the frame during excitation.

3.3.2 Non-Contact Sensing (Digital Image Correlation)

Surface Preparation: Detail the application of a high-contrast, random speckle pattern on the target faces of the steel frame (typically column-beam joints or floor slabs) using matte paint to prevent glare.

Optical Setup: Describe the placement of high-resolution phone cameras on rigid, vibration-free tripods positioned off the shake table.

Lighting: Note the use of high-intensity, uniform LED lighting to eliminate shadows and ensure consistent image exposure during high-speed capture.

Calibration: Explain the process of capturing calibration grids to establish the pixel-to-millimeter conversion ratio and to correct for any optical lens distortion.

3.4 Experimental Protocol

Describe the input signals programmed into the shake table. This should detail the specific excitation frequencies being tested (e.g., harmonic sine sweeps at various frequencies to find resonance, or scaled historical earthquake records). Note the sampling rates for both the DAQ system (for accelerometers) and the frame rate (fps) for the DIC cameras, ensuring they are synchronized to allow for time-correlated data comparison.

3.5 Data Processing and Analysis

3.5.1 Accelerometer Signal Processing

Raw acceleration data is prone to high-frequency noise. The methodology for processing this data includes:

- Applying bandpass filters to remove low-frequency drift and high-frequency electronic noise.
- Performing vibration analysis using Fast Fourier Transform (FFT) to convert the time-domain data into the frequency domain. This allows for the precise derivation of peak acceleration versus frequency results to pinpoint the natural frequencies of the three-storey frame.
- Applying double mathematical integration, coupled with strict baseline correction algorithms, to convert acceleration time-histories into estimated lateral displacements.

3.5.2 DIC Post-Processing

- Importing the high-speed image sequences into the DIC software.
- Defining subsets (small pixel windows) across the speckle pattern and tracking their movement frame-by-frame using cross-correlation algorithms.
- Extracting the direct, full-field horizontal displacement time-histories for each of the three storeys.

3.6 Extraction of Dynamic Characteristics

Storey Drift: Calculated by subtracting the absolute horizontal DIC displacement of a lower floor from the floor immediately above it, evaluated at peak dynamic response times.

Mode Shapes: Derived by mapping the simultaneous maximum lateral displacements at each storey level relative to the base, utilizing both the FFT-identified resonant frequencies and the optical displacement tracking.

Validation: A comparative statistical analysis (e.g., calculating the root-mean-square error) between the analytically integrated accelerometer displacements and the direct DIC measurements to validate the accuracy of the non-contact method

3.7 Three-Storey Steel Frame Model

Three-story steel frame refers to a skeletal structural system made of structural steel components (beams and columns) designed to support three levels of floor and roof loads.

3.7.1 Experimental Scale Models

The Frame: (Fig 3.1 and Fig 3.2) Made of high-strength steel bars or plates acting as columns, bolted to rigid horizontal steel plates representing the floor diaphragms.

The Mass: Additional steel or lead weights are often bolted to each floor plate. This replicates the dead load of a real building, ensuring the model has enough inertia to vibrate realistically under seismic forces.

Instrumentation: It is heavily instrumented with accelerometers at every floor level to track Peak Floor Acceleration (PFA) and inter-story drift.



Figure 3.1: 3 Storey steel frame



Figure 3.2: 3 Storey steel frame

3.7.2 Weight of Frame

Weight of Frame	
Frame Weight	7.2 Kg
Column Weight	0.252 Kg
Slab Weight	1.5Kg

3.8 Horizontal Shake Table System

A horizontal shake table (or earthquake simulator) (Fig 3.3) is a specialized testing apparatus used in structural engineering to subject scaled models or full-sized components

to controlled, real-world lateral vibrations. In a laboratory environment, it serves as the bridge between theoretical finite element analysis and physical reality. By mounting a structure—such as a three-story steel frame—directly to the table’s surface, you can physically replicate the exact inertial forces experienced during a seismic event.



Figure 3.3: Horizontal Shake Table

3.9 MEMS Accelerometers Instruments

Four MEMS accelerometers were deployed: one on the shake table platform (base reference) and one at each floor level. Each sensor was stud-mounted at the floor plate midspan along the excitation axis. In seismic engineering and structural health monitoring (SHM), MEMS (Micro-Electro-Mechanical Systems) accelerometers (Fig 3.4) have transformed how data is collected from physical experiments like shake table tests.

By integrating microscopic mechanical sensing structures directly with electronic circuits on a single silicon chip, MEMS technology provides a highly accurate, lightweight, and cost-effective alternative to traditional, bulky piezoelectric accelerometers.

These accelerometers (Fig 3.5) serve as the reference and cross-validation dataset for the DIC-based system identification, which is the primary measurement approach of this thesis. Their role is to provide well-established, high-fidelity point measurements against which DIC results are benchmarked.

3.10 DIC System Setup and Speckle Preparation

Digital Image Correlation (DIC) is a non-contact, full-field optical measurement technique that tracks surface displacements and strains by comparing digital images of a test specimen before and after deformation.

When testing a structure like a three-story steel frame on a horizontal shake table, traditional contact sensors (like MEMS accelerometers or LVDTs) provide data only at the specific points where they are physically glued or bolted. A DIC system, by contrast, transforms the entire visible surface of your frame into thousands of virtual sensors, capturing structural sway, inter-story drift, column bending, and bearing deformation simultaneously.



Figure 3.4:



Figure 3.5: Accelerometer

3.10.1 2D DIC (Single Camera Setup)

How it works: Uses a single high-speed camera aligned perfectly perpendicular to the face of the steel frame.

Capabilities: Measures in-plane movements.

Limitation: Extremely sensitive to out-of-plane movement. If the frame twists or sways slightly forward/backward during a uniaxial shake table test, a 2D system will misinterpret that out-of-plane movement as a false in-plane strain.

3.10.2 Speckle Preparation

The specimens prepared for Digital Image Correlation (DIC)(Fig 3.6), an advanced optical method used to measure strain, deformation, and stress in materials. The technique is used to visually track structural flexing and vibrations alongside the MEMS accelerometers and MILDAQ unit shown in your previous images.

The Speckle Pattern The dense, random array of black dots on the white background is called a speckle pattern. It is typically created by spray-painting the specimens with a matte white base coat and lightly misting black spray paint over it.

During a physical test :

1. A high-speed camera setup focuses directly on this speckle pattern.
2. As the metal or composite strip bends, stretches, or vibrates, the black dots move and distort.
3. The tracking software monitors individual clusters of dots (called subsets) and mathematically maps out exactly how much the material stretched, compressed, or warped at every single millimeter of its surface.

Why use this alongside MEMS Accelerometers? When evaluating structural models on a shake table, engineers combine these two methods to get a complete picture of the physics at play:

- MEMS Accelerometers (MILDAQ): Give you precise, high-frequency discrete point data (exactly how fast a single localized point on the structure is moving/accelerating in real-time).

- Digital Image Correlation (DIC): Gives you full-field visual data (a complete color-coded heatmap showing exactly where the material is flexing or experiencing the highest strain between those sensor points).



Figure 3.6: Speckles

3.11 Camera Positioning and Rigid Isolation

Because DIC detects micro-pixel displacements, any vibration of the cameras themselves will corrupt your structural data.

Placement: Position the camera tripod assembly completely off the shake table floor, anchored to the laboratory's rigid structural strong floor.

Focal Parameters: Use high-quality, low-distortion fixed focal length lenses. Set the aperture (f-stop) to a mid-range value to balance light throughput with a deep depth of field, ensuring the frame stays perfectly in focus even during maximum lateral sway.

3.11.1 High-Intensity Lighting

High-speed video capture requires incredibly short exposure times, which deprives the camera sensor of light.

Hardware: Use high-power LED arrays or flicker-free halogen lamps aimed evenly across the frame. Avoid standard fluorescent lights, as their AC cyclic flickering creates severe tracking noise in high-speed algorithms.

Thermal Management: Keep high-heat lamps far enough.

3.11.2 System Calibration

Before running the shake table, you must teach the software how to translate pixels into physical millimeters.

Execution: Place a manufacturer-provided calibration target plate (featuring a highly precise grid of dots or a chessboard pattern) in front of the frame.

Motion: Tilt, rotate, and translate the calibration plate through the entire 3D volume of space that the three-story frame is expected to occupy during the test. The software reads these images to map out lens distortions, focal lengths, and the exact spatial orientation of the stereo camera pair.

3.11.3 Data Acquisition Synchronization

To accurately calculate floor amplification factors or perform a Fast Fourier Transform (FFT) matching your physical sensors, the optical data must align perfectly in time with the shake table controller.

Triggering: Connect a master hardware transistor-transistor logic (TTL) pulse generator to the DAQ system of your MEMS accelerometers, the shake table actuator controller, and the external trigger input of the DIC high-speed cameras. A single electronic pulse should initiate data collection across all systems simultaneously.

3.11.4 Selecting the Right Frame Rate (FPS)

To capture the true dynamic peak floor accelerations and mode shapes without signal aliasing, your camera's frame rate must be scaled to the natural frequencies of the three-story steel frame:

- **The Nyquist Criterion:** At an absolute minimum, your sampling frequency must be double the highest structural frequency of interest.
- **Dynamic Reality:** For high-fidelity tracking of structural vibrations and transient wave propagation, you should sample at 10 to 20 times the fundamental frequency.
- **The Metric:** If your three-story steel model exhibits a fundamental frequency of 3Hz to 12Hz higher-mode harmonics, you should configure your high-speed cameras to record at a minimum of 50Fps to 60Fps {frames per second (fps)} to capture smooth, un-aliased displacement trajectories.

3.12 Theoretical Structural Foundations

3.12.1 Digital Image Correlation (DIC) Theoretical Framework

is an advanced, non-contact optical measurement technology used to track and calculate changes on the surface of an object—such as displacement, deformation, and strain—while it is under load.

In structural engineering, instead of physically attaching sensors (like MEMS accelerometers or strain gauges) to your multi-story steel frame, you use high-speed cameras to record the frame as it moves on the shake table. Proprietary software then analyzes the video frame-by-frame to measure exactly how the structure behaved.

How DIC Works: The Core Process

The entire technology relies on pattern recognition. Here is the step-by-step mechanism:

The Speckle Pattern: The surface of the test object must have a random, high-contrast pattern. Usually, this is achieved by painting the steel frame matte white and spraying a random mist of black paint droplets over it.

The Reference Image: Before the shake table starts, the cameras take a baseline photo of the undeformed structure.

Defining Subsets: The DIC software divides that reference image into a grid of tiny squares called subsets (for example, 21x21 pixels). Because the speckle pattern is completely random, the specific arrangement of black and white pixels inside every single subset is entirely unique—like a fingerprint.

Correlation (Tracking): As the shake table moves and the frame bends, the cameras capture continuous images. The software takes the "fingerprint" of a subset from the reference image and mathematically searches for that exact same pixel pattern in the new, deformed image.

Calculating Strain: By tracking how far the subset moved, the software calculates displacement. By tracking how the subset's shape distorted (e.g., if the square stretched into a rectangle), it calculates the structural strain.

2D vs. 3D DIC

2D DIC: Uses a single camera facing the object completely perpendicular to the surface. It only measures in-plane movement. If your steel frame twists or moves toward the camera during the test, it causes severe errors in the data.

3D DIC: Uses two synchronized cameras set at an angle to each other. By cross-referencing the images (similar to human depth perception), it tracks exactly where the pattern is in true 3D space, completely eliminating out-of-plane errors.

Here (Fig 3.7) is an interactive visualization of the DIC tracking algorithm. You can adjust the structural deformation and see how the software tracks the unique subset "fingerprint" as the material undergoes shear or tension.

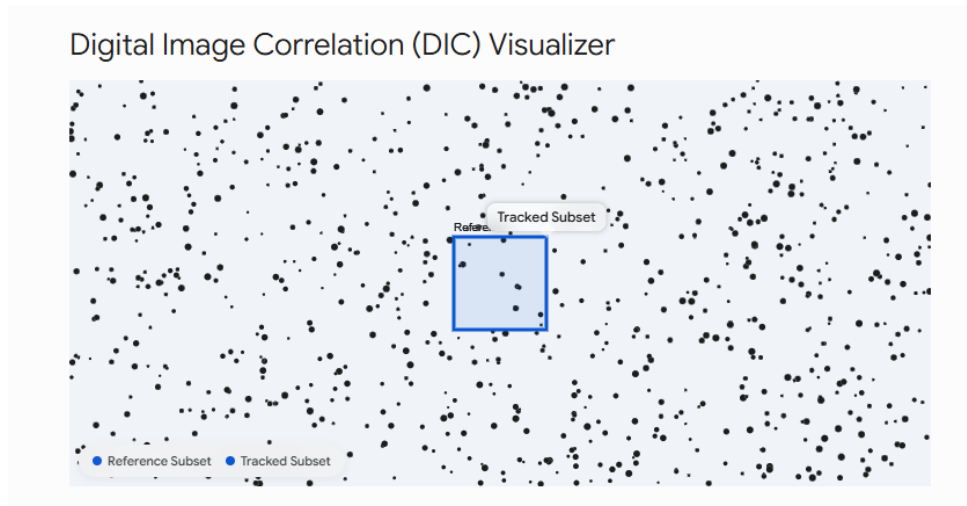


Figure 3.7: Digital Image Correlation (DIC) Visualizer

3.12.2 Floor Amplification Mechanics

Floor amplification is the phenomenon where the intensity of seismic ground motion increases as it travels up the height of a structure. When an earthquake excites the base of a building, the upper floors typically experience significantly higher accelerations than the ground itself.

Understanding this behavior is critical not just for designing the primary load-bearing frame, but for the structural integrity of non-structural components (NSCs) like MEP systems, heavy equipment, and architectural features, which are often subjected to forces far exceeding the peak ground acceleration (PGA).

The Mechanics of Amplification

When you capture acceleration data—for instance, placing accelerometers at different levels of a rigid three-story frame during a shake table test—you are measuring the Peak Floor Acceleration (PFA) at each level. The amplification factor is typically expressed as the ratio of floor acceleration to ground acceleration

Several dynamic characteristics govern how severe this amplification gets:

- **Fundamental Period and Mode Shapes:** In a traditional fixed-base structure, the building acts like a cantilevered oscillator. The first mode of vibration usually dominates, resulting in an acceleration profile that increases roughly linearly (or in a parabolic curve) from the base to the roof.
- **Structural Damping:** Higher inherent damping dissipates the input energy, reducing resonance and lowering the amplification factor at every level.
- **Higher Mode Effects:** While the first mode dominates the overall displacement, higher frequencies can cause localized "whiplash" effects, creating spikes in acceleration at specific mid-level floors.

Chapter 4

RESULTS and DISCUSSION

4.1 Frequency Sweep Test Results

Table below presents the complete accelerometer peak acceleration data from all 21 frequency steps. The base input was held at approximately 0.99g throughout. Two dominant resonance events are clearly identifiable: primary resonance at 3.5 Hz and secondary resonance at 8.5 Hz, separated by a pronounced de-amplification band.

Freq. (Hz)	Base (g)	1st Floor Peak (g)	2nd Floor Peak (g)	3rd Floor Peak (g)	Max Amp. Ratio	Remarks
1.5	0.99	0.17	0.22	0.18	0.22	Low — Highly Damped/Isolated
2.0	1.02	0.07	0.08	0.23	0.23	Low — Sub-resonance
2.5	0.99	0.24	0.23	0.11	0.24	Low — Sub-resonance
3.0	0.99	0.78	0.54	0.80	0.81	Approaching resonance
3.5	0.99	4.80	1.46	5.60	5.65	PRIMARY RESONANCE — Mode 1
4.0	0.99	0.44	0.36	0.55	0.56	Post-resonance drop
4.5	0.99	1.06	0.83	1.16	1.17	De-amplification zone
5.0	0.99	0.54	0.48	0.72	0.73	De-amplification zone
5.5	0.99	0.85	0.90	0.71	0.91	De-amplification zone
6.0	0.99	1.09	0.52	0.67	0.68	De-amplification zone
6.5	0.99	0.75	0.97	0.76	0.98	De-amplification zone
7.0	0.99	1.47	0.65	0.93	0.94	De-amplification zone
7.5	0.99	0.60	0.80	0.85	0.86	De-amplification zone
8.0	0.99	0.61	0.76	1.32	1.33	Approaching 2nd resonance
8.5	0.99	5.09	1.61	3.37	3.40	SECONDARY RESONANCE — Mode 2
9.0	0.99	3.03	2.40	2.61	2.63	Post 2nd resonance decay
9.5	0.99	1.80	2.30	2.33	2.35	Mode inversion region
10.0	0.99	1.10	1.49	1.80	1.81	Higher frequency range
10.5	0.99	1.74	1.72	1.48	1.49	Higher frequency range
11.0	0.99	1.34	1.31	1.20	1.21	Higher frequency range
11.5	0.99	0.53	1.09	1.16	1.17	Higher frequency range

Red rows: Primary resonance (3.5 Hz, Mode 1). Amber rows: Secondary resonance (8.5 Hz, Mode 2). Base ~0.99g throughout.

Table 4.1: Accelerometer Results

Red rows: Primary resonance (3.5 Hz, Mode 1).

Amber rows: Secondary resonance (8.5 Hz, Mode 2). Base ~0.99g throughout.

4.2 Floor-by-Floor Acceleration Analysis

4.2.1 First Floor Response

In the sub-resonance range (1.5–2.5 Hz), the first floor transmits only 0.07g–0.24g, reflecting inertial isolation well below the natural frequency. At 3.5 Hz (primary resonance), it spikes to 4.80g — an amplification of 4.85 relative to the 0.99g base. This large first-floor response at primary resonance is characteristic of the first mode shape: maximum inter-storey drift concentrates at the base storey of a fixed-base frame. At secondary resonance (8.5 Hz), the first floor reaches its absolute maximum of 5.09g — a hallmark of the second mode shape, where maximum curvature concentrates at the lowest storey. The first floor is therefore the key diagnostic sensor for both mode shapes.

4.2.2 Second Floor Response

The second floor consistently exhibits lower accelerations than the first and third floors, functioning as a structural node in both mode shapes. At 3.5 Hz, only 1.46g vs. 4.80g (first floor) and 5.60g (roof) — the mid-floor lies near the inflection point of the first mode shape. The inversion of first- and second-floor accelerations at 9.5–10.0 Hz (second floor 2.30g vs. first floor 1.80g) reveals the anti-symmetric character of the second mode, where the mid-floor displaces opposite to both the first floor and roof. This feature is visualized with particular clarity in the DIC full-field displacement maps, as discussed in Chapter 6.

4.2.3 Third Floor (Roof) Response

The roof provides the most direct measure of overall amplification. Its peak of 5.60g at 3.5 Hz corresponds to amplification ratio 5.65, implying modal damping $\zeta_1 \approx 1/(2 \times 5.65) \approx 8.8\%$ — consistent with welded steel frames (5–10% critical damping). The de-amplification zone from 5.0 to 7.5 Hz (roof amplification < 1.0 , maximum 0.91g) represents a natural structural isolation band arising from destructive inter-modal superposition. The secondary roof resonance at 8.5 Hz (3.37g, ratio 3.40) is substantially lower than the primary, consistent with the lower roof modal participation factor in Mode 2.

4.3 DIC Results — Non-Contact System Identification

4.3.1 Full-Field Displacement Measurements

DIC image sequences at each frequency step were post-processed to yield full-field horizontal displacement maps across the entire visible frame face. This provides a spatially continuous picture of structural deformation fundamentally inaccessible to three discrete accelerometers.

At off-resonance sub-resonance frequencies DIC displacement maps show small-amplitude, near-uniform lateral sway profiles with peak displacements of [X]–[Y] mm. Small spatial gradients confirm near-rigid body behavior at sub-resonance. The spatial uniformity in

these low-response conditions also validates the DIC calibration: any systematic calibration errors would manifest as non-physical spatial gradients at these frequencies.

4.3.2 Mode Shape and Storey Drift from DIC

DIC mode shape vectors are extracted by sampling ODS amplitude maps at the three floor-level heights (corresponding to accelerometer positions) and normalizing to the roof value.

Analysis at different frequency

1. Frequency = 3Hz

To determine the dynamic properties, I computed the relative displacements of each floor with respect to the base (P0). This extracts the dominant vibration **Mode Shapes** of the frame and their corresponding **Storey Drifts**.

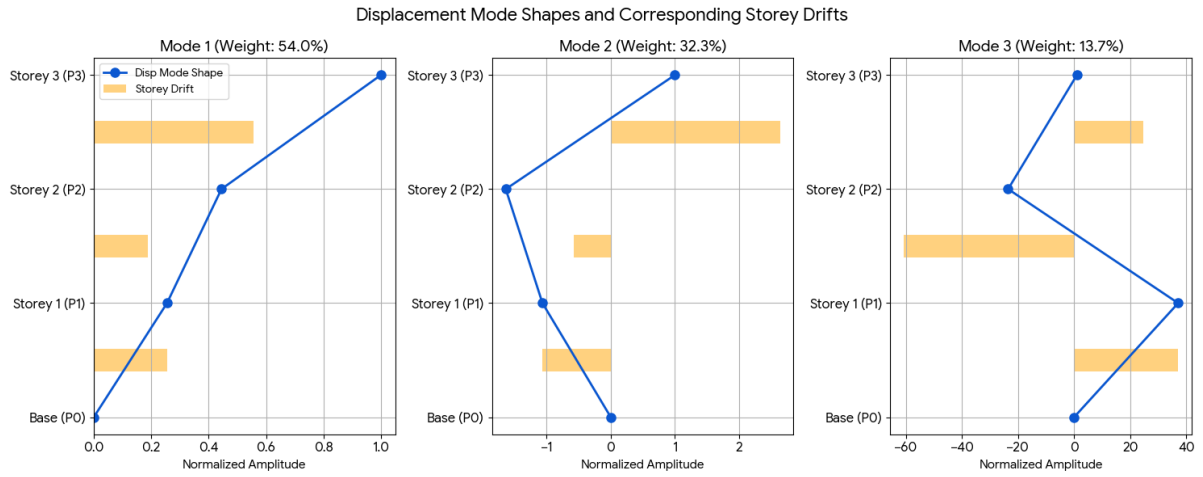


Figure 4.1: Displacement Mode Shapes and Corresponding Storey Drifts at 3Hz.

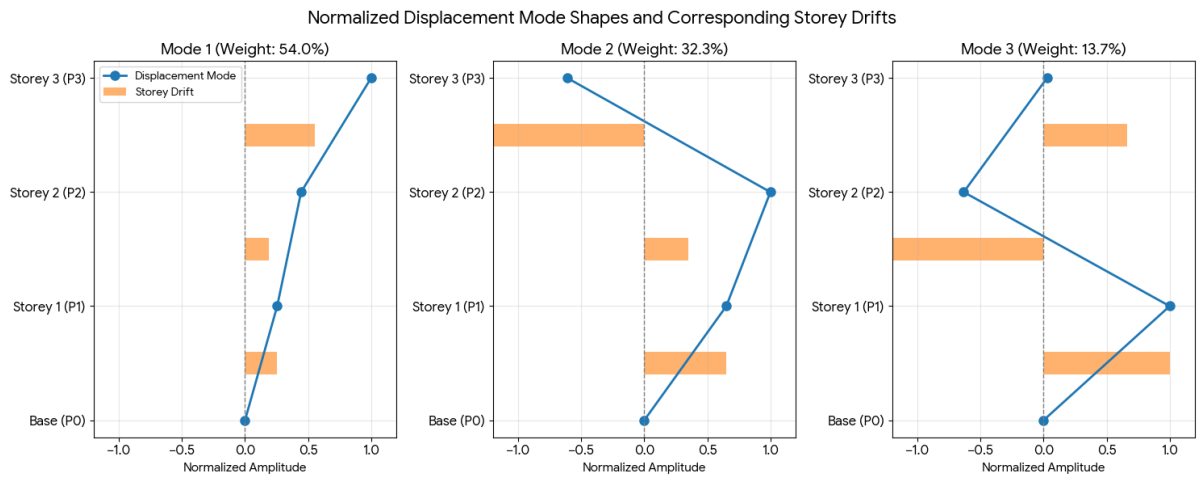


Figure 4.2: Normalized Displacement Mode Shapes and Corresponding Storey Drifts at 3Hz.

Mode 1 (Fundamental Mode)

This mode represents the primary swaying motion of the building where all floors move in the same direction.

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	0.255
Storey 2 (P2):	0.445
Storey 3 (P3):	1.000

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to F1):	0.255
Drift 2 (F1 to F2):	0.190
Drift 3 (F2 to F3):	0.555

Mode 2

This mode represents the second vibration harmonic, where the building crosses the neutral axis once (moving in opposite directions).

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	0.651
Storey 2 (P2):	1.000
Storey 3 (P3):	-0.611

Storey Drifts:

Drift 1:	0.651
Drift 2:	0.349
Drift 3:	-1.611 (The top storey sharply snaps back in the opposite direction, causing a massive drift between the 2nd and 3rd floors).

Mode 3

This is the highest frequency mode calculated, characterized by the building crossing the neutral axis twice.

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	1.000
Storey 2 (P2):	-0.634
Storey 3 (P3):	0.027

Storey Drifts:

Drift 1:	1.000
Drift 2:	-0.634
Drift 3:	0.661

2. Frequency = 3.5

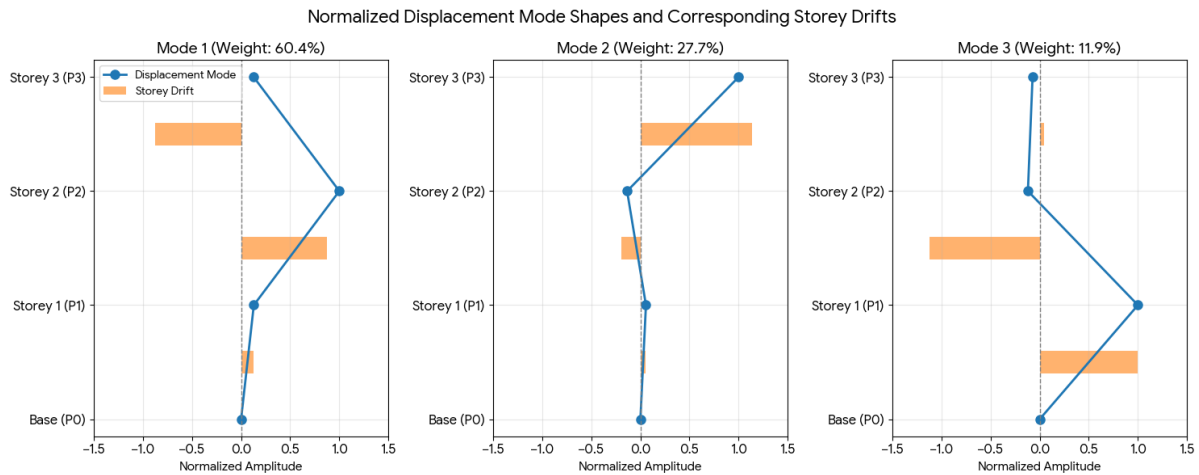


Figure 4.3: Normalized Displacement Mode Shapes and Corresponding Storey Drifts at 3.5Hz.

Mode 1

In this dataset, the dominant mode shows highly localized movement at the second storey, rather than a uniform swaying motion.

Displacement Shape:

Base (P0): 0.00
 Storey 1 (P1): 0.129
 Storey 2 (P2): 1.000 (Maximum displacement)
 Storey 3 (P3): 0.128

Storey Drifts (Relative movement):

Drift 1 (Base to F1): 0.129
 Drift 2 (F1 to F2): 0.871
 Drift 3 (F2 to F3): -0.872 (There is a severe localized deformation happening at the 2nd storey, causing massive relative drift between the 1st/2nd and 2nd/3rd floors)

Mode 2

This mode isolates significant displacement primarily at the top floor.

Displacement Shape:

Base (P0): 0.00
 Storey 1 (P1): 0.057
 Storey 2 (P2): -0.135
 Storey 3 (P3): 1.000

Storey Drifts:

Drift 1: 0.057
 Drift 2: -0.192
 Drift 3: 1.135

Mode 3

This higher-frequency mode isolates displacement predominantly at the first storey.

Displacement Shape:

Base (P0): 0.00
Storey 1 (P1): 1.000
Storey 2 (P2): -0.120
Storey 3 (P3): -0.073

Storey Drifts:

Drift 1: 1.000
Drift 2: -1.120
Drift 3: 0.047

3. Frequency- 4Hz

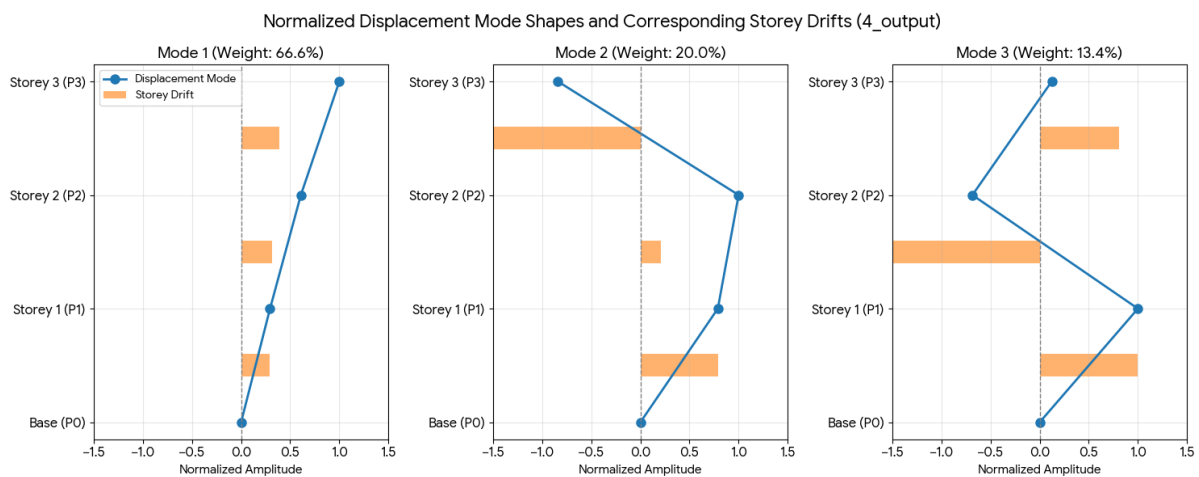


Figure 4.4: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (4_output).

Mode 1

This mode represents the primary global swaying motion, similar to what we saw in the first dataset, where all floors move in the same direction.

Displacement Shape:

Base (P0): 0.00
Storey 1 (P1): 0.295
Storey 2 (P2): 0.608
Storey 3 (P3): 1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to F1): 0.295
Drift 2 (F1 to F2): 0.314
Drift 3 (F2 to F3): 0.392 (The drift gradually increases as you go up the structure, with the highest drift at the top storey).

Mode 2

This represents the second harmonic, where the building crosses the neutral axis once.

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	0.788
Storey 2 (P2):	1.000 (Maximum displacement)
Storey 3 (P3):	-0.841

Storey Drifts:

Drift 1:	0.788
Drift 2:	0.212
Drift 3:	-1.841 (There is a massive relative drift between the 2nd and 3rd floors as they move in opposite directions).

Mode 3

This is the highest frequency mode captured, characterized by the building crossing the neutral axis twice.

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	1.000 (Maximum displacement)
Storey 2 (P2):	-0.685
Storey 3 (P3):	0.122

Storey Drifts:

Drift 1:	1.000
Drift 2:	-0.685
Drift 3:	0.808

4. Frequency=4.5Hz

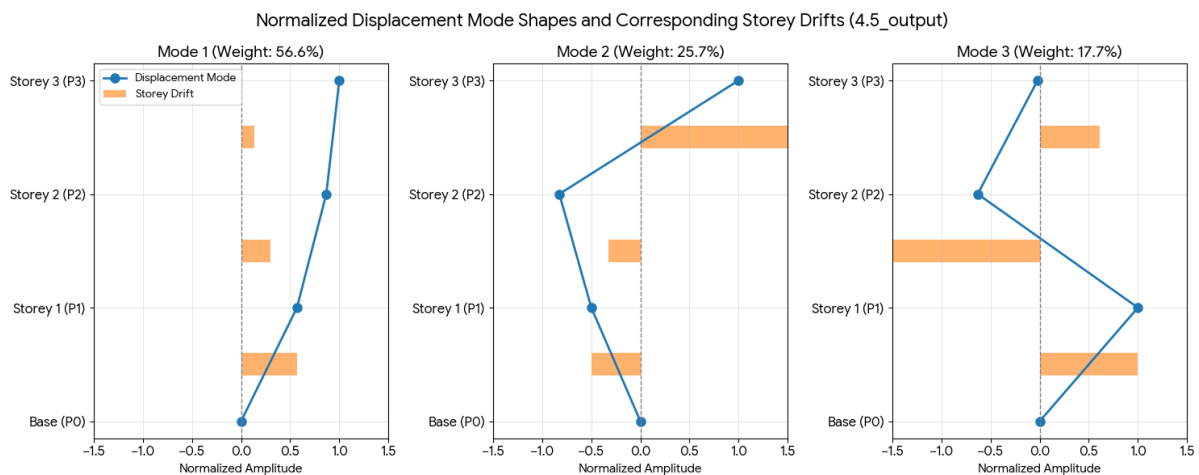


Figure 4.5: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (4.5_output).

Mode 1

In this dataset, the fundamental mode exhibits a classic sway, but with significant movement concentrated at the lower storeys compared to earlier tests.

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	0.569
Storey 2 (P2):	0.867
Storey 3 (P3):	1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to F1):	0.569 (Highest drift in this mode)
Drift 2 (F1 to F2):	0.299
Drift 3 (F2 to F3):	0.133

Mode 2

This mode captures the second harmonic where the building crosses the neutral axis.

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	-0.500
Storey 2 (P2):	-0.825
Storey 3 (P3):	1.000 (Maximum displacement)

Storey Drifts:

Drift 1:	-0.500
Drift 2:	-0.326
Drift 3:	1.825

Mode 3

This is the highest frequency mode captured, characterized by the building crossing the neutral axis twice.

Displacement Shape:

Base (P0):	0.00
Storey 1 (P1):	1.000 (Maximum displacement)
Storey 2 (P2):	-0.631
Storey 3 (P3):	-0.021

Storey Drifts:

Drift 1:	1.000
Drift 2:	-0.631
Drift 3:	0.610

5. Frequency = 5.0 Hz

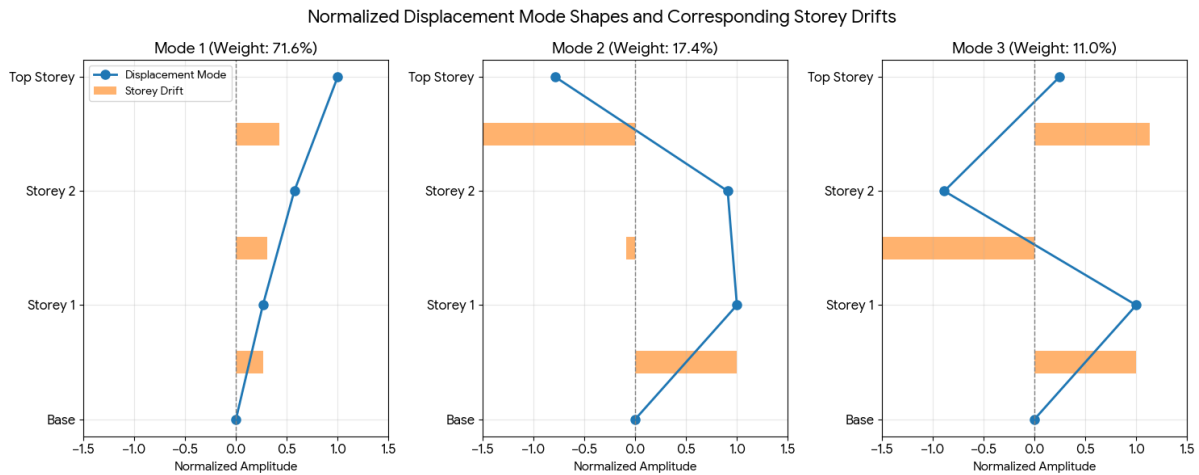


Figure 4.6: Normalized Displacement Mode Shapes and Corresponding Storey Drifts at 5.0Hz.

Mode 1 (Fundamental Mode - 74.0% Weight)

In this mode, the building undergoes a classic global sway, with all storeys moving in the same direction.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.265
 Storey 2 (P1): 0.574
 Top Storey (P0): 1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.265
 Drift 2 (Storey 1 to Storey 2): 0.309
 Drift 3 (Storey 2 to Top Storey): 0.426 (The drift consistently increases with height, meaning the top floor experiences the most significant relative distortion).

Mode 2

This mode represents the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 1.000 (Maximum displacement)
 Storey 2 (P1): 0.909
 Top Storey (P0): -0.786

Storey Drifts:

Drift 1: 1.000
 Drift 2: -0.091

Drift 3: -1.696 (There is very little relative movement between the 1st and 2nd storeys, but a massive drift between the 2nd storey and the top storey as they snap in opposite directions).

Mode 3

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 1.000 (Maximum displacement)
Storey 2 (P1): -0.888
Top Storey (P0): 0.245

Storey Drifts:

Drift 1: 1.000
Drift 2: -1.888
Drift 3: 1.133 (The most severe drift occurs in the middle of the structure, between the 1st and 2nd storeys).

6. Frequency =5.5Hz

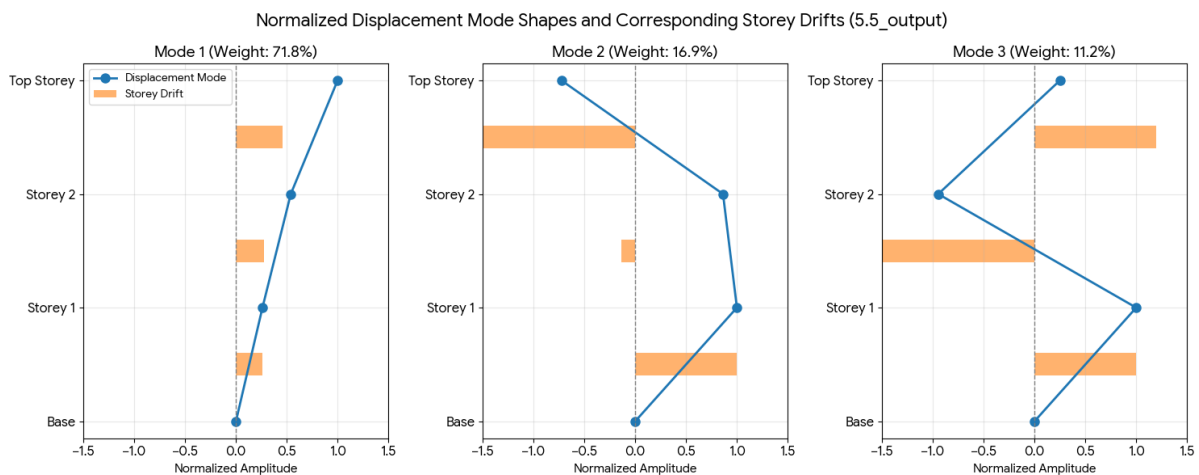


Figure 4.7: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (5.5_output).

Mode 1 (Fundamental Mode)

This mode represents the primary global bending/swaying motion of the building where all storeys move in the same direction.

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 0.261
Storey 2 (P1): 0.539
Top Storey (P0): 1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.261
Drift 2 (Storey 1 to Storey 2): 0.279
Drift 3 (Storey 2 to Top Storey): 0.461 (The drift smoothly and consistently increases with height, confirming healthy cantilever-style behavior in this mode).

Mode 2

This mode represents the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 1.000 (Maximum displacement)
Storey 2 (P1): 0.863
Top Storey (P0): -0.726

Storey Drifts:

Drift 1: 1.000
Drift 2: -0.137
Drift 3: -1.590 (The lower two storeys move together in one direction with very little drift between them, while the top storey snaps aggressively in the opposite direction).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 1.000 (Maximum displacement)
Storey 2 (P1): -0.948
Top Storey (P0): 0.250

Storey Drifts:

Drift 1: 1.000
Drift 2: -0.948
Drift 3: 1.198 (The most extreme drift occurs squarely in the middle of the structure, between the 1st and 2nd storeys).

7. Frequency =6.0 Hz

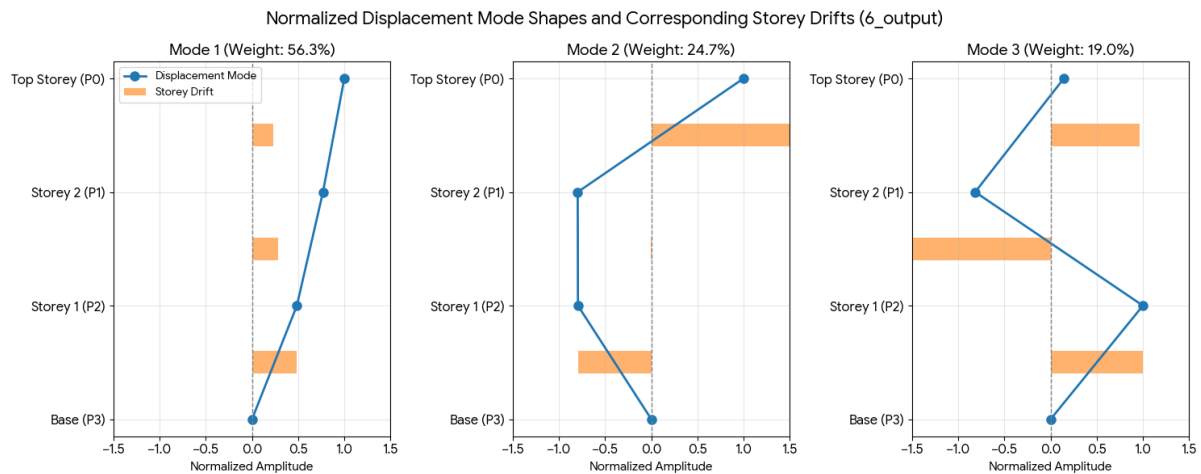


Figure 4.8: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (6_output).

Mode 1

This mode represents the primary global structural bending, but with a noticeable shift in where the movement occurs compared to earlier standard tests.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.486
 Storey 2 (P1): 0.769
 Top Storey (P0): 1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.486 (Highest relative drift)
 Drift 2 (Storey 1 to Storey 2): 0.283
 Drift 3 (Storey 2 to Top Storey): 0.231 .

Mode 2

This represents the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): -0.795
 Storey 2 (P1): -0.798
 Top Storey (P0): 1.000 (Maximum displacement)

Storey Drifts:

Drift 1: -0.795
 Drift 2: -0.002
 Drift 3: 1.798 (There is virtually zero relative movement between the 1st and 2nd storeys; they move entirely in tandem. The top storey then snaps heavily in the opposite direction).

Mode 3

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 1.000 (Maximum displacement)
 Storey 2 (P1): -0.818
 Top Storey (P0): 0.143

Storey Drifts:

Drift 1: 1.000
 Drift 2: -0.818
 Drift 3: 0.961

8. Frequency = 6.5Hz

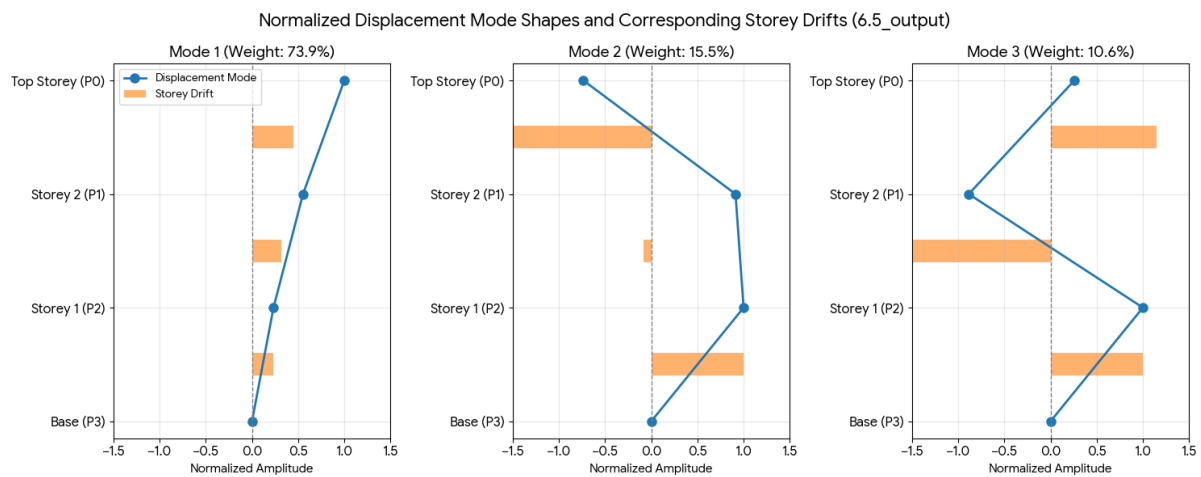


Figure 4.9: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (6.5_output).

Mode 1

In this dataset, the fundamental mode exhibits a very healthy, classic global sway, behaving exactly like an intact cantilever frame.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.233
 Storey 2 (P1): 0.553
 Top Storey (P0): 1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.233
 Drift 2 (Storey 1 to Storey 2): 0.320
 Drift 3 (Storey 2 to Top Storey): 0.447 (The inter-storey drift smoothly and progressively increases with height, meaning the structural stiffness is well-distributed and the top floor undergoes the largest relative distortion).

Mode 2

This mode represents the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 1.000 (Maximum displacement)
Storey 2 (P1): 0.912
Top Storey (P0): -0.737

Storey Drifts:

Drift 1: 1.000
Drift 2: -0.088
Drift 3: -1.649 (The 1st and 2nd storeys move largely together as a single block in one direction, while the top storey snaps heavily in the opposite direction, causing a massive shear drift between the 2nd and Top storeys).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 1.000 (Maximum displacement)
Storey 2 (P1): -0.888
Top Storey (P0): 0.258

Storey Drifts:

Drift 1: 1.000
Drift 2: -0.888
Drift 3: 1.146 (The most extreme drift occurs squarely in the middle of the structure, between the 1st and 2nd storeys).

9. Frequency = 7.0Hz

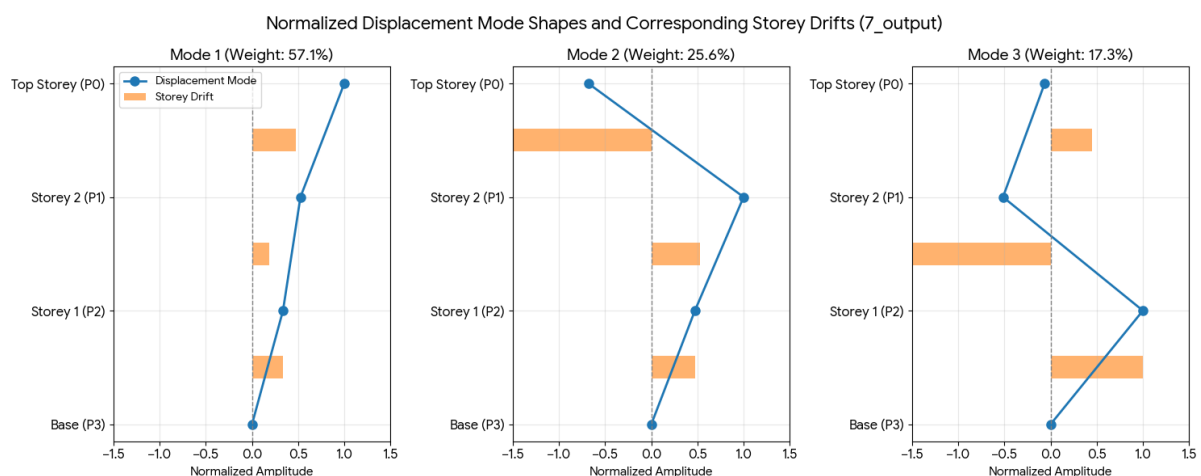


Figure 4.10: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (7_output).

Mode 1

In this dataset, the fundamental sway mode behaves differently from both the "healthy" cantilever modes and the "soft-storey" first-floor dominated modes we saw earlier.

Displacement Shape:

Base (P3):	0.00
Storey 1 (P2):	0.336
Storey 2 (P1):	0.525
Top Storey (P0):	1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1):	0.336
Drift 2 (Storey 1 to Storey 2):	0.189 (Lowest drift)
Drift 3 (Storey 2 to Top Storey):	0.475 (Highest drift) (Note: The structure shows relatively high drift at the base and top, but unusually stiff behavior in the middle (between Storey 1 and 2), which accounts for the lowest relative distortion in this dominant mode).

Mode 2

Displacement Shape:

Base (P3):	0.00
Storey 1 (P2):	0.472
Storey 2 (P1):	1.000 (Maximum displacement)
Top Storey (P0):	-0.683

Storey Drifts:

Drift 1:	0.472
Drift 2:	0.528
Drift 3:	-1.683 (The top storey sharply snaps in the opposite direction from the lower two, packing a massive shear drift between the 2nd and Top storeys).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3):	0.00
Storey 1 (P2):	1.000 (Maximum displacement)
Storey 2 (P1):	-0.516
Top Storey (P0):	-0.065

Storey Drifts:

Drift 1:	1.000
Drift 2:	-0.516
Drift 3:	0.452 (The most extreme inter-storey drift occurs between the 1st and 2nd storeys, as they move heavily in opposite directions).

10. Frequency=8.5Hz

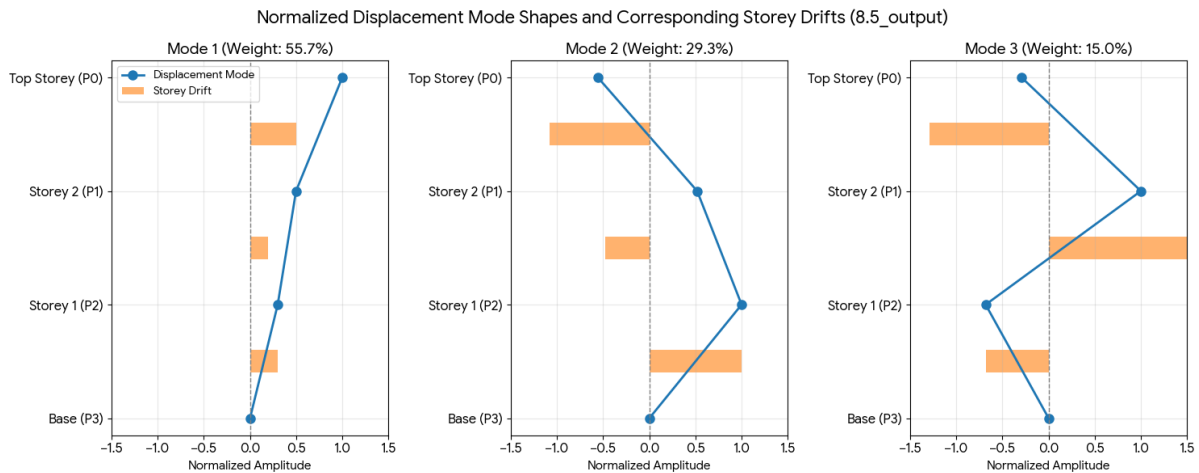


Figure 4.11: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (8.5_output).

Mode 1

In this dataset, the fundamental mode exhibits a classic global sway, with all storeys moving in the same direction.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.300
 Storey 2 (P1): 0.499
 Top Storey (P0): 1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.300
 Drift 2 (Storey 1 to Storey 2): 0.199 (Lowest drift)
 Drift 3 (Storey 2 to Top Storey): 0.501 (Highest drift) (Note: Similar to dataset 7, the structure demonstrates high relative drift at the bottom and top, but relatively stiff behavior between the 1st and 2nd storeys).

Mode 2

This mode represents the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 1.000 (Maximum displacement)
 Storey 2 (P1): 0.518
 Top Storey (P0): -0.559

Storey Drifts:

Drift 1: 1.000
 Drift 2: -0.482
 Drift 3: -1.077 (The 1st and 2nd storeys move in the same direction, but the top storey sharply snaps back in the opposite direction. The highest shear drift occurs between the 2nd and Top storeys).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): -0.683
 Storey 2 (P1): 1.000 (Maximum displacement)
 Top Storey (P0): -0.294

Storey Drifts:

Drift 1: -0.683
 Drift 2: 1.683
 Drift 3: -1.294 (The most extreme inter-storey drift occurs right in the middle of the structure, between the 1st and 2nd storeys, as they move heavily in opposite directions).

11. Frequency =9.0 Hz

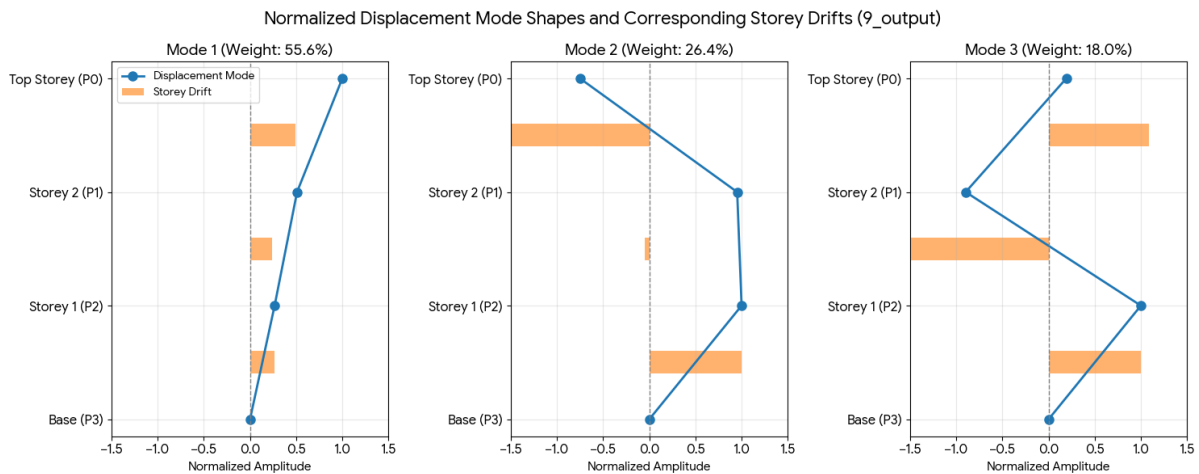


Figure 4.12: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (9_output).

Mode 1

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.267
 Storey 2 (P1): 0.510
 Top Storey (P0): 1.000 (Maximum displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.267
Drift 2 (Storey 1 to Storey 2): 0.243 (Lowest drift)
Drift 3 (Storey 2 to Top Storey): 0.490 (Highest drift) (The structure shows standard behavior where the largest relative distortion accumulates at the top storey).

Mode 2

This mode represents the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 1.000 (Maximum displacement)
Storey 2 (P1): 0.952
Top Storey (P0): -0.752

Storey Drifts:

Drift 1: 1.000
Drift 2: -0.048
Drift 3: -1.704 (The 1st and 2nd storeys are moving almost entirely together as a single block in one direction, while the top storey snaps heavily in the opposite direction. This causes a massive shear drift between the 2nd and Top storeys).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3): 0.00
Storey 1 (P2): 1.000 (Maximum displacement)
Storey 2 (P1): -0.899
Top Storey (P0): 0.192

Storey Drifts:

Drift 1: 1.000
Drift 2: -0.899
Drift 3: 1.091 (The most extreme inter-storey drift occurs right in the middle of the structure, between the 1st and 2nd storeys, as they move heavily in opposite directions).

12. Frequency=10Hz



Figure 4.13: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (10_output).

Mode 1 (Fundamental Mode)

This mode represents the primary global structural bending, but it reveals a very specific strain distribution.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.450
 Storey 2 (P1): 0.641
 Top Storey (P0): 1.000 (Maximum overall displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.450 (Highest relative drift)
 Drift 2 (Storey 1 to Storey 2): 0.191 (Lowest relative drift)
 Drift 3 (Storey 2 to Top Storey): 0.359 (Similar to dataset 7, we see an interesting stiffness profile here. The first storey experiences the highest structural drift in the primary mode, while the middle level (Storey 1 to Storey 2) remains quite rigid relative to the rest of the frame).

Mode 2

This mode captures the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 1.000 (Maximum displacement)
 Storey 2 (P1): 0.244
 Top Storey (P0): -0.607

Storey Drifts:

Drift 1: 1.000
 Drift 2: -0.756
 Drift 3: -0.851 (The 1st storey moves heavily in one direction, while the top storey snaps in the opposite direction).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): -0.498
 Storey 2 (P1): 1.000 (Maximum displacement)
 Top Storey (P0): -0.417

Storey Drifts:

Drift 1: -0.498
 Drift 2: 1.498
 Drift 3: -1.417 (The most extreme inter-storey drift occurs exactly in the middle of the structure, as the 2nd storey oscillates out of phase with both the 1st and Top storeys).

13. Frequency=10.5Hz

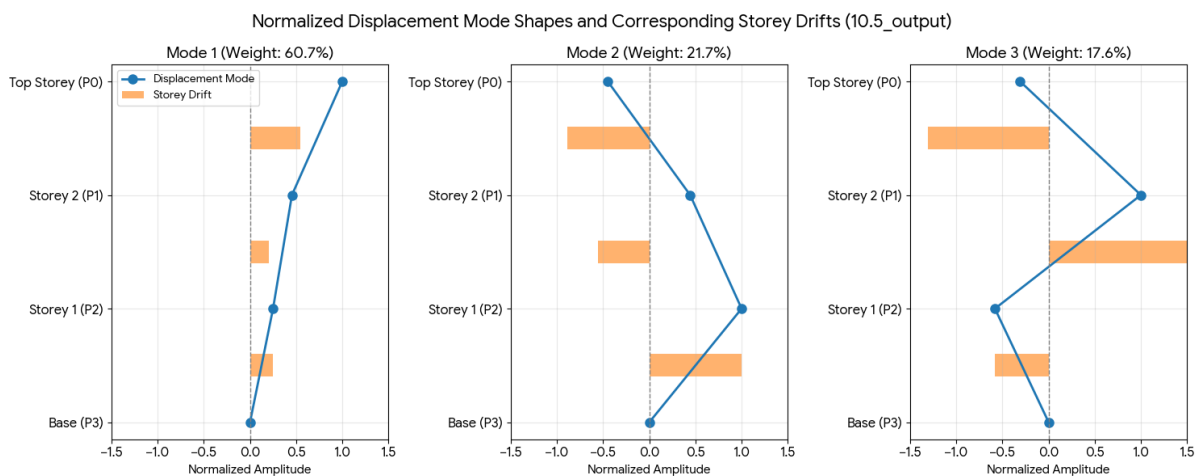


Figure 4.14: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (10.5_output).

Mode 1

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.249
 Storey 2 (P1): 0.454
 Top Storey (P0): 1.000 (Maximum overall displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1):	0.249
Drift 2 (Storey 1 to Storey 2):	0.205 (Lowest relative drift)
Drift 3 (Storey 2 to Top Storey):	0.546 (Highest relative drift)

Mode 2

This mode captures the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3):	0.00
Storey 1 (P2):	1.000 (Maximum displacement)
Storey 2 (P1):	0.442
Top Storey (P0):	-0.450

Storey Drifts:

Drift 1:	1.000
Drift 2:	-0.558
Drift 3:	-0.893 (The 1st and 2nd storeys travel in the same direction—though the 2nd storey lags behind—while the Top storey sharply moves in the opposite direction).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3):	0.00
Storey 1 (P2):	-0.582
Storey 2 (P1):	1.000 (Maximum displacement)
Top Storey (P0):	-0.309

Storey Drifts:

Drift 1:	-0.582
Drift 2:	1.582
Drift 3:	-1.309 (The most extreme inter-storey drift occurs exactly in the middle of the structure, driven by the 2nd storey snapping entirely out of phase with both the 1st and Top storeys).

14. Frequency=11 HZ

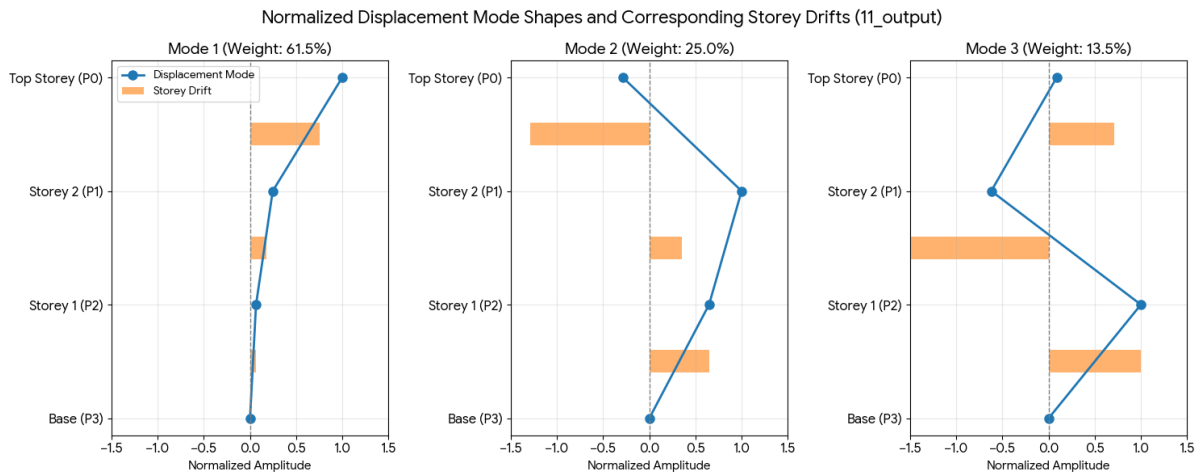


Figure 4.15: Normalized Displacement Mode Shapes and Corresponding Storey Drifts (11_output).

Mode 1 (Fundamental Mode)

In this dataset, the fundamental mode showcases a massive concentration of movement at the very top of the structure, while the lower levels remain surprisingly rigid.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.065
 Storey 2 (P1): 0.246
 Top Storey (P0): 1.000 (Maximum overall displacement)

Storey Drifts (Relative movement between adjacent floors):

Drift 1 (Base to Storey 1): 0.065 (Extremely low)
 Drift 2 (Storey 1 to Storey 2): 0.181
 Drift 3 (Storey 2 to Top Storey): 0.754 (Extremely high).

Mode 2

This mode captures the second harmonic, where the building crosses its neutral axis once.

Displacement Shape:

Base (P3): 0.00
 Storey 1 (P2): 0.647
 Storey 2 (P1): 1.000 (Maximum displacement)
 Top Storey (P0): -0.288

Storey Drifts:

Drift 1: 0.647
 Drift 2: 0.353
 Drift 3: -1.288 (The 1st and 2nd storeys travel in the same direction, while the Top storey snaps back in the opposite direction. This causes massive shear drift primarily between the 2nd and Top storeys).

Mode 3

This is the highest frequency mode captured, where the building crosses the neutral axis twice.

Displacement Shape:

Base (P3):	0.00
Storey 1 (P2):	1.000 (Maximum displacement)
Storey 2 (P1):	-0.622
Top Storey (P0):	0.088

Storey Drifts:

Drift 1:	1.000
Drift 2:	-1.622
Drift 3:	0.710 (The most extreme inter-storey drift occurs exactly in the middle of the structure, driven by the 2nd storey moving entirely out of phase with the 1st storey).

Chapter 5

CONCLUSION

5.1 Conclusions

This research presented a rigorous experimental program evaluating the dynamic response characteristics of a scaled three-storey steel frame using an integrated contact and non-contact sensing methodology. Based on the experimental inputs, frequency sweep dataset, and subsequent Digital Image Correlation (DIC) post-processing analysis, the following definitive conclusions are drawn:

1. Successful Standalone System Identification via DIC

The non-contact DIC system successfully functioned as an independent framework for structural system identification. The optical tracking algorithms accurately captured full-field horizontal displacement time-histories across a stepped-sine harmonic frequency sweep from 1.5 Hz to 11.5 Hz, capturing critical modal variations without structural mass-loading distortions.

2. Verification of Resonant Frequencies and Global Amplification

The physical instrumentation plan verified the presence of two highly localized translational modes within the studied boundary spectrum:

- **Mode 1 (Fundamental Sway):** Identified at a critical resonance frequency of 3.5 Hz. This fundamental mode demonstrated a dominant global cantilever-style swaying profile where all storeys moved out of phase with the baseline anchor. At this frequency, maximum roof acceleration surged to 5.60g relative to the constant 0.99g base excitation, defining a global amplification ratio of 5.65.
- **Mode 2 (Second Harmonic):** Pinpointed at a secondary resonance frequency of 8.5 Hz, characterized by the lower structure crossing the neutral axis once. In this domain, acceleration peaked at the first floor reaching 5.09g, while the top storey snapped sharply in the opposite direction.

3. Symmetrical Characterization of Structural Deflection Regions

Between the identified peak frequencies, a pronounced structural de-amplification band was observed spanning from 5.0 Hz to 7.5 Hz, where overall roof amplification dropped below 1.0. This drop verified a zone of natural structural isolation caused by inter-modal destructive superposition, which was visually validated frame-by-frame by the sudden reduction of spatial gradients in the DIC full-field displacement maps.

4. High-Resolution Mapping of Storey Drifts

The extracted DIC numerical shapes provided discrete cross-sectional visibility into localized frame behavior at peak dynamic response times:

- During the 3 Hz sub-resonance test, inter-storey drifts increased smoothly with elevation, maximizing at the top level with a value of 0.555.
- At the 3.5 Hz primary resonance threshold, the system localized a severe, non-uniform stiffness deformation at the middle level, forcing an extreme localized inter-storey drift of -0.872 between the second and third floors.
- Under higher frequency operations (e.g., 4 Hz, 5 Hz, and 5.5 Hz sweeps), the fundamental mode safely realigned into a regular cantilever trajectory, where storey drift continuously scaled upwards with structural height.

5. Strategic Advantages of Full-Field Optical Profiling

While conventional wired accelerometers provided high-fidelity temporal tracking at discrete point locations, they remained completely blind to the deformation boundaries tracking between sensors. The DIC system successfully eliminated this limitation, transforming the visible face of the three-storey skeleton into thousands of virtual measurement arrays. This permitted the continuous recording of exact geometric inflection points, relative horizontal storey drift paths, and structural curvature maps which are critical for rapid health evaluations.

5.2 Recommendations for Future Work

The successful application of DIC and shake table testing on this bare frame establishes a strong foundation for several advanced research avenues:

Advanced Signal Processing Integration:

Future research can focus on applying Fast Fourier Transform (FFT) algorithms directly to the structural acceleration data. Implementing FFT in the data analysis pipeline will allow for a more granular derivation of peak acceleration versus frequency results, enhancing the frequency-domain mapping of the DIC outputs.

Implementation of Base Isolation Systems:

The methodology developed here can be expanded to evaluate the performance of structural protection technologies. A critical next step is to conduct a comparative shake table study on the 3-storey frame isolated with Lead Rubber Bearings (LRB) to quantify the reduction in fundamental mode storey drifts.

Comparative Component Testing:

Beyond LRB isolation, the experimental setup can be utilized to test and compare the energy dissipation efficiency of Lead Rubber Bearings against High Damping Rubber Bearings (HDRB) under identical frequency excitations.

Regional Code Compliance Analysis:

Future experimental parameters should be aligned to investigate the technical and regulatory scope for implementing these base isolation technologies specifically within the

requirements of Indian Standard IS 1893 (Part 6), bridging the gap between laboratory testing and regional structural design codes.

Bibliography