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Experimental investigation of 3D-steel frame with bracings under dynamic loading

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Abstract: The main objective of this study is to investigate the 3D-steel frame with bracings under dynamic loads. The steel frame with bracings was designed and fabricated according to IS codal provisions. Tests were conducted in order to evaluate the performance of the bare frame and also the frame with additional loads of mass 0.275 and 0.55 Ton placed on the frame under similar seismic conditions. The dynamic properties of the test structure were determined by computational modeling before performing the resonance search test. Finite element packages such as SAP and STAAD software's were used to obtain the performance of the above structure under similar dynamic loading. Resonance search test (sine sweep test) was conducted on the frame using shake table in order to find the resonant frequency, damping values, magnification factor, stiffness and max acceleration of the structure. Initially the steel frame was mounted on the shake table for earthquake excitations with acceleration levels of 0.1g, 0.2g and 0.3g along x-axis, y-axis and z-axis. A mass of 0.275Ton was placed on the steel frame designed to withstand earthquake excitations with acceleration levels of 0.1g, 0.2g, and 0.3g along x-axis. Test was repeated placing 0.55T with acceleration levels of 0.1g at x-axis. The response of the structure along x-axis, y-axis & z-axis are recorded mounting accelerometers at pre-indentified locations. Strain gauge was mounted on the steel structure in order to find out the strain at the respective point. Results of resonance search test (sine sweep test) are compared with the results obtained from FEM packages.

Keywords: *3D-Steel frame, Resonance search test, Sine sweep test, Natural frequency, Accelerometers, Stiffness and Shake table*

Introduction:

Earthquakes are phenomena that result from the sudden release of stress in rocks that radiate seismic waves. At the Earth's surface, earthquakes may manifest themselves by a shaking or displacement of the ground and sometimes tsunamis, which may lead to loss of life and destruction of property. Recent Earthquakes have clearly demonstrated that the houses, bridges, public buildings constructed in many third world countries are not engineered to resist even moderate earthquakes. Recently in India, earthquakes caused huge economic losses and death toll, however not much attention is given in preventing such structural damages caused by earthquakes. Prediction of time of occurrence, location and intensity of future earthquakes are unfortunately not yet possible. Recent earthquakes have shown that effective prevention has to be based mainly on adequate design, construction and maintenance of new civil engineering structures, and retrofitting of existing structures and monuments lacking appropriate seismic resistance characteristics. Since so many catastrophes caused by severe earthquakes were experienced in the past, it is essential that the construction industry, government and people should be aware of the danger and should be prepared against earthquakes by constructing earthquake resistant structures. However the recent earthquakes proved once again that no lesson was learnt from the past catastrophes. Many of the collapses or heavy structural damages were due to poor structural systems. Structural systems that do not have frames with enough shear and/or flexural strength may be one of the common reasons of damage due to earthquakes. Experience in past earthquakes has demonstrated that many common buildings and typical methods of construction lack basic resistance to earthquake forces. In most cases this resistance can be achieved by following simple, inexpensive principles of good building construction practice. Adherence to these simple rules will not prevent all damage in moderate or large earthquakes, but life-threatening collapses should be prevented, and damage limited to repairable proportions. The actual capacity of these structures and their ability to withstand moderate and strong earthquakes needs to be evaluated using accurate methods for predicting the behaviour of structures subjected to dynamic loads. Historically, several different methods have been used for the validation of the seismic capability of structures that had been designed. Earlier methods usually involved some form of static calculations to estimate the forces generated during a seismic event of a given ground acceleration, and then comparing this force to the capability of the structure, which may have been derived from calculations or from actual measurements. Extensive experimental and analytical research on steel frames is being carried out worldwide in the last 50 years to establish design procedures that would realistically predict structural behaviour during an earthquake. These methodologies have been verified mainly using static, cyclic or pseudo-dynamic tests.

Description of Steel Frame:

1 Steel Frame with Bracings:

Steel frame with bracings was fabricated for the analysis and testing. Beams and Columns are fabricated using channel section and the bracings using angle section. Length of the beam is 2.4m and the height of the column is 2m. The dimensions of the steel frame are given in **meters** is shown in fig 1 and fig 2. The boundary conditions of the supports are fixed. Member's section properties are shown in table 1.

Table 1: Member Section Properties

S. No	Member	Dimensions
1	Column	ISMC-75
2	Beam	ISMC-75
3	Bracings	ISA-50X50X6

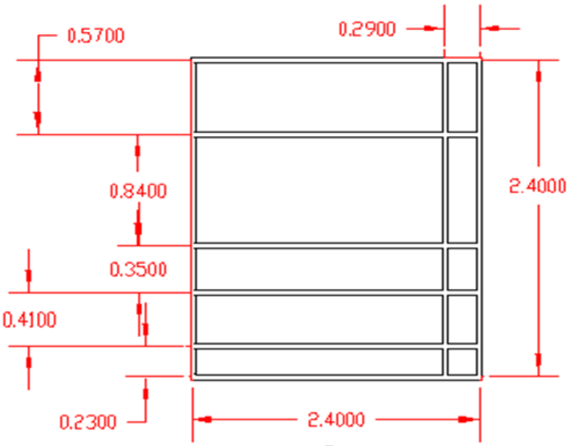


Figure 1: *Top view of Steel frame with bracings*

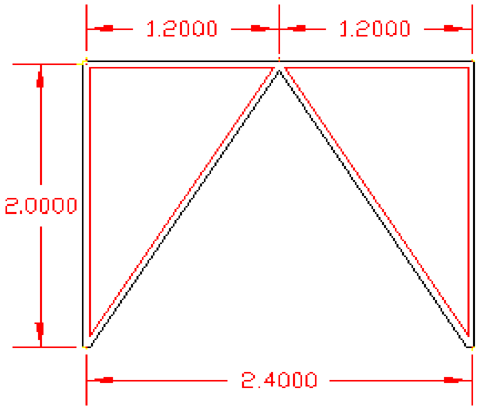


Figure 2: *Front view of Steel frame with bracings*

Shake Table:

1 Tri-Axial Shaker System at CPRI, Bangalore:

Earthquake engineering laboratory housing the tri-axial shaker system with six degrees of freedom shown in figure 3 capable of performing a diverse range of seismic qualification test requirements on equipment, sub-assemblies and components as per National / International standards has been established at Central Power Research Institute CPRI, Bangalore in the year 2003. The tri-axial shaker system consisting of a shaking-table is a unique facility that can strictly simulate the earthquake ground motion without any distortion. The shaking table can vibrate in one axis to three axes having six degrees of freedom with the help four vertical and horizontal actuators shown in figure 4. The advanced control system allows the reproduction of earthquake ground motions with high fidelity and little distortion. Table 2 shows salient features of high-performance shaker system at CPRI, Bangalore. The seismic qualification tests are being conducted using the tri-axial earthquake simulation system, which features a 10-ton payload capacity shake table of all-welded steel construction. An advanced control system allows the reproduction of earthquake ground motions with high fidelity.

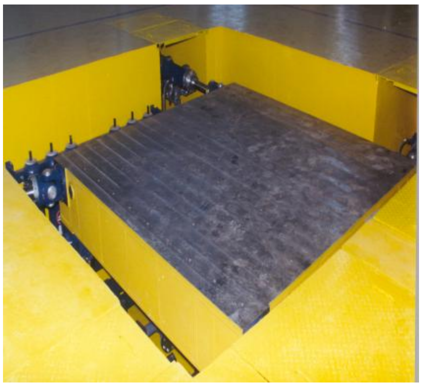


Figure 3: *Shake Table*

(a) *Horizontal*

(b) *Vertical*

Figure 4: *Shake Table Actuator*

Table 2: Salient Features of Shaking Table Facilities of CPRI, Bangalore

S. No	Item	Performance
1.	Maximum payload	10 tons
2.	Table dimension	3m × 3m
3.	Exciting direction	X, Y, Z (Simultaneous / Sequential)
4.	Degrees of Freedom	Six, 3 translation and 3 rotational
5.	Max. Height of the specimen	10 m
6.	Displacement/ Max. Stroke X &Y Direction Z - Direction	± 150 mm ± 100 mm
7.	Velocity	1000 mm/s (X, Y&Z direction)
8.	Acceleration	±1 g (X, Y&Z direction)
9.	Maximum specimen channels	128
10.	Frequency range	0.1 to 50 Hz
11	Yawing moment	10 ton-m
12	Overturning moment	40 ton-m
13	Actuators Vertical Horizontal	4 nos. of 180 KN 4 nos. of 150 KN

Table 3: Specification for horizontal actuator and vertical actuator

Horizontal actuator		Vertical actuator	
Item	Specification	Item	Specification
Dynamic Thrust	170 KN	Dynamic Thrust	120 KN
Static Thrust	+211 KN	Static Thrust	+154 KN
Supply Pressure	280 Bar	Supply Pressure	280 Bar
Max .Velocity	1.0 m/sec	Max .Velocity	1.0 m/sec
Working Stroke	+100 mm	Working Stroke	+150 mm

4. Resonance Search Test (Sine Sweep Test):

In this test, a sinusoidal input with continuously varying frequency at constant acceleration is applied to the structure. The frequency covers the range for which the frame structure is to be qualified. The percentage of steady-state resonance response obtained depends on the sweep rate and the damping of the frame structure. Maximum response is obtained separately at every frequency in the test range. At resonance frequency the transfer function (TF) of response to input motion generally exceeds 2, there will be a phase shift between input and response motion and also there will be a sudden dip in the coherence at the point.

Table 4: Shake table parameters for sine sweep test

a) Type of vibration	Sinusoidal sweep
b) Axis of vibration	X,Y & Z– Axis
c) Frequency (range)	1.0 to 50 Hz
d) Acceleration (Peak)	1 m/s^2
e) Sweep rate (Logarithmic)	1.0 octave/minute
f) Number of Sweeps	One up sweep per axis

1. Sine Sweep Test For Steel Frame With And Without Mass

Sine sweep test is conducted using shake table on the scale down model of steel frame with and without additional mass. Tests are conducted to identify the natural frequencies or resonant frequencies along X-axis, Y-axis and Z-axis with acceleration levels of 0.1g, 0.2g and 0.3g for the steel frame without mass. Tests are conducted to identify the resonant frequencies along X-axis for steel frame placing 0.275T mass with acceleration levels of 0.1g, 0.2g, and 0.3g and same test is conducted by placing 0.55T with acceleration levels of 0.1g along x-axis.

Figure 4: *Steel frame without mass*

Figure 5: *Steel frame with 0.275 Ton mass*

Figure 6: *Steel frame with 0.55 Ton mass*

2. Shake Table Results

2.1 Steel frame without mass

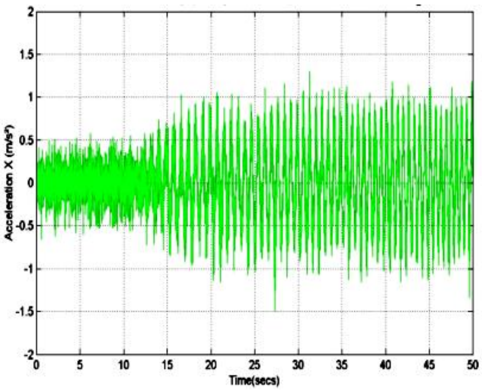


Figure: 7(a) *Table time history of accelerometer in X-direction for 0.1g*

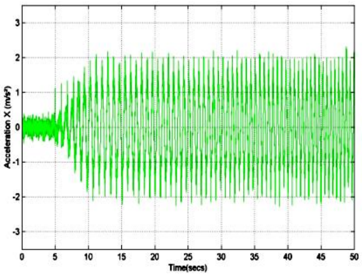


Figure: 7(b) *Table time history of accelerometer in X-direction for 0.2g*

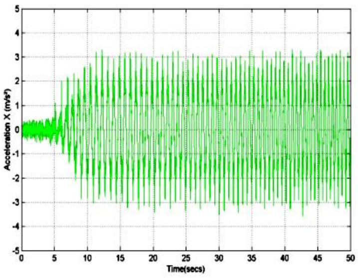


Figure: 7(c) *Table time history of accelerometer in X-direction for 0.3g*

Figure7: *Table Time History of Accelerometers in X-direction*

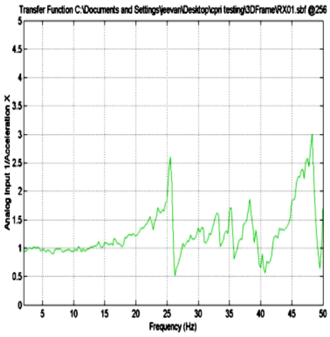


Figure: 8(a) *TF of Accelerometer in X-direction at 0.1g, Resonance Frequency =25.50Hz*

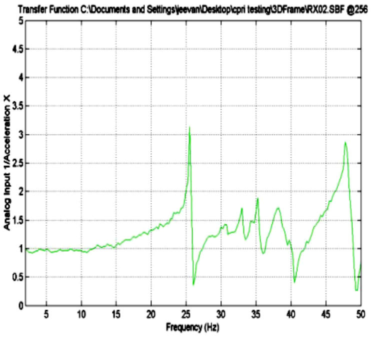


Figure: 8(b) *TF of Accelerometer in X-direction at 0.2g, Resonance Frequency =25.50Hz*

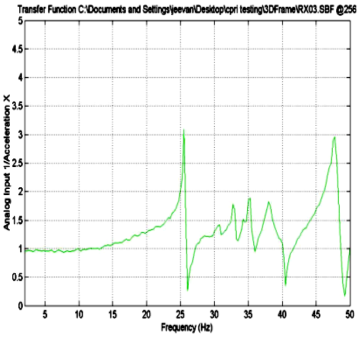


Figure: 8(c) *TF of Accelerometer in X-direction at 0.3g, Resonance Frequency =25.50Hz*

Figure 8: *Typical transfer functions in X- direction:*

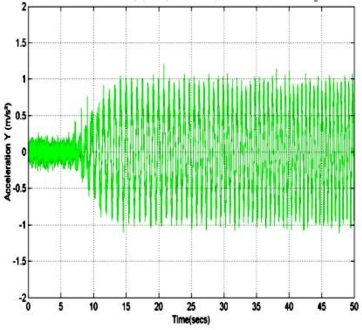


Figure: 9(a) *Table time history of accelerometer in Y-direction for 0.1g*

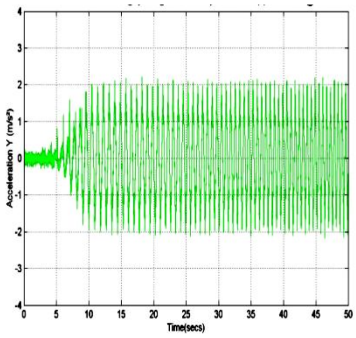


Figure:9(b) *Table time history of accelerometer in Y-direction for 0.2g*

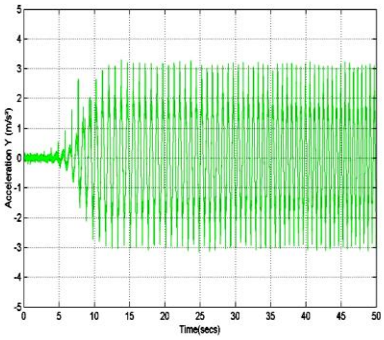


Figure: 9(c) *Table time history of accelerometer in Y-direction for 0.3g*

Figure 9*: Table Time History of Accelerometers in Y-direction*

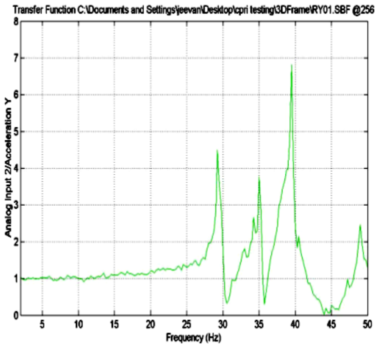


Figure: 10(a) *TF of Accelerometer in Y-direction at 0.1g, Resonance Frequency =29.25Hz*

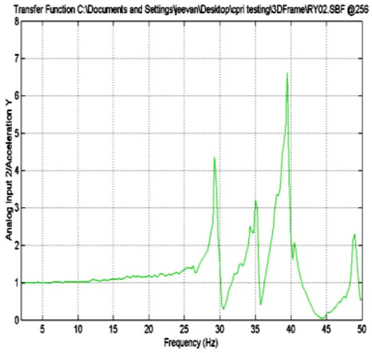


Figure: 10(b) *TF of Accelerometer in Y-direction at 0.2g, Resonance Frequency =29.25Hz*

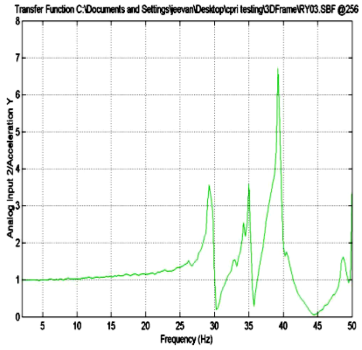


Figure: 10(c) *TF of Accelerometer in Y-direction at 0.3g, Resonance Frequency =29.25Hz*

Figure 10: *Typical transfer functions in Y- direction:*

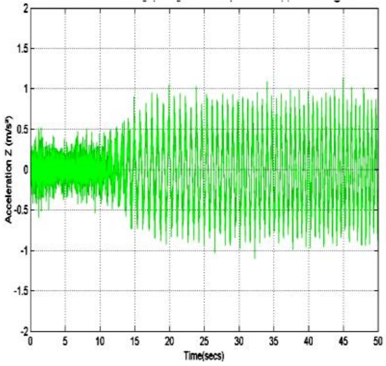


Figure: 11(a) *Table time history of accelerometer in Z-direction for 0.1g*

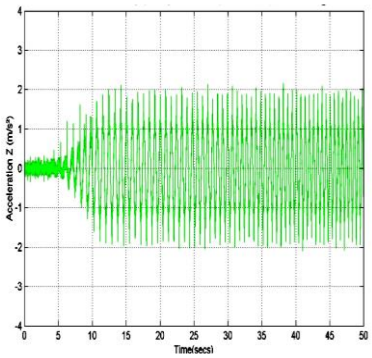


Figure: 11(b) *Table time history of accelerometer in Z-direction for 0.2g*

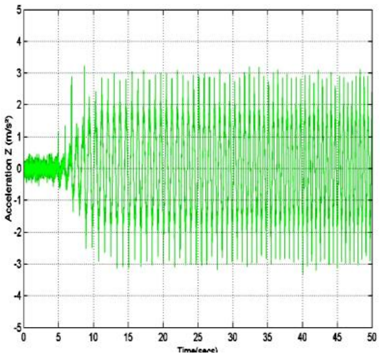


Figure: 11(c) *Table time history of accelerometer in Z-direction for 0.3g*

Figure 11*: Table Time History of Accelerometers in Z-direction*

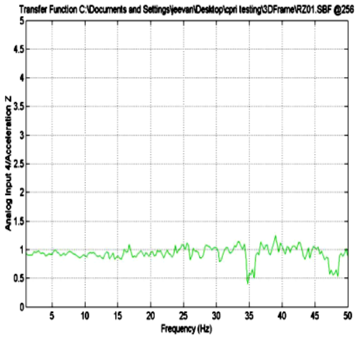


Figure: 12(a) *TF of Accelerometer in Z-direction at 0.1g, Resonance*

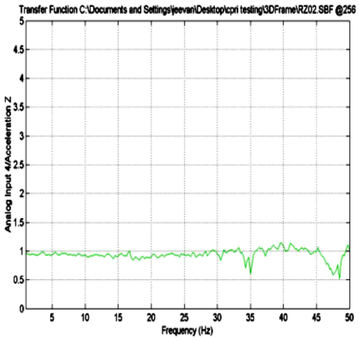


Figure: 12(b) *TF of Accelerometer in Z-direction at 0.2g, No Resonance*

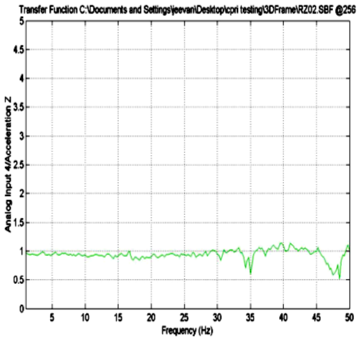


Figure: 12(c) *TF of Accelerometer in Z-direction at 0.3g, No Resonance*

Figure 12: *Typical transfer functions in Z- direction:*

4.2.2 Steel frame with 0.275T mass

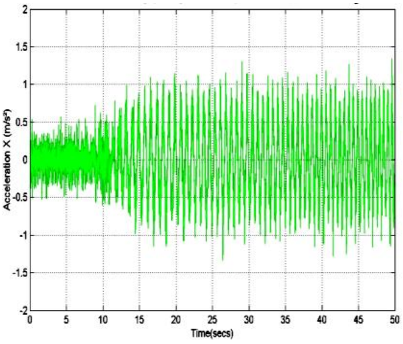


Figure: 13(a) *Table time history of accelerometer in X-direction for 0.1g*

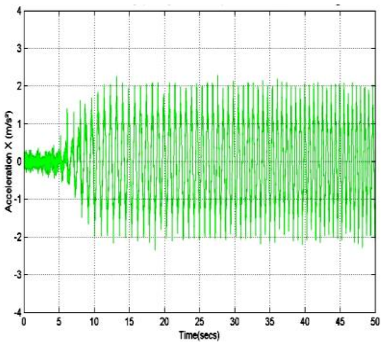


Figure: 13(b) *Table time history of accelerometer in X-direction for 0.2g*

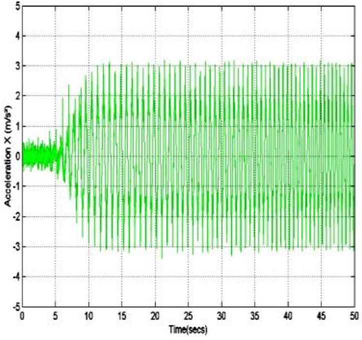


Figure: 13(c) *Table time history of accelerometer in X-direction for 0.3g*

Figure 13: *Table Time History of Accelerometers in X-direction*

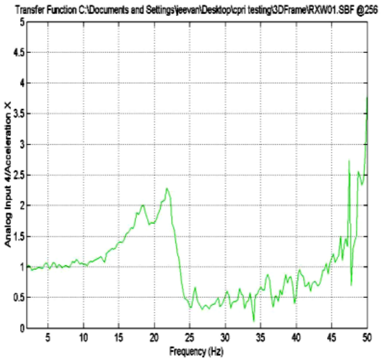


Figure: 14(a) *TF of Accelerometer in X-direction at 0.1g, Resonance Frequency =21.75Hz*

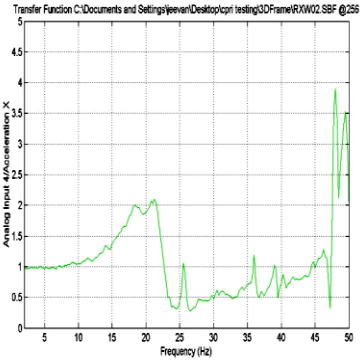


Figure: 14(b) *TF of Accelerometer in X-direction at 0.2g, Resonance Frequency =21.25Hz*

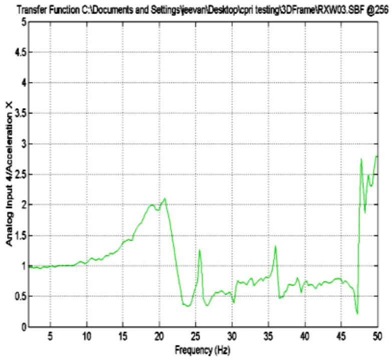


Figure: 14(c) *TF of Accelerometer in X-direction at 0.3g, Resonance Frequency =20.75Hz*

Figure 14*: Typical transfer functions in X- direction:*

4.2.2 Steel frame with 0.55T mass

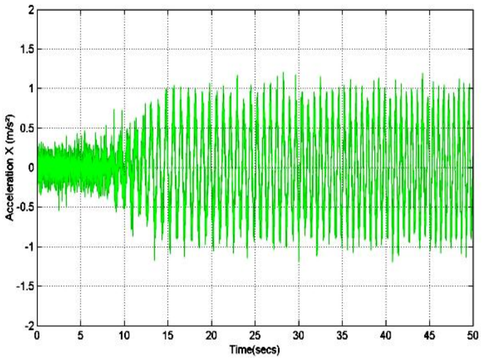


Figure: 15 *Table time history of accelerometer in X-direction for 0.1g*

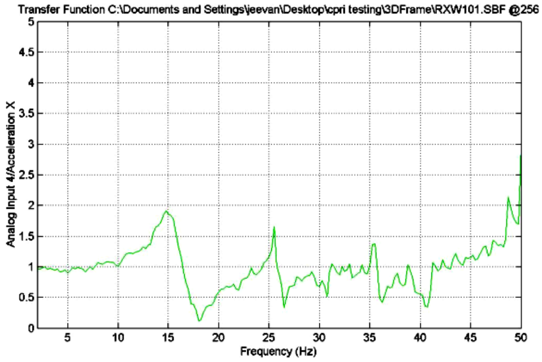


Figure: 16 *TF of Accelerometer in X-direction at 0.1g, Resonance Frequency =14.75Hz*

5. Modal Analysis of Steel Frame:

Modal Analysis is the study of the dynamic characteristics of structures. This analysis characterizes the dynamic properties of an elastic structure by identifying its mode of vibration. The response of the structure is different at each of the different natural frequencies. The natural frequency which depends on the mass and stiffness distributions in structure which in turn helps in the design of structural system mainly for vibration applications. An attempt has been made to find the natural frequencies using STAAD and SAP is then compared with experimental results.

6. Results and Comparisons:

6.1 Frequency Comparisons: Resonance frequencies obtained using software and shake table tests for the model are compared in table 5 and 6.

Table 5: Resonant frequencies obtained from FEA packages and Sine sweep test in X-axis

MODELS	Resonant Frequencies (Hz)		
	STAAD PRO	SAP	SINE SWEEP TEST
Steel frame without mass	24.06	23.92	25.5
Steel frame with 0.275T mass	20.49	20.87	21.75
Steel frame with 0.55T mass	16.64	17.96	14.75

Table 6: Resonant frequencies obtained from FEA packages and Sine sweep test in Y-axis

MODELS	Resonant Frequencies (Hz)		
	STAAD PRO	SAP	SINE SWEEP TEST
Steel frame without mass	29.66	27.42	29.25

6.1.1 Magnifation Factor (Mf) and Damping Values

The responses of the structure at three locations as accelerometer output are recorded during testing. In order to evaluate the damping values and identify the resonant frequencies in each axis, the recorded accelerometers output were analyzed using Data Analysis Package (DAP) software. For each location, Transfer Function (TF) details of Phase and Coherence were obtained. From the Transfer Function, the resonant frequencies and magnification factor were identified and the corresponding damping values were obtained using Half-Power Band width method and tabulated in table 7 to table 10.

Table 7: Resonance Frequency and Damping of steel frame without mass along X-axis:

Steel frame without mass				
S. No	AXIS	FREQ	MF	Damping
1	X=0.1g	25.5	2.61	1.57%
2	X=0.2g	25.5	3.13	0.7%
3	X=0.3g	25.5	3.09	0.92%

Table 8: Resonance Frequency and Damping of steel frame without mass along Y-axis:

Steel frame without mass				
Sl. No	AXIS	FREQ	MF	Damping
1	Y=0.1g	29.25	4.89	0.77%
2	Y=0.2g	29.25	4.36	0.94%
3	Y=0.3g	29.25	3.56	1.67%

Table 9: Resonance Frequency and Damping of steel frame with 0.275T mass along X-axis:

Steel frame with 0.275t mass				
Sl. No	AXIS	FREQ	MF	Damping
1	X=0.1g	21.75	2.29	13.91%
2	X=0.2g	21.25	2.10	15.77%
3	X=0.3g	20.75	2.11	12.80%

Table 10: Resonance Frequency and Damping of steel frame with 0.55T mass along X-axis:

Steel frame with 0.55t mass				
Sl. No	AXIS	FREQ	MF	Damping
1	X=0.1g	14.75	1.915	10.06%

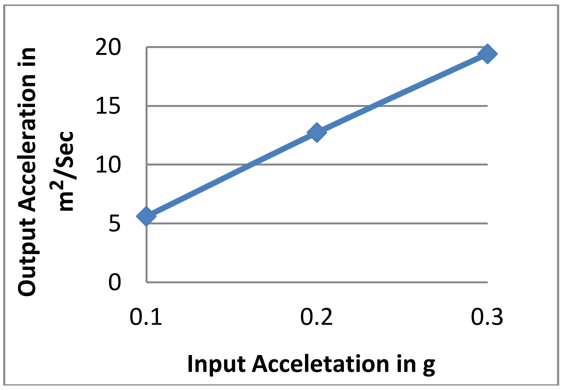
6.3 Amplification of Acceleration:

6.3.1 Steel frame without mass

The specimen was tested in X-direction for 0.1g, 0.2g, and 0.3g .The maximum amplification of acceleration values were obtained from the DAP software of shake table.

Table 11: Response of the frame in X direction for different values of g (input acceleration)

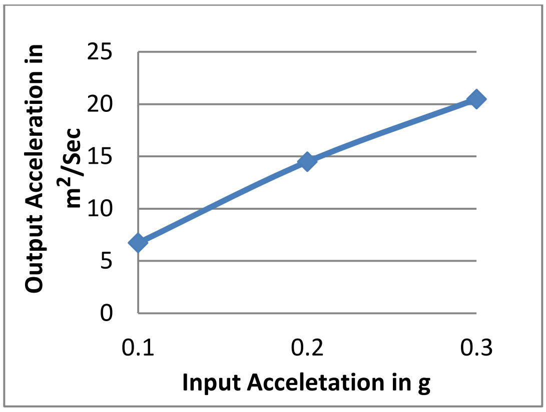
Sine sweep (X) (m/sec^2)	**Bare frame**
	Max (m/sec^2)
0.1g	5.613
0.2g	12.732
0.3g	19.425



The specimen was tested in Y-direction for 0.1g, 0.2g, and 0.3g .The maximum amplification of acceleration values were obtained from the DAP software of shake table.

Table 12: Response of the frame in Y direction for different values of g (input acceleration)

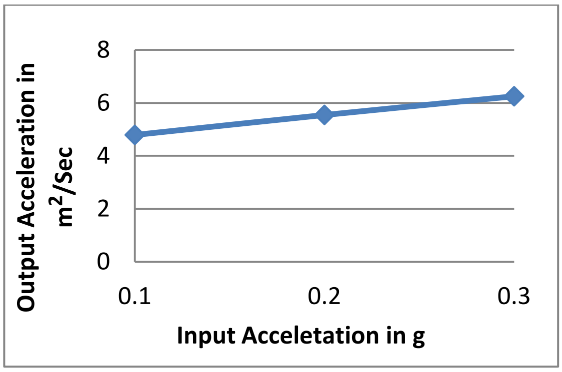
Sine sweep (Y) (m/sec^2)	**Bare frame**
	Max (m/sec^2)
0.1g	6.724
0.2g	14.481
0.3g	20.466



The specimen was tested in Z-direction for 0.1g, 0.2g, and 0.3g .The maximum amplification of acceleration values were obtained from the DAP software of shake table.

Table 13: Response of the frame in Z direction for different values of g (input acceleration)

Sine sweep (Z) (m/sec^2)	**Bare frame**
	Max (m/sec^2)
0.1g	4.789
0.2g	5.543
0.3g	6.249

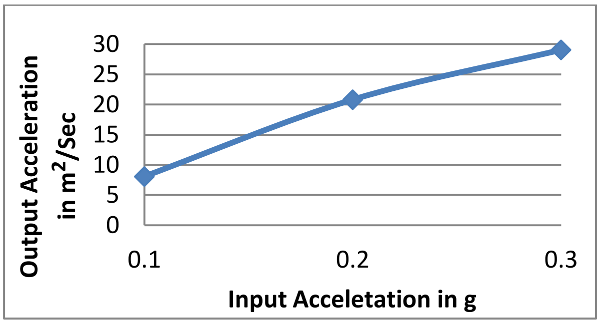


6.3.1 Steel frame with 0.275T mass:

The specimen was tested in X-direction for 0.1g, 0.2g, and 0.3g .The maximum amplification of acceleration values were obtained from the DAP software of shake table.

Table 14: Response of the frame in X direction for different values of g (input acceleration)

Sine sweep (X) (m/sec²)	Placing 0.275Ton mass on the frame
	Max (m/sec²)
0.1g	8.076
0.2g	20.813
0.3g	29.068



6.4 Stiffness of the Structure:

Stiffness's were computed below in the table 14 and a comparison have been made for the steel frame without load and placing 0.275 & 0.55Tons on the frame based on the results obtained from experimental approach.

Table 15: Stiffness comparison table

Designation	Direction	Weight in kg	Stiffness (k) 10^6 in N/m
Steel frame without mass	X	400	10.27
	Y		13.51
Steel frame with 0.275T mass	X	675	12.51
Steel frame with 0.55T mass	X	950	12.98

6.5 Strain Gauge Readings for Earthquake Excitations:

Strain gauge readings for earthquake excitations with acceleration levels of 0.1g, 0.2g, and 0.3g along X-axis placing 0.275T on the frame is shown in table 16 and strain gauge readings for earthquake excitations with acceleration levels of 0.1g along X-axis placing 0.55T on the frame is shown in table 17.

Table 17: Maximum strain gauge readings for steel frame with 0.55T mass

Axis	Strain (µm/m)	
	Tension	Compression
X=0.1g	6.012	4.008
X=0.2g	12.778	6.488
X=0.3g	14.206	10.119

Table 16: Maximum strain gauge readings for steel frame with 0.275T mass

Axis	Strain (µm/m)	
	Tension	Compression
X=0.1g	10.345	8.313

Table 18: Maximum stresses obtained for steel frame with 0.275T

Axis	Stress (N/mm²)	
	Tension	Compression
X=0.1g	2.069	1.663

Table 19: Maximum stresses obtained for steel frame with 0.55T

Axis	Stress (N/mm²)	
	Tension	Compression
X=0.1g	1.202	0.802
X=0.2g	2.566	1.298
X=0.3g	2.841	2.024

7. Conclusion:

1. Dynamic characteristics of steel frame were evaluated using software SAP and STAAD. The resonance frequencies obtained from these software's are compared with experimental results. The values obtained from software's ar
2. e closely matching with the experimental results.
3. Shake table tests were carried out to determine the dynamic characteristics viz resonance frequencies, magnification factor and damping values. The variation in dynamic characteristics of the structure due to additional loads of 0.275Ton and 0.55T is also studied. From these results we can come to the conclusion that damping values are within the range of 2% for the frame without mass but in case of frame with mass damping values are exceeding 2% by large periphery.
4. It can be concluded from the experimental results that the steel frame is within the elastic limit. The response of the structure is directly proportional to the base acceleration.
5. Maximum strain values have been recorded for the frame with mass by mounting strain gauge at the critical point nearer to support. Using these maximum strain values maximum tensile and compressive stresses have been calculated.

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