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Structural health monitoring of two storey steel frame using accelerometer sensor: a numerical and experimental study

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ABSTRACT

External forces generated due to earthquakes, wind, and blasts cause damage to the structure by which its structural integrity gets compromised. A method is to be developed to find the current state of the structure after the damage has occurred. This can be done by finding the natural frequency of the structure using modal analysis. In this study, a two-storey steel frame bolted structure has been studied experimentally on a one-dimensional shake table. Results obtained through the experiment have been verified using the numerical study of the same structure. COMSOL Multiphysics was used for additional numerical analysis, and the various eigenfrequencies and mode shapes were identified. Additionally, numerical research was carried out to simulate damages ranging from 10 mm to 20 mm, and the findings indicate that the natural frequencies decrease as the damage increases. Thus, Modal analysis can be used to determine the current state of the structure. For various mode shapes, the experimental and numerical frequency variations are 0.37, 1.61, and 3.16 %, respectively.

KEYWORDS

experimental modal analysis • COMSOL Multiphysics • shake table • accelerometer • damage study numerical study

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Introduction

The condition of the civil infrastructure has been carefully monitored through the implementation of the structural health monitoring (SHM) system [1,2]. Different methods of SHM have been developed to detect damage in various kinds of steel structures [3–7]. An intelligent method was created to detect structural damage, such as cracking in steel gusset plate joints. It is argued that bolt joint loosening and cracking are two of the most common types of damage in bolted steel frames [8]. For steel frames, connection stiffness is important because it affects the structure's overall integrity and dynamic responsiveness. The impact of bolt loosening on the mechanical behaviour of steel frames has been examined in numerous studies. A reduced-order numerical modal for damage diagnosis upon loss of the frame connecting bolt was suggested in [9]. In [10], a technique is provided based on variations in the intrinsic frequencies of the structure to identify defects, such as the loosening of bolted connections, in space frame construction with L-shaped beams. Based on piezoelectric impedance frequency shifting, a bolt looseness detection system was created by Shao et al. [11]. Consequences of joint damage in steel frame structures under seismic excitations were investigated in [12]. In [13], it was developed a model that detects changes in modal parameters and compares them to a reference state, giving a way to anticipate structural defects in steel frames.

System identification principles were the foundation for early operational and experimental modal analysis research. Numerous studies have been done on system identification [14–20]. Assessing how vibrations affect structures and how they behave has rapidly grown in recent years, both domestically and internationally. Since many historically significant buildings are situated in seismically active zones, more research is being carried out on how buildings react to vibrations, particularly after earthquakes. Currently, researchers utilize soft computing techniques such as genetic algorithms [20], artificial neural networks (ANN) [21–23], fuzzy logic [24], etc., for this purpose. Many older buildings have experienced significant damage due to design flaws, construction errors, natural disasters, and excessive loads. Given our country's active seismic zones and large population, evaluating such damage is crucial. Structures are continually exposed to vibrations from wind, earthquakes, waves, explosions, and vehicular traffic, which can result in cracks or severe damage. Understanding how a structure behaves under these conditions is essential for its longevity and often requires experimental studies, as numerical models may not entirely capture real-world behaviour. Structural design generally starts with developing Numerical models for static and dynamic analyses under various loads. However, these modals often do not accurately represent actual building behaviour. With advanced technologies, it is now possible to create safer structures and also continuously monitor them. To accurately determine dynamic parameters, it is essential to correctly define the structure's parameters.

Many studies have found discrepancies between the dynamic parameters derived from operational modal analysis and the steel frame structure finite element model. The permissible range for these variances is usually between 2 to 5 %. The range greater than this is due to finite element model flaws. Errors in the finite element model usually stem from incorrect material properties, dimensional measurement inaccuracies, etc. Measurement errors can be due to issues such as improper placement of accelerometers and other environmental effects, such as noise. In this study, special care was taken to avoid errors in both the operational modal analysis measurement and the finite element model, which were positively reflected in the outcomes. To bridge this gap, comparing dynamic parameters offers a practical solution [25]. Many structures in earthquake-prone regions endure various forms of damage from seismic loads, especially column damage during earthquakes. Strengthening columns without increasing the overall structure's mass is essential for improving building performance during seismic events. This requires examining technical repair and strengthening methods concerning column capacity. Ongoing research aims to optimize structural performance under seismic loads from different angles. In civil engineering, reinforced cement concrete, engineered wood, structural steel, and fiber-reinforced plastic are examples of materials used in framing, determining how structures behave when they vibrate, and impacting their longevity. It is possible to accurately evaluate a structure's behavior under vibration through numerical and experimental research. Operational modal analysis is frequently used to assess the vibration of existing structures. It also serves to confirm the assumptions made during the construction of the finite element model, update the initial numerical model of existing structures based on experimental data, and identify those dynamic properties of structures. In cases where numerical model is not possible, the structural health monitoring process is used to monitor the structures [26–30].

Numerical and experimental modal analysis for the dynamic properties of the structure work was carried out for this aim, and a 3D finite element Model of the building was produced based on the design drawings. Using ground-level recorded microtremor ambient vibration data, ambient excitation was produced. For output-only Modal identification, enhanced frequency domain decomposition was used. The structure is first represented by numerical Modal, which are then subjected to static and dynamic study under various loading scenarios. Nonetheless, the majority of the time, the numerical Model falls short of accurately describing the building's actual behaviour. Differentiations in building behaviour can be effectively identified and addressed by comparing dynamic metrics. Due to seismic loads, the majority of structures in earthquake-prone areas sustained various types of damage. Particularly affecting parts of the building, such as the columns. Considering the performance of buildings during seismic events, it is essential to strengthen the columns without increasing the overall building mass. This necessity highlights the importance of investigating the relationship between technical repair or strengthening methods and column capacity. Condition assessment can be accomplished by evaluating the dynamic and static characteristics of the structure, such as its inherent frequency [31,32] and degrees of stiffness [33,34] or flexibility [35]. Nevertheless, these kinds of techniques usually require computational measurement of the transfer function or experimental modal analysis. Therefore, online damage detection is unsuitable for in-service structures, requiring manual processes or equipment to obtain experimental measurements. Global-based damage detection involves numerical methods that use the overall vibration characteristics of a structure, such as mode shapes and natural frequencies, to identify damage. This approach was initially developed with the advent of structural monitoring systems capable of collecting response time histories from the structure. However, due to the high cost of structural monitoring systems, most installations involve a low number of sensors, typically only 10–20 per structure. This limited sensor density is often inadequate for capturing localized damage behaviour, and implementing globe-based damage detection is challenging. This problem is particularly severe for structures subjected to various operational and environmental pressures, such as civil structures (bridges, buildings, dams), where it becomes even more difficult to detect deterioration using global vibration characteristics.

Modal parameter extractions

The basic frequency domain (BFD) methodology, commonly called the Peak-Picking technique, is expanded upon by the frequency domain decomposition (FDD) method. This method is based on the idea that, under the assumption of white noise input and a lightly damped structure, modes can be predicted from the computed spectral densities. As a non-parametric method, FDD directly derives modal parameters through signal processing. It estimates modes by applying singular value decomposition (SVD) to every measurement data collection. For any single value, this decomposition enables a Single Degree of Freedom (SDOF) identification of the measured system [36]. The FDD approach is expanded upon by the enhanced frequency domain decomposition (EFDD) technique. EFDD is a simple, easy-to-use method that locates the modes in singular value decomposition (SVD) plots created from the responses' spectral density Spectra, making mode identification easier. EFDD offers better accuracy in predicting natural frequencies and can manage situations with modal damping, in contrast to FDD, which depends on a single frequency line from fast Fourier transform (FFT) analysis and does not account for modal damping.

Conversely, the EFDD provides a more sophisticated approximation of the natural frequencies, mode shape, and damping ratio [37]. The inverse discrete Fourier transform (IDFT) is used in that EFDD approach to return the single degree of freedom (SDOF), power spectral density (PSD) functions, which are located close to a resonance peak, to the time domain [38]. The function of time is used to count zero crossings to calculate the eigen frequency.

The study presented in this paper shows the experimental and numerical modal analysis of the two-storey steel frame structure. The results obtained from the analysis were verified numerically. After that, a damage study was done on the structure to detect the pattern in the structure's natural frequencies as the damage increased.

Materials and Methods

Description of steel frame structure and shake table

The steel frame structure height is 1.1 m. As shown in Fig. 1, a 3D steel frame was built in the laboratory. The height of each floor is 550mm, and the plan of the frame structure is 530 × 550 mm^2. The steel angle structure profile was selected for the columns and beams of the steel frame shown in Table 1, while the Indian Standard Angle (ISA) 24.4 × 24.4 × 2 mm^3 profile was used for the joints. M6 bolts are used in all the column-beam joints. E250 grade steel was chosen as the material, with nonlinear material properties represented in Table 2. The frame is connected to the Shake Table, with each beam secured by five M10 bolts and a 2 mm-thick angle.

Uniaxial bench-scale shake table used for the analysis of the steel frame structures shown in Fig. 2. Time history data acquired through the data acquisition system (DAQ) is used to extract accelerometer data from the shake table. It works well for a wide range of civil engineering Modal and structural experiments. Table 3 gives the specifications for the shake table.

Fig. 1. Two storey steel moment frame

Fig. 2. Shake table

Table 1. Physical property of the steel frame structure

Physical properties	Parameter	Values, mm
Front beam dimension	Length	530
	Width	24.4
	Thickness	2.0
Side beam dimension	Length	550.0
	Width	24.4
	Thickness	2.0
Column dimension	Length	1100.0
	Width	24.4
	Thickness	2.0

Table 2. Material characteristics of the steel frame structure

Material properties	Parameter	Values
Structural steel	Young's modulus, GPa	18.0
	Density, kg/m^3	7850.0
	Poisson ratio	0.3

Table 3. Shake table specifications

Parameters	Values
Model mounting table size, mm^2	900 × 1500
Maximum specimen mass, kg	500
Material thickness, mm	16
Temperature resistance, °C	50
Automation type	Automatic
Material	Mild steel
Shape	Rectangular

Two-storey steel frame building was set up on the shake table with four bottom beams connected with columns were positioned and fastened to the shaking table by using twenty M10 bolts. Beam-column Joints were fastened at corners by using twenty-four M6 bolts. Accelerometers were installed at the mid beam. After fixing the accelerometer on the beam, DAQ was used to acquire time history.

Numerical analysis

Numerical studies are an essential tool for monitoring structural health and ensuring its durability and safety. Because numerical studies offer a comprehensive and accurate examination of the structure's performance, they are employed in the structural health monitoring of steel frame structures. In addition, it ensures the longevity and safety of the construction while being cost-effective. Using the software program COMSOL Multiphysics 6.2 (2023), the finite element (FE) model of the three-dimensional, two-storey steel frame test specimen was modelled. The FE models are categorized into the following groups, beginning with the definition of the geometry of the steel frame structure. This involves specifying the dimensions and shapes of beams, columns, and other structural elements. Assign material properties to the elements. For steel, we need to input properties such as Young's modulus, Poisson's ratio, density, and yield strength [39–41]. For structural analysis, the Solid Mechanics or Shell interface is typically used, depending on the nature of the frame elements. Define the study type (e.g., static, dynamic, eigen-frequency, buckling) and configure the solver settings. Discretize the geometry into finite elements. Choose an appropriate mesh size that balances accuracy and computational efficiency. A finer mesh generally provides more accurate results but requires more computational resources. Apply boundary conditions to the model, which includes constraints (Fixed supports), and determine the mode shape. After running the simulation, the results analyses. This may include stress and strain distributions, deformation, patterns, Modal shapes, and natural frequencies.

Other methods for SHM were also formulated numerically such as, the electro-mechanical impedance (EMI) technique in which real component of the impedance obtained from the coupled-field FE model and the finite element analysis (FEA)-based impedance model (semi-analytical) was compared with the experimental results [40]. Applying a thermoelastic analogy and using FEA codes that are widely available and incorporate a formulation for a piezoelectric element, they used the commercial program COMSOL Multiphysics 6.2 to perform dynamic FEA of ring and steel structures to predict the structural response that arises from induced strain actuation. Fairweather created an impedance Model based on finite element analysis. This Model utilizes finite element method (FEM) to calculate the mass-normalized eigenfrequency and eigenvalues to determine the host structure's impedance. using the impedance-based electromechanical coupling equation, the mechanical impedance acquired for the EMI approach could be utilized to calculate the Admittance signature of the bonded piezoelectric lead zirconate titanate (PZT) patch as if measured by an impedance analyzer. These models were initially applied to relatively low-frequency simulation, usually below. 1KHz. For a 1D thin beam construction [13,15,17,19], research investigated simulating several SHM approaches using a PZT sensor using FE Modals. It was researched basic models, such as a 1D beam with a PZT patch and a free piezo patch of various forms to simulate the EMI approach. A long beam with many PZT patches that were simulated by tone burst signals to propagate elastic waves along the beam, with echo reflections caused by fractures, was employed. Bhalla [42] used 3D FE modelling to simulate the PZT−concrete interaction. The three-dimensional numerical Model of the host structure, A concrete block, was connected with a one-dimensional impedance Modal. The integrated crack propagation scheme in ANSYS was used to simulate damage. A reasonably good agreement of electrical impedance between experiment and the FEA-based impedance Model for an aluminium beam, truss, and concrete cube was demonstrated [43]. This paper also studies the further improvement of modelling by introducing the definition of effective impedance, thereby enhancing the interaction simulation. Because they coupled the FE output of the structural displacement response with the impedance-based numerical model without incorporating the coupled field theory into the FE formulations, these models were semi-analytical [39]. demonstrated that FEM could yield fairly accurate results for dynamic harmonic problems, even up to frequencies in the gigahertz range. With these developments, FEM's ability to Model the EMI technique's PZT-structure interaction has greatly enhanced.

The research methodology is constructed as follows to use accelerometer to evaluate the structural health of a two-storey steel frame structure as shown in Fig. 3. To accurately depict the size and layout of the building, the first step is to define

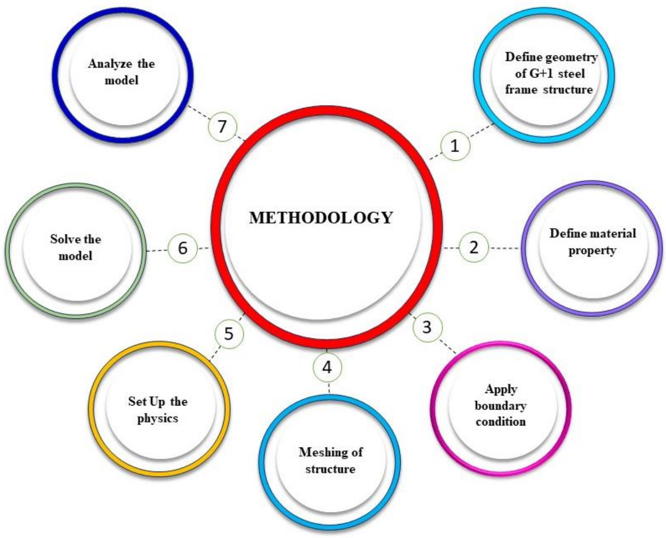


Fig. 3. Methodology of numerical study

the geometry of the two storey steel frame structure shown in Fig. 4. This involves defining how the floors, beams, and columns are arranged. The mechanical properties of the steel material, such as its density, yield strength, and Young's modulus, are then entered into the Modal to determine the steel frame's material properties. Then, suitable boundary conditions—such as fixed support at the base and constraints resulting from connections—are imposed to replicate the restrictions and support conditions of the structure as they exist in real life. Through the meshing process (Fig. 5), the structure is discretized into a finite element model once the geometry, material properties, and boundary conditions shown in Fig. 6 are established. This entails breaking down

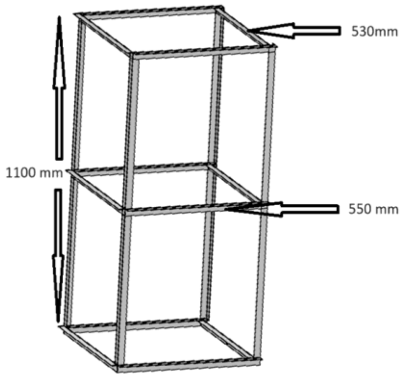


Fig. 4. Geometry of steel frame structure

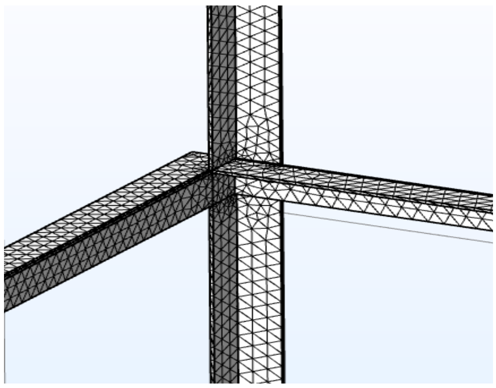


Fig. 5. Meshing of the steel frame modal

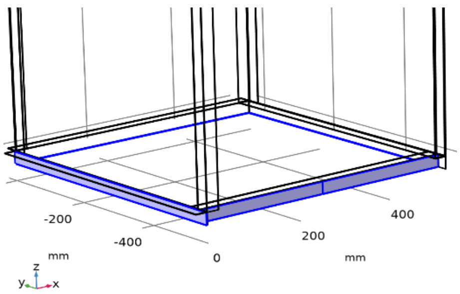


Fig. 6. Fixed support of the steel frame in FEM analysis

the structure into smaller components in order to precisely represent the behaviour of the complete frame under various loading scenarios. Physics of the problem are established following meshing, including the application of loads and external factors that the structure will encounter, like dynamic loads or vibrations [38]. After the model is completely defined, the finite element model must be solved to get information about the structural reactions, including displacements, stresses, and natural frequencies. In order to evaluate the structural soundness of the two-storey steel frame, the Modal results are finally examined. As part of this research, real accelerometer sensor values are compared with the simulated data to look for any anomalies or discrepancies that might point to possible structural problems. This all-encompassing method guarantees a precise assessment of the structural soundness and the efficiency of accelerometer sensors in keeping an eye on the structural integrity of the steel frame building.

Steel frame of a two-storey building geometry design in COMSOL Multiphysics, which includes defining the angle, beam, and column lengths, widths, and heights. In the Materials section, select steel from the Material Library and describe the material properties of steel, including Poisson's ratio and Young's modulus, and density. Define the fixed support at the bottom beam. With the help of a conversion study, define the mesh size.

Results and Discussion

Experimental modal analysis of steel frame structure

The ambient vibration measurements were carried out using two accelerometer sensors capable of measuring vibrations in both X and Y directions, as shown in Fig. 7. One accelerometer was used as a reference sensor and was permanently positioned on the beam, while the other sensors acted as roaming sensors. Two distinct measurement datasets were recorded, each with a duration of 20 sec. The acquired accelerometer signals were used to generate the ambient excitation data through the data acquisition (DAQ) system, as shown in Fig. 8. Data acquisition and preliminary processing were performed using a dual-computer system, where one system continuously collected data and the second system handled data processing. Quality control procedures were applied to ensure data reliability, and datasets showing signal drift, noise contamination, or corruption were discarded and re-measured. Eigenfrequencies were identified using the peak-picking method (PPM) based on nonparametric spectral density estimation. However, due to the limitations of PPM in the presence of closely spaced modes and noise, frequency domain operational modal analysis (OMA) techniques were employed for more reliable modal parameter extraction. The experimentally obtained modal parameters were subsequently used for validation of the finite element model developed in COMSOL Multiphysics 6.2.

Vibration sensors are extensively used in various products, including automobiles, aircraft, circuit boards, suspension bridges, and buildings, for vibration measurements and to study the dynamic behavior of structures, such as through defined Modal analysis. Accelerometers, a type of vibration sensor, are employed to evaluate responses to outside pressures, validate the modal that simulation programs employ, and forecast reactions in

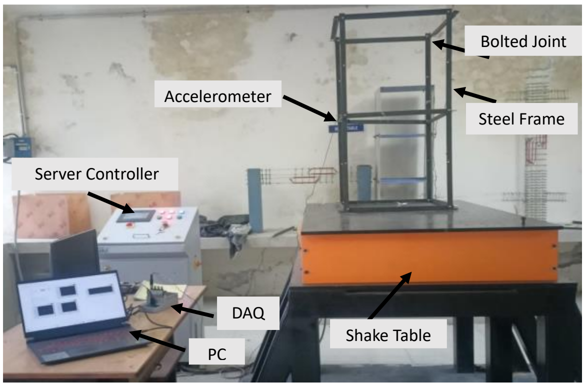


Fig. 3. Lab setup

Fig. 8. DAQ with sensor

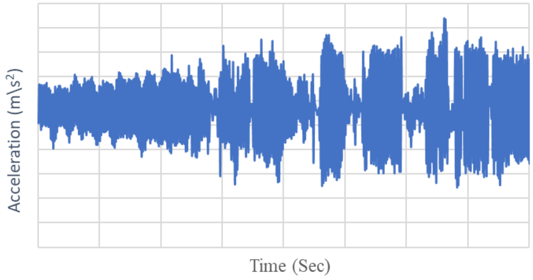


Fig. 9. Accelerometer data through shake table

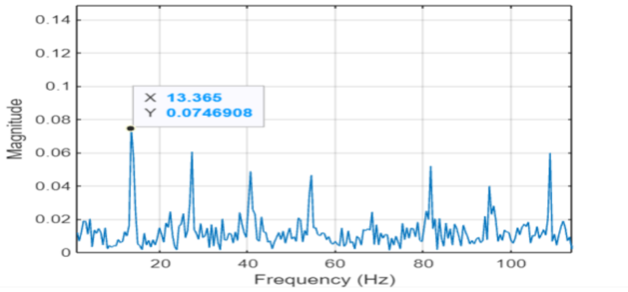


Fig. 10. FFT analysis data from the MATLAB software

various operational scenarios. Vibration sensor monitoring has emerged as the most widely used method for evaluating the condition of major machinery and buildings in both the industrial and civil sectors. Vibration trends over time can be used to forecast when deterioration will start and to take corrective action before failure happens. "Predictive maintenance" is the term for this type of ongoing or sporadic observation of a plant's operational state. An accelerometer works by measuring the inertia of a mass that is being accelerated. A sensor measures the displacement of the mass for the device's permanent structures while it is suspended by an elastic element. Because of its inertia, the mass accelerates and moves from its rest position according to the acceleration that is sensed. The displacement is transformed by the sensor into an electrical signal that contemporary measurement equipment can obtain. Various types of sensors have been developed based on this principle. Data obtained from the accelerometer sensor with the help of LabVIEW software is shown in Fig. 9. The obtained mode shape frequency results through FFT analysis are shown in Fig. 10.

Convergence study

Finding a reasonably decent final solution through numerous separate optimization runs is a typical method in metaheuristic structural optimization. while this approach is often feasible for a small-scale design optimization problem, it is typically not feasible computationally for more complicated cases like steel frames that are the actual size. This is clear from the present literature on structural optimization, where the large computing cost of the examples usually results in the final Optimal solution being reported based on a small number of optimization runs. being investigated. In Fig. 11, the Convergence study showed that as the increment in the number of elements increased, the eigen frequency decreased. After an optimum number of elements, the value of the eigen frequency is approximately constant or varies with very small percentages.

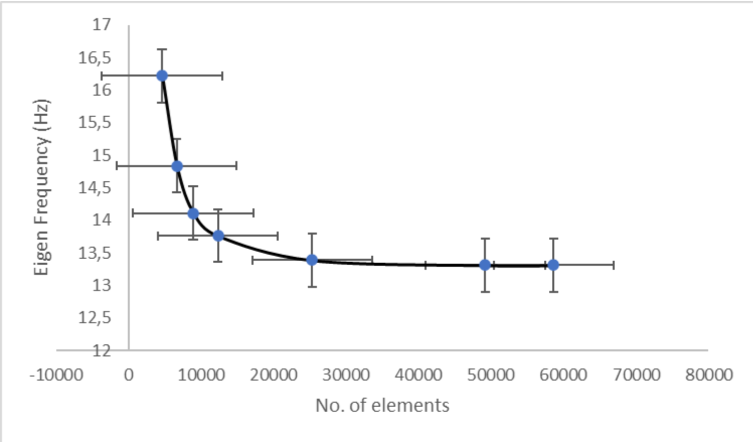


Fig. 11. Convergence study

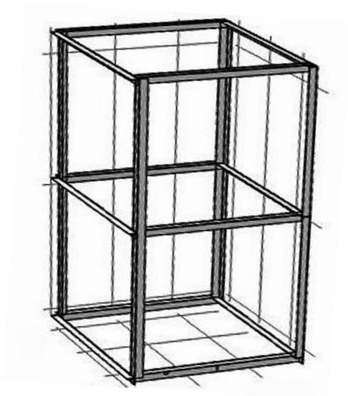


Fig. 12. Finite element model of steel frame structure

Eigenfrequency of the steel frame. Modal is added to the software relevant to physics. Utilize the Study section to specify the type of analysis and execute the Modal. This could include a static study for analysing displacement and stress, a frequency study for determining natural frequencies, or a transient study for investigating time-dependent behaviour. The frame system is modal as depicted in Fig. 12. Two equal spaces separate the outside surface of the L24.4x24.4x2 profile arms in the joints. These outside surfaces were divided into frictionless sections. And the terminal portions were chosen under a tie constraint. Furthermore, normal contact qualities were simulated using hard contacts. Surface-to-surface contact was used to modal the interaction between the beam and column connection as frictionless. To avoid Anomalies, the junction regions of the system mesh were meticulously partitioned. field-variable-dependent conductivity elements, each with eight nodes and three degrees of freedom, were used to mesh the Modal. The mesh was improved close to the connections. for the computation, reduced integration was employed. The Modal was initially subjected to gravity loads, which include applied load and self-weight. Dynamic parameters were obtained through implicit analysis.

Analysis results

In Fig. 13, FEM analysis fixed support created at the bottom beam in the steel frame structures. During the analysis, the effect of rotation in the frame systems is rigid. Semi-rigid. The joint was explained. The outcomes revealed an increase in displacement for eigen frequency 13.30 in the joint regions, as shown in Fig. 9. The rotation impact on the joints was amplified by the greatest tension at the mode.

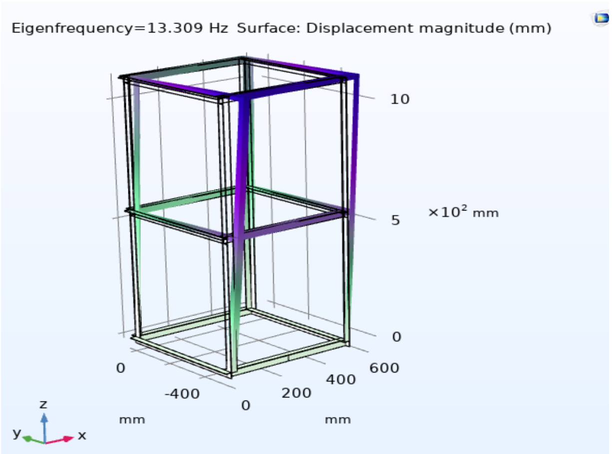
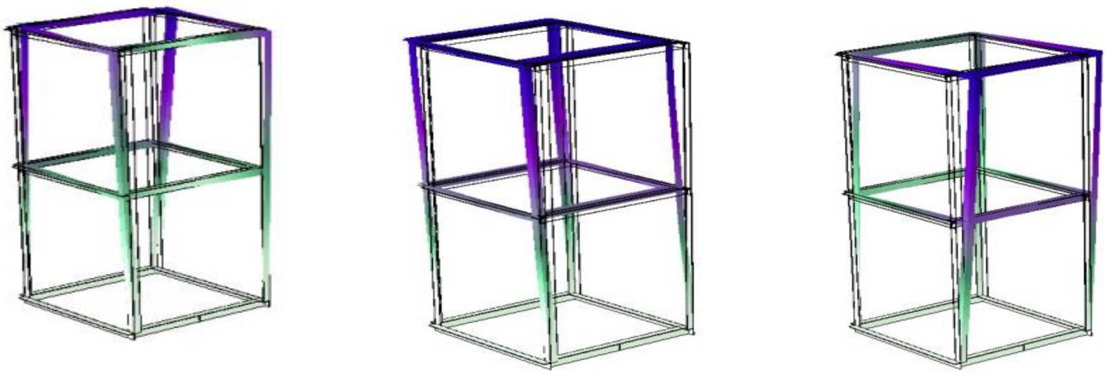
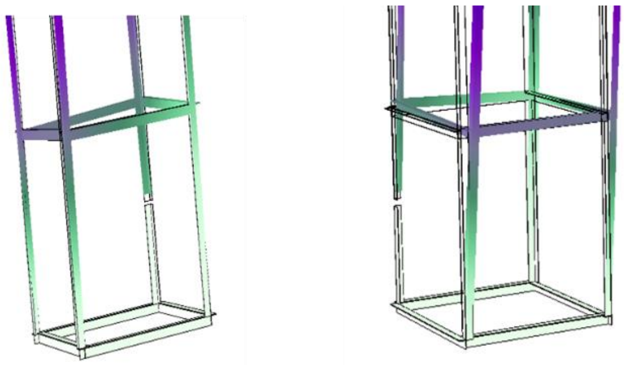


Fig. 13. Displacement for mode shape I



(a) (b) (c)

Fig. 14. Numerical analysis mode shape for two storey frames: (a) mode-1 (13.309), (b) mode-2 (26.79), (c) mode-3 (39.25)



(a) (b)

Fig. 15. Damage column front and back side: (a) 10 mm damage, (b) 20 mm damage

Natural frequencies and vibration modes significantly affect essential dynamic attributes and the dynamic performance of structures. Three natural frequencies in all, 13.31, 22.21, and 28.85 Hz, of the structure were obtained, which are shown in Fig. 14 and developed beam damage shown in Fig. 15.

Damage analysis

This section's goal is to investigate how cracking affects the frame's mechanical response. As seen in Fig. 15, the crack is inserted into the structure's three columns. Frequency is measured from the accelerometer sensor, and the accelerometer sensor is placed in the sensing location shown in Fig. 16. First, the damage condition is analysed without the bolts being removed or loosened. After that, the outcomes for strain and acceleration are compared to examine how cracking affects the behaviour of the frame. Determining whether the eigenfrequency and acceleration are more susceptible to damage of the type Fractures is the specific goal of this section. When cracking is introduced to the first three columns, the first mode shape frequency for partial damage column of 10 and 20 mm are 13.30, 13.28, 13.26, 13.29, 13.27, and 13.24 Hz, respectively shown in Table 4. First mode shape frequency for fully damaged columns of 10 and 20 mm are 9.22, 4.62, 0.55, 9.22, 4.63, and 0.56 Hz, respectively, as shown in Table 5.

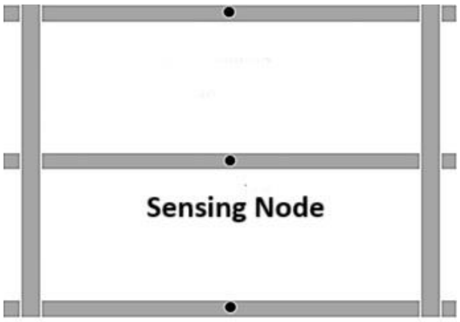


Fig. 16. Sensor place at the sensing node

Table 1. Mode shape frequency for partial damage

Damage level	Mode-1, Hz	Mode-2, Hz	Mode-3, Hz
10 mm	13.30	21.95	28.35
10 × 10 mm^2	13.28	21.91	28.35
10 × 10 × 10 mm^3	13.26	21.74	27.77
20 mm	13.29	21.92	28.34
20 × 20 mm^2	13.27	21.86	28.32
20 × 20 × 20 mm^3	13.24	21.70	27.69

Table 2. Mode shape frequency for partial damage

Damage level	Mode-1, Hz	Mode-2, Hz	Mode-3, Hz
10 mm	9.22	17.00	23.77
10 × 10 mm^2	4.62	7.61	19.80
10 × 10 × 10 mm^3	0.55	2.07	4.99
20 mm	9.22	17.00	23.78
20 × 20 mm^2	4.63	7.63	19.86
20 × 20 × 20 mm^3	0.56	2.07	5.01

Table 3. Variation in frequency of first mode shape

Damage level	Partial damage, Hz	Full damage, Hz	Percentage variation
10 mm	13.30	9.22	30.62
10 × 10 mm^2	13.28	4.62	65.21
10 × 10 × 10 mm^3	13.26	0.55	95.85
20 mm	13.29	9.22	30.62
20 × 20 mm^2	13.27	4.63	65.10
20 × 20 × 20 mm^3	13.24	0.56	95.77

Table 4. Eigen frequency value comparison between experimental and numerical data

Mode shape	1	2	3
Experimental frequency, Hz	13.36	27.22	40.49
Numerical frequency, Hz	13.31	26.79	39.25
Percentage variation	0.37	1.61	3.16

The percentage variation in the first mode shape of partial and full damage for the first three columns is shown in Table 6. 30.62, 65.21, 95.85 % variation in 10 mm damage in column, 30.62, 65.10, 95.77 % variation in 20 mm damage in column are shown in Table 6. Experimental frequency and numerical frequency variation are shown in Table 7 and Fig. 17. The generated finite element model was validated by comparing the findings of numerical modal analysis and experimental modal analysis. The comparison between numerically calculated eigenfrequencies from the finite element model and experimentally acquired natural frequencies from ambient vibration testing is shown in Table 7. For Mode 1, Mode 2, and Mode 3, the percentage difference between experimental and numerical frequencies was 0.37, 1.61, and 3.16 %, respectively. There is a high agreement between the experimental and numerical results, as these fluctuations fall within the permissible range (usually 2–5 %) stated in the structural dynamics literature. This high degree of agreement confirms the accuracy of the finite element modeling, the assignment of material properties, the boundary condition determination, and the operational modal analysis method. In order to validate the model through ambient vibration testing, experimental investigations were restricted to the healthy structure. To simulate cracking and stiffness deterioration, damage scenarios were then numerically added to the verified finite element model. Therefore, rather than being experimental damage testing, the partial and full damage studies are model-based prediction simulations.

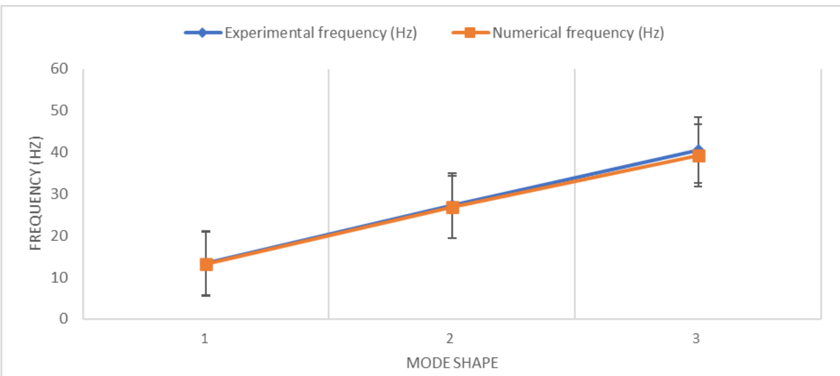


Fig. 17. Variation in experimental and numerical data

Conclusions

The modal analysis of a steel moment frame is presented in this study using both experimental and numerical methods. First mode shape frequency for partial damage column of 10 and 20 mm are 13.30, 13.28, 13.26, 13.29, 13.27, and 13.24 Hz, respectively. The variation in frequency in the first mode shape is very small compared to other higher mode shapes. These variations are due to inaccurate modelling of the experimental steel-framed structure in the FE numerical package. The unwanted noise captured by the accelerometer during the experimental data acquisition is also one of the reasons for it. The noise can be due to any physical environmental forces near the structure. The study shows that the structure's natural frequency gets reduced by increasing the damage. This is due to the reduction in the stiffness of the structure. When damage is induced in the structure, its moment of inertia changes, which is responsible for the reduction in stiffness. For various mode shapes, the experimental and numerical frequency variations are 0.37, 1.61, and 3.16, respectively.

CRediT authorship contribution statement

Kumar Mohit: investigation, writing – investigation review & editing, writing – original draft; **Sachin K. Singh** Sc: data curation, validation, software, resources, methodology, formal analysis, supervision; **Abhishek Mishra** Sc: validation, software, resources, methodology, formal analysis, supervision.

Conflict of interest

The authors declare that they have no conflict of interest.

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