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NUMERICAL EVALUATION OF RESPONSE BEHAVIOR OF FRAME STRUCTURE USING SMA DAMPER

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ABSTRACT - Shape Memory Alloys are materials that can be deformed at one temperature but when heated or cooled, return to their original shape. They also exhibit superelasticity or pseudo elasticity where, a small force induces considerable deformation but when the force is removed, the material automatically recovers its original shape without the need for heating. This project work focuses on the development of a FeMnNiAl Shape Memory Alloy damper, in the most possible configurations with the steel structure and by providing loading patterns where static conditions were evaluated i.e., deformation and stresses. Multiple configurations were proposed and evaluated. Of those, the most suitable configuration was found out, and then were analysed with the Ground acceleration data to check whether the structure sustains the deformation and remains stiffened. And hence concluded that the structure offers better stiffness by the introduction of an SMA damper, owing to an optimisation study is thus presented through the project work.

Keywords: *Shape memory alloys (SMAs), Superelasticity, One-way shape memory, Two-way shape memory.*

1. INTRODUCTION

Framed structure is one that is made stable by a skeleton that is able to stand by itself as a rigid structure without depending on floors or walls to resist deformation. Materials such as wood, steel and reinforced concrete, which are strong in both tension and compression, make the best members for framing. Steel framing is much simplified by the greater strength of the material, which provides more rigidity with fewer members. Energy imparted to a structure by a dynamic loading gets absorbed and gets dissipated, inorder to allow the building to move elastically, dampers are being used. Damper systems are designed to control structural damages, and to prevent injuries to the residents by absorbing seismic energy and reducing deformations in the structure.

Imparting better elastic properties or re-centering abilities to the structure plays a major role and hence the concept of Shape Memory Alloy arises. Shape Memory Alloys are a class of novel functional materials that possess unique properties, including Shape Memory Effect (SME), Superelasticity Effect (SE), extraordinary fatigue resistance, high corrosion resistance, high damping characteristics, and temperature-dependent Young's modulus.

2. OBJECTIVES

1. To design a SMA Damper based on multi axial condition.
2. To determine the frequency and deformation of structure under normal condition.
3. To determine the most suitable configuration of SMA that imparts better stability to the structure.
4. To determine the deformations and responses in the structure under static and dynamic loading.

3. METHODOLOGY

DATA COLLECTION
⇩
LITERATURE REVIEW
⇩
SOFTWARE STUDY - ANSYS 2023 R2
⇩
VALIDATION
⇩
MODELLING OF STRUCTURE - SOLIDWORKS
⇩
ANALYSIS OF STRUCTURE
⇩
RESULTS AND DISCUSSION
⇩
CONCLUSION

4. MODELLING OF STRUCTURE

Structure was modelled using SolidWorks with reference to experimental study, "Seismic performance of modular steel frames equipped with SMA braces" by Papia *et.al- Bull Earthquake Engineering.*

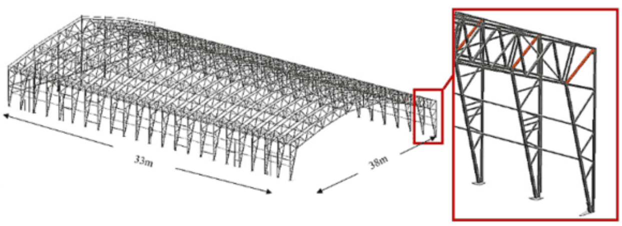

Fig -1: Modelled structure

The structure is having a span of 38 metres in the X-direction; 11.796 metres in the Y-direction and 33 metres in the Z-direction. Structural steel being used. BEAM188 is suitable for analysing slender to moderately stubby/thick beam structures. The element is based on Timoshenko beam theory which includes shear-deformation effects.

Table -1: Properties of structural steel

PARAMETER	VALUE
Young's Modulus	2e+11 Pa
Poisson's Ratio	0.3
Bulk Modulus	1.6667e + 11 Pa
Shear Modulus	7.6923e + 10 Pa
Isotropic Coefficient of Thermal Expansion	1.2e – 051/^{0}C
Comp. Yield Strength	2.5e + 08 Pa

The model was assigned particular names that enable them to be identified easily.

Table -2: Model detail

MODEL NAME	MODEL ID
Base Structure	C
Bottom Stiffened Structure	CB
Top and Bottom Stiffened Structure	CTB

5. ANALYSIS OF STRUCTURE

The model C was analyzed using Ansys workbench 18.1. The **Fig - 2** given below shows the deformation of the structure due to self-weight.

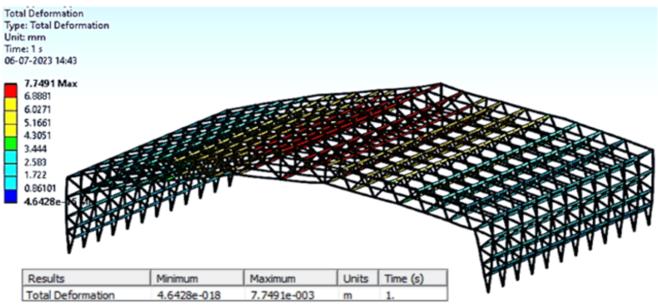

Fig -2: Deformation of the structure

The boundary conditions were assigned as fixed and the gravitational load was applied onto the structure to evaluate the total deformation and the joint stresses within the structure. The total deformation was found out to be 7.749mm and joint stresses were found out to be 12.585MPa.

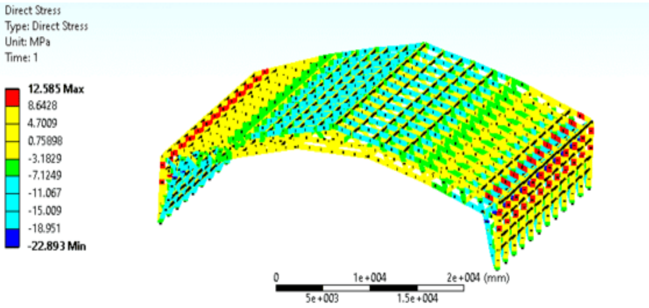

Fig -3: Direct stress

Modal analysis was done to find out the frequency for which the structure would resonate and further the deformations for the same. The frequency corresponding to each modes and their deformation are given in the table given below.

Table -3: Frequency and deformation data of respective modes of C

MODE	FREQUENCY (Hz)	DEFORMATION (mm)
1	1.418	0.15672
2	3.156	0.15679
3	3.737	0.12184
4	4.022	0.16231
5	4.612	0.16118
6	4.950	0.16559

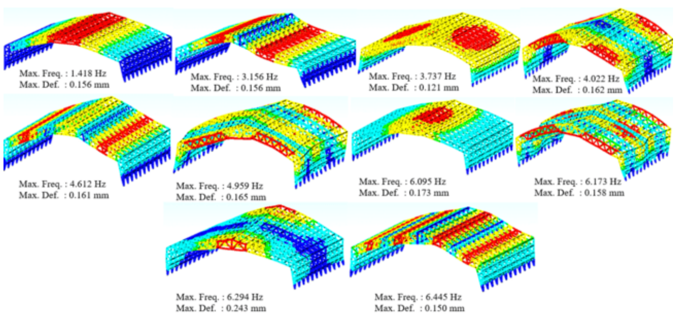

Fig -4: Mode shapes, Max. frequency and Max. deformations of C

6. COMPARISON OF ALLOYS

Amongst all the shape memory alloys, the iron-based FeMnNiAl has emerged as one of the most promising compositions with a huge superelasticity temperature window. Various alloy compositions have been investigated over the years providing insight into the properties, advantages, and some of the limitations of the developed Fe-SMAs. In general, the available Fe-based SMAs compositions have multiple elements including Mn, Co, Ni, and Ti which can be used to modify transformation temperatures, flow stresses, and transformation strains. For, FeMnNiAl the elastic moduli can vary from 100 to 195 GPa and fracture toughness from 19 to 33 MPa depending on the crystal orientations. The FeMnNiAl SMA exhibits similar fracture toughness compared to NiTi, however the moduli (stiffness) range is considerably higher which improves the elastic strain energy storage capacity of this Fe-based SMA.

The clear benefits of FeMnNiAl alloys are the unprecedented window of superelasticity, the high transformation stresses, and the relatively small temperature rise during transformation. The ability to achieve superelastic response over such a large range of temperatures, with a single heat treatment, enables huge simplifications from a practical perspective. For example, NiTi SMA transformation temperatures can be adjusted and shifted to exhibit superelasticity or shape memory effect over a 100℃ temperature range. However, and unlike FeMnNiAl, the gap between the transformation temperatures is not as wide and custom heat treatments are therefore required for each set of conditions. FeMnNiAl only requires a single heat treatment to exhibit superelasticity over a 500℃ temperature range. In addition, the relatively lower cost of FeMnNiAl compared to other SMA alloys and the high stiffness compared to NiTi and Cu based SMAs can be exploited in certain applications requiring larger load carrying capacities and/or larger elastic strain energy storage capacity (e.g., for structural damping applications). The FeMnNiAl SMA can exhibit shape memory response when subjected to certain aging treatments.

With proper control, this Fe-based SMA can be tailored to show superelasticity, shape memory effect, or both upon unloading.

7. ANALYSIS WITH SMA

For further analysis, SMA incorporating FeMnNiAl alloy in two different configurations was considered.

Type I having SMA in the form X-bracings placed at the bottom of the structure (assigned as CB). The activation temperature being used here is 100°C to 200°C and the elastic moduli of the range 100GPa.

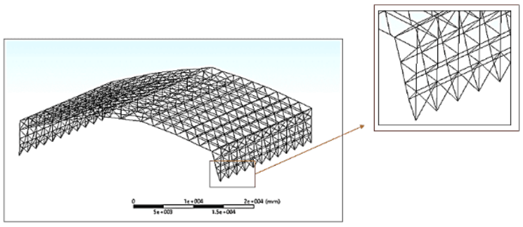

Fig -5: Model of CB

The boundary conditions were assigned as fixed and the gravitational load was applied onto the structure to evaluate the total deformation within the structure. The total deformation of the structure along with SMA at the bottom was found out to be 7.7397mm. The frequencies with respect to each mode and corresponding deformations were found out.

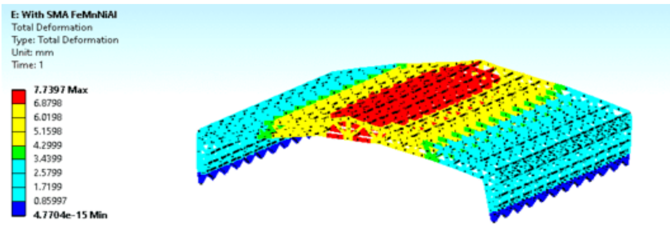

Fig -6: Total deformation of C

MODE	FREQUENCY (Hz)	DEFORMATION (mm)
1	1.430	0.15743
2	3.198	0.15795
3	3.731	0.12152
4	4.020	0.16144
5	4.701	0.16579
6	4.952	0.16511

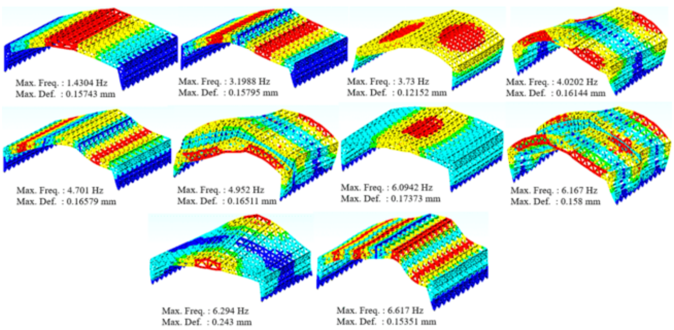

Fig -7: Mode shapes, Max. frequency and Max. deformations of CB

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Type II having SMA in the form X-bracings placed at the bottom as well as on the top of the structure (assigned as CTB). The evaluation is done based on normal activation temperature and at a higher activation temperature with varying modulus of elasticity. Here, the activation temperature being used here is 100^0 to 200^0 and the elastic moduli of the range 100GPa. For easier identification, the model has been assigned as follows.

Table -4 : Model detail of CTB

MODEL NAME	MODEL ID
Top and Bottom Configuration (i) At 100GPa	CTB@100
(ii) At 195GPa	CTB@195

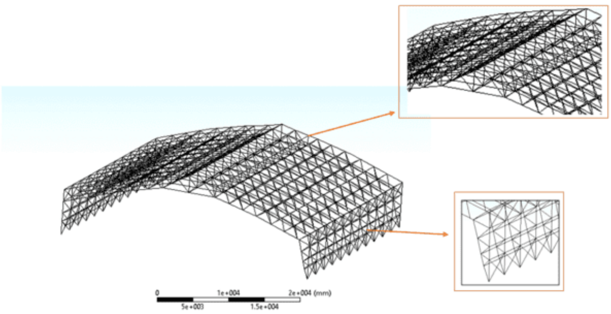

Fig -8: Model of CTB@100

The total deformation of the structure along with SMA at the bottom was found out to be 10.835mm and the joint stresses were about 13.056MPa. The frequencies with respect to each mode and corresponding deformations were found out.

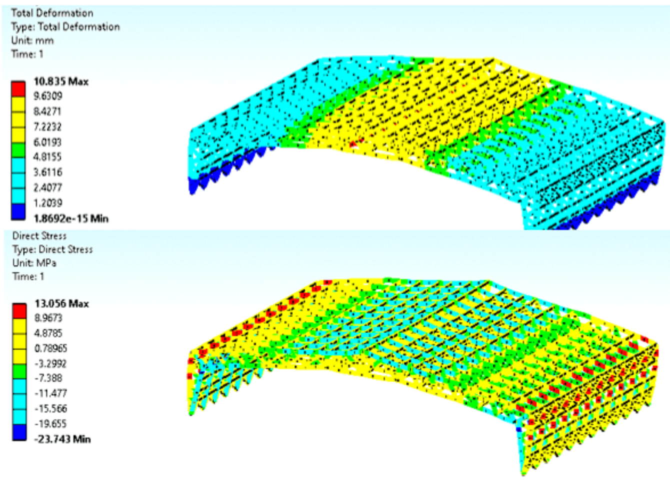

Fig -9: Total deformation and direct stress

Table -5 : Frequency and deformation of each mode of CTB@100

MODE	FREQUENCY (Hz)	DEFORMATION (mm)
1	2.5066	0.14289
2	3.6772	0.12752
3	4.3488	0.18261
4	5.5678	0.15711
5	5.9878	0.29645
6	6.2074	0.42570

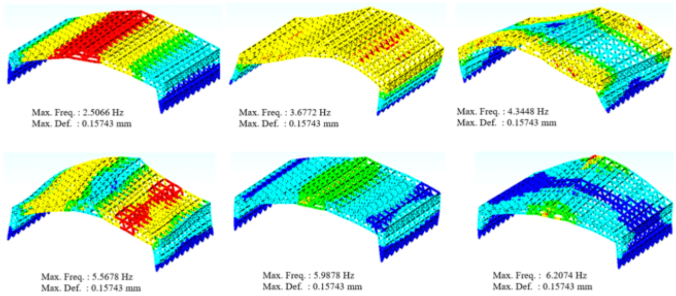

Fig -10: Mode shapes, Max. frequency and Max. deformations of CTB@100

Frequency, and deformations obtained for CTB@195 are as follows. Here, the activation temperature being used here is 300^0C to 400^0C and the elastic moduli of the range 195GPa.

Table -6 : Frequency and deformation of each mode of CTB@195

MODE	FREQUENCY (Hz)	DEFORMATION (mm)
1	3.4331	0.14226
2	5.0718	0.12694
3	5.9644	0.18059
4	7.6305	0.15757
5	8.2553	0.29497
6	8.5450	0.42209

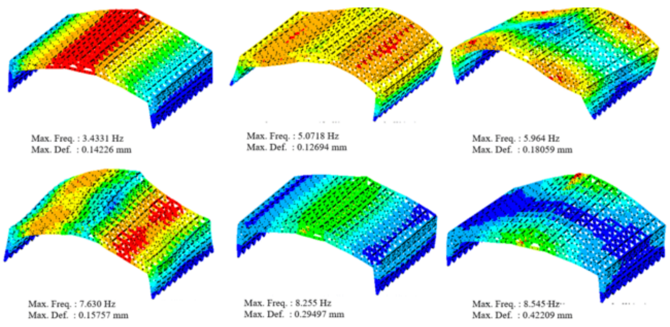

Fig -11: Mode shapes, Max. frequency and Max. deformations of CTB@195

8. RESPONSE SPECTRUM

A response spectrum is a plot of the peak or steady-state response (displacement, velocity or acceleration) of a series of oscillators of varying natural frequency, that are forced into motion by the same base vibration or shock. The resulting plot can then be used to pick off the response of any linear system, given its natural frequency of oscillation. One such use is in assessing the peak response of buildings to earthquakes. The science of strong ground motion may use some values from the ground response spectrum (calculated from recordings of surface ground motion from seismographs) for correlation with seismic damage. Response spectra are very useful tools of earthquake engineering for analysing the performance of structures and equipment in earthquakes, since many behave principally as simple oscillators (also known as single degree of freedom systems). Thus, if you can find out the natural frequency of the structure, then the peak response of the building can be estimated by reading the value from the ground response spectrum for the appropriate frequency. In most building codes in seismic regions, this value forms the basis for calculating the forces that a structure must be designed to resist (seismic analysis).

For evaluation, Ground Acceleration curve was considered with reference to, ‘‘Deterministic Seismic Hazard Analysis for the State of Haryana, India”. The obtained Time v/s Acceleration curve were converted to corresponding Frequency v/s Acceleration curve. Computations were done based on these values.

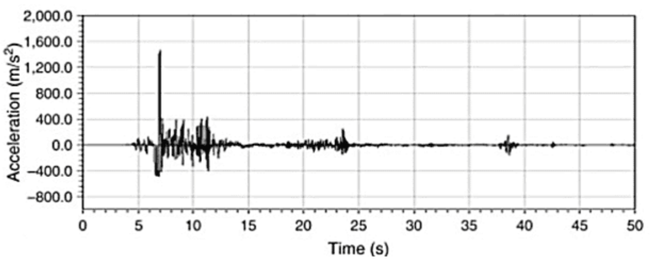

Fig -12: Time v/s Acceleration data for evaluating Response spectra

The obtained values were assigned to each of the above configurations and the mode shapes, deformations, directional deformations were plotted for each.

For CB, i.e., structure having SMA in the bottom, mode shape denoting the variation of deformation with respect to the frequency are as follows.

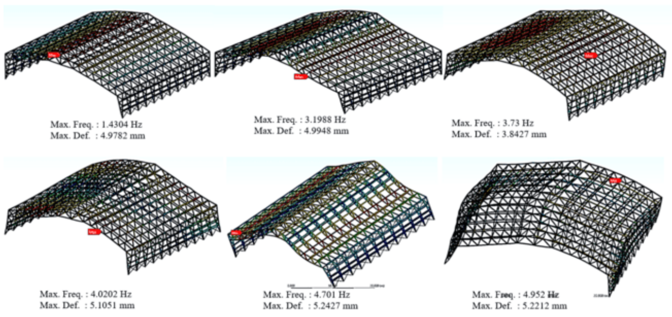

Fig -13: Max. frequency and Max. deformations of CB

Table -7 : Frequency and deformation of each mode of CB

MODE	FREQUENCY (Hz)	DEFORMATION (mm)
1	1.430	4.9782
2	3.198	4.9948
3	3.731	3.8427
4	4.020	5.1051
5	4.701	5.2427
6	4.952	5.2212

On the application of RS Acceleration, change in deformation was observed in the total as well as in directional basis.

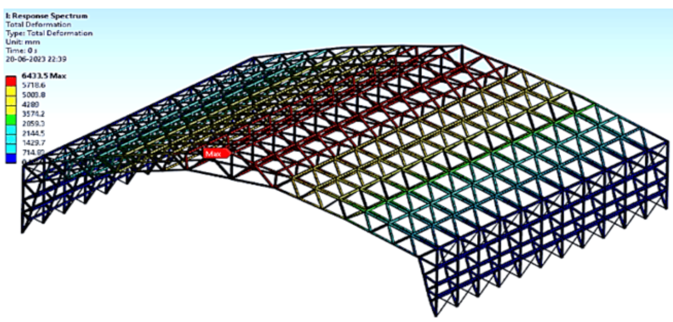

Fig -14: Total Deformation in the structure

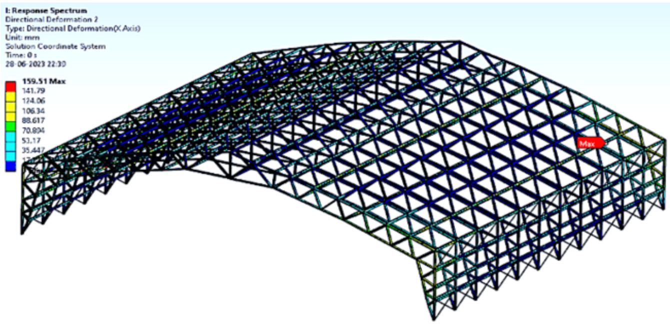

Fig -15: Directional Deformation of C (X axis

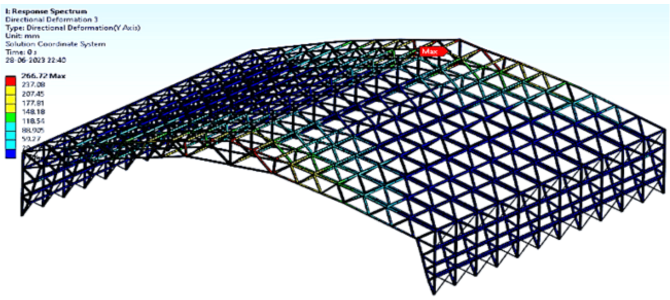

Fig -16: Directional Deformation of C (Y axis)

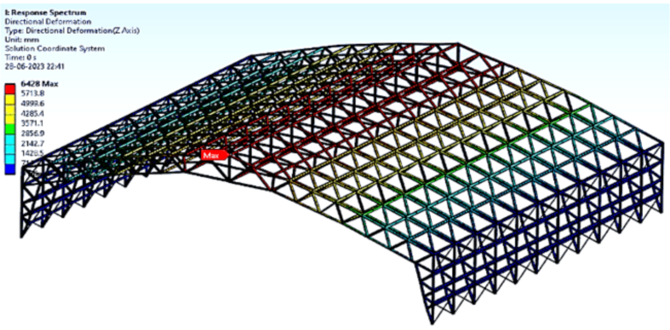

Fig -17: Directional Deformation of C (Z axis)

The total deformation of the structure was found out to be 6433.5mm. The directional deformations was found out to be 159.51 mm on the X-axis, 266.72 mm on the Y-axis and 6429 mm on the Z-axis respectievely.

For CTB, i.e., structure having SMA at top and bottom, both @100 and @195GPa, the variation of deformation and directional deformations are plotted and are as follows.

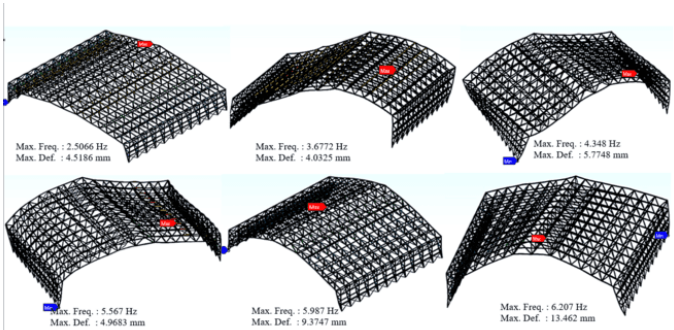

Fig -18: Max. frequency and Max. deformations of CTB@100

Table -8 : Frequency and deformation of each mode of CTB@100

MODE	FREQUENCY (Hz)	DEFORMATION (mm)
1	2.5066	4.5186
2	3.6772	4.0325
3	4.3488	5.7748
4	5.5678	4.9683
5	5.9878	9.3747
6	6.2074	13.4620

The total deformation of the structure was found out to be 2092.7mm. The directional deformations was found out to be 247.86 mm on the X-axis, 326.97 mm on the Y-axis and 2065.9 mm on the Z-axis respectievely.

For, CTB@195 the frequencies and corresponding deformations are as follows.

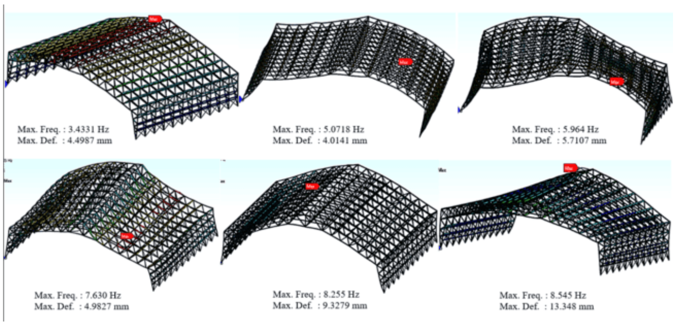

Fig -19: Max. frequency and Max. deformations of CTB@195

Table -9 : Frequency and deformation of each mode of CTB@195

MODE	FREQUENCY (Hz)	DEFORMATION (mm)
1	3.4331	4.4987
2	5.0718	4.0141
3	5.9644	5.7107
4	7.6305	4.9827
5	8.2553	9.3279
6	8.5450	13.348

The total deformation of the structure was found out to be 1117.5mm. The directional deformations was found out to be 130.21 mm on the X-axis, 179.78 mm on the Y-axis and 1103.6 mm on the Z-axis respectievely.

9. RESULTS AND DISCUSSION

The results obtained from the response spectrum analysis i.e., the frequency and deformations are compared and are depicted graphically.

Table -10 : Comparison of Frequency values of different configurations (Response spectrum)

MODE (1)	CB (2)	CTB@100 (3)		CTB@195 (4)		CTB (5)
		CTB@100 (Hz)	% INCREASE IN FREQUENCY (3) and (2)	CTB@195 (Hz)	% INCREASE IN FREQUENCY (4) and (2)	% INCREASE IN FREQUENCY (4) and (3)
1	1.4304	2.5066	42.9346	3.4331	58.3350	26.9872
2	3.1988	3.6772	13.0169	5.0718	36.9296	36.9296
3	3.7300	4.3488	14.2292	5.9644	37.4622	37.4622
4	4.0202	5.5678	27.7955	7.6305	47.3140	47.3140
5	4.7015	5.9878	21.4820	8.2553	43.0487	43.0487
6	4.9520	6.2074	20.2242	8.5450	42.0479	42.0479

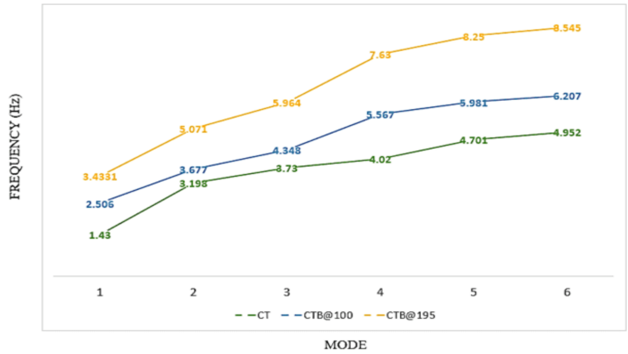

Fig -20: Plot of frequency with respect to each mode for all configurations

Table -11 : Comparison of Deformation values of different configurations (Response spectrum)

MODE (1)	CB (mm) (2)	CTB@100 (3)		CTB@195 (4)		CTB (5)
		CTB@100 (mm)	% CHANGE IN DEFORMATION (2) and (3)	CTB@195 (mm)	% CHANGE IN DEFORMATION (2) and (4)	% CHANGE IN DEFORMATION (4) and (3)
1	4.9782	4.5186	09.2322	4.4987	09.6319	09.2322
2	4.9948	4.0325	19.2660	4.0141	19.6344	00.4562
3	3.8427	5.7748	33.4574	5.7107	32.7105	01.1099
4	5.1051	4.9683	02.6796	4.9827	02.3976	00.2889
5	5.2427	9.3747	44.0760	9.3279	43.7954	00.4992
6	5.2212	13.4620	61.2152	13.3480	60.8840	00.8468

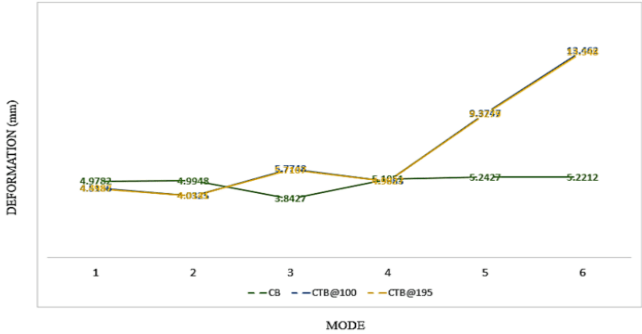

Fig -21: Plot of deformation with respect to each mode for all configurations

Table -12 : Comparison of total and directional deformation values of different configurations (Response spectrum)

PARAMETER (1)	CB (mm) (2)	CTB@100 (3)		CTB@195 (4)		CTB (5)
		CTB@100 (mm)	% CHANGE IN DEFORMATION (2) and (3)	CTB@195 (mm)	% CHANGE IN DEFORMATION (2) and (4)	% CHANGE IN DEFORMATION (4) and (3)
Total Deformation	6433.50	2092.00	67.48	1117.5	82.62	46.58
Directional Deformation (i) X-axis	159.51	247.86	35.64	130.21	18.36	47.46
(ii) Y-axis	266.72	326.97	18.42	179.78	32.59	45.01
(iii) Z-axis	6429.00	2065.90	67.86	1103.60	82.83	46.58

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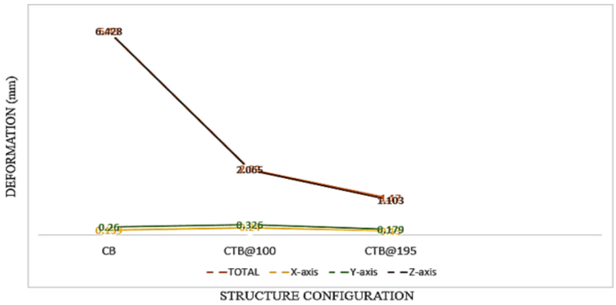

Fig -22: Plot of total and directional deformation with respect to each mode for all configurations

10. CONCLUSION

Shape memory alloys (SMAs) are unique materials that have the ability to achieve great deformations and to return to a predefined shape after unloading or upon heating. Amongst all the Fe-SMAs being used, FeMnAlNi based SMA proves to be more feasible for application in steel structures as they exhibit better SE properties. Conclusions regarding the study are as follows:

- Initial deformation of CTB was found to be 10.835mm which is 28.48% more than C having 7.7491mm
- Computations for frequency and corresponding deformations were done both at normal and elevated temperatures
- CB shows about 0.72% increase in frequency was observed on an average when compared to C
- CTB@100 shows about 23.76% increase in frequency on an average when compared to C
- CTB@195 shows about 44.54% increase in frequency on an average when compared to C
- CTB@195 shows about 27.23% increase in frequency on an average when compared to CTB@100
- About 0.84% change in deformation was observed for C – CB
- About 28.44% change in deformation was observed for C – CTB@100
- About 28.30% change in deformation was observed for C – CTB@195
- Structure having CB and CTB configuration offers better frequency compared to C
- Structure exhibits better frequency when CTB configuration of SMA being used both in 100GPa and 195GPa (Average of 44.54% increase in frequency)
- Ground accelerations were considered
- Based on Frequency v/s Acceleration data, analysis was done; considering top stiffened and combination of both
- Total deformations, directional deformations and responses were evaluated
- Maximum displacement of the structure subjected to seismic motion was found out
- CTB@100 shows about 23.28% increase in frequency was observed on an average when compared to CB
- CTB@195 offers 44.18% increase in frequency was observed on an average when compared to CB
- CTB@195 offers 38.96% increase in frequency was observed an average when compared to CTB@100
- About 28.32% change in deformation was observed for CB – CTB@100
- About 28.16% change in deformation was observed for CB – CTB@195
- About 2.072% change in deformation was observed for CTB@100 – CTB@195
- CTB@100 offers 67.48% reduction in total deformation when compared to CB
- CTB@195 offers 82.62% reduction in total deformation when compared to CB
- CTB@195 offers 46.53% reduction in total deformation when compared to CTB@100
- CTB@100 shows 35.64% increase in deformation, whereas CTB@195 shows 18.36% reduction in deformation when compared to CB in X axis
- CTB@195 offers 47.46% decrease in deformation when compared to CTB@100 in X axis
- CTB@100 shows 18.42% increase in deformation, whereas CTB@195 shows 32.59% reduction in deformation when compared to CB in Y axis
- CTB@195 offers 45.01% decrease in deformation when compared to CTB@100 in Y axis
- CTB@100 shows 67.86% decrease in deformation, similarly CTB@195 shows 82.83% reduction in deformation when compared to CB in Z axis
- CTB@195 offers 46.58% decrease in deformation when compared to CTB@100 in Z axis
- Even though not being economical, still the structure can be made to stiffened enough at the temperature varying between 100^0C to 200^0C in tension stage and from 300^0C to 400^0C in compression stage.

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