Vibration And Stress Analysis of Multi-story Steel Structure with and without crack

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CERTIFICATE OF RESEARCH

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DECLARATION

*I hereby declare that this thesis entitled "***Vibration and Stress Analysis of Multi-story Steel Structure with and without crack***" is an authentic report of our study carried out as requirement for the award of degree B.Sc. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Dr. Md. Zahid Hossain, Professor, MPE, IUT in the year 2022-2023.*

The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.

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Abstract

Modal characteristics of buildings and machinery are essential for predicting dynamic behavior throughout operational phases. To avoid any catastrophic collapse, it is essential to identify the dynamic properties and optimize the structure during the design process. In order to throw some insight on the equivalent stresses created in the structure using numerical methods, the study will concentrate on the modal characteristics of steel structures both computationally and experimentally. Not only have the modal parameters been established, but also the experimental confirmation of the findings. This will enable precise numerical analysis of high-rise steel buildings without spending money on expensive trials. Moreover, the purpose of using I-beam instead of rectangular or square shaped beam has been studied. Through simulation in ANSYS, the mode shapes and natural frequencies of the 10-story building have been determined for both loaded and unloaded situations. The first six modes were taken out since it has been seen that they have the most effects on the structure during dynamic loading conditions like earthquakes. In order to determine the relative stresses that generated in the 10-story unloaded structure under various mode shapes and natural frequencies, Von Mises stress analysis has also been carried out. The diverse mode forms and natural frequencies have been discovered from the various stress conditions of the structure. The mode shapes and natural frequencies alter along with the loads from floor to floor. The natural frequencies and forms are very different from the unloaded structure. The research is innovative in that it compared the modal characteristics under various loading circumstances to those under an unloaded structure.

Furthermore, this study will examine how cracks affect the dynamic behavior and stress distribution of steel structures. The structure is modeled using the finite element method, and the outcomes are evaluated against available experimental data. The study shows that the presence of a fracture has a substantial impact on the structure's dynamic behavior and raises the stress concentration. The findings imply that a break can both lower the structure's inherent frequency and raise the vibration's amplitude. The results of this study can be extremely helpful in designing and maintaining steel structures, especially when determining how safe and long-lasting they are.

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Chapter 1

1.1 Introduction

Structures are made up of a number of sections that are connected by a number of different elements to form a supporting framework. This might be a component of a structure, a ship, or a car [1]. Knowing a structure or machine's dynamic behavior under operational circumstances is essential throughout the design process. To avoid any unaccounted failures, this is done. The standard technique for forecasting a structure's dynamic properties is modal analysis. It demonstrates how the resonance frequencies impact the structure and also enables the designer to spot areas that need improvement and make those improvements throughout the design process. In essence, modes are structural identifiers that are closely related to resonance. Although modes are independent of external forcing (f(t) = 0), they do alter in response to material characteristics including density, stiffness, and damping. Modes can be found experimentally, numerically, and analytically. Investigating complicated structures using numerical methods is quick and easy, and it doesn't cost as much as using experimental approaches may. But in order to verify the numerical conclusions, experimental approaches are crucial. One cannot simply accept the computer results blindly. (ref- M. L. Chandravanshi and A. K. Mukhopadhyay, "Modal analysis of structural vibration," ASME Int. Mech. Eng. Congr. Expo. Proc., vol. 14, pp. 1–9, 2013, doi: 10.1115/IMECE2013-62533.)

1.1.1 Structural Vibration and Control: The frequency and amplitude of structural vibration are governed by two parameters. The applied excitation and the reaction to that stimulation are these two components. The vibration stimulated will change if either of these are altered. These excitations can manifest in a variety of ways, including ground foundation vibration, cross winds, waves and currents, earthquakes, and internal sources like moving loads and machinery.

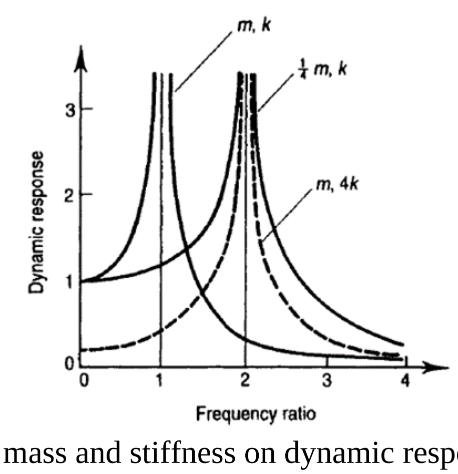


Figure 2: Effect of mass and stiffness on dynamic response of structure

These vibrations might have a periodic, harmonic, impulsive, or random character. The application and position of these stimulating forces affect the structure's reaction. The dynamics depend on the natural frequency and the damping. (ref- C. Eng, "Structural vibration analysis: Modelling, analysis and damping of vibration structures," *Eng. Anal.*, vol. 1, no. 1, p. 63, 1984, doi: 10.1016/0264-682x(84)90015-7.)

Early constructions were heavy and heavily dampened since they were constructed with hefty timbers, casting, and stones. Before the industrial revolution, there were relatively few sources of vibration outside wind, gravity, and seismic stresses. This reduced their ability to respond structurally to dynamic loads. Nowadays, more expertise than ever is used in the construction process. Buildings nowadays are different because to greater design and lighter materials. Since then, the structural mass has reduced, the damping has increased, and the excitation has increased. Since the required dynamic performance is acceptable, many structures are being erected without comprehensive vibration studies. Still, structures have failed or have not met their design criteria due to resonance, fatigue, or excessive vibration. Therefore, it is necessary to perform vibration analysis of structures at their design phase [1]. The design of steel buildings become a broad topic when considering the seismic effects. With keeping that in mind, the designs have been focusing on seismic-force resistant systems. Some of these notable systems described by Chia-Ming Uang et al. include moment frame systems, concentrically braced frames, eccentrically braced frames, buckling restrained braced frames and shear wall systems [3]. Theodore V. Galambos describes the recent research and design of steel buildings in the USA. In his studies, he has described the researches that is being conducted on the steel frames and members, cold-rolled steel structures, steel-concrete composite structures, connections and the impact of seismic forces, research on high performance steel and so on. [4]

To reduce unwanted situations and creating long lasting structures, it is necessary to devise ways to control or reduce these phenomena. One way may be to designing a stage that separates the structure to reduce incoming vibration. Another way is to alter the mass, stiffness or increasing the damping the structure or removing any sources of excitation forces from the weakest parts after reviewing it [1]. To decrease the structural vibration, many methods have been in development since the 1980s. Khaled Ghaedi et al. has talked about the application of active and passive of control of steel structures. In active vibration controlling, the essential dynamic loading data is received by the controller and through actuators, the forces are countered. Various mass dampers, such as active mass damper, active tuned mass damper, active tendon damper etc. have been in use to improve the serviceability and longevity of the structure. Passive vibration control systems are embedded into the structural members. Usually, TMD or tuned mass dampers are used with optimum damping ratio, TMD mass etc. [5] The use of smart materials have been seen in controlling the building vibrations. G Song et al. have presented the use of piezoceramic smart materials for active vibration control. These are low-cost, light-weight, easy to incorporate and can be available in different configurations such as patch, stack, micro-fiber composite etc. [6] . The energy dissipation capacity of a building is very important during earthquakes. To design the energy dissipation rate, a 3-stage grip is introduced within each story to control the vibration. These have been proven as satisfactory under high dynamic loading [7]. There has been development in tuned mass dampers. The passive mass dampers include TMD, TLCD, TLCBD, PTLCD etc. For active mass dampers, ATMD, MRD, MR-TMD, NSD, VD-STMD etc. are being used [8].

1.1.2 Modal and Frequency Response Analysis: Among many reasons, rotary, and static equipment or in our case, multi-story steel structures, fail when they are subjected to high vibration during operation that causes them to vibrate at near-resonance or resonance frequency. One can reduce these high levels of perturbation forces by balancing, aligning, or adding flow straighteners for rotary machines. Sometimes altering the frequency of the perturbation forces become impossible. That's when natural frequency of the structure is altered to stabilize it. But this is not possible to do without knowing the mode shapes where mode shapes or deflection allows one to determine the maximum deflection of the structure. By knowing that, one can either stiffen that location or make it flexible. So, the exploration of the natural frequencies and mode shapes can be called in short as 'modal analysis.' Modal analysis may be performed analytically or through finite element analysis. For simple structures, it is easy to perform analytical calculations. But structures with complex geometry, multi-degrees of freedom make analytical process impossible. That where FEA comes into play. With its versatility, one can easily determine the modal parameters. But this too has its limitations when the boundary condition selection becomes a challenge, and the calculation becomes very large. That's when experimental methods come into the picture. To validate the numerical results, it is essential to perform experiments. The experimental procedure can be of two types. In one method, a harmonic excitor is used for applying a constant load to measure the modes. Another method is using an impact hammer and analyzing the signal in FFT to determine the modes. Both methods have their pros and cons and depending on the use cases, either of the two methods can be used quite effectively.

1.1.3 Mathematical Models: Now, the discussion continues for the mathematical models that have been incorporated into finding the mode shapes, natural frequencies, harmonic response, and stresses.

1.1.4 Block-Lanczos Mode Extraction Method: An adaptation of the power method, the Lanczos algorithm is an iterative method used to find the m 'most useful' eigenvalues and eigenvectors of an n*n Hermitian matrix and m is most of the time smaller than n. A natural extension to the original Lanczos algorithm can be found using the Block-Lanczos algorithm for multiple vectors. K and M, a given pair of matrices, and a set of k starting vectors R = [r1, r2, … rk], the method generates n*k matrix sequence, [R, K-1MR, (K-1M)2. R, … (K-1M)j.R], during j iterations. This is known as the Kyrlov sequence and the set of vectors in the sequence is simply a block. This method is a two-step procedure. First, a set of vectors in individual blocks are orthogonalized and then it is imposed among the blocks. After that, a linear combination is taken, and a new set of blocks are obtained which are orthogonal.

1.1.5 Mode Superposition Method: There are two methods to perform harmonic response analysis. One is using the mode superposition method and the other is full harmonic. The full harmonic is costly is terms of computer memory and processing time. Therefore, mode superposition method is used for its advantages in terms of cost and efficiency. To measure the dynamic response efficiently, the mode superposition method has been used. It can allow for approximating the dynamic response of a structure using a small number of the eigenmodes. When the frequency content of the loading is limited, the mode superposition method becomes very useful. Its usefulness can be seen when performing analyses in the frequency domain since the loading frequencies are already known.

1.1.6 Von Mises Stress Analysis: Different behavior when non-simple tension or non-uniaxial stress applied to ductile material are much larger than the ones observed in the simple tension experiment and that gave birth to the maximum distortion energy theory. Widely used for metals and other ductile materials, the criterion for yielding is the von Mises stress. This criterion states that the stress components acting on a body being greater than the criterion will cause yielding of the body.

1.1.7 Structure forming cracks: Steel constructions are frequently employed in the building sector because of its great strength, long lifespan, and adaptability. However, if cracks are not quickly repaired, they can cause catastrophic failure and jeopardize the structural integrity of steel structures. Numerous variables, such as fatigue, corrosion, overload, and poor design or manufacturing, can result in the creation of cracks in steel structures.

Significant study on the causes and effects of fracture formation in steel structures has been conducted recently. For instance, Jiao et al. (2018) conducted research on the life prediction and fatigue fracture growth behavior of welded joints in steel structures [35]. They discovered that using high-strength steel and employing suitable welding procedures can greatly enhance the fatigue performance of welded joints and lower the possibility of fracture development. Kim and Kim (2018) also looked into the experimental and numerical elements of fracture initiation and spread in steel structures [36]. They discovered that residual loads and weld flaws can drastically alter the behavior of fracture propagation and cause premature failure.

Therefore, it is essential to comprehend the causes of fracture formation in steel buildings and create practical mitigation and remediation plans. This study uses I-beams with and without cracks to analyze the vibration and stress of a multi-story steel structure. This study can offer useful insights for the design and maintenance of steel structures, particularly in determining the safety and durability of these buildings, by examining the impacts of crack on the dynamic behavior and stress distribution of steel structures. Buildings with steel frames are susceptible to cracking for a number of reasons. Fatigue, corrosion, overload, and poor design or manufacturing are the main reasons why cracks arise in steel structures. One of the main causes of crack formation in steel constructions is fatigue. It happens when the material experiences cyclic stress repeatedly, which leads to the formation and spread of microcracks. These tiny fissures have the potential to develop into larger ones over time.

Structures made of steel may develop cracks as a result of corrosion. Steel can become weakened and more prone to crack formation when exposed to corrosive environments. Structures in coastal regions, those exposed to chemicals, and those built with other corrosive materials are particularly prone to this. Cracks can also develop in a steel structure that has been overloaded or overstressed. The steel may bend or fail, resulting in the production of cracks, when the loads placed on the structure are greater than its design capacity. This is frequently seen in structures that have experienced earthquakes or strong winds. Crack formation can also be influenced by poor steel structural design or construction. For instance, insufficient or poor welding can produce stress concentrations that can cause the commencement and spread of cracks. Similar to this, inadequate detailing or the wrong choice of materials can also cause cracks to appear in a steel structure. In conclusion, there are a number of causes for fracture formation in steel structure buildings, including fatigue, corrosion, overload, and poor design or manufacturing. To preserve the stability and safety of the structure, it is critical to recognize and treat these problems as soon as possible.

A steel structure's inherent frequency can be greatly impacted by cracks. The frequency at which a building vibrates naturally is the frequency at which it is excited by an outside stimulus, such as wind or earthquakes. The presence of a crack can vary the structure's natural frequency by changing the stiffness and mass distribution of the object. A drop in stiffness might result from a crack that develops in a steel structure in the affected area. This can consequently lower the structure's inherent frequency. Furthermore, cracks can modify the structure's mass distribution, which further alters the natural frequency. Resonance, which can produce vibrations of significant amplitude and perhaps result in failure, might become more likely to affect the structure.

In numerous studies, the impact of cracks on natural frequency has been examined. For instance, Zhou et al. (2016) studied the impact of a through-thickness crack on a steel beam's natural frequency [37]. They discovered that the crack caused the beam's inherent frequency to drop significantly. Another study by Li et al. (2018) looked into how many cracks affected a steel frame structure's natural frequency [38]. They discovered that the cracks caused a decrease in the structure's inherent frequency and an increase in its displacement and acceleration response. The natural frequency of steel constructions can be significantly impacted by cracks. When building and assessing steel structures, it's crucial to take the impacts of cracks on natural frequency into account to ensure their longevity and safety.

1.2 Literature Review

It is important to evaluate the modal parameters of the structure in its design phase. When designing frames, considering the rigid or pinned joints, S. Chan [13] has shown that the assumption may not be justifiable for certain reasons. His studies have shown by using matrix method of analysis, the dynamic characteristics of steel frames can be assessed which is crucial for determining the vibration properties. The soil-foundation-structure-interaction is an important part of the dynamic properties of the structure under seismic loading. B. Vivek et al. [14] has shown that the fundamental natural frequency increases up to 20% when the base is fixed compared to when it is resting on a soil base. Similar effects have been seen when the structure is resting on loose sand compared to rigid sand base. The mode shapes are also affected by the various loading conditions. Loading can be in the form of wind induced loads, gravity loads, seismic load etc. Yin Zhou et al. [15] used high frequency base balance data to obtain the response during wind loading from the non-ideal mode shapes and compared to the ideal mode shapes of the building. Another study done by Yin Zhou et al. [16] focuses on the torsional effects of wind loading on the building. Due to the unbalanced distribution of the instantaneous pressure on the building surface, the torsional response is caused by wind effects. In this study, a framework is provided for estimating the torsional effects by utilizing the aerodynamic loading data base to be incorporated into the building codes. Human loading also affects the mode shapes of buildings. A numerical investigation done by S. Silva et al. [17] looks at the dynamic characteristics of the floors of the building during human loading. From the study, it has been found that the loading pattern heavily affects the response, and the loading must be realistic for a comprehensive vibration evaluation. In a study by Yunsang Kwak et. al [18] found through impact loading that the different loading on the lower and higher floors of a 12-story building affected the vibration propagation levels. Various other research have been conducted on the stability and operability of buildings under wind loading [19]–[23]. Gravity loads are also a contributing factor in the dynamic characteristics of buildings. They play an important role on the linear and non-linear behavior of buildings during earthquake. A study by M. Shahin et. al [24] shows that the gravity forces are an important parameter. Gravity adds a moment distribution which is a function of relative shear in the walls. Similar studies have been done that describes the effect of gravity during seismic loading. [25], [26].

R. M. GRICE presented a technique for built-up structure analysis that is the machinery foundation of a ship which is constructed from a collection of large beams and flexible plates. (R. M. GRICE, n.d.) They found that the frequency response of the plate-stiffened beam which compares well with laboratory measurements, thereby supporting the method. Functionally graded (FG) open-section beams with thin walls were the subject of Tan-Tien Nguyen's study on free vibration. For thin-walled FG mono-symmetric I- and channel-section beams with various material distributions, they were able to get the natural frequencies and related vibrational modes. They discovered that if the materials tended toward metal or the span-to-height ratios got lower, the natural frequencies of a FG beam were reduced. They employed the metal-ceramic material Al/Al2O3 for their study. The material properties of alumina Al2O3 as ceramic are Ec = 380 GPa, ρc = 3960 kg/m3 and aluminum Al standing for metal are Em = 70 GPa, ρm = 2702 kg/m3. Poisson's ratio is taken as 0.3. The ceramic thickness ratios of flanges are given as α1 = 0:9, α2 = 0:1 for section M1; α1 = 0:1, α2 = 0.9 for section M2 and in the web α3 = 0:3 for both two sections. The length-to-height ratio of the beam is L/b3 = 40.

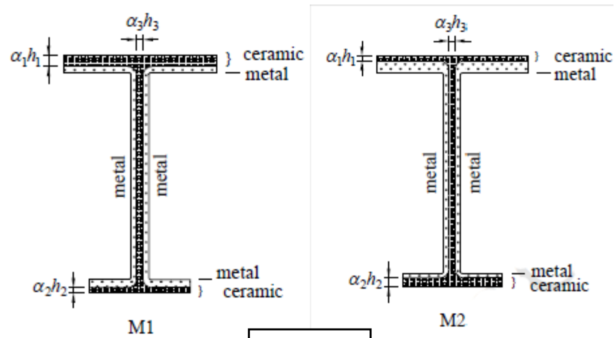


Figure 4

First, as illustrated in Figs. 5, the impacts of ceramic thickness ratios on the lowest non-dimensional natural frequency of mono-symmetric I-sections are examined. These figures show that when the ceramic thickness of the flanges grows, the natural frequency of the beam rises.

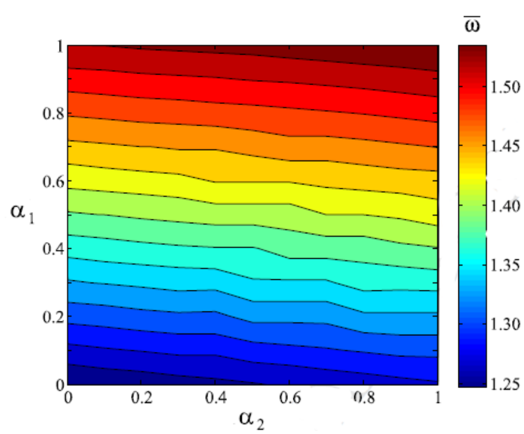


Figure 5

On the other side, it marginally decreases due to the web's thicker ceramic coating. The data shown further show that, compared to the web and bottom flange, the top flange's ceramic thickness has a substantial impact on the beam's free vibration characteristics. Additionally, it is discovered that for relatively low values of the volume fraction exponent, the gradual law significantly affects the natural frequency and the ceramic flange thickness plays a critical role. [34]

Due to their extreme durability and strength, steel structures are frequently employed in the construction sector. However, the development of cracks in steel structures can have a substantial impact on the structure's dynamic behavior and stress distribution, potentially causing failure. Vibration and stress analysis, which examines the dynamic behavior and stress distribution of structures under various loading circumstances, is a crucial component of structural design and evaluation. The impact of fractures on the dynamic behavior and stress distribution of steel structures have been examined in earlier studies. However, further study is still needed, especially in the analysis of multi-story steel buildings using I-beams with and without fractures. The impact of fractures on the dynamic behavior and stress distribution of steel structures has been studied recently. For instance, Raut et al. (2019) used finite element analysis to examine the vibration analysis of a broken cantilever steel beam. They discovered that when the crack size rose, the beam's inherent frequency reduced. Similar research was done by Huang et al. (2020) on the dynamic behavior of a broken steel beam under axial loading. They discovered that the existence of cracks resulted in a large amount of deformation and stress concentration in the beam. The effects of corrosion and fatigue on the structural integrity of steel constructions have been the subject of other investigations. For instance, Zhao et al. (2018) investigated the fatigue behavior of an I-beam made of welded steel under various stress scenarios. They discovered that corrosion considerably shortened the beam's fatigue life. Wu et al.'s (2019) experimental study on the dynamic behavior of corroded steel beams was also completed. They discovered that the level of corrosion had an impact on the inherent frequency and mode forms of the beams.

Additionally, studies on the design and optimization of steel structures have been done. In order to build steel frames that take into account dynamic response and material utilization, Song et al. (2021) suggested a multi-objective optimization approach. They discovered that the ideal design could keep the desired dynamic performance while reducing the structural weight. A similar analytical model was created by Liu et al. (2020) to forecast the ultimate strength of steel I-beams with welded flange plates. Additionally, Moustafa and Alsayed (2016) used experimental and numerical methods to research the effects of fractures on the dynamic behavior of steel structures. They discovered that the presence of fractures had a substantial impact on the structure's mode shapes and that the natural frequency of the structure reduced as the crack size rose. Similar to this, Li et al. (2019) used numerical simulations to examine the influence of crack location on the dynamic behavior of steel beams. They discovered that the beam's inherent frequency and mode geometries were considerably impacted by the crack's position. An experimental investigation on the dynamic behavior of steel beams with and without web holes was done by Alshibli and Filippou (2020). They discovered that the stress distribution in the beams as well as the natural frequency and mode geometries of the beams were considerably impacted by the existence of web holes. Similar to this, Alshibli et al. (2017) used experimental and numerical techniques to investigate the effects of various boundary conditions on the dynamic behavior of steel beams. They discovered that the beams' inherent frequencies and mode shapes were greatly impacted by the boundary conditions.

The significance of understanding how fractures and other factors affect the dynamic behavior and stress distribution of steel structures is brought home by this research. This study can offer important insights for the design and upkeep of steel buildings, especially in determining the safety and durability of these structures, by doing a vibration and stress analysis of a multi-story steel structure employing I-beams with and without cracks.

1.3 Significance of The Research

From literature review it is seen that, there are few papers directly discussing on the mode shapes and natural frequency of the steel structures. These parameters are important when considering the design of buildings. One of the notable literatures that has been found is by M.L Chandravanshi et al. [2] which focuses on the modal parameters that have been verified through both simulation and experiment. In that work, the effect of loading criteria has been studied as well.
This study focuses on the modal parameters of 4-story structures. It investigates the modal parameters for unloaded conditions as well as the differently loaded conditions of the structure. The change in natural frequency for unloaded structure and loaded structure has been observed. It has been seen that the natural frequency and mode shape change significantly with the change of loading conditions in the structure. From stress analysis, the von Mises stresses developed in the unloaded structure have been found through simulation.

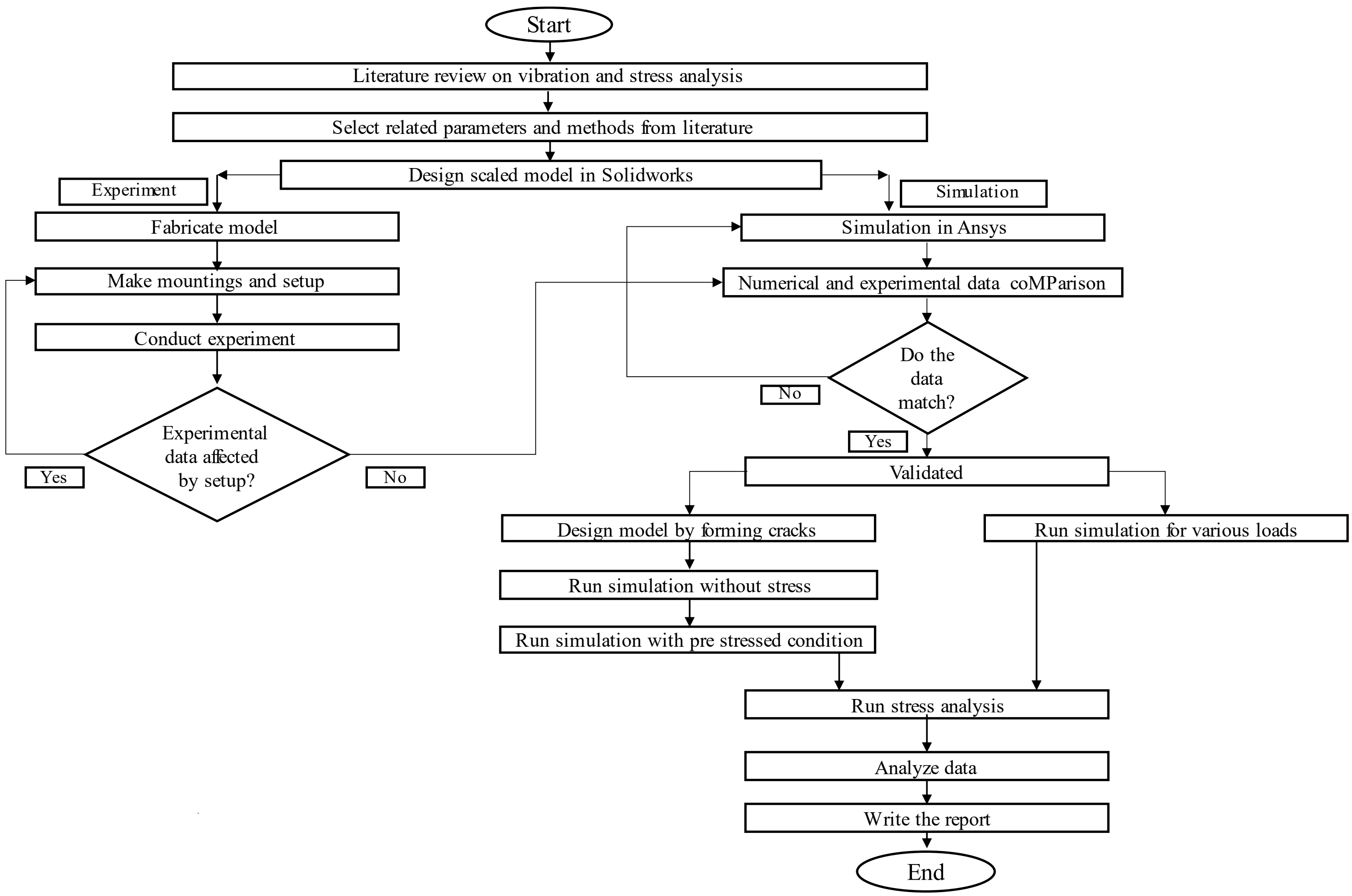
The proposed study will examine how cracks affect the vibration and stress behavior of I-beam-based multi-story steel constructions. The initiative is significant because steel structures, which are frequently utilized in the construction sector, are susceptible to structural integrity loss due to fractures, particularly when subjected to dynamic loading. The proposed research can offer important insights into how multi-story steel structures behave under various stress circumstances because little research has been done on the effects of cracks on them. To make more precise predictions of the dynamic response and stress distribution in steel structures with fractures, the study will employ sophisticated computational techniques including finite element analysis. Overall, the research project can help to improve the methods for ensuring the dependability and safety of multi-story steel structures that have cracks.

Despite the importance of this field of study, it is significant to emphasize that there have only been a few studies conducted thus far. Because there are so few previous studies, it is imperative that more research be done in order to better understand how multi-story steel structures with cracks behave. The results of such research projects could aid in the development of crack detection and monitoring methods, allowing engineers to identify cracks early on and take appropriate action to maintain the structural integrity and safety of these structures. Although there are few published publications in this important research area, multi-story steel constructions with and without fractures are subject to vibration and stress analysis. To successfully address the problems caused by crack-induced structural weaknesses and eventually ensure the safety and dependability of these structures, it is crucial to broaden the body of knowledge in this subject.

1.4 Objectives

- To find the modal parameters, such as mode shapes and natural frequency of I-cross section structure.
- To investigate the loaded and unloaded conditions on different floors of a structure based on their natural frequency and mode shape.
- To investigate the characteristic of vibration on a multi-structure with and without cracks.
- To validate the result experimentally to compare with the simulation in.

1.5 Methodology



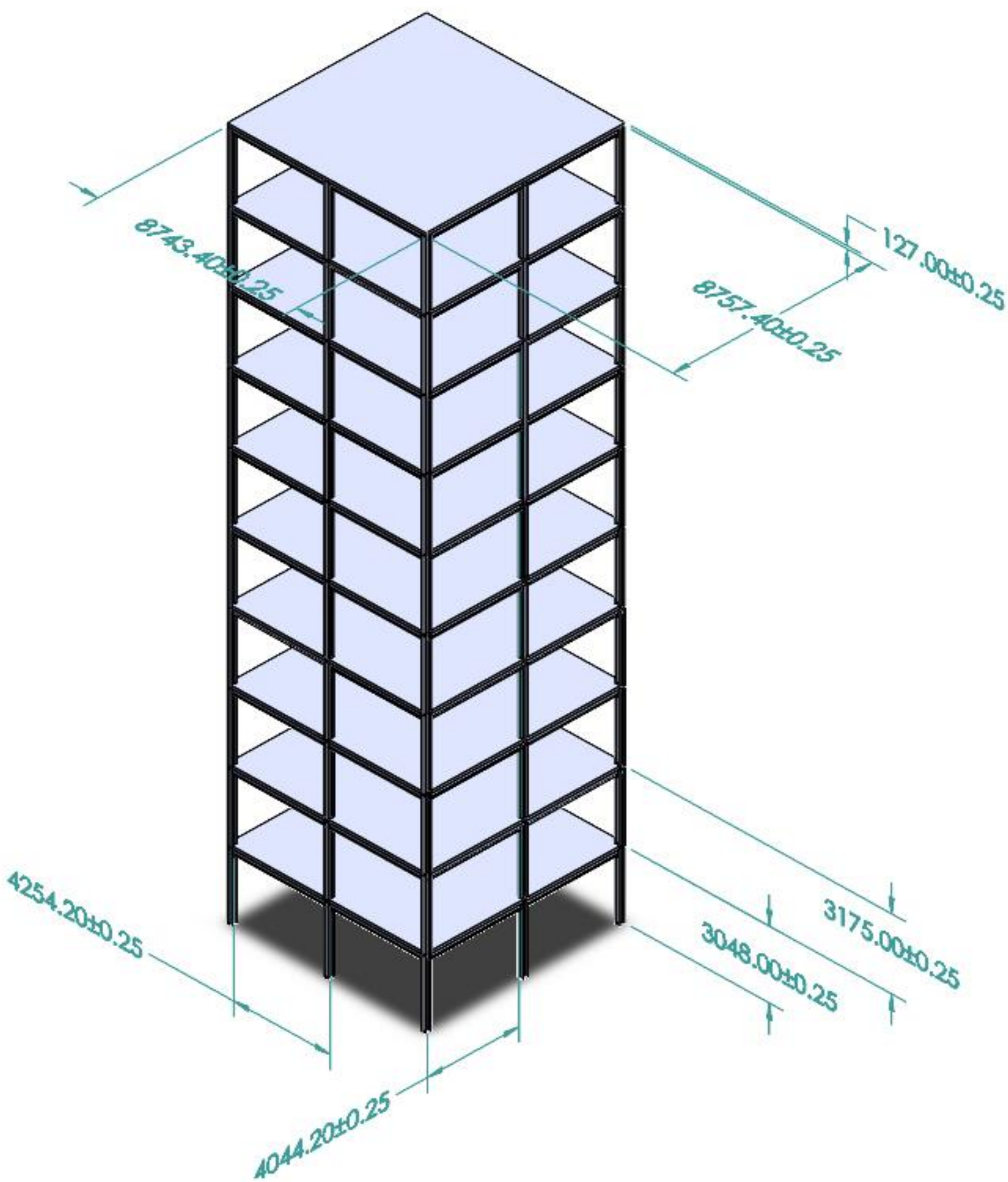
After reviewing a number of literatures, we came to a decision of using I-beam. A validation is done in order to verify our cause. A full-scale model was designed and was scaled down to 1:10 ratio. Modal analysis was performed on the scaled down model. To validate the result another model with 3 floors was used with different dimensions. Modal analysis and harmonic analysis were performed in order to find out the developed stresses for different mode shapes. Static structural analysis was done to find out the stress distribution and equivalent stress(Von-mises). Then cracks were introduced to the model and analysis were done to find out the characteristics of them. All the models are designed in Solidworks 2020 SP4.0 and all the analysis have been done in Ansys 2020 R1.

Chapter 2

2.1 Geometry and Specifications for Model

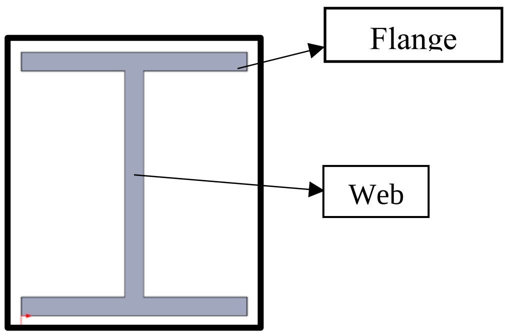
For simulation purposes, a 10-story steel structure building has been modelled using the Solidworks 2020 design software. It's made up from floors, columns and beams. The columns and beams are welded at their interface of connection. The floors are on the beams and also welded. The bottom floor is level zero (ground).

The original (full scale) dimension of the building is as follows-



These dimensions were calculated according to the self-weight of columns, beams, floors and to the elevation of the building. We maintained the rules and regulations of IBC (International Building Code) and BNBC (Bangladesh National Building Code).

For columns, standard W8*58 size I beam are used and for beams, standard S10*25.4 are used.

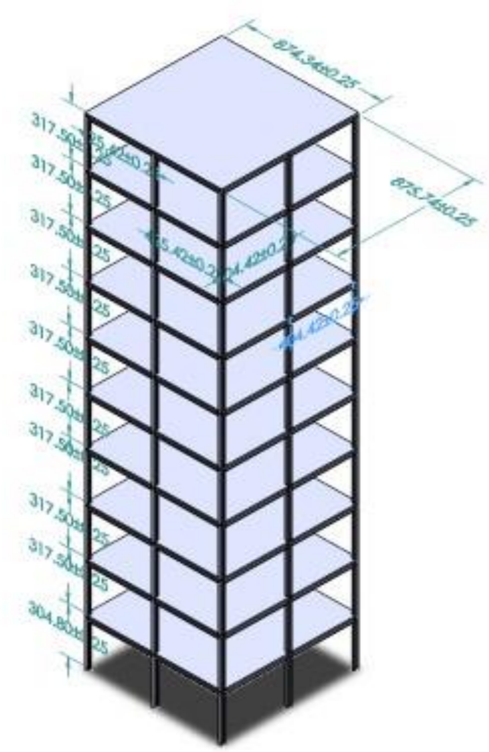


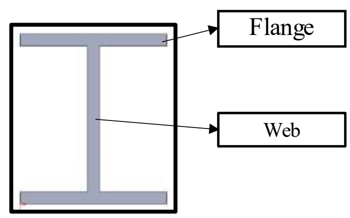
Building Specifications (mm)	
Floor thickness	127
Floor width	8757.4
Floor length	8743.4
Total floors	310
Column Height	3175

Cross Sectional View			
Column Specifications (mm)		Beam Specifications (mm)	
Height	223	Height	254
Width	209	Width	119
Flange thickness	21	Flange thickness	8.5
Web thickness	13	Web thickness	8.5

To ease our work and simplify Ansys difficulties, we scaled down the model 1:10. After scaling down the model, the new dimensions are found to be –

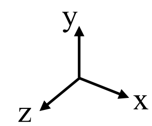
CAD model for Simulation (1:10)



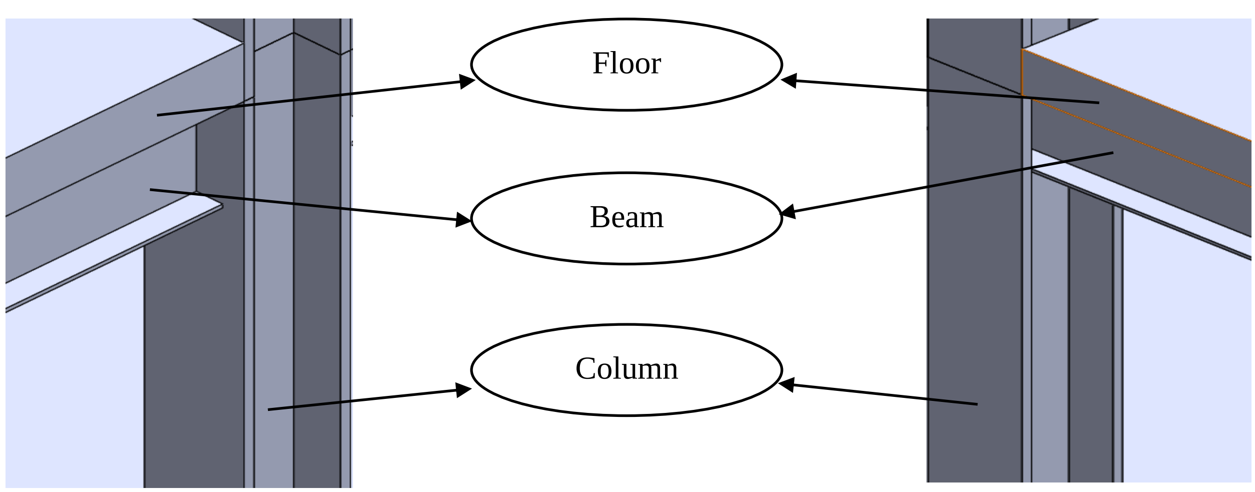


Cross Sectional View			
Column Specifications (mm)		Beam Specifications (mm)	
Height	22.3	Height	25.4
Width	20.9	Width	11.9
Flange thickness	2.1	Flange thickness	0.85
Web thickness	1.3	Web thickness	0.85

Building Specifications (mm)	
Floor thickness	12
Floor width	874.34
Floor length	875.74
Total floors	10
Column Height	317.5



Column-Beam connections-



2.2 Simulation

To calculate the mode shapes and natural frequencies numerically, ANSYS 2020 has been used for the simulation procedure. In ANSYS Workbench, the integrated ANSYS Mechanical Module for modal analysis 'MODAL' has been used. The figure below shows the Workbench interface.

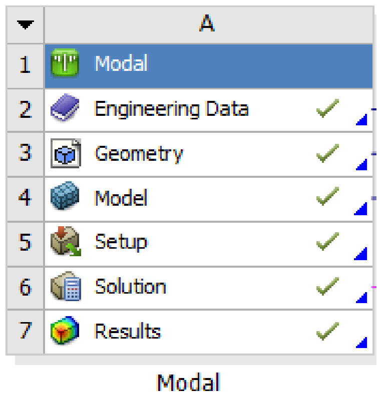


Figure : Modal analysis module (ANSYS 2020 Workbench Interface)

Mild steel (Structural Steel) has been used as material. This material is easily available and low in cost. So, in the simulation, the standard mild steel data has been taken. Here, the important factors are density, Young's modulus and Poisson ratio.

Material	Mild Steel		
Property	Symbol	Value	Unit
Density	ρ	7800	$Kg.m^{-3}$
Young's Modulus	E	2.1E+11	Pa
Poisson Ratio	υ	0.295	-
Bulk Modulus	K	1.5447E+11	Pa
Shear Modulus	G	7.3359E+10	Pa
Thermal Expansion coefficient	α	1.2E-05	C^{-1}

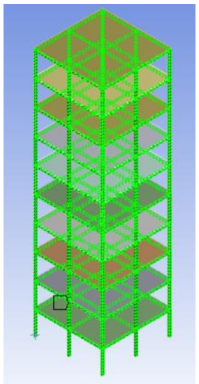
Table : Engineering Data

Geometry: The 3D model has been imported into ANSYS Workbench in the STEP format. It is a 2D-3D design exchange file format which is independent of source file format. It allows for exchange of design information about, in our case – wireframes, between two independent systems. This simulation was done for unloaded condition.

Meshing: The most important step is the meshing of the 3D model. A perfect mesh yields a proper solution. For this model, since the geometry is very simple, the program-controlled mesh settings have been chosen. 3 meshing methods were taken to mesh the entire building.

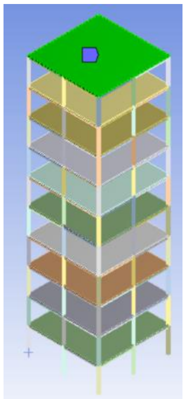
Body sizing 1 -

Settings	Description
Physics Preference	ANSYS Mechanical
Element Type	Rectangular
Element Order	Program Controlled
Element Size	10 mm
Scoping Method	Geometry Selection
Geometry	210 Bodies



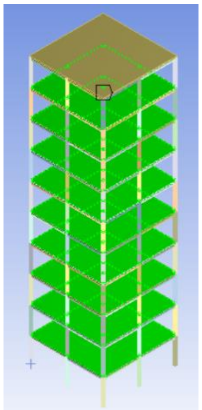
Body sizing 2 -

Settings	Description
Physics Preference	ANSYS Mechanical
Element Type	Rectangular
Element Order	Program Controlled
Element Size	25 mm
Scoping Method	Geometry Selection
Geometry	1 Body



Refinement -

Settings	Description
Physics Preference	ANSYS Mechanical
Scoping Method	Geometry Selection
Geometry	18 Faces
Refinement	3

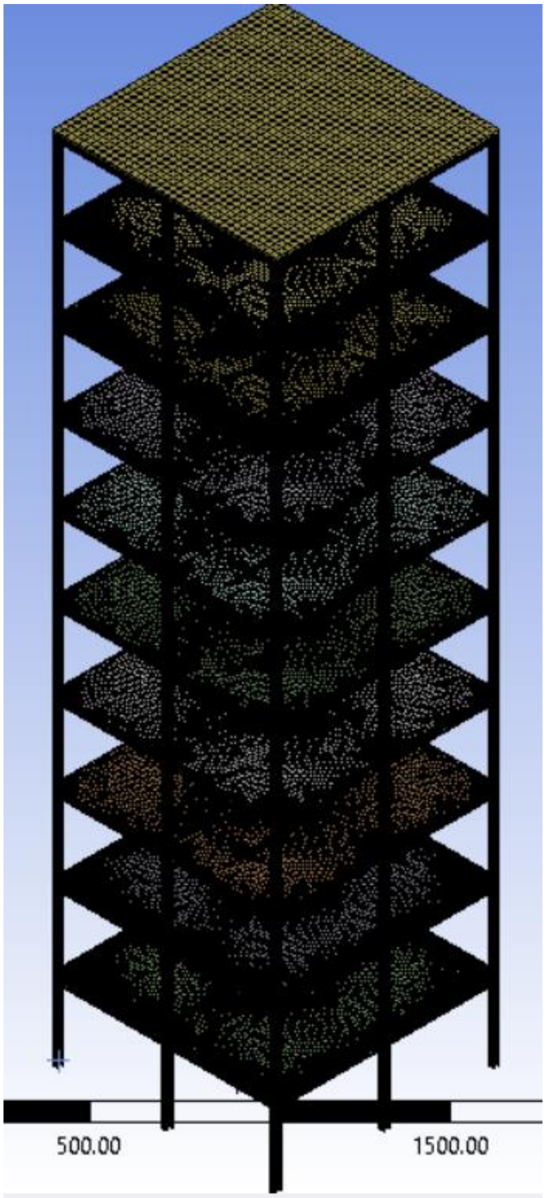


Statistics –

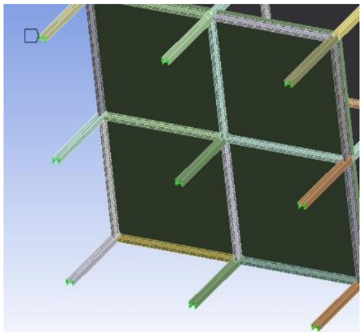
Number of nodes = 1094370

Number of elements = 359073

Fully meshed geometry -



Boundary Conditions: For the simulation to be run, necessary boundary conditions have been applied. The base columns of the structure have been fixed with ground. Rest of the structure is set free. The columns have been welded to the beams and beams to the floors. All the other conditions have been kept as default.



Modal Analysis: To perform the modal analysis, the solver has been set to extract the first 6 modes. Here, the 'Block-Lanczos mode extraction method' has been used as the solver. No damping has been incorporated.

2.3 Simulation Result

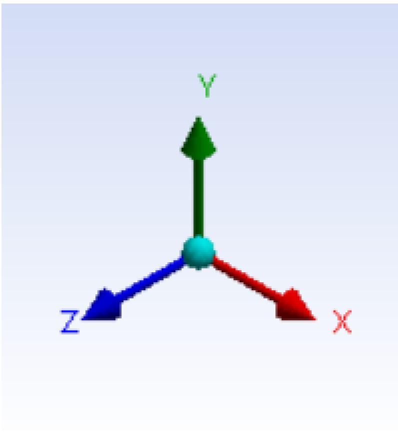
Here, the results obtained from the simulation are presented and discussed. The results are presented sequentially. First, the mode shapes and natural frequencies of the 10-story structure is shown.

2.3.1 Modal analysis of 10-storey unloaded structure:

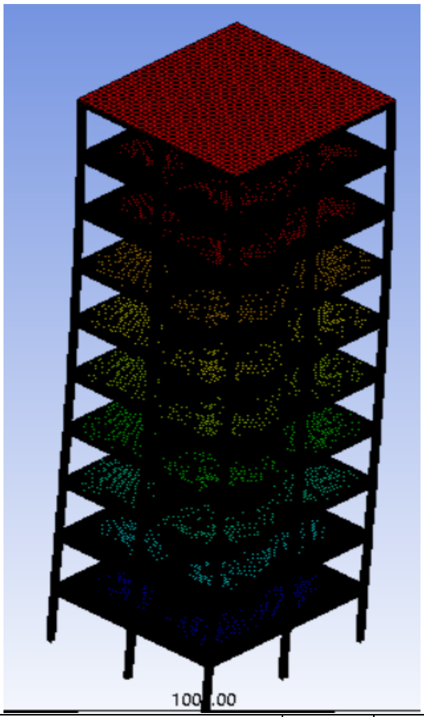
The natural frequency data for the unloaded 10-story structure is found from the modal analysis in ANSYS. From the simulation, the natural frequency of the first mode is 5.7612 Hz, and the sixth mode is 29.047 Hz. As the mode number increases so does the natural frequency. The mode shapes are also changing in the different axes. The first mode is bending in the X axis. The second mode is bending in the Z axis. A torsional or twisting mode can be seen in the Y axis. Rest of the modes are in the X and Z axis. A tabulated version of the modes is given in below.

Mode	Mode shape	Frequency (Hz)	Minimum Stress	Maximum Stress	Average Stress
1	1st mode bending in x-direction	3.653	2.8432*10^-4 MPa	79.703 MPa	1.9566 MPa
2	1st mode of bending in z direction	5.0044	3.3181*10^-4 MPa	53.904 MPa	2.6764 MPa
3	1st mode twisting in y-direction	10.019	1.2773*10^-3 MPa	626.6 MPa	4.4838 MPa
4	2nd mode of bending in x-direction	10.971	1.6188*10^-3 MPa	233.23 MPa	5.934 MPa
5	2nd mode bending in z-direction	15.219	1.3088*10^-3 MPa	155.86 MPa	8.3395 MPa
6	3rd mode bending in x-direction	18.469	1.9337*10^-3 MPa	373.87 MPa	9.8174 MPa

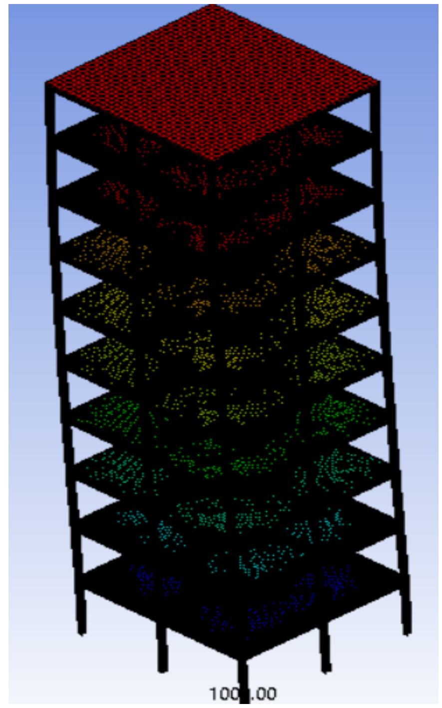
Direction -



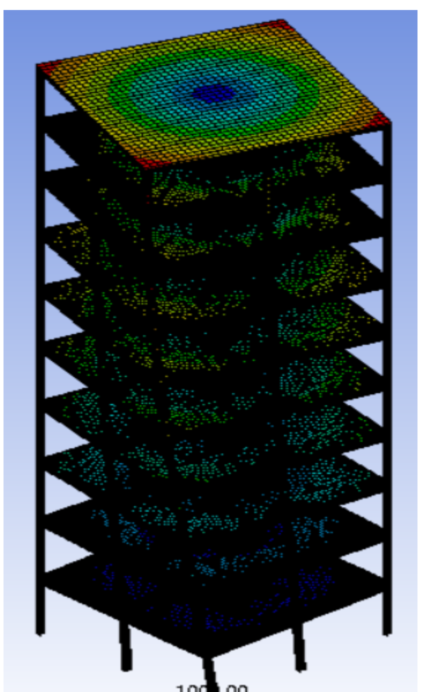
Mode shapes according to the modes are shown below –



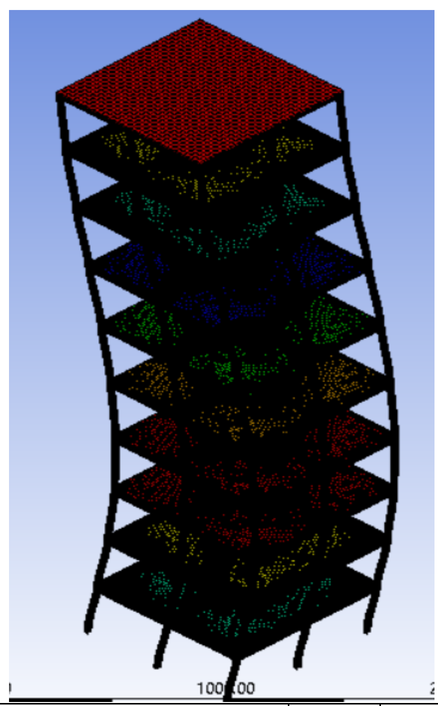
1	1st Mode of bending	X	3.653



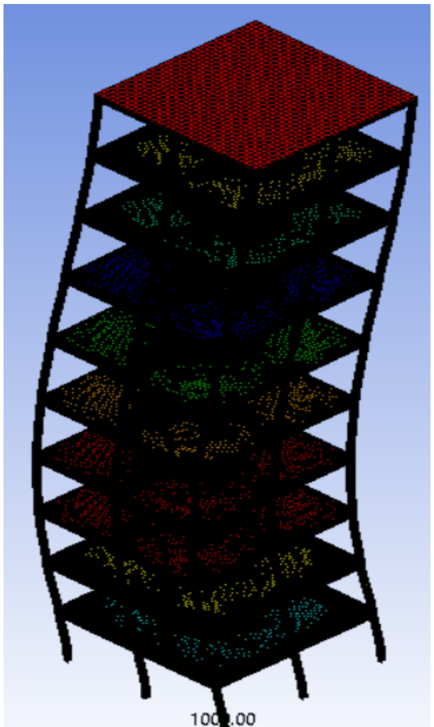
2	1st Mode of bending	Z	5.0044



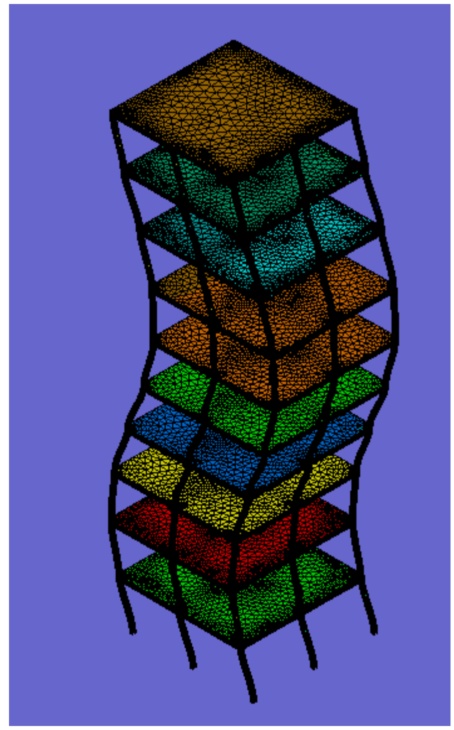
3	1st Mode of twisting	Y	10.019



4	2nd Mode of bending	X	10.971



5	2^{nd} Mode of bending	Z	15.219

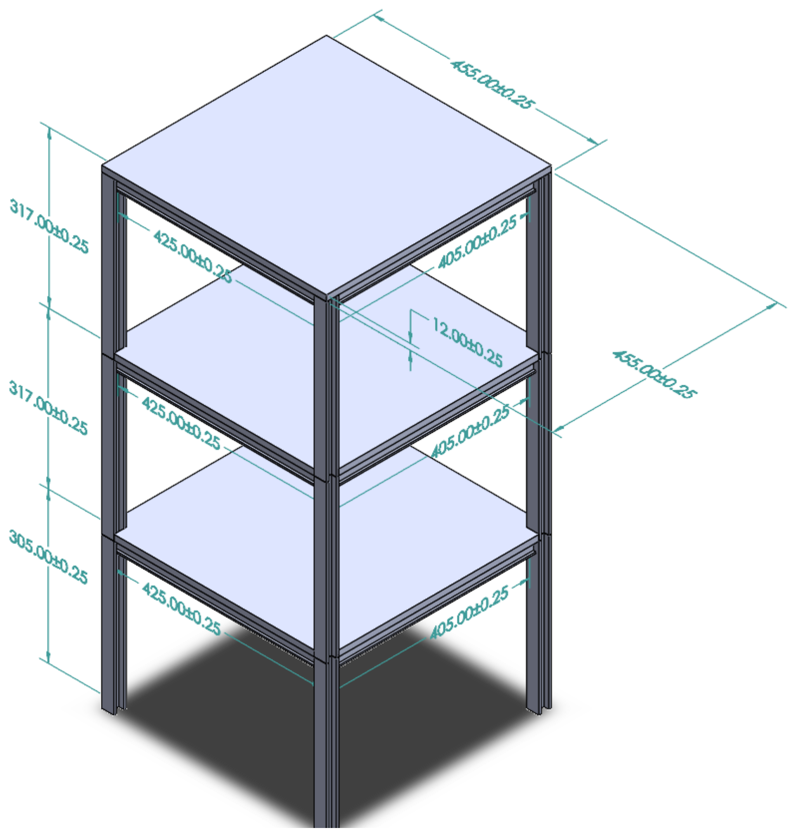


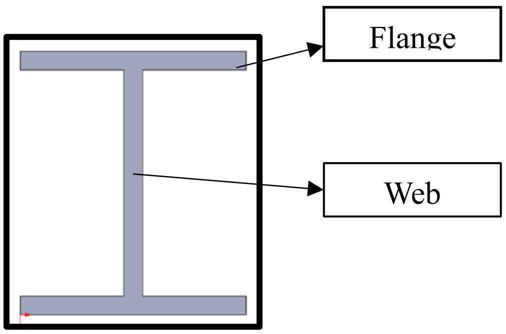
6	3^{rd} Mode of twisting	X	18.469

Chapter 3

3.1 Cracks

3.1.1 Model Design: A three-story steel structure has been modeled in SolidWorks so that simulations in ANSYS may be run while taking both cracked and crack-free scenarios into account. Appropriate crack geometries, which represent actual sizes and orientations, are added in the SolidWorks model to study the impact of cracks. The locations of these fissures are carefully chosen to be at stress-prone key places. A model without cracks is also used as a benchmark for comparison. The structural behavior of both the fractured and crack-free models is then simulated using the ANSYS program under various loading circumstances.





Building Specifications (mm)	
Floor thickness	12
Floor width	455
Floor length	455
Total floors	3
Column Height	317

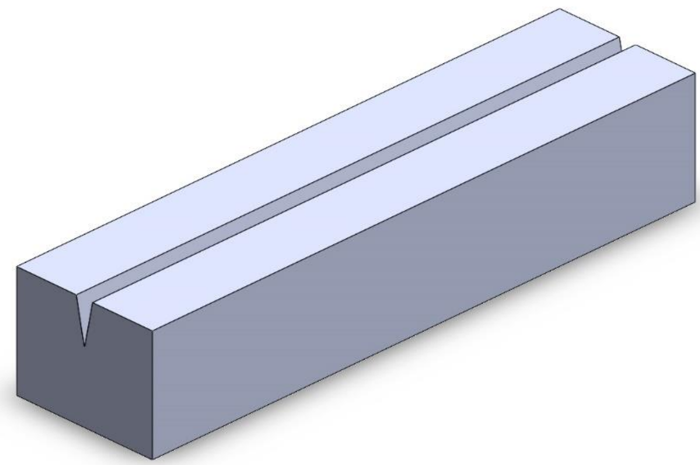
Cross Sectional View			
Column Specifications (mm)		**Beam Specifications (mm)**	
Height	25	**Height**	25
Width	25	**Width**	12
Flange thickness	5	**Flange thickness**	3.5
Web thickness	5	**Web thickness**	3

3.1.2 Types of cracks

Two types of cracks were used.

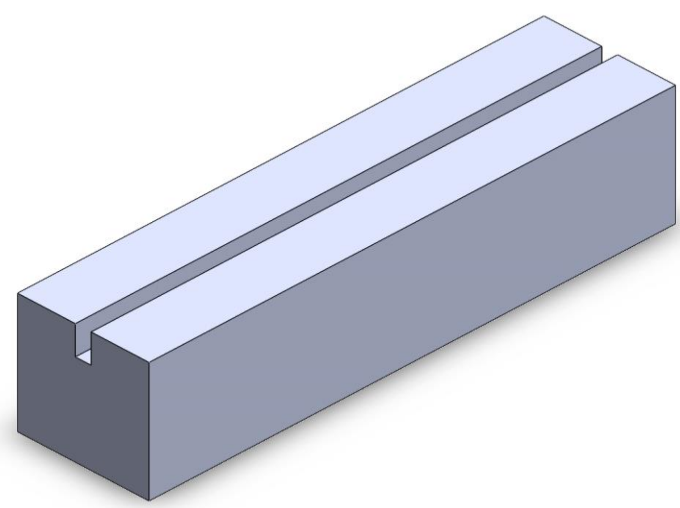
V-crack

A "V crack" refers to a crack that propagates in a V-shaped pattern, often found in welds or areas of high stress concentration, which can compromise the structural integrity of the steel.



Slit Crack

A "slit crack" in steel structures refers to a type of crack characterized by a long, narrow opening or separation in the material, often caused by stress concentration or material defects.



Cracks were introduced to the model. We performed simulation implementing cracks of different types, dimensions and different locations to identify changes in natural frequency. 17 of the mentionable models are shown here with results.

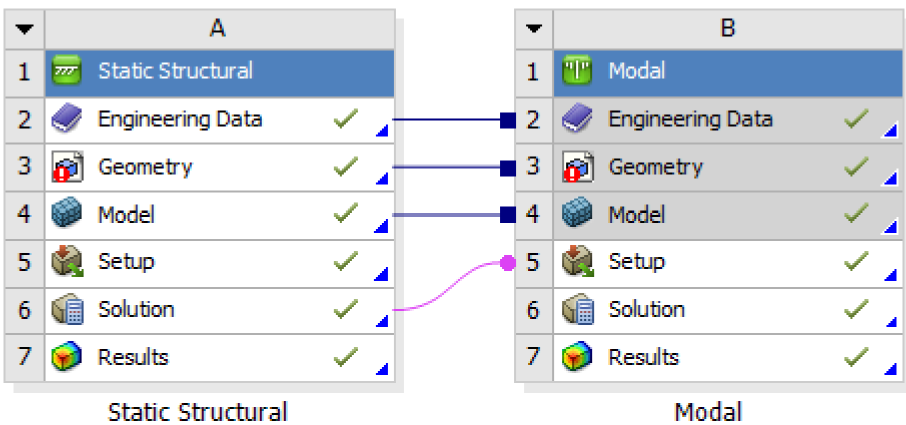
We performed modal analysis in both not pre-stressed and prestressed form. The reason behind choosing pre-stressed condition is that some portion of the ground floor column remains under the ground. So, stress is formed within the body. To find out the characteristics of our model, it was necessary to implement this idea.

3.1.3 Simulation properties: Same as mentioned earlier.

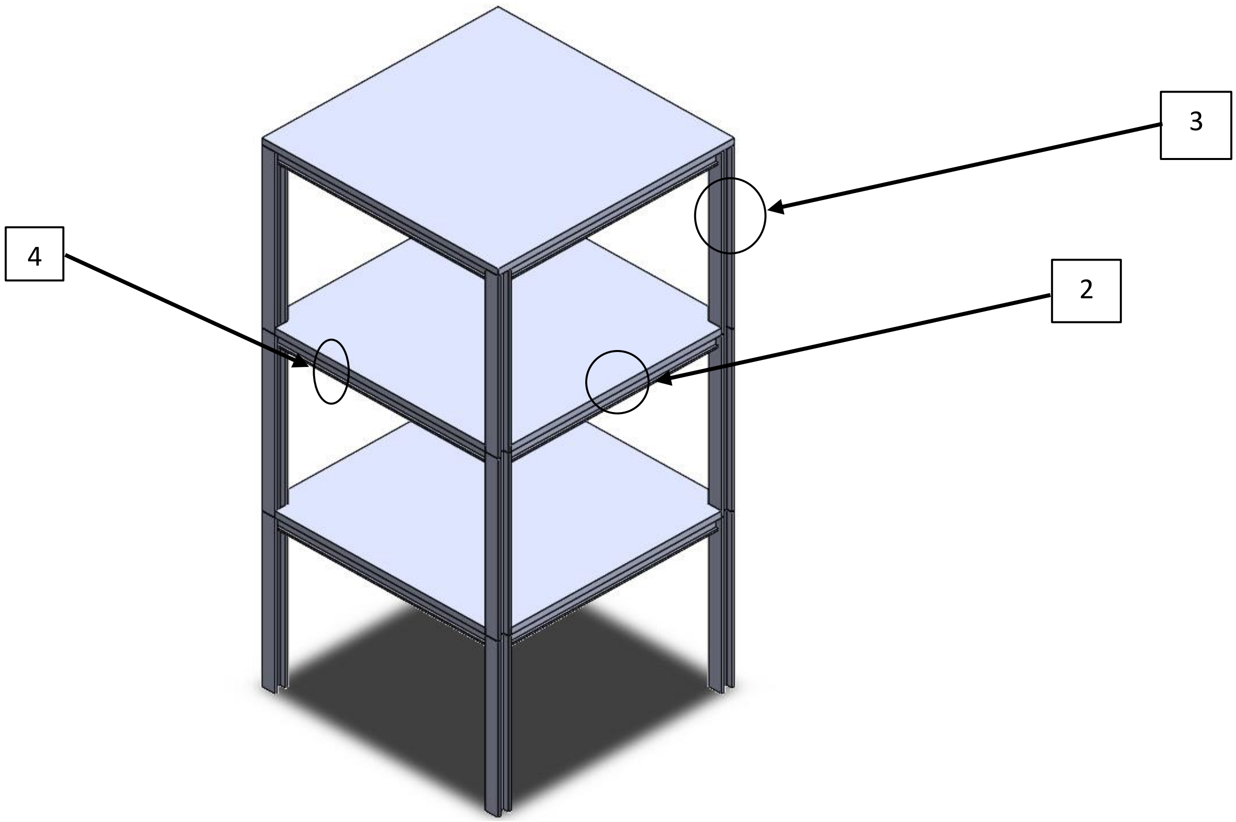
3.1.3.1 Modal analysis: Ground floor columns were fixed.

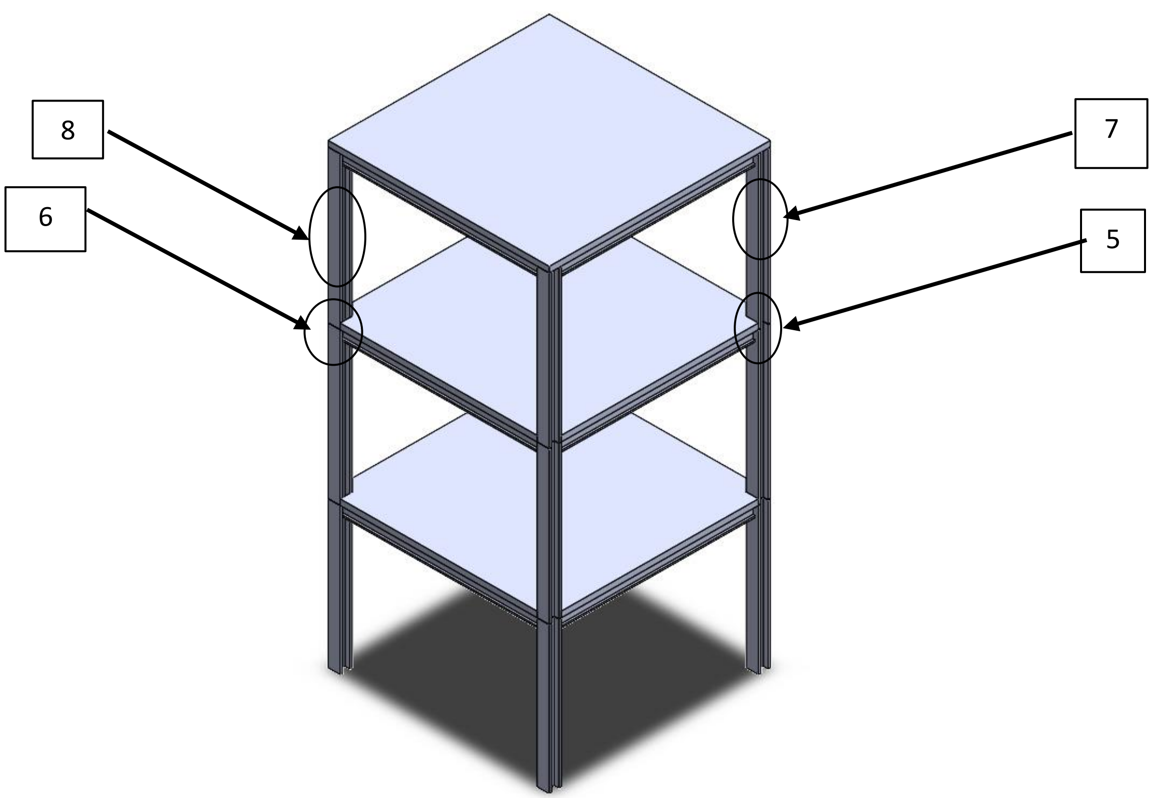
3.1.4 Pre-stress formation:

In a steel construction, pre-stress refers to the intentional application of internal forces or stresses to structural components in order to improve their performance. Pre-stress in steel buildings is often achieved by designing the structural components to be under initial tension or compression, as opposed to reinforced concrete constructions where pre-stress is done through pre-tensioning or post-tensioning processes. This pre-stressing aids in reducing any predicted tensile or compressive stresses that the structure might encounter from service loads. Pre-stressing the steel members increases the structure's overall strength and stability by making it more resistant to deflection, deformation, and probable failure. In a steel construction, pre-stressing is frequently accomplished using meticulous design considerations and fabrication methods that maximize the distribution of forces throughout the structure.



In static structural analysis settings, pressure of 100, 200, 300 MPa were applied on ground floor column(s). Then modal was linked with static structural. Pressure was applied on one column of ground floor and then it was applied on all columns of ground floor equally distributed.


3
4
2


8
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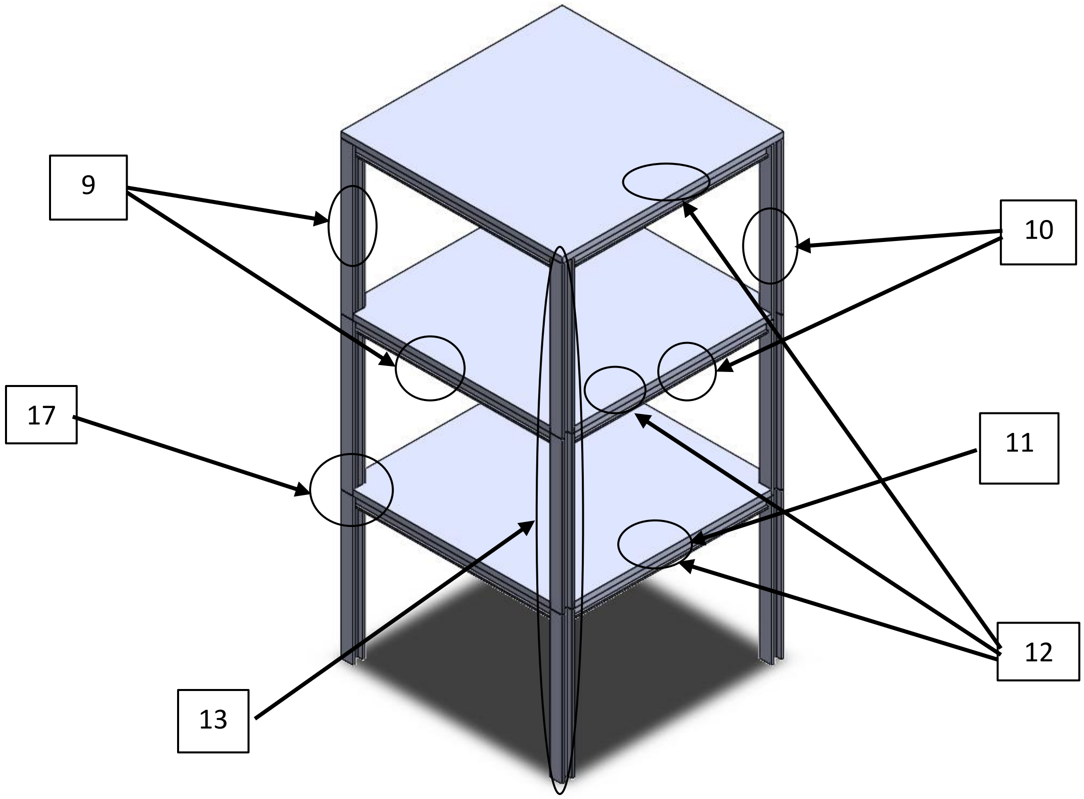
5


9
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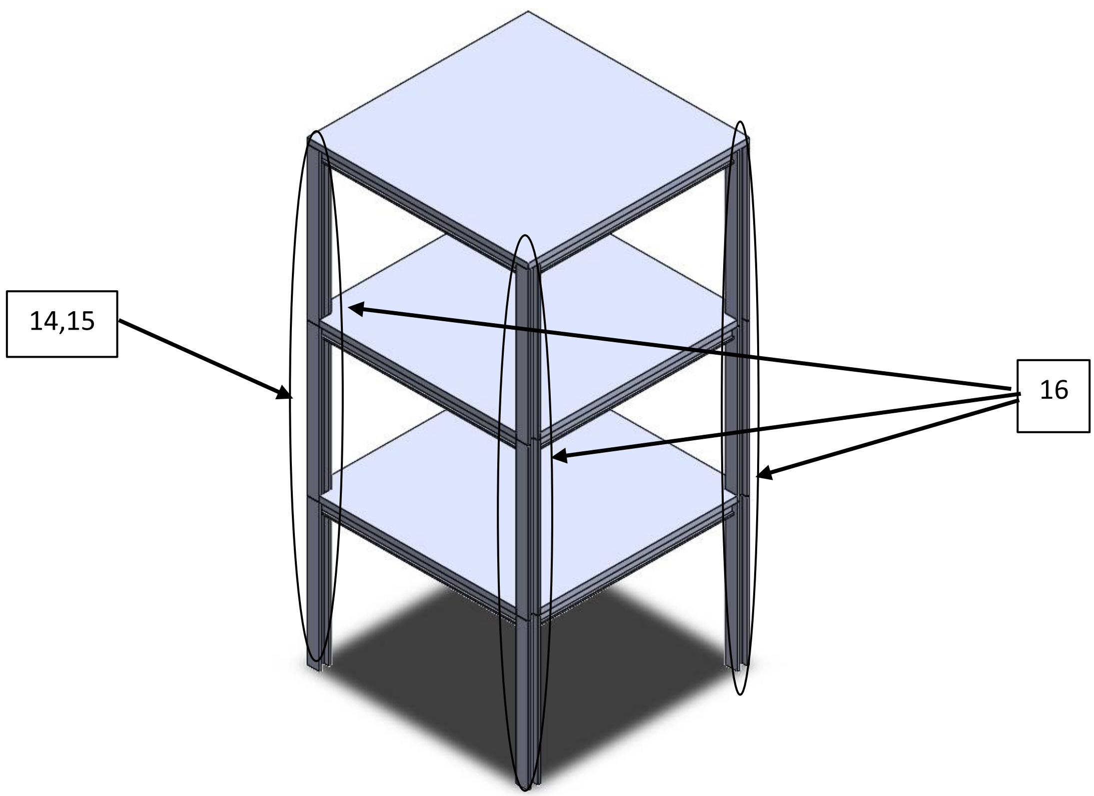
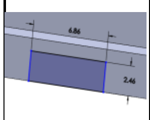
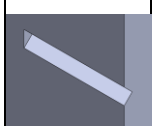
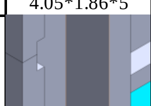
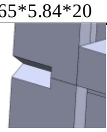
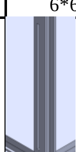
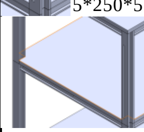
17
11
12
13

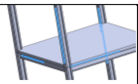
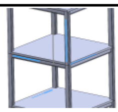
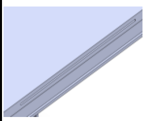
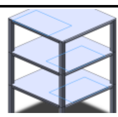
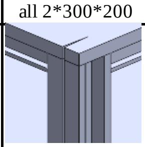
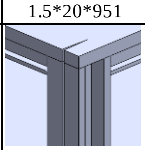
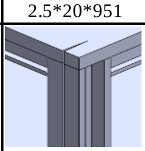
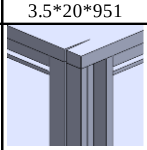
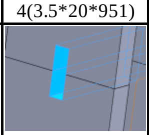

14,15
16

3.2 Simulation Result

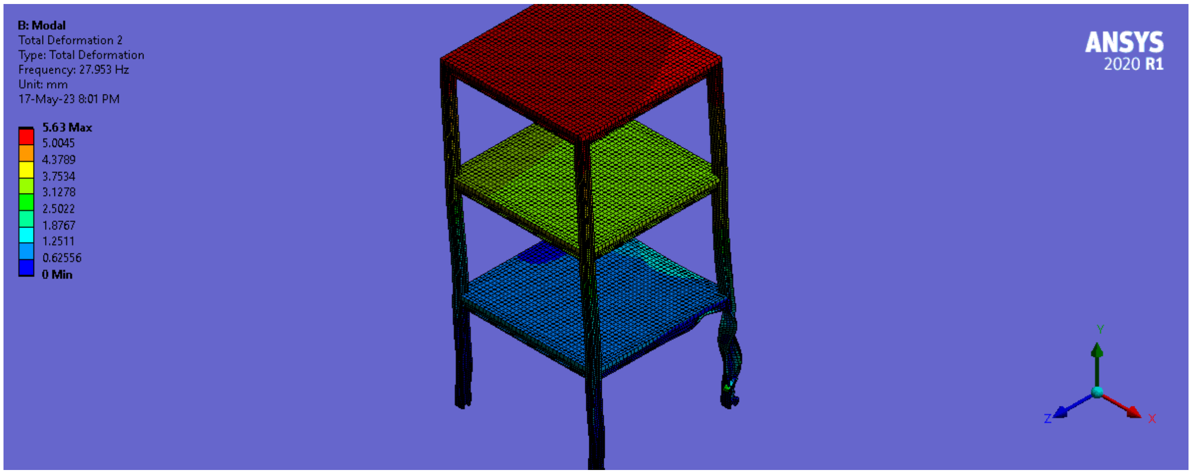
3.2.1 Natural frequencies from Modal analysis:

					Pre-stressed					
					Pressure applied 100 Mpa on ground (1st) floor column	Pressure applied 100 Mpa on ground (1st) floor distributed in all columns	Pressure applied 200 Mpa on ground (1st) floor column	Pressure applied 200 Mpa on ground (1st) floor distributed in all columns	Pressure applied 300 Mpa on ground (1st) floor column	Pressure applied 300 Mpa on ground (1st) floor distributed in all columns
crack number and type		**crack location**	**crack photo (dimensions in mm)** length*width*depth	**Only Modal Natural Frequency**	**natural frequency**	**natural frequency**	**natural frequency**	**natural frequency**	**natural frequency**	**natural frequency**
1	no crack	n/a	n/a	25.602 31.135 42.702 76.808 98.315 120.38	15.602 30.913 39.128 65.707 97.973 115.47	30.86 41.35 91.985 97.548 111.53 163.1	30.861 34.753 61.467 98.094 105.64 144.51	26.429 28.216 51.108 88.847 92.334 117.22	21.466 30.087 37.998 76.837 95.812 111.2	32.332 48.933 52.682 98.949 129.08 156.51
2	1 Slit-crack through beam	on beam of 2nd floor	 6.86*2.46*10	25.608 31.139 42.711 76.818 98.325 120.4	16.022 30.957 39.251 65.952 98.075 115.61	30.864 41.363 92.019 97.558 111.55 163.1	30.866 34.763 61.509 98.104 105.66 144.55	26.437 28.219 51.115 88.869 92.345 117.24	21.47 30.091 38.015 76.845 95.822 111.22	32.343 48.972 52.696 98.965 129.1 156.56
3	1 V-crack on column	on 3rd floor column	 1.7*1.7*20	25.603 31.138 42.706 76.824 98.335 120.39	16.02 30.956 39.249 65.948 98.085 115.6	30.863 41.356 92.02 97.568 111.54 163.11	30.864 34.757 61.486 98.112 105.66 144.54	26.431 28.218 51.113 88.879 92.354 117.23	21.467 30.09 38.004 76.847 95.833 111.23	32.336 48.952 52.691 98.973 129.11 156.55
4	1 Slit-crack on beam edge		 4.05*1.86*5	25.608 31.139 42.711 76.82 98.324 120.4	16.021 30.957 39.251 65.956 98.075 115.61	30.864 41.365 92.023 97.558 111.55 163.1	30.865 34.764 61.514 98.104 105.66 144.55	26.438 28.219 51.115 88.872 92.345 117.24	21.47 30.091 38.018 76.845 95.822 111.22	32.344 48.984 52.697 98.963 129.14 156.57
5	1 Slit-crack between 2 columns	between 2nd and 3rd floor column	 1.65*5.84*20	25.605 31.141 42.709 76.811 98.318 120.37	16.023 30.959 39.253 65.94 98.069 115.57	30.867 41.37 92.088 97.552 111.54 163.08	30.867 34.764 61.52 98.094 105.63 144.61	26.465 28.232 51.169 88.94 92.361 117.26	21.484 30.093 38.009 76.851 95.82 111.2	32.359 49.594 52.821 98.983 129.85 157.61
6	1 V-crack between 2 columns	between 2nd and 3rd floor column	 6*6*15	25.595 31.126 42.709 76.68 98.169 119.96	15.346 30.948 39.107 64.907 97.951 114.68	0. 30.883 41.1 94.743 97.412 111.49	29.963 32.083 49.032 97.573 107.81 118.7	28.033 28.884 53.67 92.51 93.49 121.67	25.504 29.981 37.878 77.361 95.662 113.94	7.8243 32.65 56.496 74.713 99.302 149.34
7	1 Slit-crack on column (long)	on 3rd floor column	 5*250*5	25.536 31.058 42.487 75.487 96.867 118.83	16.013 30.87 39.184 64.665 96.407 114.49	30.784 41.176 87.024 96.819 111.38 161.61	30.797 34.664 59.436 97.259 105.04 139.72	26.318 28.202 51.141 84.168 91.783 117.2	21.466 29.988 37.622 76.75 93.35 108.26	32.148 48.615 52.004 96.836 126.26 152.1
8	2 Slit-cracks on beam and column (long)	on 2nd floor beam and 3rd floor column	 Both 5*250*5	25.529 31.065 42.489 75.463 96.88 118.86	16.013 30.876 39.189 64.615 96.419 114.52	30.79 41.154 87. 96.829 111.4 161.63	30.804 34.65 59.392 97.271 105.06 139.75	14.62 26.311 28.235 51.155 84.14 91.792	21.466 29.994 37.598 76.755 93.361 108.28	32.128 48.642 51.999 96.852 126.27 152.15

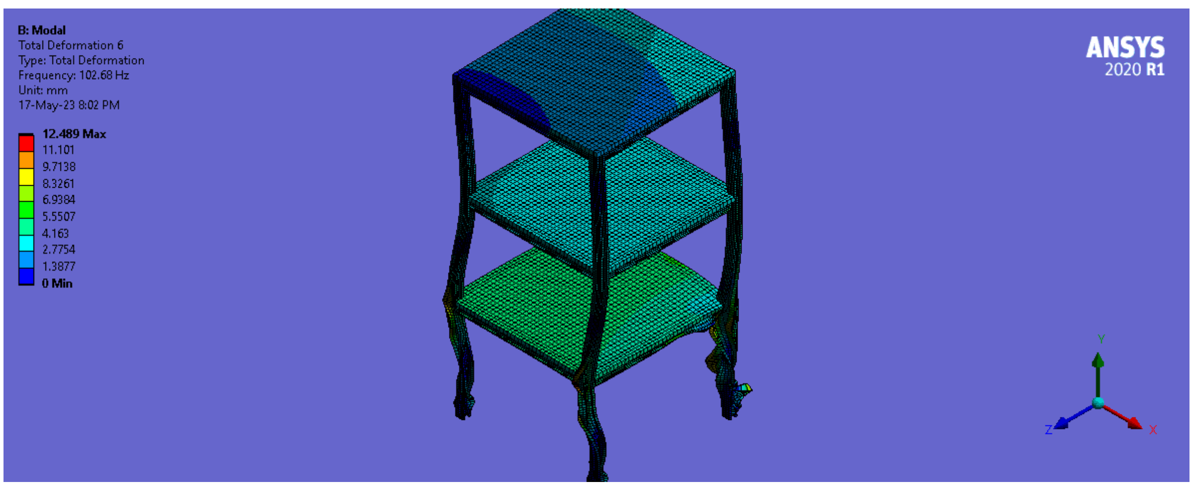
Natural frequencies from Modal analysis: (continued)

9	4 Slit-cracks on beams, columns and floor	on 2nd and 3rd floor beams and columns	 All 5*250*5	25.406 30.656 41.951 75.253 96.169 117.99	15.994 30.635 38.726 64.443 95.682 113.81	30.259 40.156 84.571 95.341 110.6 159.55	30.518 33.781 57.352 96.284 104.33 133.93	11.333 26.21 27.7 48.482 83.479 90.252	19.342 29.511 37.017 75.154 92.768 106.68	32.099 44.41 50.218 97.029 122.37 148.51
10	3 Slit and 1 V-cracks on beams, columns and floor	on 2nd and 3rd floor beams and columns	 All 5*250*5	25.564 31.119 42.561 75.546 96.979 119.07	16.127 30.931 39.273 64.739 96.518 114.74	0. 30.868 41.36 89.042 97.167 111.92	30.868 34.928 60.627 97.462 105.38 142.24	26.68 28.364 38.009 52.766 85.122 92.453	22.518 30.063 37.984 77.521 93.54 108.87	32.391 53.622 58.134 97.284 135.63 162.8
11	1 Slit-crack on floor (long)	on 1st floor	 2*300*200	25.631 30.755 42.378 77.575 98.99 121.56	16.103 30.555 38.895 66.675 98.747 116.33	30.396 40.752 85.684 98.184 111.01 164.64	30.597 34.648 61.313 98.713 105.82 144.43	17.154 28.055 36.883 65.009 93.454 114.51	20.594 29.75 37.543 77.358 96.588 111.49	28.147 31.147 47.983 93.12 96.89 137.51
12	3 Slit-crack on floors (long)	on 1st , 2nd and 3rd floor	 all 2*300*200	26.088 31.067 42.702 78.086 99.46 122.77	16.392 30.863 39.11 67.14 99.203 117.69	30.711 41.1 85.829 98.653 112.3 166.26	30.926 35.02 61.617 99.33 107.13 144.96	17.216 28.401 37.336 65.021 94.263 115.72	20.732 30.081 38.3 77.336 96.884 112.66	28.463 31.751 48.58 93.662 98.556 137.74
13	1 V-crack up to bottom	on columns	 1.5*20*951	25.055 30.959 42.259 75.501 97.807 119.09	14.505 30.745 38.76 64.11 97.488 114.14	28.846 38.71 68.163 93.461 107.69 155.98	30.584 33.475 56.062 97.179 103.71 136.91	33.473 36.623 55.644 101.08 114.67 155.71	15.475 28.841 35.819 74.349 92.566 108.42	28.546 31.007 47.268 90.716 97.446 135.63
14	1 V-crack up to bottom	on columns	 2.5*20*951	25.023 30.868 42.19 75.43 97.518 119.03	14.375 30.644 38.67 63.991 97.178 114.05	16.192 35.709 56.868 82.034 104. 148.23	30.475 33.348 55.623 96.818 103.53 136.24	17.206 23.252 42.908 65.902 93.661 112.52	23.615 34.177 69.684 77.655 108.02 113.38	29.046 32.053 54.661 91.49 96.943 130.44
15	1 V-crack up to bottom	on columns	 3.5*20*951	24.986 30.761 42.109 75.346 97.183 118.94	14.222 30.524 38.566 63.851 96.813 113.94	32.638 41.839 55.391 98.842 132.04 169.31	30.334 33.198 55.135 96.359 103.31 135.52	14.61 38.911 56.012 84.262 109.57 128.5	4.5728 29.868 35.824 73.308 89.642 107.6	28.733 41.903 71.922 92.499 135.6 167.62
16 (most impact)	4 V-crack up to bottom	on columns	 4(3.5*20*951)	29.135 36.776 50.355 92.089 111.77 142.26	29.342 36.885 47.515 96.291 105.43 132.05	19.552 27.953 46.908 55.883 84.3 102.68	29.393 39.58 48.732 94.694 109.63 138.98	27.52 37.784 49.159 86.347 122.57 137.01	30.039 41.992 45.524 90.244 98.606 135.49	24.738 36.205 67.022 86.331 117.94 151.98
17	4 Slit-cracks on intersection of beam columns and floor	on intersection of beam columns and floor of 2nd and 3rd floor	 4(3*10*455)	25.63 27.291 40.276 76.541 85.832 120.54	16.102 27.183 37.469 65.473 85.564 113.98	27.09 40.68 79.591 85.036 110.08 153.32	27.149 34.103 54.629 85.618 103.61 134.34	25.099 26.228 47.192 79.17 83.077 115.03	20.621 26.687 36.73 73.373 83.713 106.98	32.421 34.058 45.144 99.254 114.47 128.77

3.2.2 Simulation due to pre-stress formation: (model no. used - 16)



Pressure applied on one ground floor column



Pressure applied on all ground floor columns

3.3 Average change in natural frequency:

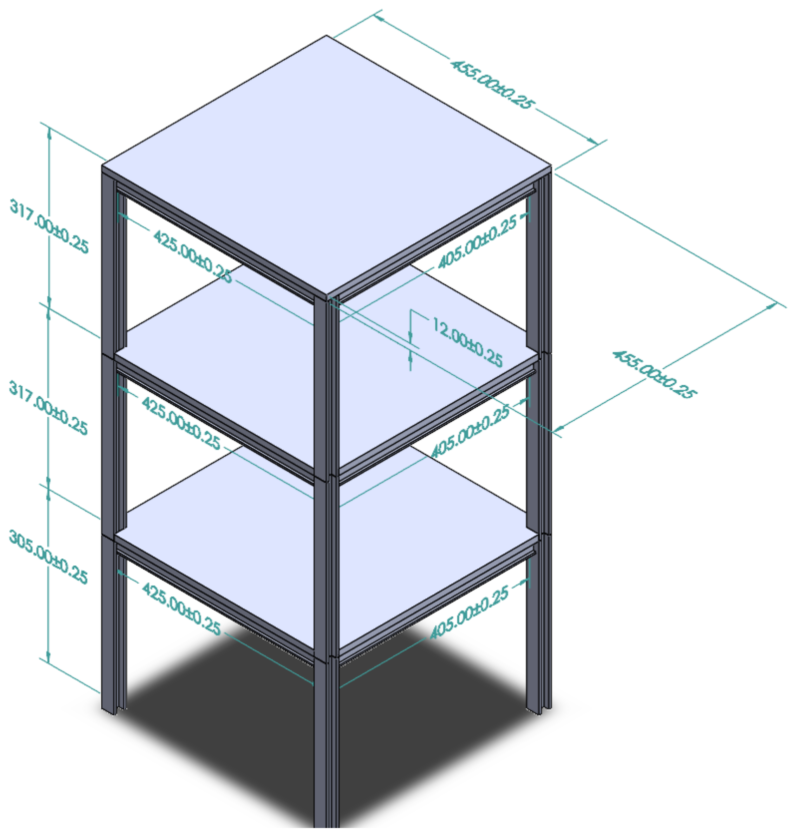
	Not pre-stressed	Pre-stressed					
		Pressure applied 100 Mpa on ground (1st) floor column	Pressure applied 100 Mpa on ground (1st) floor distributed in all columns	Pressure applied 200 Mpa on ground (1st) floor column	Pressure applied 200 Mpa on ground (1st) floor distributed in all columns	Pressure applied 300 Mpa on ground (1st) floor column	Pressure applied 300 Mpa on ground (1st) floor distributed in all columns
Serial no	Average change in natural frequency (%)	Average change in natural frequency (%)	Average change in natural frequency (%)	Average change in natural frequency (%)	Average change in natural frequency (%)	Average change in natural frequency (%)	Average change in natural frequency (%)
2	0.016194027	0.182125244	0.018257834	0.028351965	0.018055901	0.01925041	0.033984739
3	0.012064936	0.331708158	0.016313569	0.018363913	0.015107877	0.01538847	0.023556279
4	0.016458487	0.614569966	0.019788717	0.029647225	0.019249287	0.01538847	0.044796585
5	0.010440952	0.740165396	0.030638297	0.032842056	0.080052396	0.01538847	0.50531723
6	0.122781233	0.584234359	37.96818847	7.860051947	3.770088431	0.026552445	25.66343351
7	0.914811826	0.232439204	1.309284921	1.41692117	1.04753443	1.10754977	1.607296235
8	0.913691512	0.233385615	1.312519378	1.423131149	28.19634212	1.108757327	1.600680855
9	1.709235787	0.852315105	3.027995174	3.501581216	31.34301586	3.970505738	4.4818722
10	0.770031066	0.033875177	38.89384732	0.550262561	15.61758041	0.201287084	4.587409643
11	0.792983721	0.744259839	1.444972496	0.110343977	15.23785634	0.771830825	16.86329711
12	1.155097607	1.70243758	0.669863591	0.700799638	14.52633566	0.072784961	15.97491378
13	1.171535491	2.098741504	8.467773782	3.564529914	22.68629356	7.818499272	17.46483524
14	1.340716209	2.426312716	21.85372644	3.970342769	16.15537634	20.46005547	14.99920412
15	1.54117282	2.812230313	1.552467429	4.446481949	4.318160828	16.56944364	2.775708771
16	16.93264937	32.88919377	37.03644738	2.516934706	13.50661317	23.58679056	9.759238976
17	5.138291918	4.56892892	7.905606271	7.783457595	7.087633866	6.5841834	12.19439357

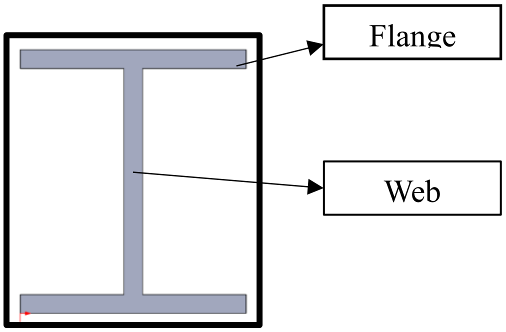
Chapter 4

4.1 Experimental Model

For validation of simulation results, it is necessary to conduct an experiment. A simple 3-story structure is made and experimented with.

4.1.1 Model Design: For experimental purposes, a 3-story structure has been constructed. The structure is unloaded. It has been modelled in Solidworks 2020 and according to the design parameters, the experimental model has been made.





Building Specifications (mm)	
Floor thickness	12
Floor width	455
Floor length	455
Total floors	3
Column Height	317

Cross Sectional View			
Column Specifications (mm)		**Beam Specifications (mm)**	
Height	25	**Height**	25
Width	25	**Width**	12
Flange thickness	5	**Flange thickness**	3.5
Web thickness	5	**Web thickness**	3

4.1.2 Simulation Setup:

To calculate the mode shapes and natural frequencies numerically, ANSYS 2020 has been used for the simulation procedure. In ANSYS Workbench, the integrated ANSYS Mechanical Module for modal analysis 'MODAL' has been used. And to compute the frequency response of the structure, the 'HARMONIC RESPONSE' module has been used. 'Static Structural' was done to find stress distribution.

Mild steel (Structural Steel) has been used as material. This material is easily available and low in cost. So, in the simulation, the standard mild steel data has been taken. Here, the important factors are density, Young's modulus and Poisson ratio.

Material	Mild Steel		
Property	Symbol	Value	Unit
Density	ρ	7800	$Kg.m^{-3}$
Young's Modulus	E	2.1E+11	Pa
Poisson Ratio	υ	0.295	-
Bulk Modulus	K	1.5447E+11	Pa
Shear Modulus	G	7.3359E+10	Pa
Thermal Expansion coefficient	α	1.2E-05	C^{-1}

Table : Engineering Data

Geometry: The 3D model has been imported into ANSYS Workbench in the STEP format. It is a 2D-3D design exchange file format which is independent of source file format. It allows for exchange of design information about, in our case – wireframes, between two independent systems. This simulation was done for unloaded condition.

Modal analysis and Static structural analysis in Ansys was done to find different mode shapes, natural frequencies and equivalent stress (Von-mises) for the CAD model.

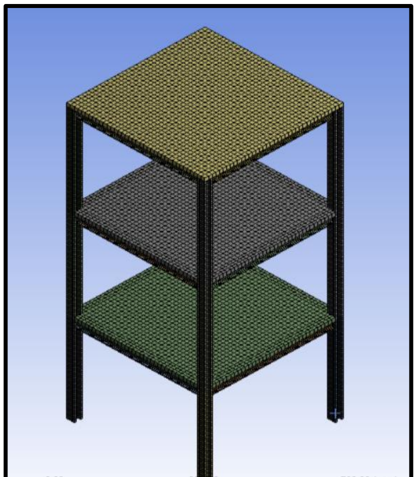
Fixed Support was given to all ground columns. Different loading condition were given.

Material used- Structural Steel. Total Bodies- 27

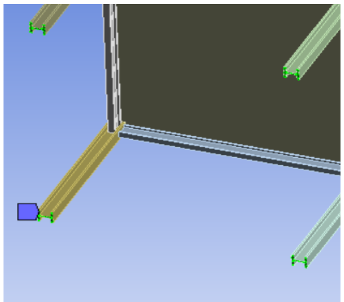
Loading condition- Loads of 10kg, 20kg, 30kg, 40kg, 50kg, 60kg were given on the three floors equally distributed in negative y-axis.

Mesh Specifications		
Type	Body Sizing	Body Sizing
Bodies selected	24 (All columns and Beams)	3 (All floors)
Element Sizing	6 mm	12 mm
Behavior	Hard	Hard

Mesh Result	
Nodes	146533
Elements	20242



Boundary Conditions: For the simulation to run, necessary boundary conditions have been applied. The base columns of the structure have been fixed with ground. Rest of the structure is set free. The columns have been welded to the beams and beams to the floors. All the other conditions have been kept as default.



Modal Analysis: To perform the modal analysis, the solver has been set to extract the first 6 modes. Here, the 'Block-Lanczos mode extraction method' has been used as the solver. No damping has been incorporated.

Von Mises stress analysis: The equivalent von-Mises stress has been determined from the static structural module. Here the relative values of the maximum, minimum and average stresses have been found. These are not the actual stress values. To know the actual values, a dynamic load must be applied to determine the stresses.

Harmonic Response: Frequency response has been taken in Z-direction as the force was applied for Z-direction.

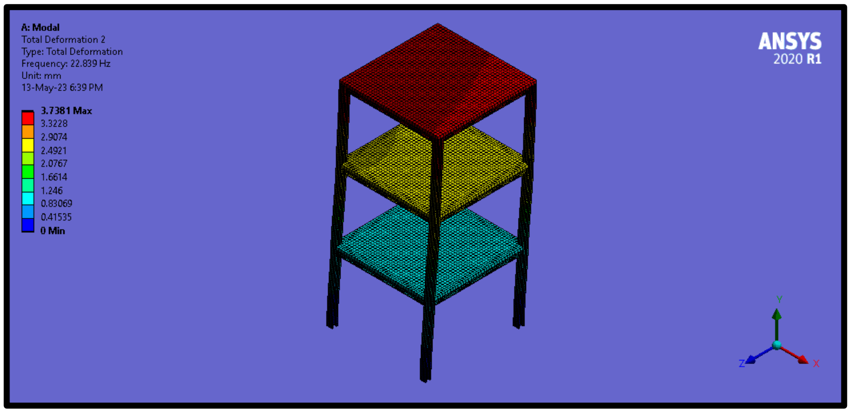
4.2 Simulation Result:

Here, the results obtained from the simulation are presented and discussed. The results are presented sequentially. First, the mode shapes and natural frequencies of the 5-story structure is shown.

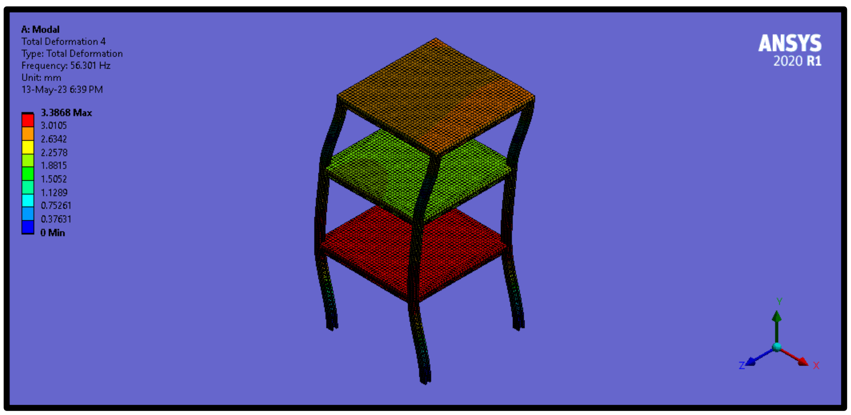
4.2.1 Modal analysis of 3-storey structure:

The natural frequency data for the 3-story structure is found under different loading conditions from the modal analysis in ANSYS.

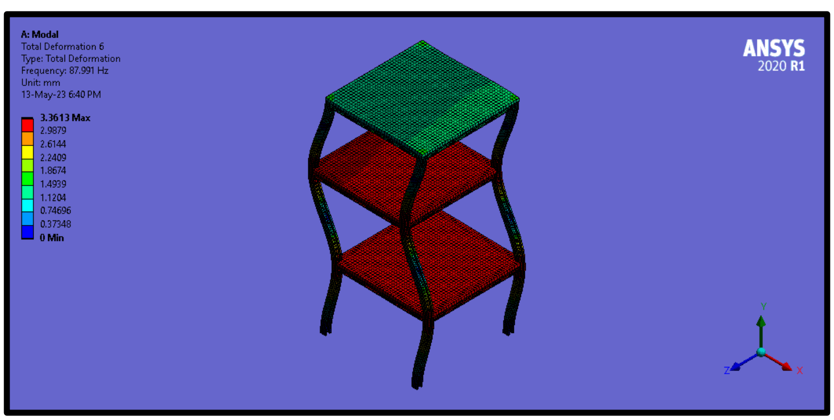
	Loading (kg)	0	10	20	30	40	50	60
Mode	**Mode shape**	**Frequency (Hz)**	**Frequency (Hz)**	**Frequency (Hz)**	**Frequency (Hz)**	**Frequency (Hz)**	**Frequency (Hz)**	**Frequency (Hz)**
1	1st mode bending in x-direction	25.602	23.948	22.578	21.42	20.423	19.553	18.786
2	1st mode of bending in z direction	31.135	29.121	27.454	26.044	24.83	23.772	22.839
3	1st mode of twisting in y-direction	42.702	40.403	38.44	36.737	35.241	33.915	32.728
4	2nd mode of bending in x-direction	76.808	71.825	67.702	64.216	61.218	58.605	56.301
5	2nd mode of bending in z-direction	98.315	91.948	86.677	82.221	78.388	75.046	72.098
6	3rd mode of bending in x-direction	120.38	112.49	105.97	100.46	95.735	91.618	87.991
Average change (reduction) in Natural Frequency due to Loading (%)			**6.30514**	**11.5464**	**15.9944**	**19.8317**	**23.1855**	**26.1494**



2 – 1st mode of bending in Z-direction



4-2nd mode of bending in x-direction



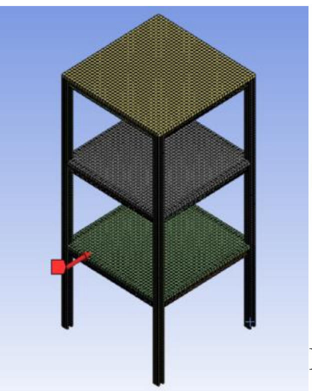
6-3rd mode of bending in x-direction

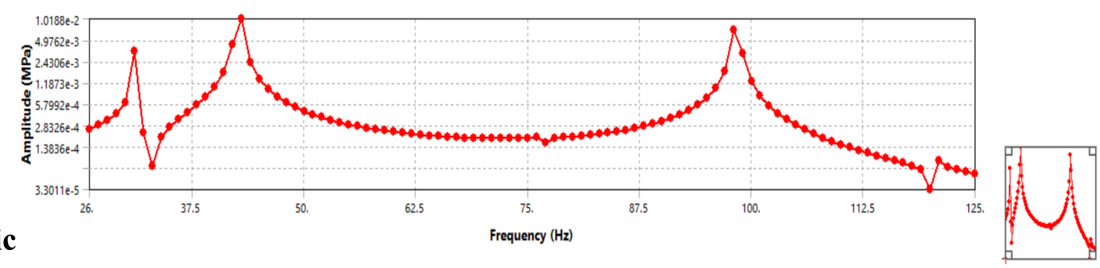
Equivalent stresses (Von-mises) found in Modal analysis for different loading conditions for all the modes-

Loading (kg)	0			10			20			30			40			50			60		
Mode	Minimum Stress (MPa)	Maxi-mum Stress (MPa)	Average Stress (MPa)	Minimum Stress (MPa)	Maximum Stress (MPa)	Average Stress (MPa)	Minimum Stress (MPa)	Maximum Stress (MPa)	Average Stress (MPa)	Minimum Stress (MPa)	Maximum Stress (MPa)	Average Stress (MPa)	Minimum Stress (MPa)	Maximum Stress (MPa)	Average Stress (MPa)	Minimum Stress (MPa)	Maximum Stress (MPa)	Average Stress (MPa)	Minimum Stress (MPa)	Maximum Stress (MPa)	Average Stress (MPa)
1	2.6334 *10^-2	411.83	30.232	3.3497 *10^-2	384.91	28.295	3.9918 *10^-2	362.65	26.688	2.6299 *10^-2	343.86	25.326	6.8496 *10^-3	327.71	24.154	2.6751 *10^-2	313.65	23.131	2.7373 *10^-2	301.25	22.228
2	**7.1788 *10^-2**	467.92	36.386	4.1874 *10^-2	437.28	34.047	6.4101 *10^-2	411.96	32.108	3.266 *10^-2	390.59	30.466	4.0122 *10^-2	372.23	29.053	2.7557 *10^-2	356.23	27.82	3.1863 *10^-2	342.14	26.732
3	1.102 *10^-2	604.81	52.23	9.5176 *10^-3	571.53	49.478	8.3566 *10^-3	543.2	47.119	7.4372 *10^-3	518.69	45.068	6.694 *10^-3	497.22	43.263	6.0827 *10^-3	478.21	41.658	5.5725 *10^-3	461.23	40.22
4	4.8504 *10^-2	1241.5	88.686	3.545 *10^-2	1161.1	82.886	0.13133	1094.5	78.094	6.211 *10^-2	1038.2	74.049	9.0374 *10^-2	989.75	70.574	4.5704 *10^-2	947.54	67.547	0.11202	910.31	64.879
5	0.12454	1250.6	115.49	0.19463	1171.9	107.99	0.17397	1106.4	101.78	0.14726	1050.7	96.535	0.21768	1002.6	92.027	0.1147	960.63	88.098	0.1166	923.47	84.634
6	4.5737 *10^-2	1766.3	133.73	5.7228 *10^-2	1653.8	124.92	7.449 *10^-2	1560.4	117.66	7.214 *10^-2	1481.2	111.54	5.9795 *10^-2	1413	106.28	3.7136 *10^-2	1353.4	101.7	1.934* 10^-2	1300.7	97.674
Reduction in Maximum and Average stress due to different loading conditions (%)					**6.287**	**6.287**		**11.519**	**11.516**		**15.961**	**15.953**		**19.795**	**19.781**		**23.147**	**23.129**		**26.110**	**26.08**

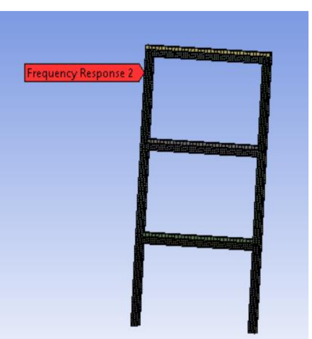
4.2.2 Harmonic analysis of 3-story structure-

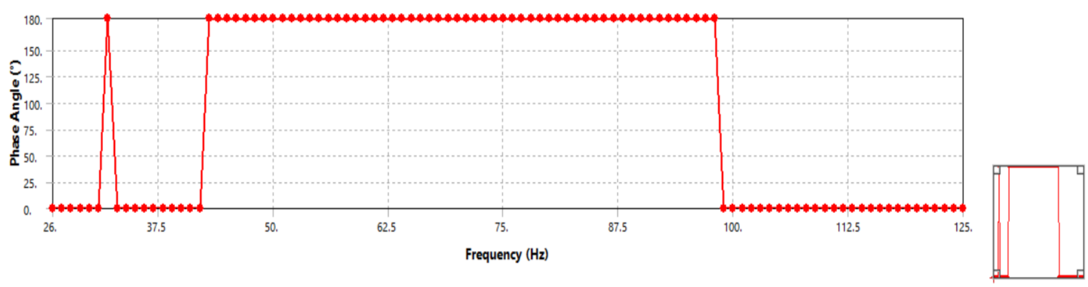
Analysis Settings	Force Applied (N)	500
	Force Location	On ground floor column face
	Force Direction	Negative Z-axis
	Orientation	Z-axis
	Minimum Frequency (Hz)	25
	Maximum Frequency (Hz)	125
	Geometry	1 node on 3rd floor column





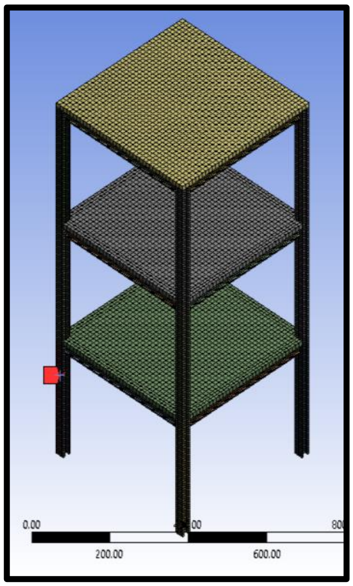
Harmonic response curve

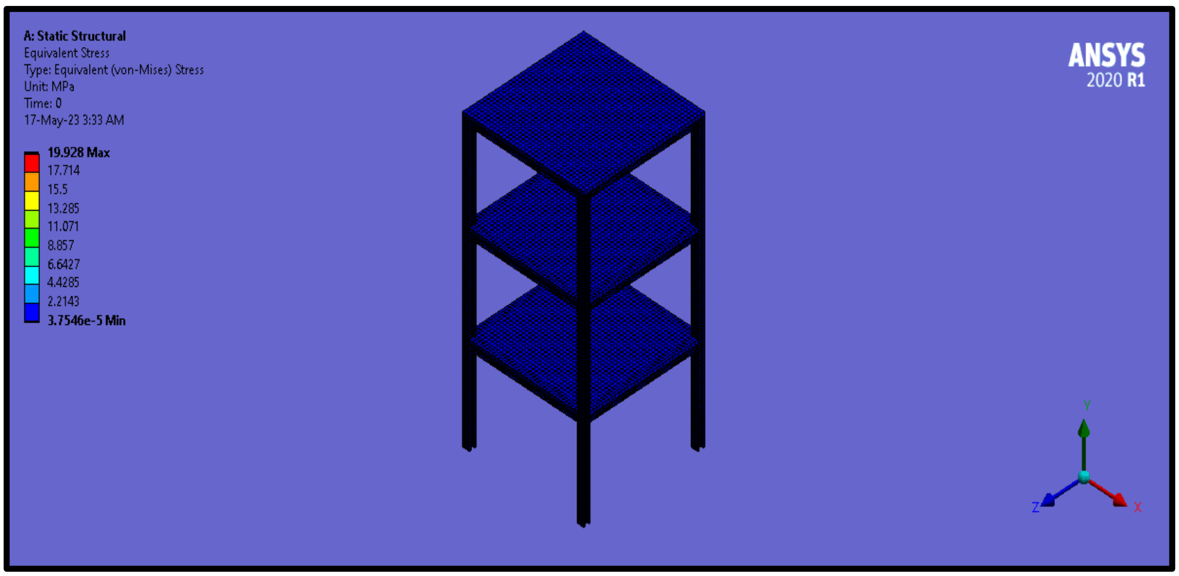




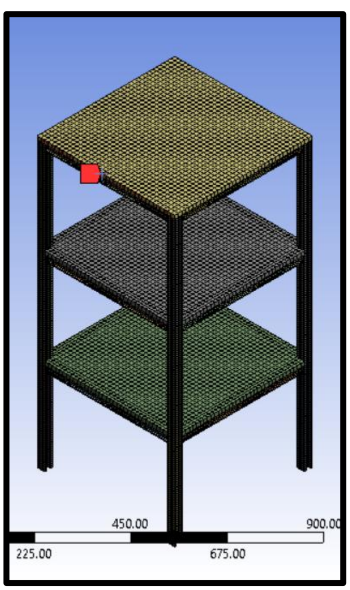
4.2.3 Static Structural analysis:

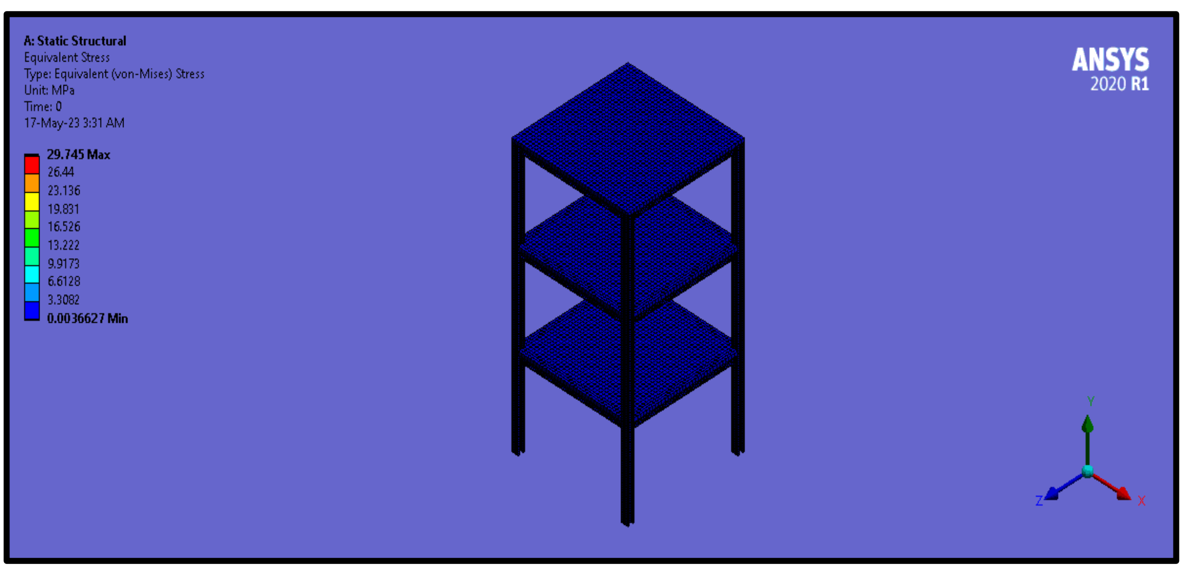
Force applied on ground floor column						Force applied on top floor					
500N		1000N		1500N		500N		1000N		1500N	
Maximum stress (MPa)	Average stress (MPa)	Maximum stress (MPa)	Average stress (MPa)	Maximum stress (MPa)	Average stress (MPa)	Maximum stress (MPa)	Average stress (MPa)	Maximum stress (MPa)	Average stress (MPa)	Maximum stress (MPa)	Average stress (MPa)
19.928	0.4198	39.856	0.83959	59.784	1.2594	29.745	2.5855	59.489	5.171	89.234	7.7566





When force is applied on ground floor column





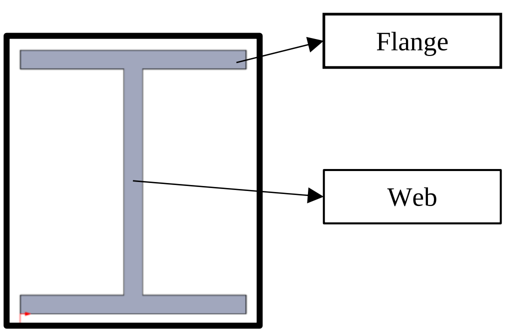
When force is applied on top floor

Chapter 5

5.1 Validation

5.1.2 Structure Fabrication: According to our CAD model the experimental structure was made. Mild steel was used to fabricate.

The geometric parameters that have been used to construct the model is given in the table below.



Building Specifications (mm)	
Floor thickness	12
Floor width	455
Floor length	455
Total floors	3
Column Height	317

Cross Sectional View			
Column Specifications (mm)		**Beam Specifications (mm)**	
Height	25	**Height**	25
Width	25	**Width**	12
Flange thickness	5	**Flange thickness**	3.5
Web thickness	5	**Web thickness**	3

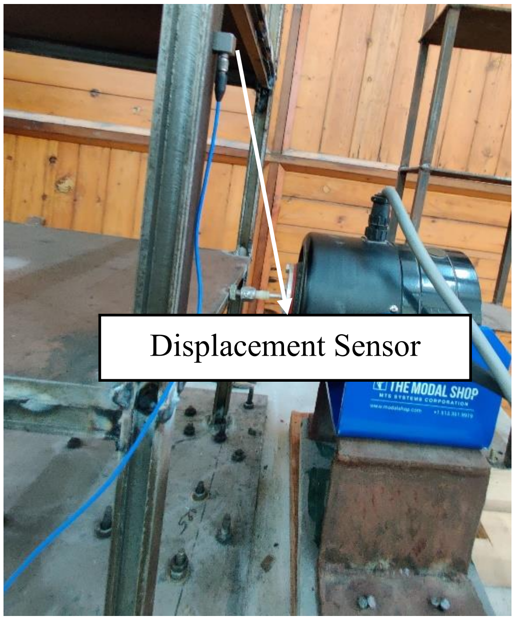
All the connections are fixed by Gas-metal arc welding.

To fix the whole structure with ground, 46 royal bolts were used. So, the structure can not move from its location.

Columns were made from 25mm square bar, slots according to dimension were cut by milling machine. For beams 25mm*12mm rectangular bars were used. Floors of the structure were made with 12mm thick plate.

5.2 Experimental setup:

At the applied mechanics lab, the experimental is situated.



The displacement sensor was attached to the model. With an impact hammer, the model was forced at different locations. Through a signal conditioner, the signal was passed to DAQ (Data acquisition card). The DAQ was connected to computer. From QuicDAQ software, the result data were collected.

To find out the natural frequencies with proper mode shapes, the whole structure was hit at different locations. The displacement sensor was also moved from one location to another to collect different data and compare them with simulation result.

The electrical signal provided by a displacement sensor is processed and optimized by a signal conditioner for displacement sensors. Potentiometers and other displacement sensors, such as linear variable differential transformers (LVDTs), measure an object's position or displacement and translate it into an electrical output. The main goal of the signal conditioner is to improve the output signal's accuracy and dependability.

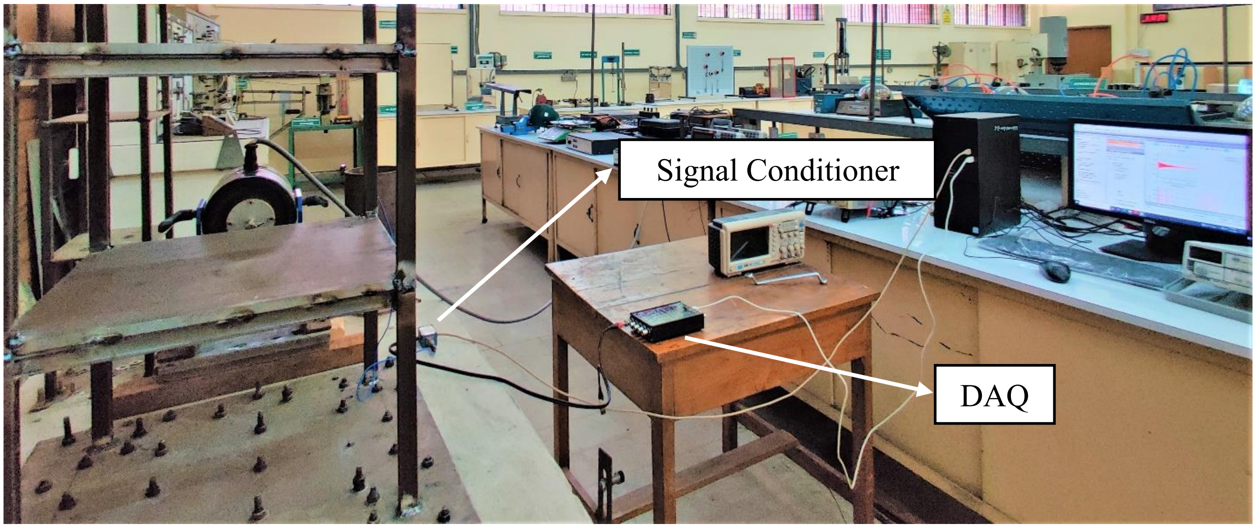


Fig: Experimental setup with all the components

5.2.1 DAQ: The term "data acquisition," abbreviated as "DAQ," describes the procedure of obtaining, analyzing, and measuring electrical or physical signals from the physical environment and transforming them into digital data for a computer or data acquisition system to process.

The following elements are commonly found in a data acquisition system:

- Sensors and transducers are tools that transform electrical or physical occurrences into quantifiable electrical signals. Examples include strain gauges, accelerometers, temperature sensors, pressure sensors, and voltage sensors. Signal conditioning is frequently required before sensor signals can be measured with accuracy. Amplification, filtering, linearization, and occasionally isolation are all methods used in signal conditioning to enhance the signal quality and make it suitable for measurement.
- Analog-to-Digital Converter (ADC): An ADC transforms analog sensor signals into digital signals. ADCs periodically take measurements of the continuous analog signal and convert it to a discrete digital value, often in binary. The accuracy of the digital representation depends on the ADC's resolution.
- Data processing and storage: A computer or special data acquisition hardware is used to process and store the digital data that the ADC has acquired. Real-time or future analyses of the data are also possible.

Scientific research, industrial monitoring and control, environmental monitoring, medical diagnostics, and many more sectors all use data acquisition systems. They enable the fast, accurate, and reliable collecting of data, allowing for its analysis, display, and use in decision-making.

5.3 Experiment Result:

Data were extracted from QuickDAQ software. In the PC the data were generated in both graphical form and in an Excel file.

QuickDAQ Data		
Sample Rate:	4000 Hz	
Measurement Type:	AutoSpectrum	
Channel Name	DT9837(00).Ain 0-FFT	
X Axis Units	Hz	
Y Axis Units	g^2 RMS	
Frequency	Magnitude	Phase
26.34375	2.27E-06	-152.698
42.96875	4.89E-04	30.93515
121.09375	7.23E-07	-103.875

5.4 Comparison and Validation:

Comparison Between Simulation and Experimental Result			
Mode shape	**Simulation** Frequency (Hz)	**Experiment** Frequency (Hz)	**Error (%)**
1st mode bending in x-direction	25.602	26.34375	**2.897235**
1st mode of twisting in y-direction	42.702	42.96875	**0.624678**
3^{rd} mode of bending in x-direction	120.38	121.0938	**0.592914**

As 3 of the Natural frequencies found in Experiment match with the simulation result with proper mode shape and error margin within 3%, the simulation performed in Ansys is validated.

Chapter 6

6.1 Discussion and Conclusion

Simulation and experimental analysis have been done for a 3-storied I-shaped cross sectioned model structure. Natural frequencies for the unloaded, three-story structure were found to range from 25.6Hz to 120.38Hz, covering a variety of bending and twisting modes. The X, Y, and Z axes were used to establish the mode forms. Bending and twisting mode form types were noted, with the twisting mode occurring about the Y axis. Three bending modes were seen along the Z axis. Change of natural frequency was also seen after applying loading in various combinations in different floors. The relationship between the structure's mass and stiffness properties is what causes the variance in natural frequencies. In some situations where a single floor is loaded, the transfer of weight from one floor to other results in a reduction in natural frequency. This decrease can be due to the lower floors' larger mass content, which produces a higher natural frequency, and the upper floors' increased loading, which raises the total stiffness and results in lower natural frequencies.

An experimental setup was set out to verify the simulation results that were achieved for the 3-story model. The experiment was done by a model with same measurements as the simulation model, which was carried out using a DAQ. The objective of this experiment was to compare and validate the simulated natural frequencies and mode shapes with the actual physical model response. The experiment was used to evaluate and validate the simulation findings' correctness and dependability. After conducting the experiment, the accuracy and reliability of the simulation results were assessed and validated within an error of 3%. Without the need for expensive tests or rigorous mathematical computations, it is possible to design and study the modal features of a structure with reliability by using numerical approaches. These numerical methods, such as finite element analysis, enable engineers and designers to simulate and study the behavior of structures under various loading conditions. This approach provides a cost-effective and efficient way to assess the modal properties of a structure, allowing for informed design decisions and optimization without the need for physical testing.

6.2 Future works and scopes

- Perform fatigue analysis.
- See the effects of wind loads, gravity loads, ambient vibration, human interaction etc. on the structure.
- Observe the effects of different materials on the dynamic behavior of the structure.
- Incorporate vibration control systems to mitigate the excitation forces affecting the structure.
- Introduce machine learning, computer vision, artificial intelligence, IoT sensors to advance the research into higher grounds.

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Index

Extended investigation on different cross sections

At first the validation for using I-beam instead of rectangular or square shaped beams are shown here. A 2-storey building structure consisting of (4+4) =8 columns has been considered. Total number of beams are also (4+4) =8. Other specifications are given with following models.

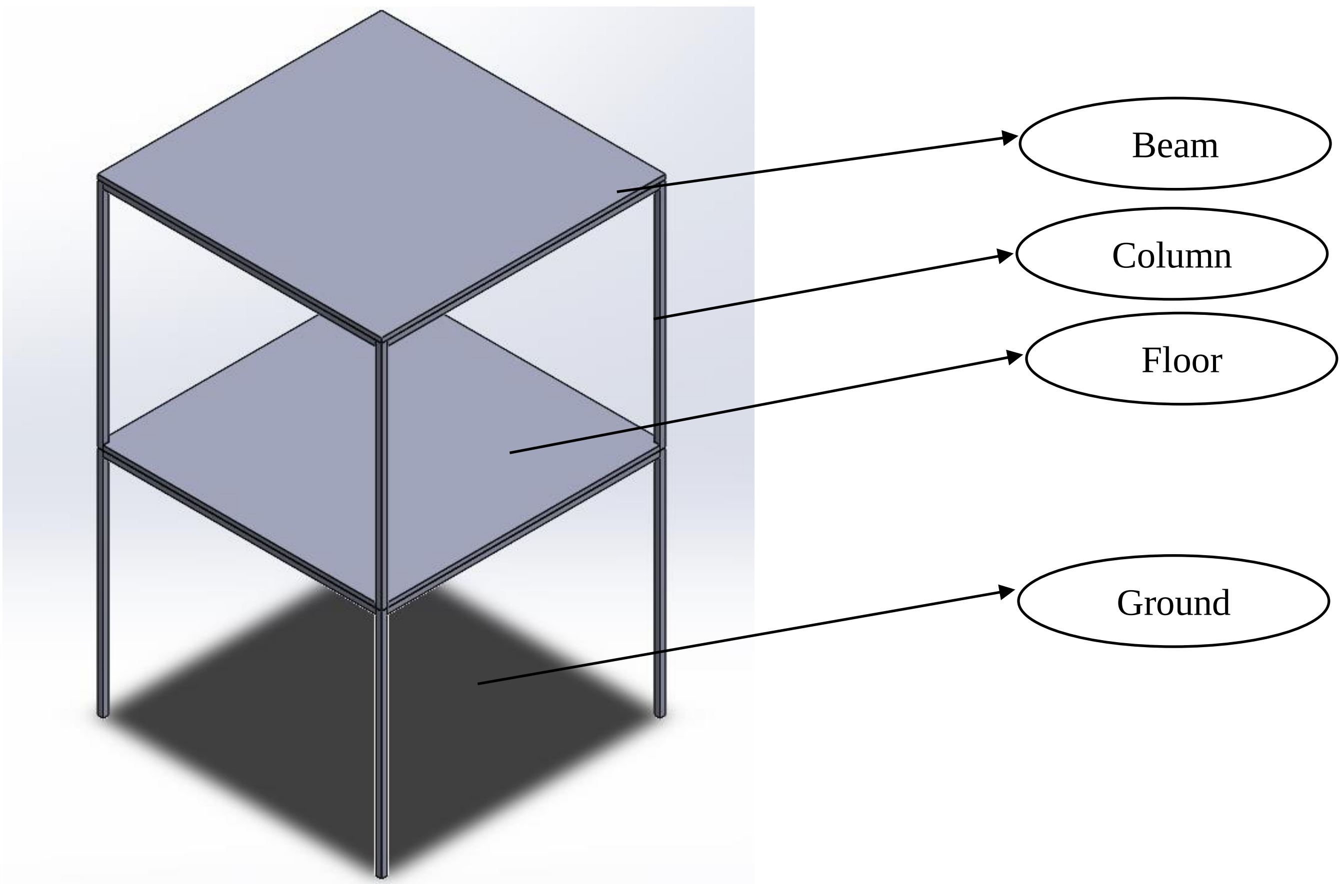


Figure: Indication of Beam, Column and Floor

Shape of columns and beams considered here are-

- Rectangular
- Square
- I or H

For all the model in this comparison, volume of a single column is constant.

Volume of a single column= 9000mm^3

All the model has been drawn in Solidworks 2020 SP4.0

Simulation (Ansys 2020 R1) Specifications-

In Solidworks, 2-story buildings were modeled using different cross sections (rectangular, square and I) for columns and beams. Modal analysis was performed in Ansys to find out natural frequencies, mode shapes and static structural analysis was done to find equivalent Von-mises stresses under different loading conditions. Volume for each column and dimensions of floors were remained same for all the models.

Mesh specifications- Body sizing: 5mm for columns and beams and 10mm for floors.

Material used – Structural steel

Properties	Dimensions
Volume of Each Column	9000 mm^3
Floor (width*length)	312 mm*314 mm

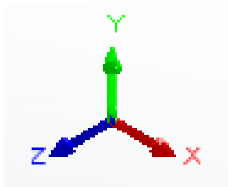
Engineering Data for Simulation	
Density (kg/m^2)	2300
Coefficient of thermal expansion (k^{-1})	1.4*10^{-5}
Young's Modulus (N/m^2)	3*10^{10}
Poisson's Ratio	0.18
Bulk Modulus (N/m^2)	1.5625*10^{10}
Shear Modulus (N/m^2)	1.2712*10^{10}

3 different loading conditions were considered. All loads are uniformly distributed load over 1st and 2nd floors.

- Unloaded
- 10 kg
- 25 kg

4-ground columns were fixed with ground.

Static Structural analysis settings:
Force applied- 100N on neg Z-direction

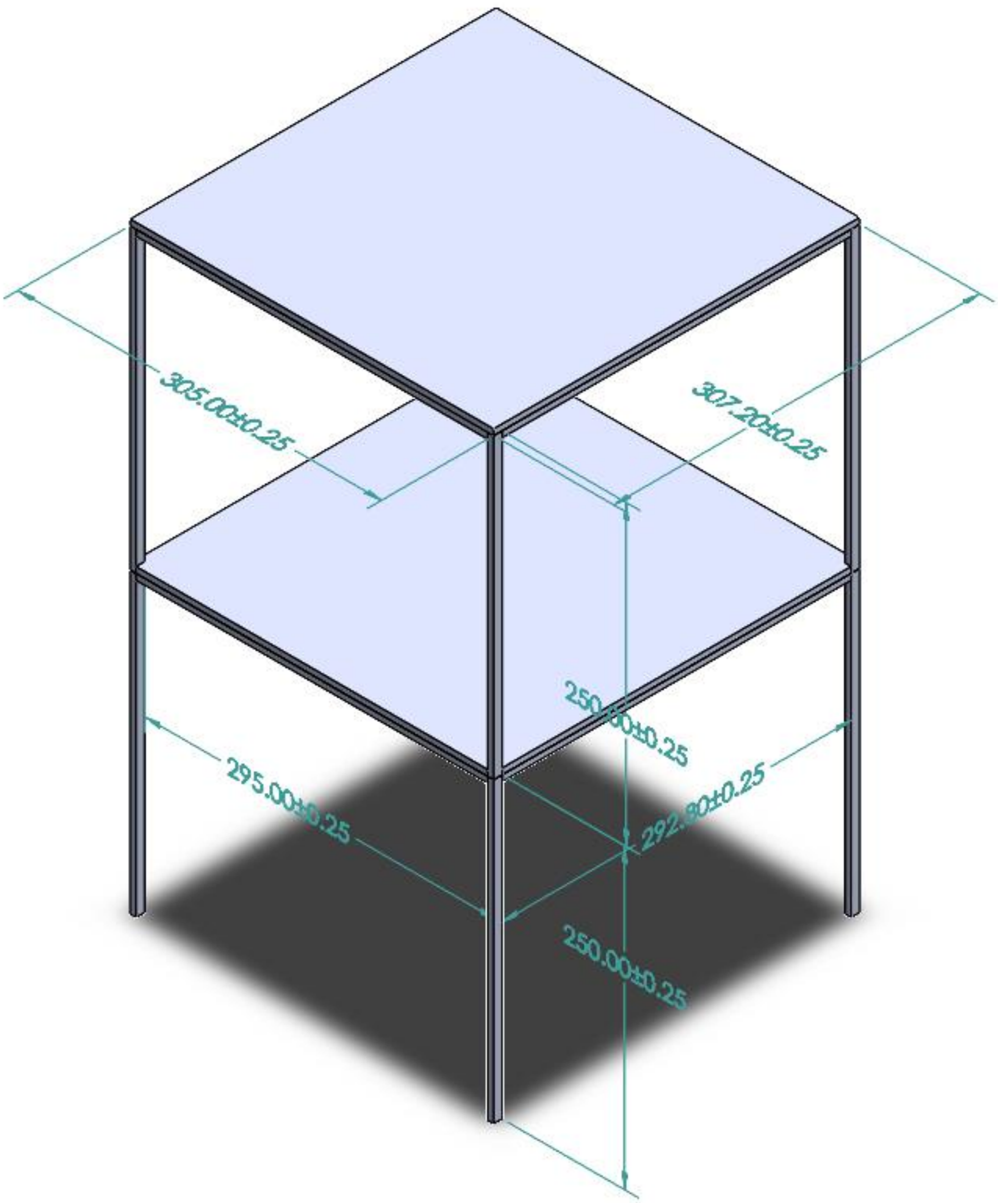


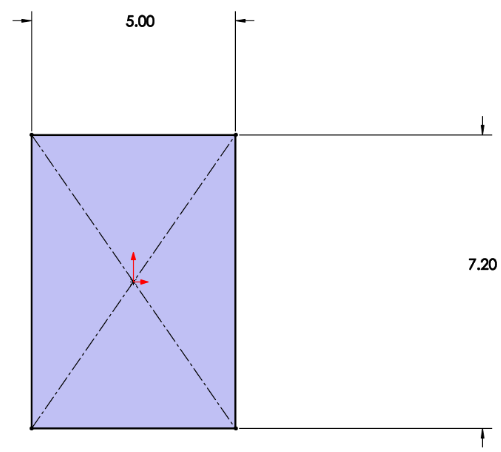
For all the simulation result, mode shape will be as followed-

Mode	Type of mode shape	Axis
1	1st Mode of bending	X
2	1st Mode of bending	Z
3	1st Mode of twisting	Y
4	2nd Mode of bending	X
5	2nd Mode of bending	Z
6	3rd mode of bending	X

Rectangular shape:

Geometry and specifications (CAD model)

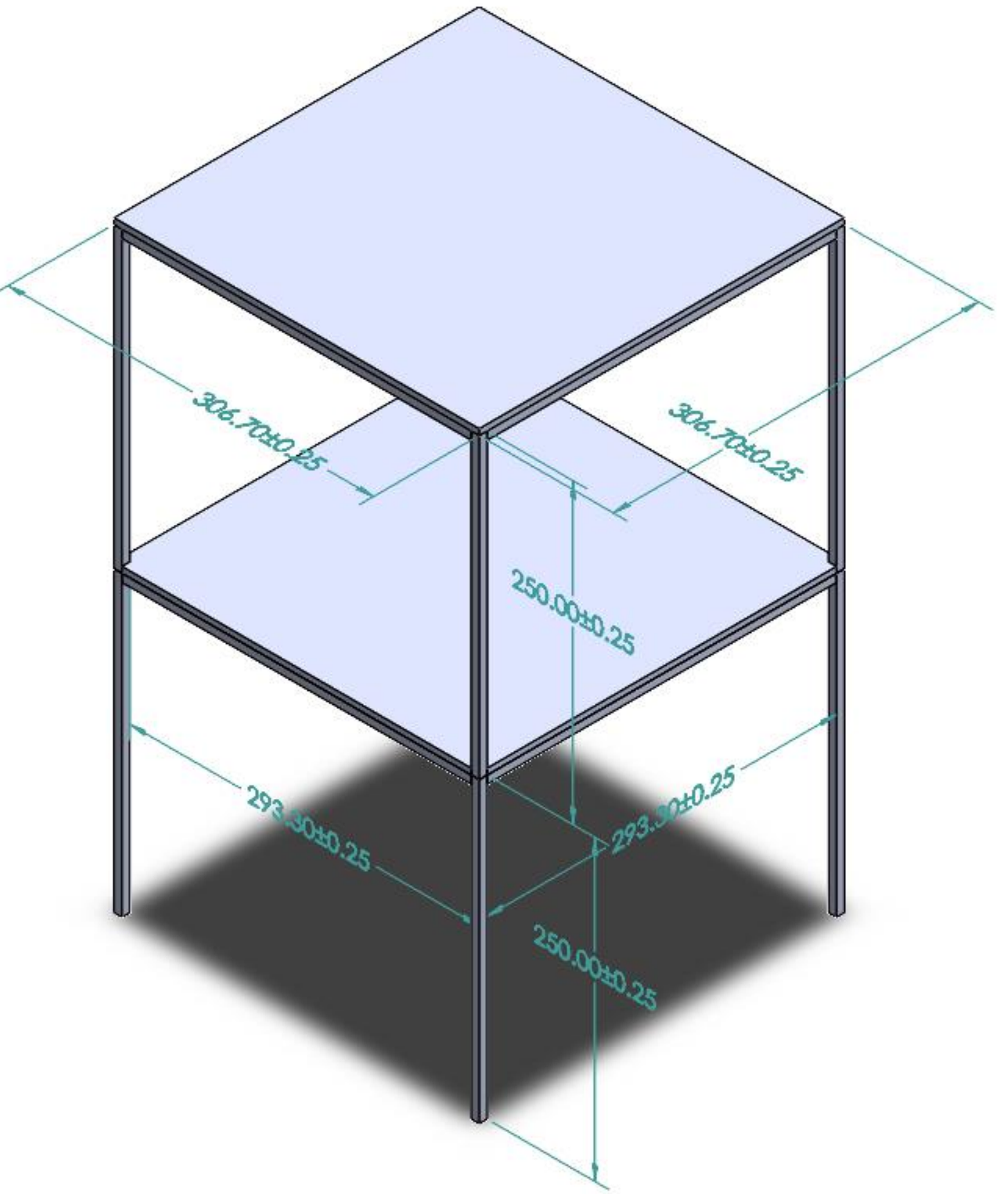


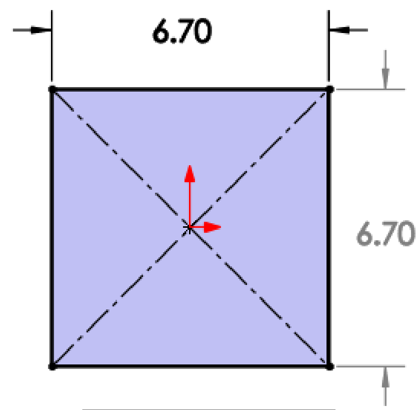


Column Dimension

Square shape:

Geometry and specifications (CAD model)

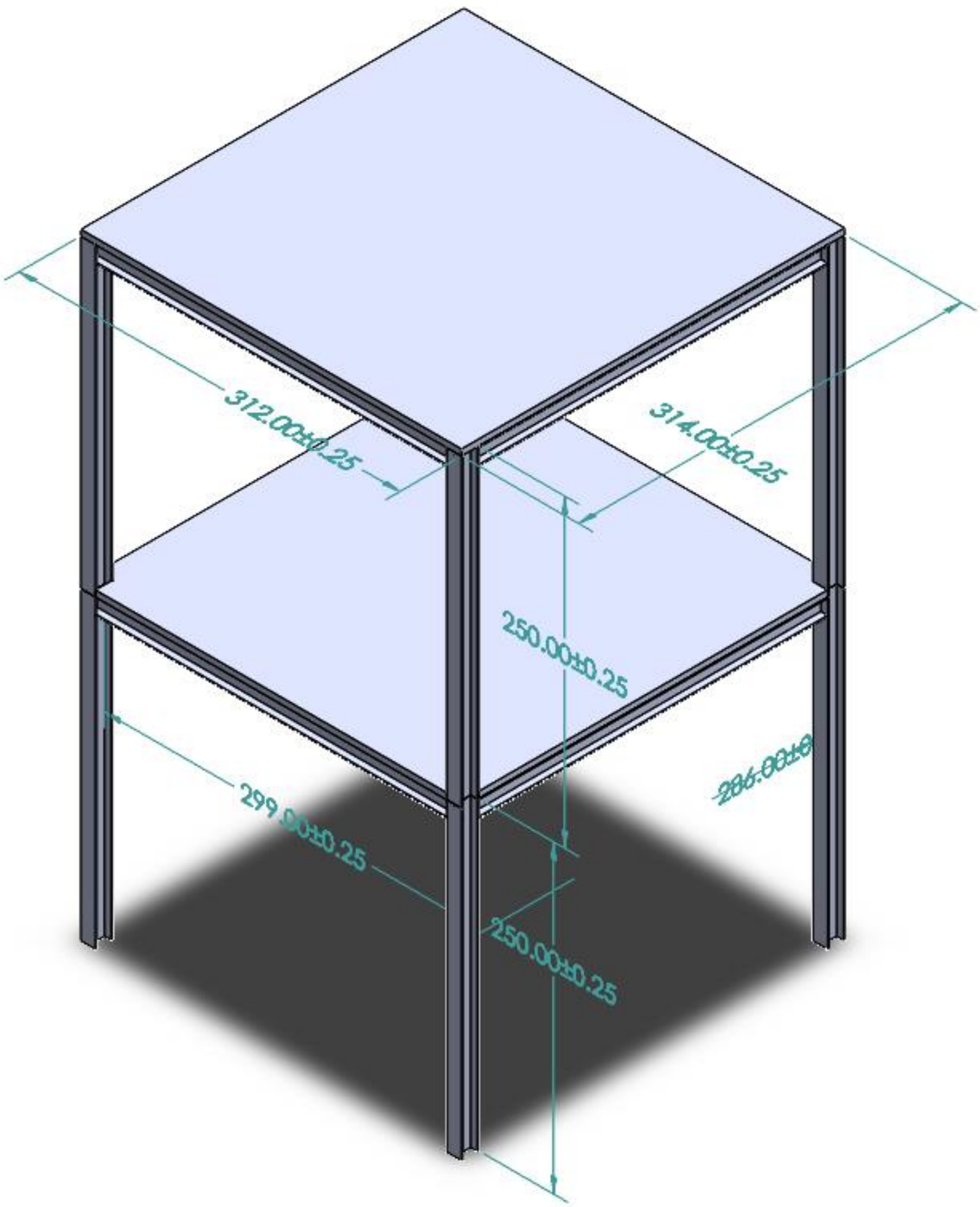


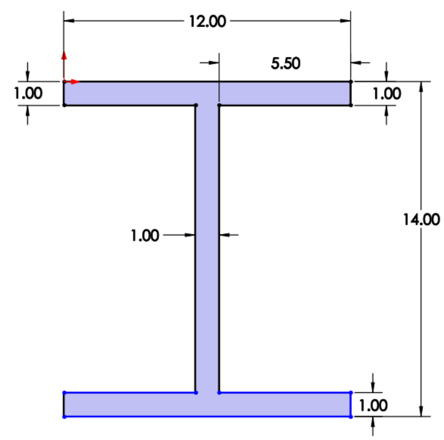


Column Dimension

I shape:

Geometry and specifications (CAD model)





Column Dimension

Simulation Result

Result- Natural Frequency from Modal Analysis

	I			Rectangular			Square		
	Unloaded	**10kg loads**	**25kg load**	**Unloaded**	**10kg loads**	**25kg load**	**Unloaded**	**10kg loads**	**25kg load**
Mode	Frequency	Frequency	Frequency	Frequency	Frequency	Frequency	Frequency	Frequency	Frequency
1	19.737	13.444	10.01	10.217	6.8888	5.1091	14.773	10.05	7.479
2	33.661	22.921	17.063	14.112	9.5142	7.0558	14.773	10.05	7.4791
3	53.314	36.29	27.012	20.256	14.155	10.647	23.957	16.997	12.866
4	79.753	56.193	42.41	27.576	18.576	13.772	40.364	27.433	20.407
5	99.587	67.808	50.477	38.912	26.215	19.436	40.364	27.433	20.407
6	138.68	97.253	73.268	55.588	38.756	29.127	65.724	46.5	35.165

	Equivalent stress (Von-mises) from Static Structural Analysis		
	I	**Square**	**Rectangular**
Minimum Stress	4.8929e-004 MPa	3.8477e-004 MPa	2.6423e-004 MPa
Maximum Stress	39.221 MPa	99.69 MPa	124.15 MPa
Average Stress	0.92042 MPa	1.2832 MPa	1.2479 MPa

Reduction rate of natural frequencies for 6 modes:

	I-beam		Rectangular		Square	
Mode	**%(for 10kg load)**	**%(for 25kg load)**	**%(for 10kg load)**	**%(for 25kg load)**	**%(for 10kg load)**	**%(for 25kg load)**
1	31.88427826	49.2830724	24.5751199	41.99412743	1.634530684	26.79847313
2	31.90636048	49.30928968	24.58078231	42.00141723	28.78401361	47.0018424
3	31.9315752	49.33413362	22.11947077	39.43779621	16.08906003	36.48301738
4	29.54120848	46.82331699	24.63707572	42.05802147	0.51856687	25.99724398
5	31.91079157	49.31366544	24.63003701	42.05139803	29.4998972	47.55602385
6	29.87236804	47.16758004	22.27991653	39.60200043	16.34885227	36.73994387

Reduction rate of Von-mises stress:

I-beam	
%(for 10kg load)	%(for 25kg load)
30.01605136	47.87385206
31.85282616	49.25275507
31.95459417	49.35691318
29.49498206	46.76151707
31.99177729	49.38577373
29.88099186	47.17770163

Findings- Under no loading condition (only body weight), natural frequencies are higher for building with I-beam than rectangular or square ones. Once loads (10kg, 25kg) were added on the floors, the reduction rate of natural frequencies was much higher than others. As axial load is increased, this reduction impacts a lot on the building characteristics. Moreover, the I-cross section one produces much less stress as can be seen from static structural analysis. Thus, we can come to a conclusion that I-beam performs better than any other cross sections.