iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 8 **Issue:** VII **Month of publication:** July 2020

DOI: https://doi.org/10.22214/ijraset.2020.30670

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue VII July 2020- Available at www.ijraset.com

Effect of Bracing Configuration on Seismic Performance of Steel Moment Resisting Frames

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Abstract: Numerous strategies are applied to increase the stability of structure against various forces. Since the advent of the industrial revolution, materials like steel have found increasing use in the construction industry. Among the many uses of steel in construction, one major application is the use of steel as bracing members in frames. Braced frames have higher stiffness and have thus show lesser deflection when subjected to seismic or other lateral loadings. Various bracing configurations can be applied to increase the stiffness of a structure. Some of these are – diagonal, X, V, inverted V, and knee among others. This paper aims to inspect the performance of unbraced and braced frames – diagonal, X, V and inverted V. The parameters for the comparison are: maximum base shear capacity, efficiency of bracing and damping factor. It was observed that the inverted V braced frame had that most base shear capacity and showed the least amount of drift at that lateral load. Additionally, the inverted V bracing also proved to be highly economical by meeting safe drift parameter while utilizing minimum bracing material. Moreover, from the spectral acceleration curves, it was noted that inverted V braced frames showed the least excitations and that the oscillations due to the excitation decayed the fastest in the V braced frame.
Keywords: Moment resisting frames, seismic analysis, pushover analysis, STAAD Pro.

I. INTRODUCTION

India is the second-most populous country in the world and, according to some estimates, is well on its way to becoming the most populous country. In such a situation, in order to house such a huge and ever-increasing populous, there has been an increase in the construction of high-rise buildings which serve multiple purposes in addition to housing. However, due to the sinking of the Indian continental plate under the Asian continental plate, the Indian subcontinent is prone to devastating earthquakes. And these earthquakes, in addition to wind and blasting pose a threat to the stability and integrity of structures.

Over time numerous strategies have evolved to increase the performance of structures against seismic and other lateral loads. These strategies mainly focus on the reduction of the lateral drift by increasing the lateral stiffness. Among these strategies, the use of steel bracing has become increasingly common in tall structures and at the same time have proven to be cost-effective. There are other strategies such as the use of base isolation, mass reduction, addition of shear walls and so on.

Since the industrial revolution, the use of steel has seen a dramatic increase in various industries. Even in the construction industry, steel has a ubiquitous presence – from bridges to the reinforcement in RCC structures. Due to its light weight, ductility, and high tensile strength as compared to concrete, steel is highly suited for the construction of earthquake-resistant structures. Various bracing configurations are used to increase the seismic performance of structures. Some of the common types of steel bracing configurations are forward diagonal, backward diagonal, X, V, inverted V and K bracing. Each of these configurations has different impacts on the performance of the structures under lateral loading.

A. Braced Frames

There are various structural systems that are designed to withstand lateral loads such as ordinary moment frames, special moment frames, and braced frames. Ordinary moment frames should be shown to withstand inelastic deformation corresponding to a joint rotation of 0.02 radians without degradation in strength and stiffness below the full yield value. Such frames cannot be used in seismic zones above III and for buildings with importance factor greater than one in seismic zone III. The connections in such frames are rigid and are formed using bolting and welding. Special moment frames (SMF) are made of E250B steel of IS 2062 and should be able to withstand inelastic deformation corresponding to a joint rotation of 0.04 radians without degradation in strength and stiffness below the full yield value. Braced frames include members that increase the stiffness of structures and carry axial (tensile and compressive) loads. These members can be angles, tubes, channels or tees. Depending upon the location of the braces and ductility characteristics, braced frames can either be concentric or eccentric. Braced frames help structures better resist lateral loads such as wind and earthquakes. Additionally, braces prevent the buckling of frames under loading. As braces increase the stiffness of the frames, they reduce the storey drift significantly.

1) *Concentrically Braced Frames:* Braced frames help structures better resist lateral loads such as wind and earthquakes. Additionally, braces prevent the buckling of frames under loading. As braces increase the stiffness of the frames, they reduce the storey drift significantly. Concentrically braced frames are comprised of members that have a common point of intersection. X, Diagonal, V and Inverted V bracings fall under concentric bracings. As per IS 800:2007, concentrically braced frames are further classified as Ordinary Concentrically braced Frames (OCBF) and Special Concentrically Braced Frames (SCBF).

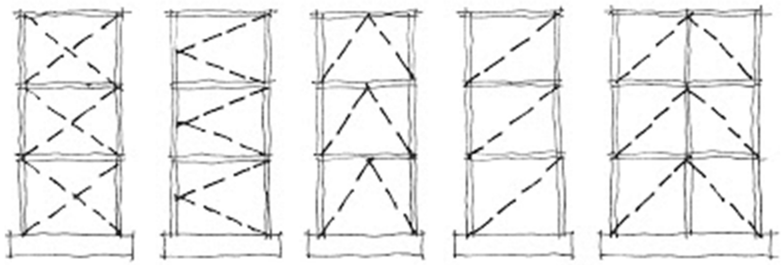

Fig. 1 OCBF configurations with links at one end of brace.

As per IS 800:2007, OCBF shall be used in seismic zones III, except buildings with importance factor greater than one in seismic zone III. Such frames should be able to withstand inelastic deformation corresponding to a joint rotation of at least 0.02 radians without degradation in strength and stiffness below the full yield value. As per IS 800:2007, SCBF may be used in any seismic zones and for buildings of any importance factor. Such frames should be able to withstand inelastic deformation corresponding to a joint rotation of at least 0.04 radians without degradation in strength and stiffness below the full yield value. The bracing members in SCBF have slenderness ratio not exceeding 160 and are made of E250B steel.

2) *Eccentrically Braced Frames:* Eccentric braced frames consist of members connected with eccentricities – usually within the beam section. These eccentric elements act as fuses that limit the amount of force taken up by the braces. When large forces act upon the structure, the braces undergo shear yielding and dissipate energy and hence the system is able to maintain stability.

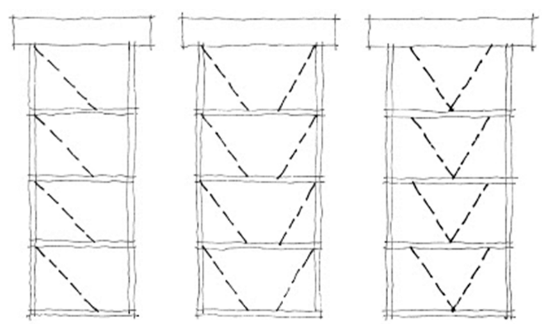

Fig. 2 EBF configurations with links at one end of brace.

II. LITERATURE REVIEW

Sheikh & Massumi [1] aim at understanding the performance of mega-braced systems' different configurations and performance of structural elements under earthquake ground movements of bracing configuration. For this reason, PERFORM-3D software was used to study steel frames with 18 and 30 floors with different settings with bracing system. Four different types of mega-braces (MBFs, for example) were used. In order to assess the structural performance in earthquake soil movements, non-linear time history analyses have been conducted. To compare the seismic response of the braced frames, the shifting roof, drift and the energy absorption were used. Four configurations were designed for analytical models and their performance were compared. Analysis of the structural performance under earthquake was conducted without a linear time history. Several results were presented to evaluate the behaviour, with respect to high roof movement, the drift and energy input, of four distinct bracing configurations. Analysis of this study showed that the roof drifts in MBFs are 12% -70% in 18-story frames and 10% -55% in 30-story frames inferior to CBF. On average, 18-story and thirty-story frame inter storey drift is reduced by 35% and 25% each.

Therefore, the use of MBF-1 and MBF-2 is the greatest effect on the upper floors of this parameter when adding structural braces to reduce the lateral displacement. MBF-2 mainly affects the reduction of the coefficient of base shear. Moreover, the use of mega bracing systems is far more cost-effective than the current braking systems due to the weight reduction of steel used in structural elements and their connections. Comparative analysis shows the cost-effectiveness of MBF-1.

Ganesh [2] in his paper analyses the seismic performance in terms of base shear and shift and comparison is made among seismic behaviour of buildings for different RCC bracing systems. The MRFs, the building of the X storey (G+10), are also three structural configurations used in this paper. On the periphery of the column the bracing systems are provided. The program for the frame models is evaluated as per IS: 1893 ETABs.

The parameters considered in this paper for the analysis of seismic impact of buildings are the displacement of base shear and storey. The results showed that when compared with moment-resistant frames and V braced frames, X-braced frames are more efficient and safer at the time of earthquake.

The parameters such as strength and stiffness are more significant in high rise buildings. So bracing system is implemented for this purpose to improve each of these parameters. MRF buildings displayed a higher degree of displacement than other braced buildings, more vulnerable to unnecessary damage during the earthquake. The base shear of braced buildings increased relative to buildings without bracing, suggesting that the building's rigidity decreased. When using XBF and VBF, the building's storage displacement is decreased from 55%to 60%. XBF's performance has more safety margin compared to VBF. The RC bracing has one advantage that it can be used to reinforce the existing structure.

Gadge, Dhawle, & Kakpure [3] deal with the study of seismic performance of a multi-story steel frame building designed according to existing Indian code provisions (IS 800 -2007). By inserting steel brackets into the structural framework, the shear ability of the structure can be increased. It can also be used as retrofit bracings. There are n "numbers of possibilities for arranging eccentric brackets of steel such as D, K, and V form. A standard eight-story steel frame building as per the IS 800- 2007 is designed for different types of eccentric bracings. D, K, and V are the various types of eccentric bracings considered for the study in question. Each frame's performance is studied through the nonlinear static analysis. The selected frame models are analysed using pushover analysis. The seismic performance of a multi-story steel frame building is designed according to the provisions of the current Indian code (IS 800 -2007).

Sarno & Elnashai [4] in their paper aims to evaluate the seismically efficient MRFs retrofitted with different bracing systems for frames resistant to the moment of steel. Special concentrated braces (SCBFs), buckling braces (BRBFs), and mega braces (MBFs) were used in three structural configurations. The 9-storey steel perimeter MRF was constructed in areas with a high seismic hazard with lateral stiffness not sufficient to meet code drift limitations. SCBFs, BRBFs, and MBFs were retrofitted to the frame. Inelastic analyses of time-history were performed to determine the structural effectiveness of the earthquakes. Deformations were used locally (member rotation) and globally (inter-storey and roof drift).

III.OBJECTIVES

The paper focuses on the effect of various bracing configurations on the seismic performance of steel moment resisting frames. Diagonal, X, V, and inverted V bracing configurations have been dealt with in this paper the comparative analyses have been divided into three separate goals.

A. Firstly, numerical pushover analyses using STAAD Pro have been carried out to calculate the maximum base shear capacity of various braced models. This objective aims to find the maximum lateral base shear each braced model can bear.
B. Secondly, a comparison from an economic point of view has been conducted to determine the most efficient bracing configuration. This objective aim to find the most frugal bracing configuration that would help achieve safe drift of top storey using the least material.
C. Finally, the behaviour of scaled down models has been tested using an accelerometer to verify the results obtained from numerical analyses. This objective also aims to find the logarithmic decrement and the damping factor of the various models.

Through the three aforementioned objectives, the paper seeks to rank the bracing configurations on various parameters such as storey drift, maximum base shear capacity and damping factor.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue VII July 2020- Available at www.ijraset.com

IV. TECHNICAL SPECIFICATIONS

A. Base Shear Comparison

In order to compute the maximum base shear capacity of the bracing configurations, a standard steel frame for mercantile purpose was deigned according to IS 800:2007. The frame was subjected to a live load of 4KN/m^2. The bracings were provided on the exterior faces and along the two vertical planes of symmetry. The following are the frame specifications:

TABLE I
Specifications of Frame I

Property	Value
Beam section	I80016A50020
Column section	I80012A40012
Brace section	ISA150x150x20
Number of storeys	G+4
Bays in X direction	4
Bays in Z direction	4
Storey height	3 m
Dimensions of bay	4 m x 4 m

Loading as per Table 1, IS:875, Part 2- 1987:

1) Dead Load

Self-Weight: Weight of the members
Floor Load:
Floor Finish = 0.75 KN/m^2
Slab Dead Load for 0.125m thick slab = 3.13 KN/m^2.

2) Live Load

Live load for mercantile building = 4 KN/m^2

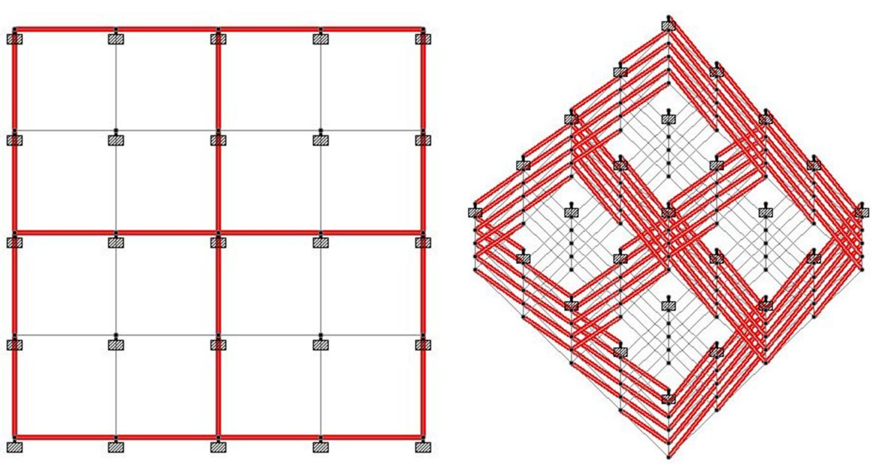

Fig. 3 Plan and isometric view of standard braced frame (Red members represent braces)

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B. Pushover Analysis Configuration

The pushover analysis provides the load-deformation curve (capacity curve) of a structure representing the base shear vs. the horizontal displacement of a control joint. In order to compute the maximum base shear capacity of the different braced frames, pushover analysis was conducted in STAAD Pro with the following configurations:

TABLE II
Configuration of pushover analysis

Property	Value
Type of frame	Moment frame
Vertical distribution of base shear	Method 1-Uniform distribution of base shear E (FEMA 356-2000 Sec 3.3.3.2.3)
Number of push load steps	500
Critical damping	2% (IS 1893 clause 7.8.2.1)
Site category	Class E (FEMA 356-2000 Sec 1.6.1.4.1)
Hinge type	FEMA
Direction of loading	Z axis
Joint displacement value	0.5 m
Control joint	26

C. Bracing Efficiency Comparison

In order to determine the most efficient bracing configuration to achieve the safe drift of top storey, seismic analysis was conducted on various bracing configurations. A different frame was designed as per IS 800:2007. The following are the specifications of the designed frame:

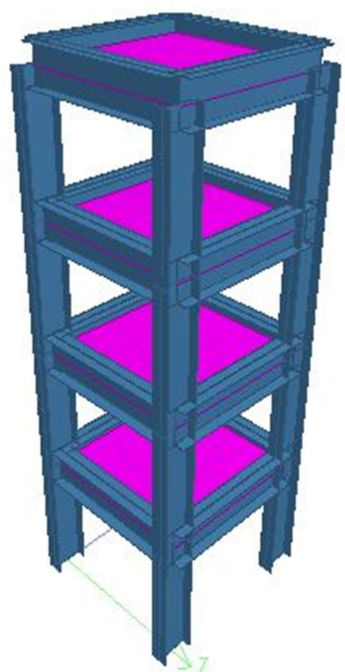

Fig.4 Isometric view of steel frame for comparison of efficient bracing

TABLE III
Specification of Frame II

Property	Value
Beam section	I80016A50020
Column section	I80012A40012
Brace section	ISA150x150x20
Number of storeys	G+4
Bays in X direction	4
Bays in Z directions	4
Height of storey	3 m
Dimension of bay	4 m x 4 m

D. Seismic Analysis Configuration

The seismic analysis provides the joint displacement of the nodes of a structure under a given earthquake loading. The seismic analysis conducted on the aforementioned frame had the following configurations:

TABLE IV
Configuration of seismic analysis

Property	Value
Lumped load (DL+0.5LL)	9.475KN/m^2
Time period	0.045 seconds (Clause 7.6.2)
Response reduction factor	4 (Table 7)
Zone factor	0.36 (Table 2)
Importance factor	1 (Table 6)
Damping ratio	2% (Clause 7.8.2.1)
Soil condition	Medium

E. Spectral Acceleration Curves

The final objective of the paper deals with the experimental verification of results from the previous objectives. In doing so, spectral acceleration curves have been plotted using an accelerometer and an Arduino Uno. These curves represent the acceleration of a structure and help understand its behaviour during an earthquake.

In order to measure the spectral acceleration of the scaled down models, the accelerometer was calibrated by measuring the offset and gain in acceleration in the direction of the excitation. The offset and gain were calculated as follows:

Gain = $0.5*(Y^+ - Y^-)$

Offset = $0.5*(Y^+ + Y^-)$, where Y^+ and Y^- represent the acceleration along Y^+ and Y^- directions.

The calibrated acceleration is computed as follows:

$a = (a_0 - \text{offset})/\text{gain}$, where a_0 represents the uncalibrated acceleration.

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F. Scale Models

The logarithmic decrement and the damping factor are calculated for the various braced models. The braced models are made according to the following specifications:

TABLE V
Specification of scale models

Property	Value
Scale	1:20
Beam size	5 mm steel rod
Column size	5 mm steel rod
Brace size	3 mm steel rod
Length	20 cm
Breadth	20 cm
Storey height	15 cm
Number of storeys	G + 4

V. METHODOLOGY

The logarithmic decrement and the damping factor are calculated for the various braced models. The braced models are made according to the following specifications:

The paper consists of three main objectives:

1) Pushover analysis to determine the maximum base shear capacity
2) Seismic analysis to determine the most economic bracing configuration
3) Experimental analysis to determine the logarithmic decrement and the damping factor.

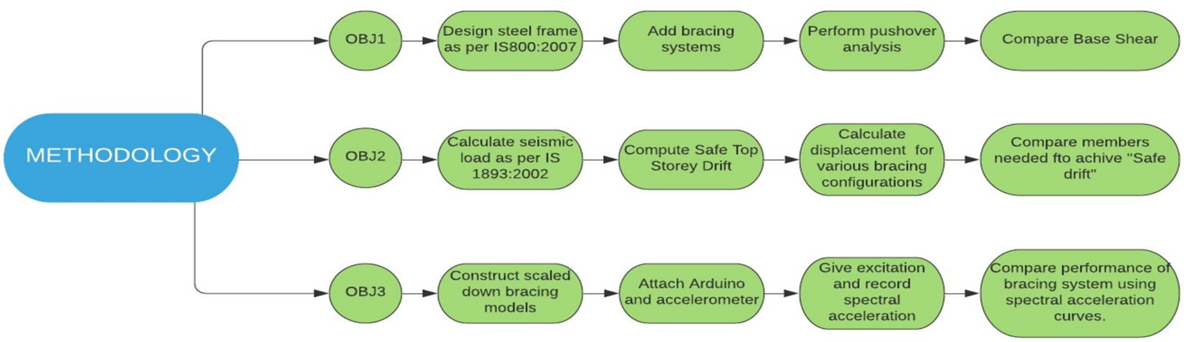

Fig. 5 Methodology flowchart

A. Maximum Base Shear Capacity

The unbraced and braced (diagonal, X, V and inverted V) frames were modelled in STAAD Pro as per the beforementioned specifications. The models were designed as per IS 800-2007 and loaded as per IS 875. The base shear is distributed uniformly along the height of the frames according to Method 1 as per FEMA 356-2000 Sec 3.3.3.2.3. The frames are loaded in a step by step fashion in 500 increments. The critical damping for the steel frames is set as 2%. The soil is classified as per FEMA 356-2000 Sec 1.6.1.4.1 and is set as Class E. The joint displacement for the control joint 26 is set s 500 mm. The maximum base shear capacity of the frames is noted from the obtained capacity curves.

B. Economic Bracing Configuration

To test the efficiency of the bracing configurations, a frame as per specification mentioned in Table III is modelled in STAAD Pro. The braced and unbraced versions of the frame are subjected to seismic analysis as per the configurations mentioned in Table III. A maximum top storey safe drift is calculated for the frame of 2nd configuration. As per IS 1893 clause 7.11.1, the safe drift index is 0.04 and therefore the safe top storey drift for the 12 m high frame is 48 mm. Each frame in added braces starting at the first floor and then seismic analysis is performed to record the tops storey drift. After analysis, braces are then added to the next floor and again the seismic analysis is performed to record the top storey drift. This is repeated till all the floors of the frame are braced.

The minimum number of braces of each type required to satisfy the drift condition are calculated and the total length of bracing members utilized is computed. The bracing configurations are then ordered based on the total amount (length) of bracing members required to just satisfy the drift condition. The configuration that consume more material is termed as less economic.

C. Damping Factor

Scaled down models as per specifications in Table V are designed to record their behaviour when given excitation. In order to give the models excitations, the models are setup using nuts and bolts on an assembly with four tires. The assembly allows the models to move along an axis. An elastic band is also attached to the assembly which is stretched and then released to set the setup in motion. A plank is held at a fixed distance to act as a barrier and abruptly stop the motion of the model on the assembly. The collision of the setup and the plank would produce an impulse and set the model into oscillations.

Fig. 6 Assembly with four tires

An Arduino UNO and accelerometer ADXL345 are also attached to the top of the model, and connected to a laptop via a USB A-B. The accelerometer is calibrated by computing the acceleration gain and offset.

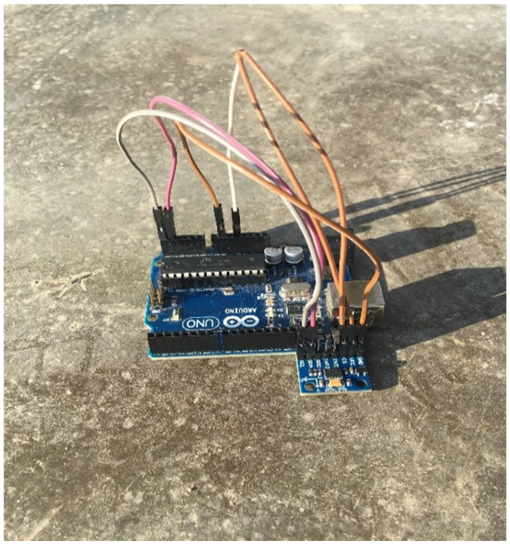

Fig. 7 Arduino UNO and ADXL345 accelerometer

The oscillations caused by the impulse are recorded by the accelerometers in the form of spectral acceleration curves. The average logarithmic decrement is computed and the damping factor is hence calculated.

The logarithmic decrement δ is calculated as $\ln \frac{Ai}{Ai+1}$, where A is the amplitude.

The damping factor ζ is calculated as $\frac{\delta}{\sqrt{(2\pi)^2+\delta^2}}$.

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VI. RESULTS AND DISCUSSIONS

A. *Maximum Base Shear Capacity*

From the pushover analysis it was observed that the unbraced frame has the minimum base shear capacity. Among the braced frames, the X braced frame has the maximum and the diagonal braced frame has the minimum base shear capacity. The V and inverted V have almost the same base shear capacities, however, the inverted V bracing outperforms the V bracing slightly.

The base share capacity of the configurations was observed to be in the following ascending order:

Unbraced < Diagonal < V < Inverted V < X

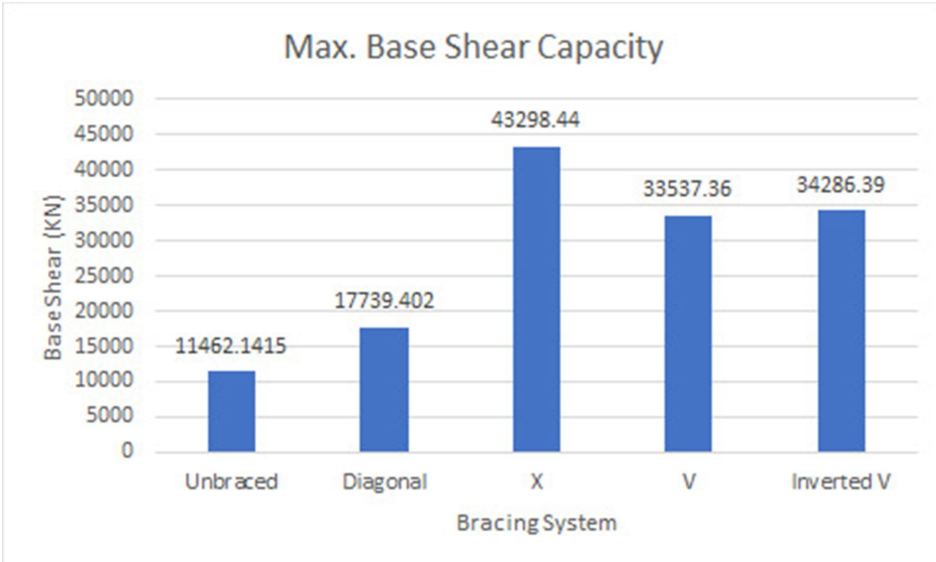

Fig. 8 Maximum base shear capacity

In addition to having the maximum base shear capacity, the X bracing system also has the minimum top storey displacement just before the failure. Meanwhile, the unbraced frame shows the most drift. The inverted V again outperforms the V bracing by showing lesser displacement. The maximum roof displacement at the above-mentioned maximum base shear for each for the frames was observed to be in the following ascending order:

X < Inverted V < V < Diagonal < Unbraced

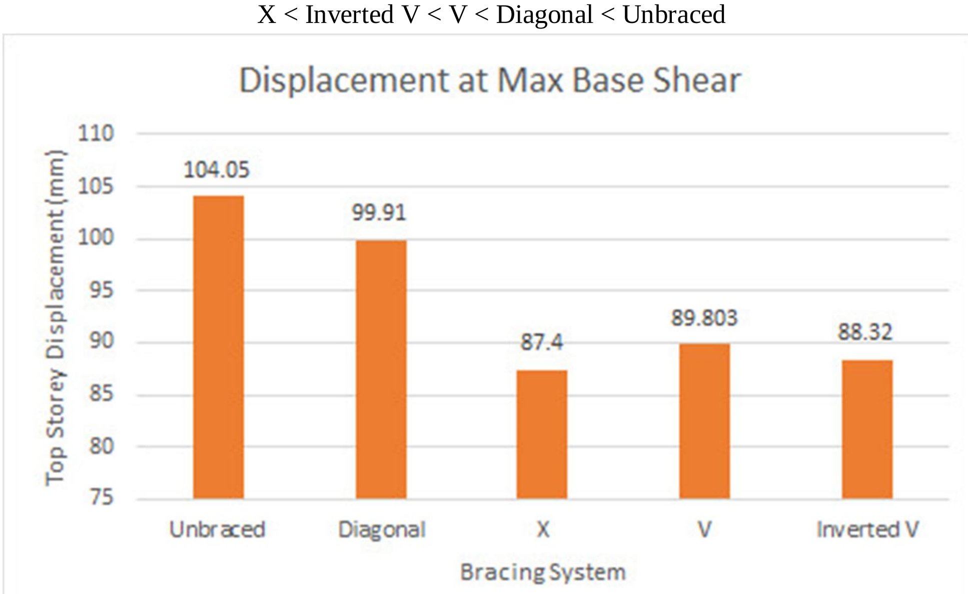

Fig. 9 Roof displacement at maximum base shear

B. Economic Bracing Configuration

As per IS 1893 clause 7.11.1, the safe drift index is 0.04 and therefore the safe top storey drift for the 12 m high frame is 48 mm. It was observed that the in case of diagonal and V the frame needed to be braced upto 3 floors to satisfy the safe drift parameter. Whereas in the case of X and inverted V bracings, the drift safety was satisfied when the first two floors were braced.

TABLE VI
ROOF DISPLACEMENT FOR BRACING UPTO VARYING FLOORS

Bracing System	Max deflection (mm) when bracing upto storey number			
	1	2	3	4
Unbraced	60.289	60.289	60.289	60.289
Diagonal	56.362	49.933	44.349	41.457
X	53.556	44.132	36.328	32.683
V	55.92	48.93	42.816	39.795
Inverted V	53.41	44.3	37.11	35.22

Therefore, to achieve drift safety, the least and the most material was used in inverted V and V configurations respectively. Hence it can be concluded that the inverted V bracing is the most efficient bracing in this scenario.

TABLE VII
Efficiency of bracing configuration

Bracing System	Floors braced for safe drift	Number of braces used	Length of brace (m)	Total length of brace used (m)	Efficiency Rank
Diagonal	3	12	5	60	2
X	2	16	5	80	3
V	3	24	3.6	86.5	4
Inverted V	2	16	3.6	57.6	1

C. Damping Factor

According to the spectral acceleration curves, the maximum acceleration amplitude was observed for the unbraced model. Whereas the inverted V braced model showed the least acceleration amplitude.

TABLE VIII
Spectral acceleration of scaled models

Bracing Configuration	Spectral Acceleration (g)			
	1st Amplitude	2nd Amplitude	3rd Amplitude	4th Amplitude
Unbraced	1.066	0.866	0.8	0.433
Diagonal	0.966	0.616	0.433	0.283
V	0.796	0.606	0.246	0.126
Inverted V	0.66	0.504	0.32	0.28

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The logarithmic decrement δ is calculated as $\ln\frac{Ai}{Ai+1}$, where A is the amplitude and the damping factor ζ is calculated as

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2+\delta^2}}.$$

It can be seen that the damping factor is the most for the diagonal braced frame and hence the acceleration decays faster than the rest of the frames. It is also observed that the damping factor of the inverted V braced frame is almost equal to that of the unbraced frame, however, the inverted V frame exhibits accelerations of much lower amplitudes.

TABLE IX
Damping factor of scaled models

Bracing Configuration	Logarithmic Decrement				Damping Factor
	δ_1	δ_2	δ_3	δ_{avg}	ζ
Unbraced	0.207	0.079	0.613	0.3	0.0477
Diagonal	0.449	0.352	0.425	0.409	0.0650
V	0.272	0.901	0.669	0.614	0.0973
Inverted V	0.269	0.454	0.133	0.285	0.0454

TABLE X
Inference from damping factor

ζ	Implication	Oscillation
$\zeta < 1$	Underdamped	Structure oscillates to reach equilibrium
$\zeta = 1$	Critically damped	Structure does not oscillate to reach equilibrium
$\zeta > 1$	Overdamped	No oscillations and slower response to reach equilibrium

VII. CONCLUSIONS

Through the examinations carried out in the paper and their corresponding results, the following conclusions are drawn:
The braced steel frames outperformed the unbraced frames when compared based on their overall seismic performance. The braced frames exhibited a significantly greater base shear capacity. Therefore, braced frames would be able to bear greater lateral loads than the unbraced frames.
The unbraced frame showed a maximum base shear capacity of 11,456.14 KN. The same for the diagonal braced frame was 17,739.40 KN. Inverted V and V braced frames had almost equal base shear capacities (34,286.39 KN and 33,537.36 KN respectively). The X bracing configuration had the maximum base shear capacity and it was noted to be 43,298.44 KN.
The unbraced steel frame showed the highest amount of top storey deflection among all the cases. The braced frames showed lesser sway even under higher base shear than the unbraced frames. The braced frames had higher stiffness and hence showed much lesser deflections.
The unbraced frame deflected the most with a top storey deflection of 104.05 mm. The same for the diagonal frame was 99.91 mm. Inverted V and V braced frames had almost equal top storey displacements of 88.32 mm and 89.80 mm respectively). The X bracing configuration had the minimum top storey deflection and it was noted to be 87.4 mm.
In the economic and efficiency comparison, it was observed that to achieve the safe drift, the diagonal braced frame required bracing upto three floors, X braced frame upto two floors, V braced frame upto three floors and inverted V upto 2 floors. It was noted that to meet the safe drift condition, the total bracing length for the diagonal braced frame was 60 m, X braced frame was 80 m, V braced frame was 86.5 m and inverted V braced frame was 57.6 m. Hence the inverted V bracing is the most economic and the V is the least economic bracing configuration.
From the spectral acceleration curves, it was noted that after excitation, the unbraced frame showed an initial acceleration of 1.066g. All the braced frames exhibited lesser accelerations than the unbraced frame. The initial acceleration just after the excitation for the

diagonal braced frame was 0.966g, V braced frame was 0.796g and the inverted V braced frame was 0.66g. Among the braced frames, the least and the most accelerations were shown by inverted V and diagonal braced frames respectively.
The average logarithmic decrement computed from the spectral acceleration curves for the models was maximum for the V braced frame (0.614). The unbraced framed and the inverted V braced frame had nearly equal average logarithmic decrement values (~0.3). The same for diagonal braced frame was 0.409. The damping factor thus calculated for the unbraced and inverted V braced frame was ~0.046. Therefore, it can be deduced that the motion of both the models will decay in a similar fashion. The damping factor for diagonal braced frame was 0.065 and the highest damping factor was observed for the V braced frame, and noted to be 0.0973. Thus, the motion would decay rapidly in the V braced frame.

VIII. FURTHER SCOPE

In order to reduce the cost of construction of a braced frame, focus can be directed to reducing the materials used. Therefore, there is scope to study the effect of using braces at particular heights and not along the full height. These points along the height maybe deduced by modal analysis of frames.

IX. ACKNOWLEDGMENT

We would like to express our gratitude to our faculty and advisor, Prof. Suganya Om, for her guidance throughout the research. It was only through her motivation and guidance that we successfully accomplished our objectives. We are immensely grateful to her for her willingness to give valuable advice and direction whenever we approached her with a problem. He keen monitoring of our progress at every juncture motivated us to accomplish our goals. We are thankful to her for providing immense guidance for this research. We would also like to thank the Vellore Institute of Technology for giving us an opportunity and provide us the necessary resources to carry out such research.

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APPENDIX A

A. Base Shear Capacity Curves

1) Unbraced Steel Frame

Maximum Base Shear = 11,462.14 KN
Roof Displacement = 104.05 mm

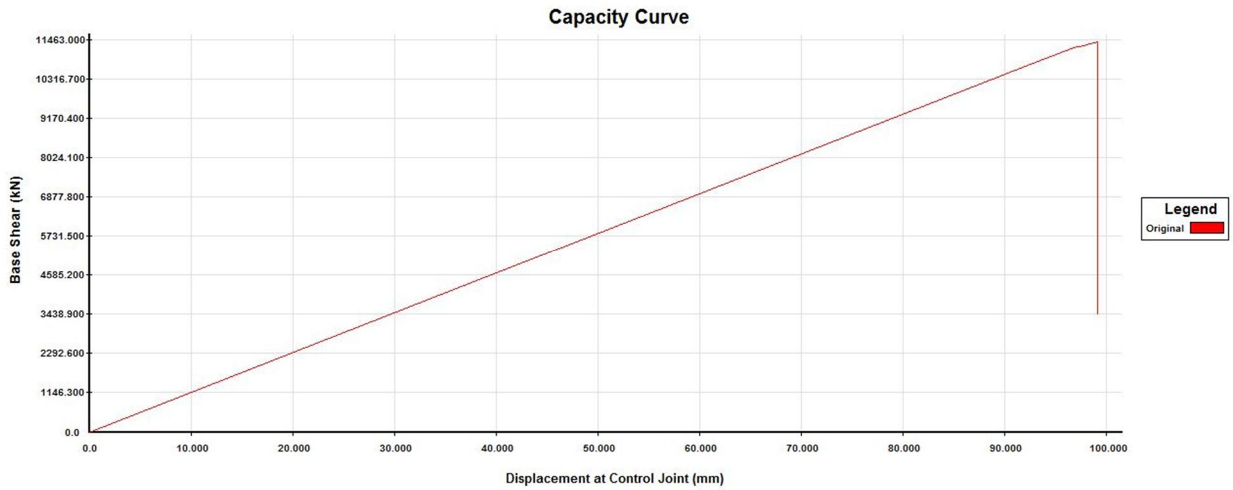

Fig.A.1 Unbraced frame capacity curve

2) Diagonal Braced Steel Frame

Maximum Base Shear = 17,739.402 KN
Roof Displacement = 99.91 mm

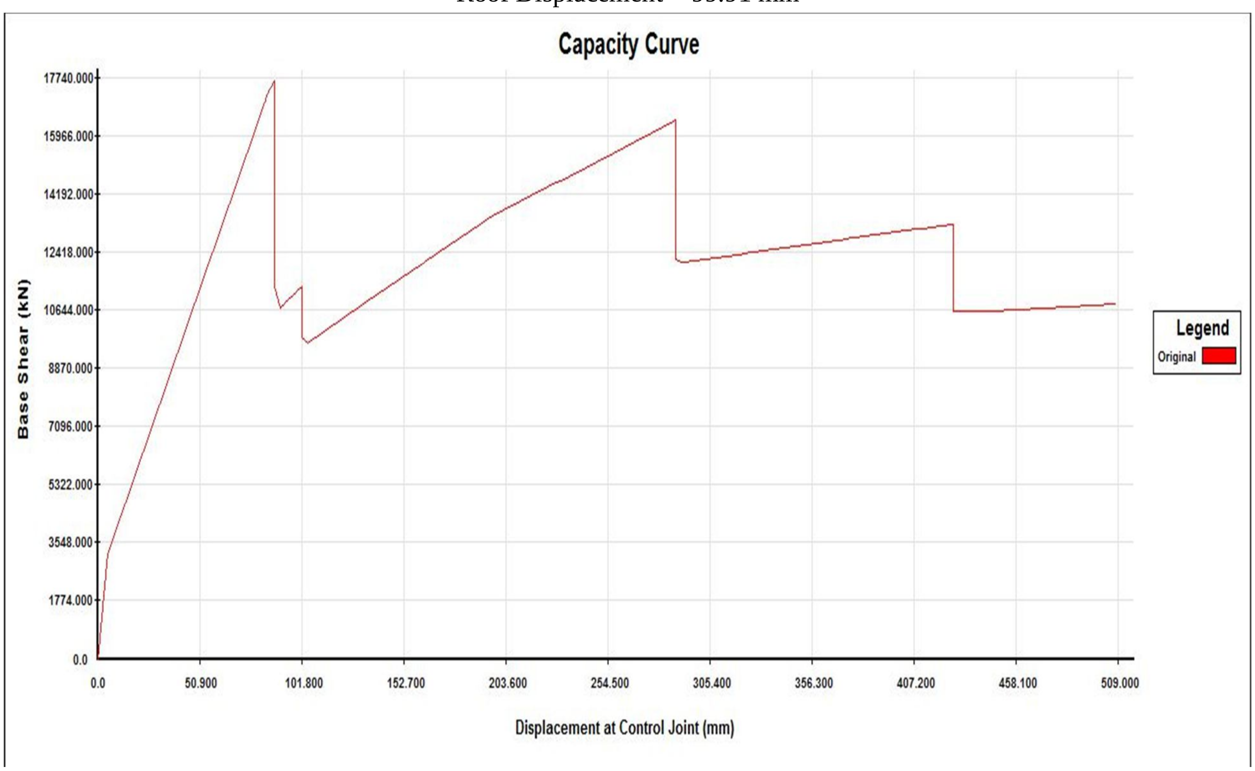

Fig.A.2 Diagonal braced steel frame capacity curve

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3) X Braced Steel Frame

Maximum Base Shear = 43,298.44 KN
Roof Displacement = 87.4 mm

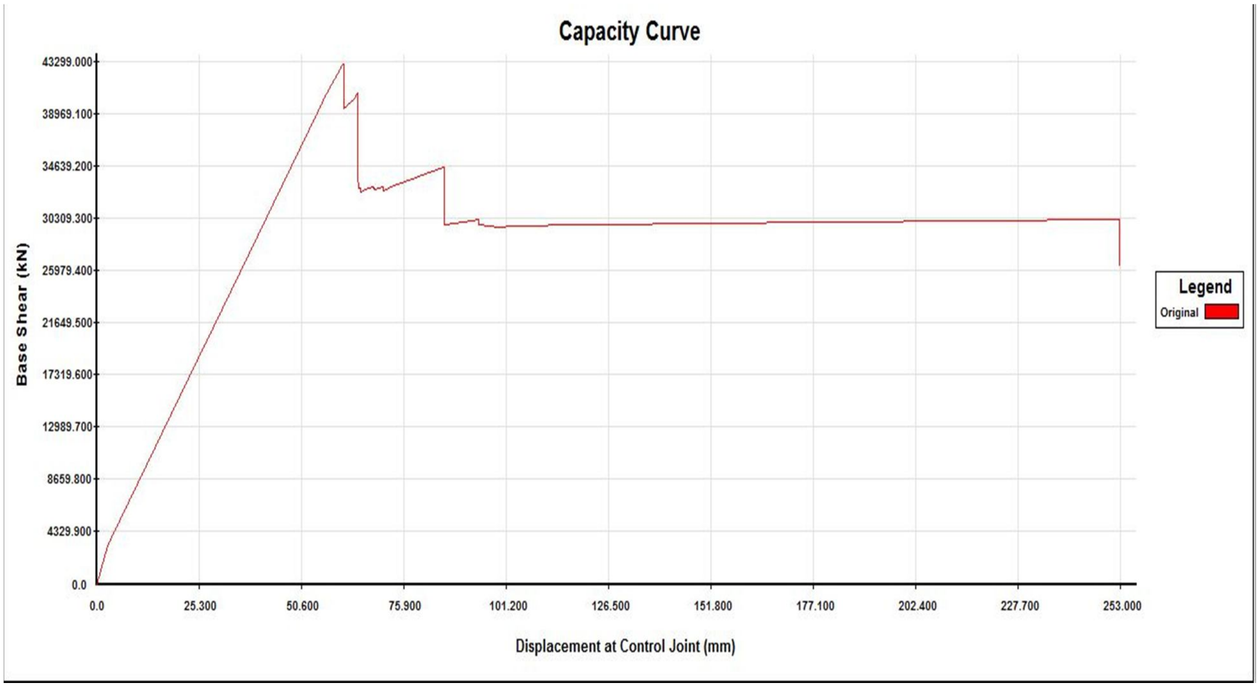

Fig.A.3 X braced steel frame capacity curve

4) V Braced Steel Frame

Maximum Base Shear = 33,537.36 KN
Roof Displacement = 89.803 mm

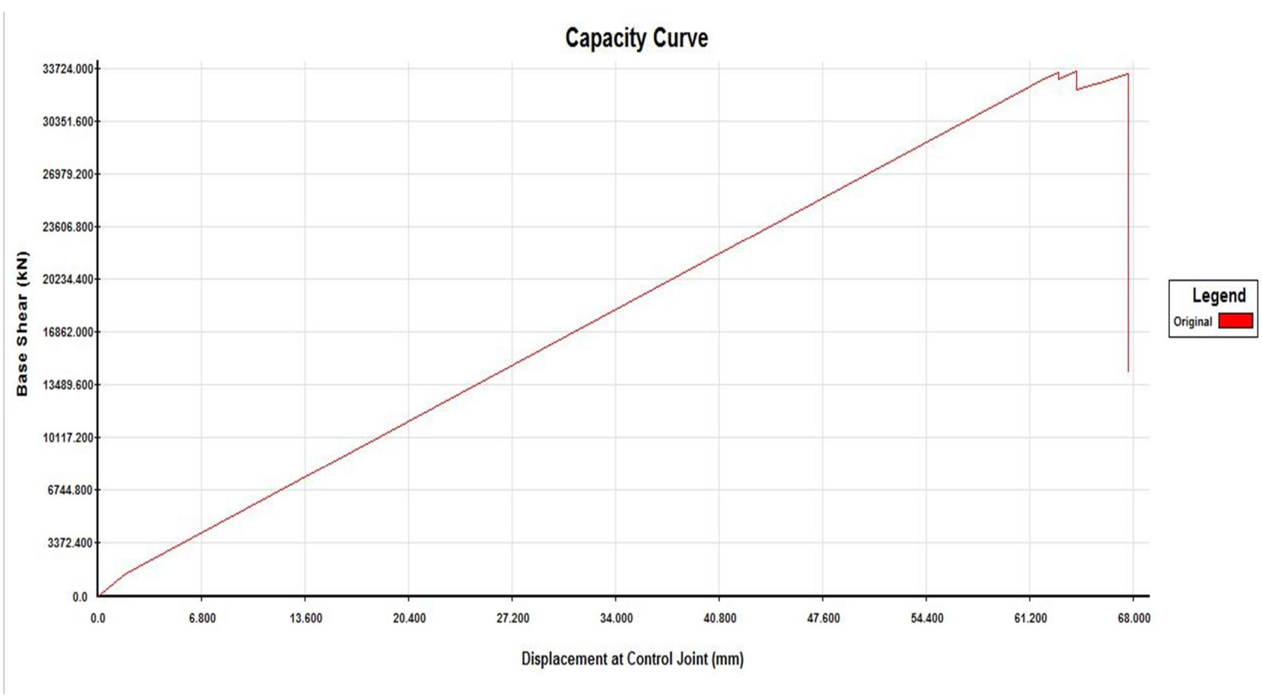

Fig.A.4 V braced steel frame capacity curve

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5) Inverted V Braced Steel Frame

Maximum Base Shear = 34,286.39 KN
Roof Displacement = 88.32 mm

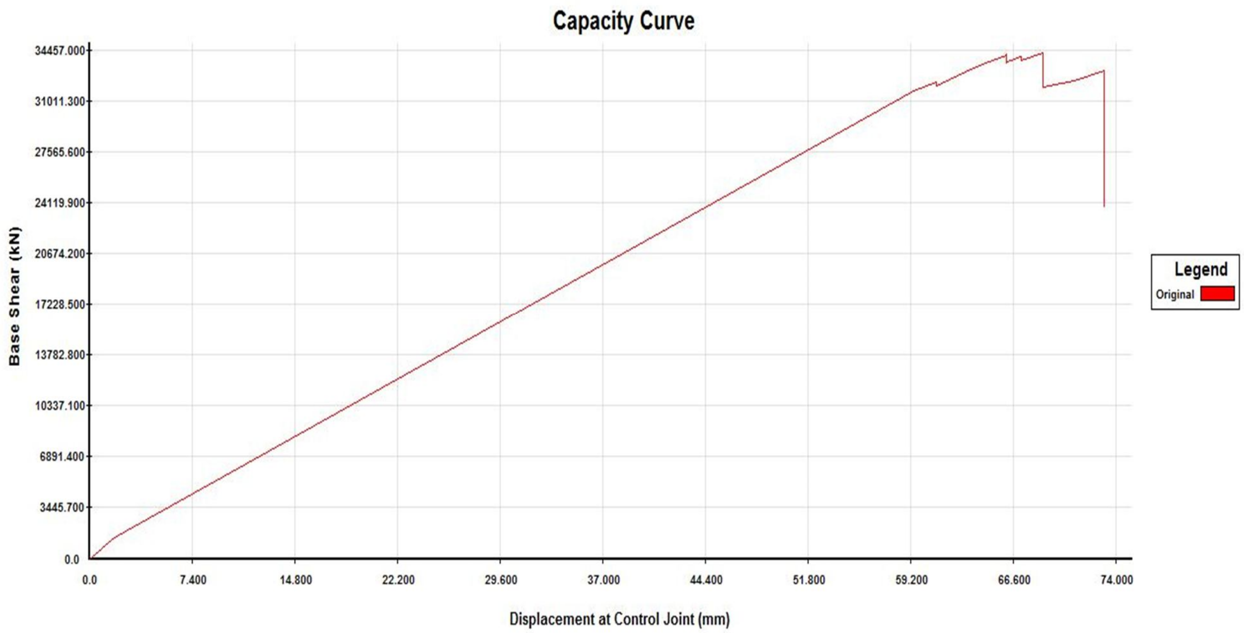

Fig.A.5 Inverted V braced steel frame capacity curve

B. Spectral Acceleration Curves

1) Unbraced Steel Frame

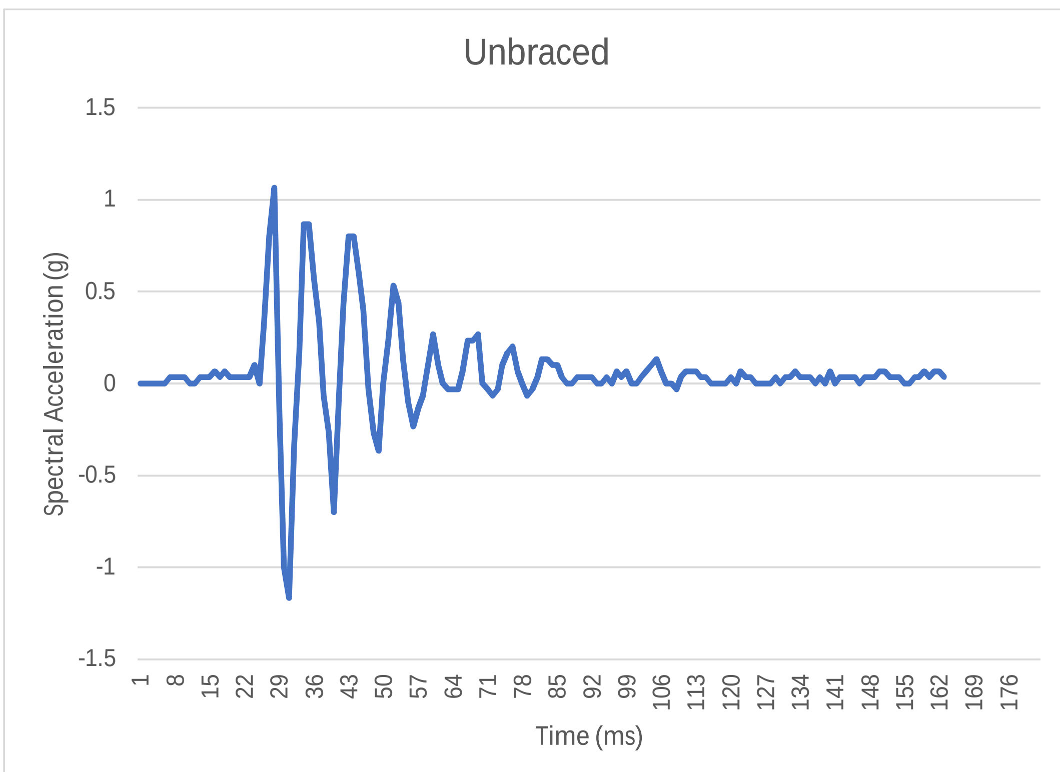

Fig.A.6 Unbraced steel frame spectral acceleration curve

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2) Diagonal Braced Steel Frame

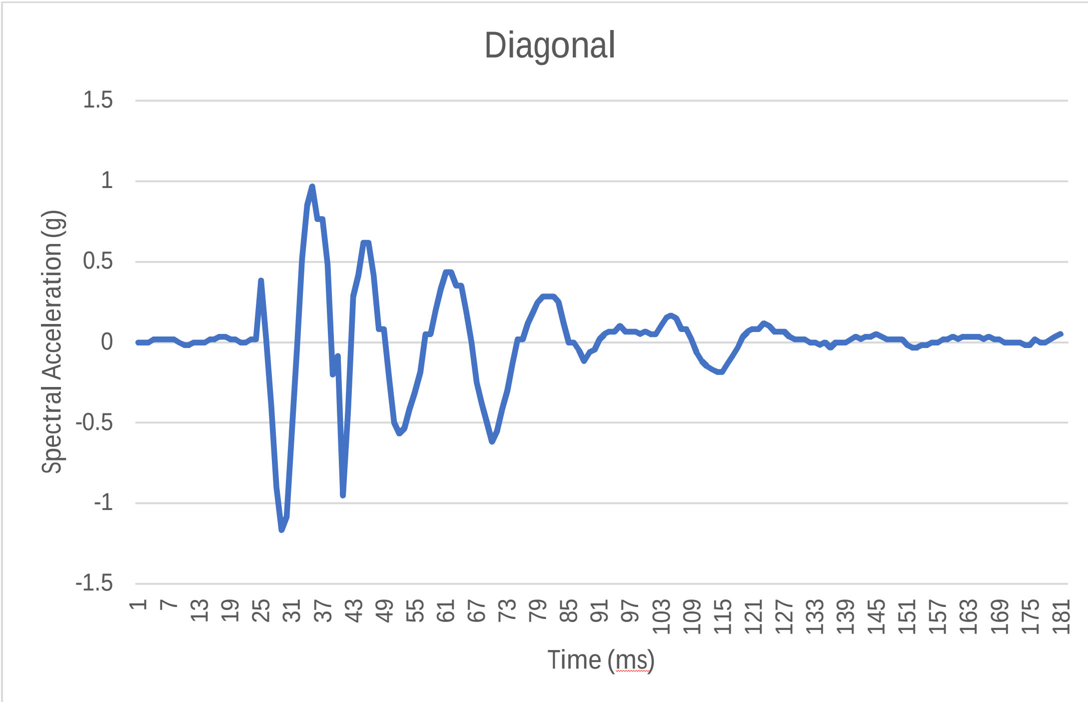

Fig.A.7 Diagonal braced steel frame spectral acceleration curve

3) V Braced Steel Frame

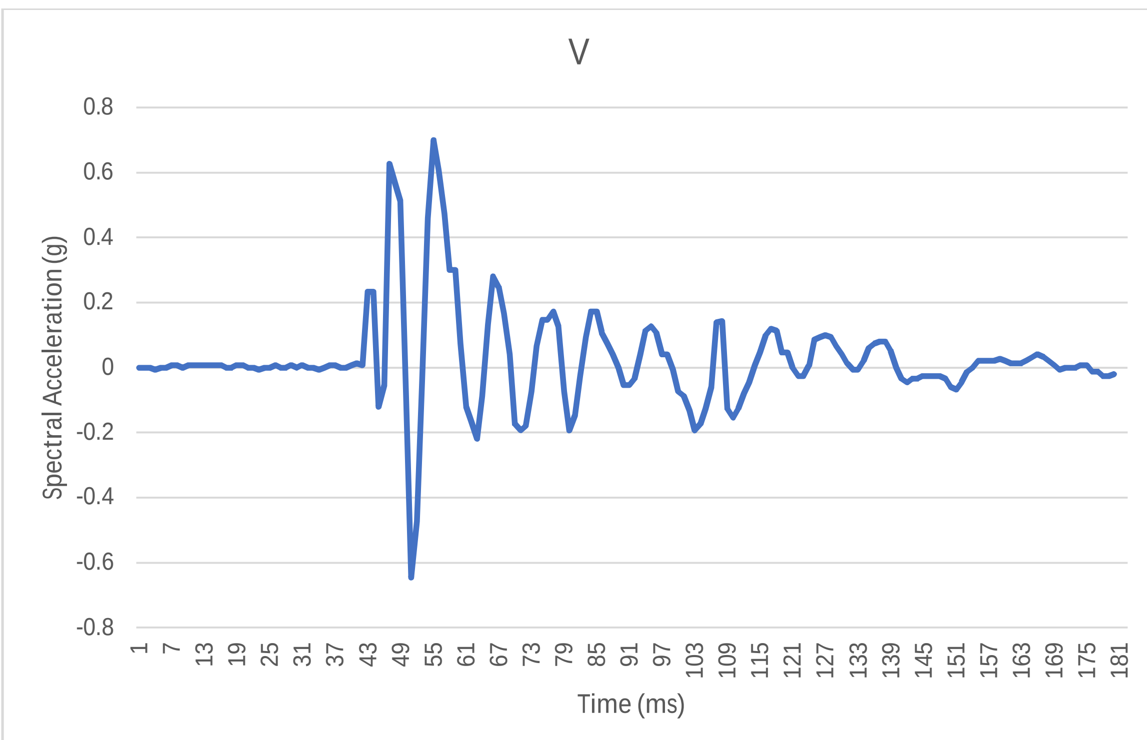

Fig.A.8 V braced steel frame spectral acceleration curve

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4) Inverted V Braced Steel Frame

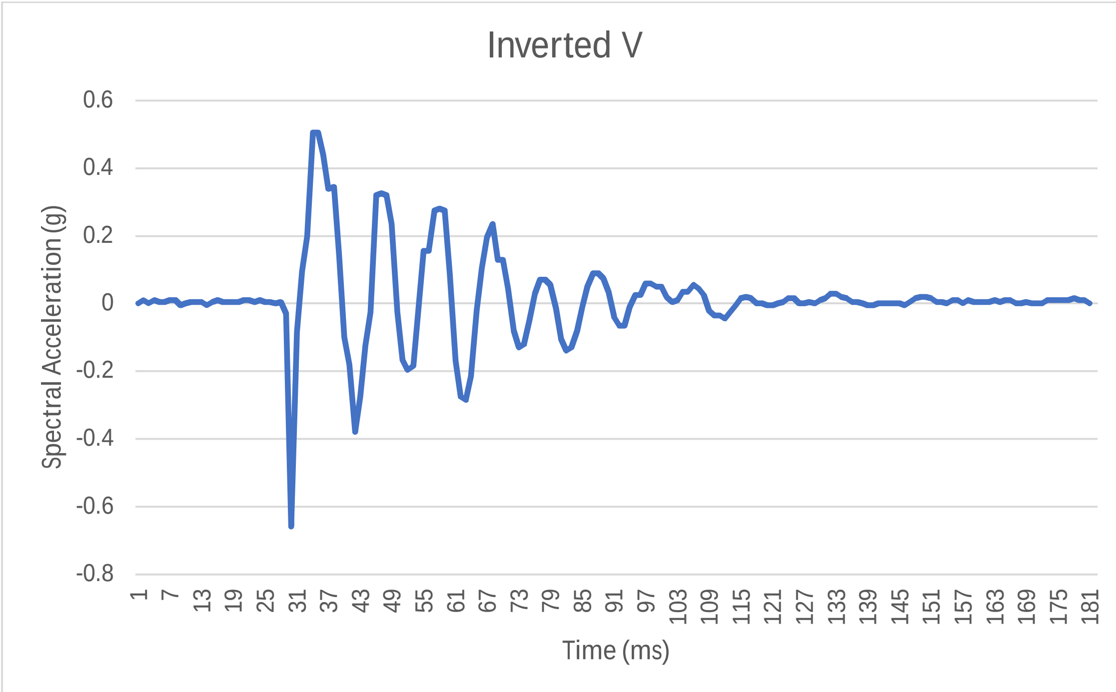

Fig.A.9 Inverted V braced steel frame spectral acceleration curve

C. STAAD Pro Models

The following as the frames modelled in STAAD Pro as per the specifications in Table I:

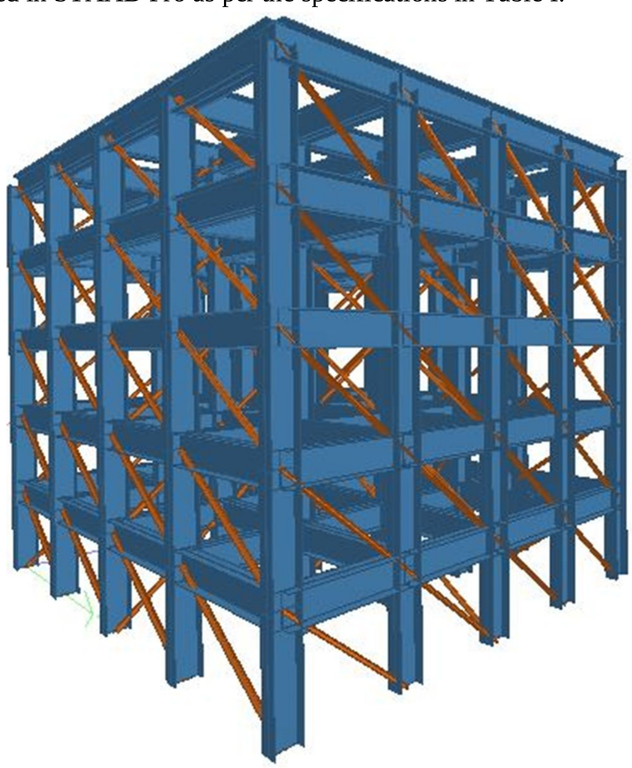

Fig A.22 Diagonal braced steel frame in STAAD Pro

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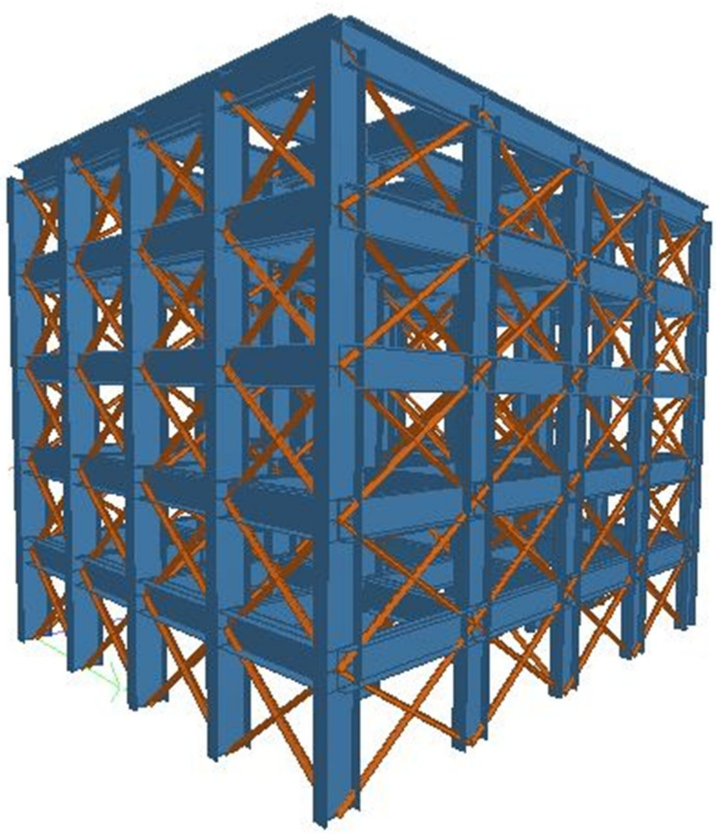


Fig A.23 X braced steel frame in STAAD Pro

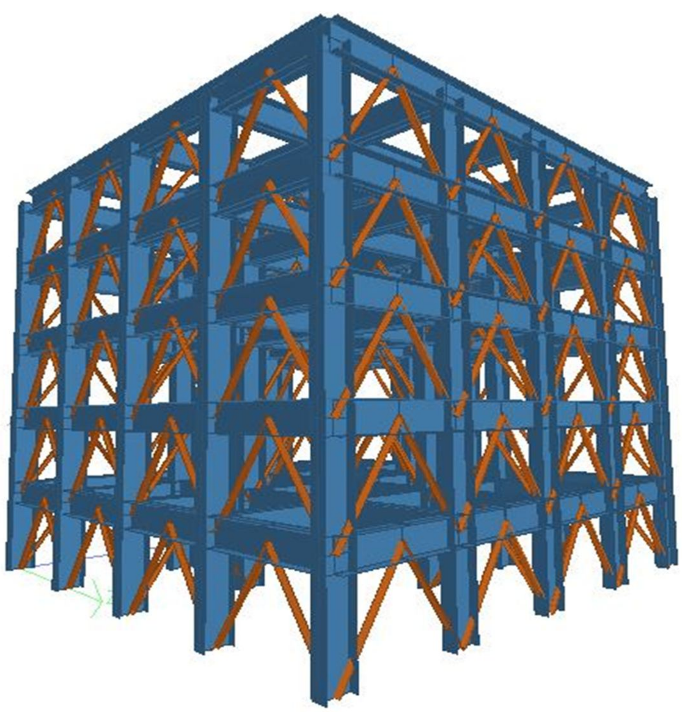


Fig A.24 Inverted V braced steel frame in STAAD Pro

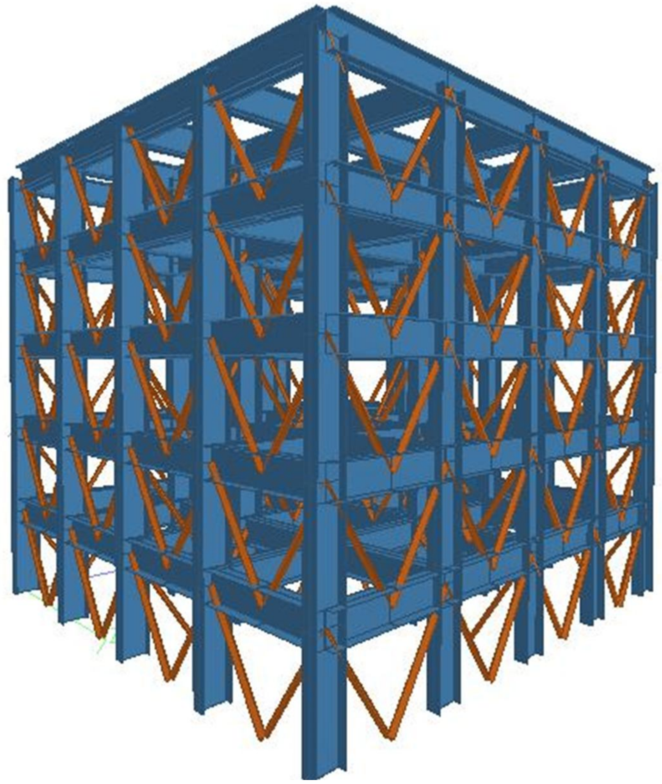


Fig A.25 V braced steel frame in STAAD Pro

D. Scale Models

The following are the scaled models prepared to find the spectral acceleration curves. The models are of 1:20 scale and follow the specifications mentioned in Table V.

Fig A.26 Unbraced steel frame model

Fig A.27 Diagonal steel frame model

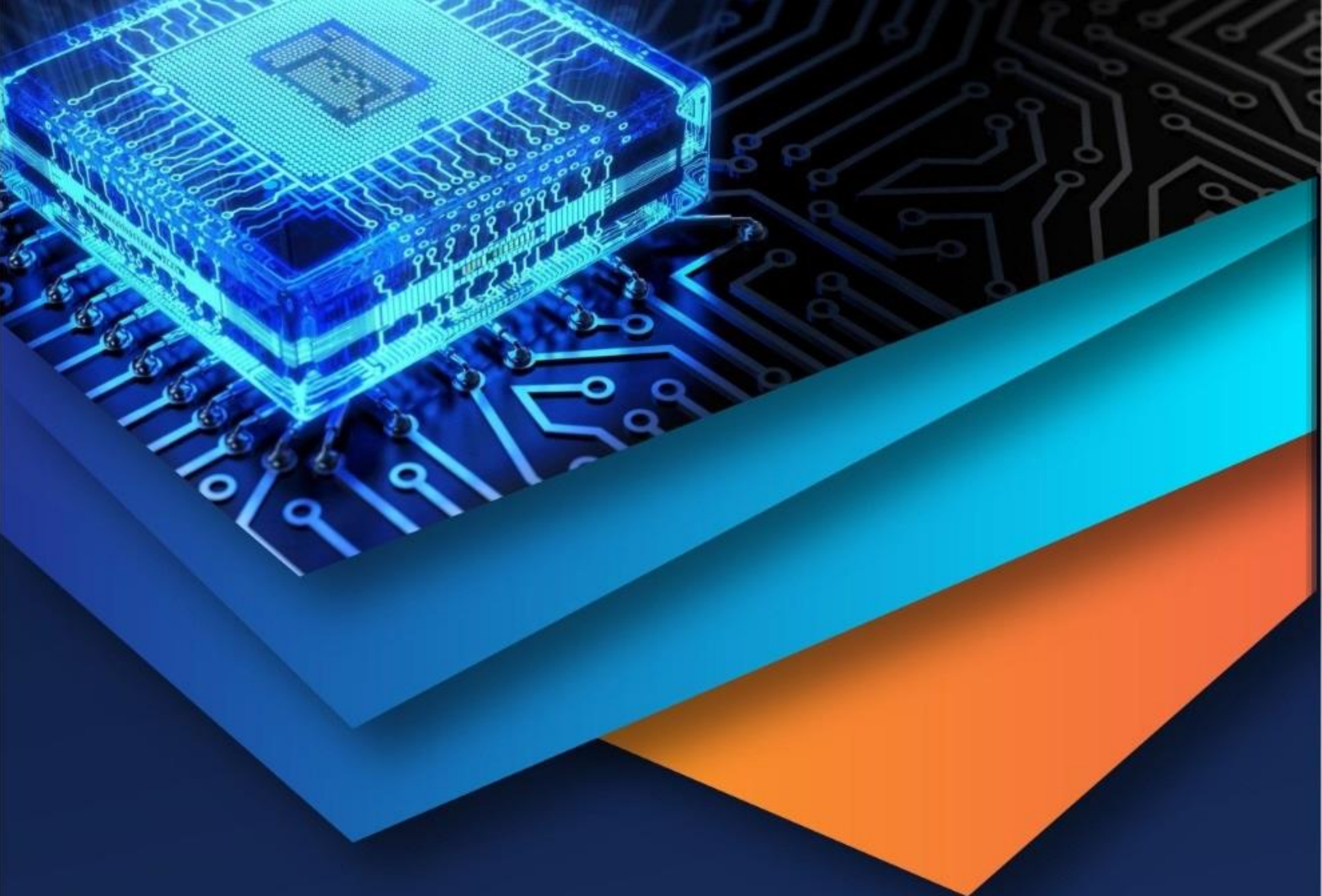
Fig A.28 V steel frame model

Fig A.29 Inverted V steel frame model

E. Experiment Setup

The experiment setup consisted of the following:

1) Scale models
2) Arduino Uno
3) Accelerometer – ADXL345
4) Breadboard
5) Female – female jumper wires
6) Male – female jumper wires
7) Male – male jumper wires
8) Laptop
9) USB A to B
10) Elastic band
11) An assembly with four tyres
12) Planks



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