Seismic Performance of Steel X-Knee-Braced Frames Equipped with Shape Memory Alloy Bars in Step Back Buildings on Hillside Slope

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Abstract - *Due to scarcity of the plain land on hills, houses built on steep slopes, pose special structural and construction problems. It was observed that the building stock in hilly regions is significantly more vulnerable to earthquakes as compared to the flat-terrain counterparts. In India, Because of steep slopes, buildings are constructed generally in step-back configuration. From the recent studies, it is observed that Step-back buildings show higher storey drift and storey shear, making the structures more vulnerable to earthquake forces. Till now there is no study is been conducted to enhance the seismic effectiveness of this type of building configurations. In the present scenario of earthquake prone zones in Indian hill regions, preventive methods and measures are very much necessary. Because, a very vast population of the world is living in seismic prone areas of Indian hill regions risking their lives and properties including buildings and other manmade structures. As a preventive measure, a model, with a combination of X-Knee braced steel frame coupled with SMA bar is assembled within the step-back configuration is introduced and the effectiveness of the same in reducing the storey drift and permanent roof displacement is carried out in the present study. Analytical results show that equipping SMA bars within the x-knee braced frame of a steel framed step-back building configuration can have a significant effect in enhancing the recentering capacity of the frame*

Key Words: **X-Knee braced steel frame, Shape Memory Alloy bar, Step back building configuration, Storey drift, Recentering capacity, Static Non-linear analysis, Dynamic Time-History analysis, ABAQUS.**

1. INTRODUCTION

Construction practices in the Indian Himalayas are very different from those in the majority of the Indian subcontinent, mainly because of the unavailability of flat land. The structural configurations of buildings in these regions generally follow the natural slope of the ground so that the foundations of a building are provided at different levels. The constraints provided by slope topography lead to highly irregular buildings both in plan and elevation and which is more vulnerable to earthquake than their counter parts resting in flat land. Main reasons for Earthquake damage in hill structures are Lack of proper earthquake design principles and Structural irregularities. From the surveys it is evident that Step back buildings (Fig-1) are the most prevalent building configuration in Indian hill regions & also which shows higher base shear, higher value of top storey displacement compared to other type of structural configuration in Indian hill region. The main cause of vulnerability is due to the unequal mass distribution in each floor of the configuration.

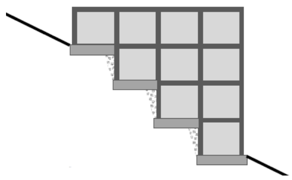


Fig-1: Step-back building configuration

X-Knee braced frame, a conventional seismic resistant frame have a suitable initial stiffness for restricting the inter-story drift ratios (which is a principal factor in decreasing the structural damages in a minor earthquake), but also, they exhibit an appropriate ductility behaviour to prevent the collapse. The seismic energy is dissipated by means of the yielding and buckling of the knee braces.

Recently, shape memory alloys with excellent microscopic and macroscopic properties such as high damping capacity, durability, fatigue and corrosion resistance, and super-elasticity have found many applications in various fields of engineering. It can be seen that most advantageous feature of SMA materials compared to typical steels, is their ability to regain the original shape after deformation to large strains. In other words, they can remove the residual/plastic deformation when the unloading occurs (this property referred as superelastic behavior). Furthermore, these materials have an excellent strength against corrosion in comparison with standard steels. In general, the dominant phase in these alloys is dependent on the temperature and state of stresses, which is expressed in terms of the chemical composition and thermo-mechanical processes of manufacturing. From a macroscopic point of view, the unique features of SMAs generate from a phenomenon that is known as martensitic phase transformation, which is a solid-solid diffusionless transformation between two basic phases:

Austenite and Martensite. The second phase involves two types of twinned and detwinned structures. As shown in Fig-2, the crystalline structure of Austenite phase (it is so-called parent phase) has a symmetric form, which is stable at high temperatures and low-stress values. Conversely, the Martensitic phase has a low symmetry (monoclinic crystal structure), which is stable at low temperatures and high-stress values.

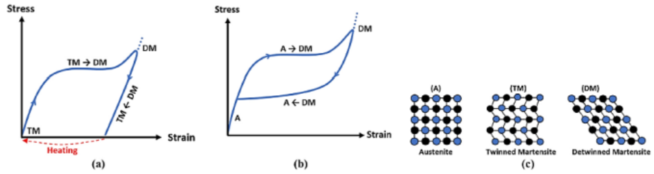


Fig -2: (a) Shape memory effect(b) super-elasticity property (c) basic phases and crystalline structures of an SMA.

Mohammada et al [3] in 2016 compared and analysed the seismic performance of step back and Step-back setback buildings by subjecting seismic forces along and across hill slope direction by using Response Spectrum Method in ETABS v 9.0. Found that the step-back buildings show higher storey drift and storey shear, making the structures more vulnerable to earthquake forces than Step-back setback buildings.

Fathima Farheen and S.P. Akshara [5] in 2019 studied and compared the seismic performance of knee braces in steel frames using non-linear static analysis. From the non-linear static analysis, it was found that the X KBF showed very good behaviour during a seismic activity. The ultimate load for X-KBF is very much higher compared to other configurations. X KBF showed more lateral stiffness compared to other configurations. Since the braces are arranged in X shape, it will provide structural stiffness and reduces the maximum inter-storey drift.

Mahmoudi et al [8] in 2018 modelled and analysed the seismic effect of shape memory alloy (SMA) bars within X-knee-braced frames (X-KBFs) by placing these super-elastic elements between the beam-column joints and knee members for three 3, 5, and 7-storey buildings. They observed that the SMA bars with relatively small Diameters of SMA can also lead to a high percentage of recentering effect in the structure. Also, to some extent, SMA bars have been effective in reducing the drift ratio, as well as increasing the elastic stiffness of models.

Retrofitting of X-KBFs with Shape Memory Alloy (SMA) bars

Considering the desirable stiffness, strength and ductility capacities of X-KBFs, if one can enhance the recentering behaviour of these structures through SMA materials, they would be one of the best options against seismic loads. Since it can lead to reducing the inelastic or permanent deformations under earthquake loading, and consequently, by decreasing the structural damages, the seismic performance will be improved. For this purpose, this study presents an approach using SMA bars in the adjacent of beam-column connection, as shown in Fig-3, to reduce the residual deformations of X-KBFs.

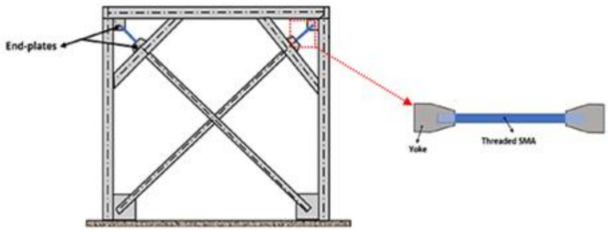


Fig-3: The location of SMA bars in the frames, along with their connection details (Yoke and Rod connection).

As displayed in Fig 3, in this case, the SMA bars first are treated at both ends; afterward, an intermediate member (yoke) is utilized to connect the SMA bars to end plates. In fact, this type of connection eliminates the problem of the sensitivity of the SMA bars to the welding process, as well as, the issue of destruction in the cross-sectional area of SMA bars due to the perforation also disappears.

DESIGN AND ANALYSIS OF MID-RISE STEEL FRAMED STEP BACK BUILDING IN ETABS

ETABS 2015 is used for the design and analysis of the steel framed four (G+4) storied step-back building and the result obtained are taken for further development of the project. The steel framed step-back building should be modelled according to the site condition and properties of the site, which is adopted for the study. After proper modelling of the building, the analysis is carried out to determine the location of maximum joint displacement by using response spectrum method.

The seismic analysis is carried out by using response spectrum method using finite element code ETABS 2015. The support and loading are chosen comply with the practical conditions of the test bed selected (Nainital). Steel, as constituent material, is assumed to be homogenous, isotropic and elastic in nature. Material properties are given in Table-1. The floor system in the all the configurations is modelled as rigid frame diaphragm and the foundation is assumed to be fixed support system. Loads acting on the building such as dead load including self-weight of the building, wall load and floor finishes, Live load, Wind load and Earthquake load are given according to site selected. The seismic parameters are assumed as per IS 1893 (Part 1): 2002.

Table-1: Material properties

Properties	Values
Modulus of elasticity	200GPa
Poisson's ratio of steel	0.3
density	7850 Kg/m^3
Yield stress	250Mpa

The building is assumed to be rest on the ground with an inclination of 45°. The inter-storey height is taken as 3m. The thickness of the slab at all floors is considered as 125mm. Across the slope a total of five bays are provided and the length of each bay is restricted to 3m. terrain properties of the ground are given in Fig-4.

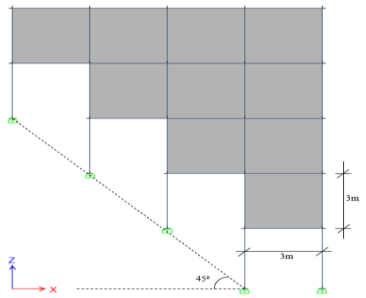


Fig-4: Terrain properties of the ground

The different members of the building are designed using the auto section assignment option included in ETABS. So that each component is different in its geometry. According to CL.5 of IS 808: 1989, the beams of the steel frame are assigned with ISJB, ISLB and ISMB sections and the columns are assigned with ISHB and ISWB sections.

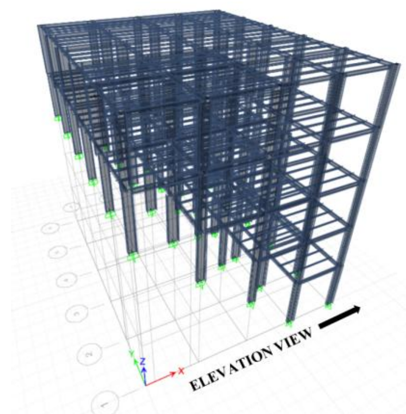


Fig-5: 3-D view of building after design in ETABS.

The maximum storey displacement of the steel framed step-back building under response spectrum analysis was found to be in storey 5 and is 28.12mm.

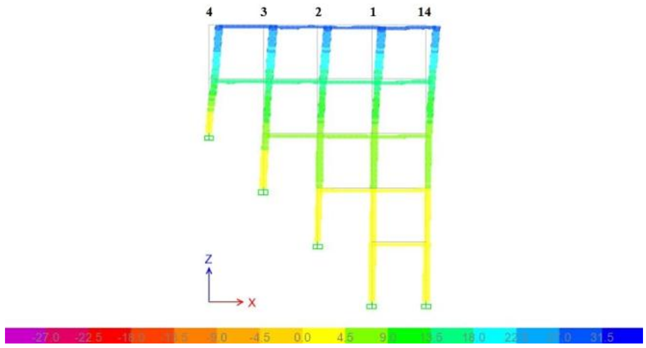


Fig-6: Critical frame region of the building with joint label which shows maximum deformation.

The dynamic analysis of the whole critical portion is complex and difficult. So that a small portion (Test frame) from the critical frame should be selected for further analysis. The joints with maximum joint displacement is taken as the test frame given in Fig-7.

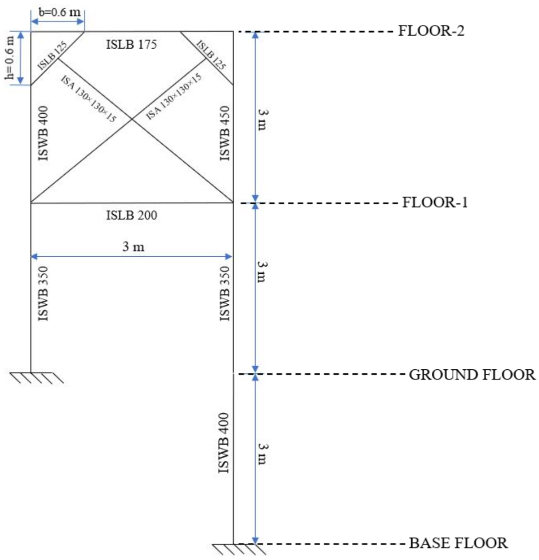


Fig-7: Structural orientation and section assignment given for test frame.

All the beams and columns are of 3m in length. The knees are inclined in 45° with respect to horizontal. For the better transmission of load, the bracings are inclined at 90° with respect to the knees provided. The b and h values are assumed to be 0.6m. The ends of the test frame are assumed to be fixed support system. All the other three sides of the frame are assumed to be free to move. The SMA bars are placed in between the beam-column joints and knee members. The orientation and length of SMA are determined based on the following two conditions.

- Attaching SMA bars in the middle of knee members.
- Locating SMA bars in the same direction with diagonal braces for better transforming of their axial forces.

Table-2: Section properties assigned to the test frame

Element	Section	Depth of the section, d (mm)	Width of the flange, b_f (mm)	Thickness of flange, t_f (mm)	Thickness of web, t_w (mm)
Column	ISWB 350	350	200	11.4	8
	ISWB 400	400	200	13	8.6
	ISWB 450	450	200	15.4	9.2
Beam	ISLB 175	175	90	6.9	5.1
	ISLB 200	200	100	7.3	5.4
Knee	ISLB 125	125	75	6.5	4.4
Brace	ISA 130×130×15	-	-	-	-

MODELLING OF SUPER-ELASTICITY IN SMA BARS

For modelling the super-elasticity of SMAs in civil engineering applications that mainly deal with the bar elements, it is evident that one-dimensional models are more suitable among other existing modelling methods. Up to now, several one-dimensional models are presented by various researchers in this regard. To define the super-elasticity in SMA materials a constitutive model, known as Fugazza model is considered in this study. This model originally was proposed by Auricchio and Sacco, and then modified by Fugazza (it is sometimes referred as Auricchio/Fugazza model). Fig-8 defines the Mathematical model for idealized stress-strain curve.

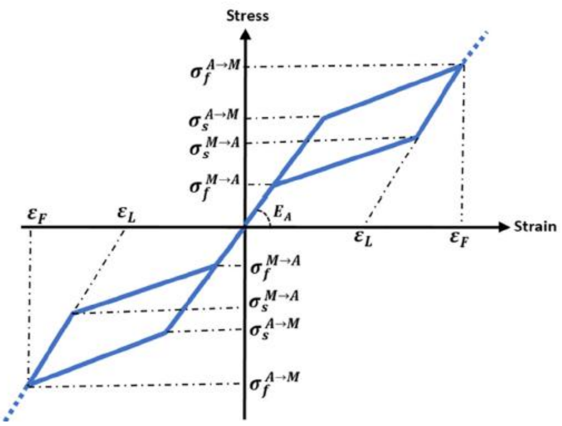


Fig-8: Mathematical model for idealized stress-strain curve

According to Fig-8, for the present study, the required parameters to define the super-elastic model are selected based on Table-3. In this table, M and A, respectively, denote the Austenite and Martensite phases; as well as, S and f represent the starting and finishing states.

Table-3: Mechanical properties of SMA given according to Fugazza model

Quantity	*Symbol*	*Value*
Austenite to martensite starting stress	$\sigma_s^{A\to M}$	414 MPa
Austenite to martensite finishing stress	$\sigma_f^{A\to M}$	550 MPa
Martensite to austenite starting stress	$\sigma_S^{M\to A}$	390 MPa
Martensite to austenite finishing stress	$\sigma_f^{M\to A}$	200 MPa
Modulus of elasticity for austenite	E_A	27.6 GPa
Maximum residual strain	ε_L	3.5%
Design strain limit	ε_F	5.5%

FINITE ELEMENT ANALYSIS OF TEST FRAME

The test frame which is modelled in previous chapter, should be subjected to finite element analysis to obtain the recentering capacity and reduction in storey displacement of frame with x-knee braces equipped with SMA bars. From this, the effectiveness of SMA bars in terms of recentering the step back buildings can be obtained. The analysis of the test frame is performed in ABAQUS platform for the numerical evaluation of residual displacement, Maximum storey displacement and storey drift.

The test frame modelled in ABAQUS with and without placing Shape Memory Alloy (SMA) bar given in Fig -9(a) and Fig-9(b). All the connections between beams and columns are assumed to be welded. Beam to column connections are done using a connection plate of size 100×150×12.5 mm. For the current study, it is assumed that the diameter and length of SMA bars in all stories is the same and does not change with the height of system.

Fig-9(a): Test Frame without equipping SMA bar

Fig-9(b): Test Frame equipping SMA bar

A yoke-and-rod connection is given to attach the SMA bar to the frame in the region between the beam-column joint and the knee members. It is assumed that a welded connection is provided between the yoke and the end plates and the ends of the SMA bar is threaded into the open end of the yoke. The yoke-and-rod connection and the connection with end plates are given in Fig-10 and Fig-11.

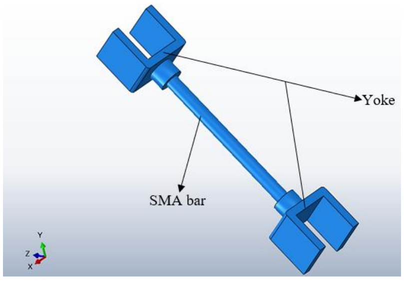


Fig-10: Yoke-and-rod connection

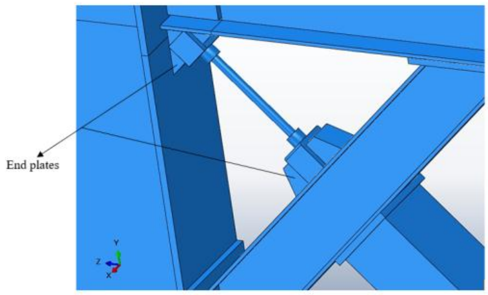


Fig-11: Location of SMA bars in the frame along with connection details

In the present study, mainly two types of analysis are performed to evaluate both the recentering capacity of SMA bars and the effect of SMA bars in reducing absolute storey displacement and storey drift for step-back buildings.

- Dynamic time history analysis
- Non-linear static analysis

Dynamic time history analysis

Time history analysis is used to determine the seismic response of a structure under dynamic loading of representative earthquake. In the present study, this type of analysis is used to determine the absolute displacement of each stories and to compare how much effective the Ni-Ti SMA bars in reducing the storey displacement and inter storey drift. Here a past earthquake data is used for the study. The acceleration-time data of an earthquake called Chi-Chi of magnitude 7.3 on the Richter scale occurred in Taiwan on 20th September 1999 of duration 12.4 seconds is used as input data. the analysis is performed on both the test frame, without equipping SMA bars and with equipping SMA bars of three different diameters (10mm,16mm and 22mm).

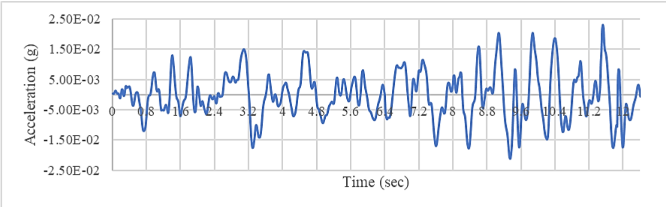


Fig-12: Time-acceleration data of Chi-Chi earthquake

Non-linear static analysis

It is practical method in which analysis is carried out under permanent vertical loads and gradually increasing lateral loads to estimate deformation and damage pattern of structure. In the present study, non-linear static analysis is performed to determine the residual displacement of the test frame with and without equipping SMA bars. Recentering refers to the ability of a material to return to its original undeformed shape upon unloading. The less amount of residual deformation indicates that the structure can better return to its original state after removing the external seismic-forces. For this, A lateral load in the direction of slope (Z-direction) is applied as a sinusoidal cyclic load ranges from 20kN to 150 KN on the left top-most portion of the test frame (Fig-13).

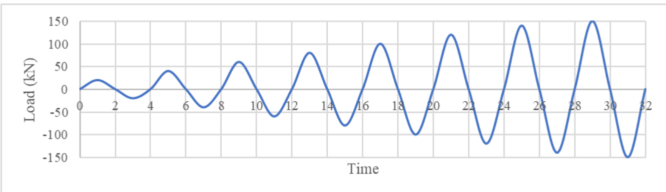
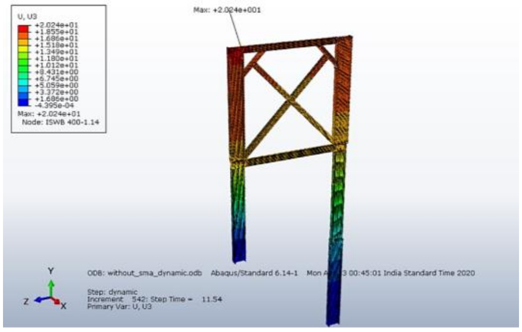


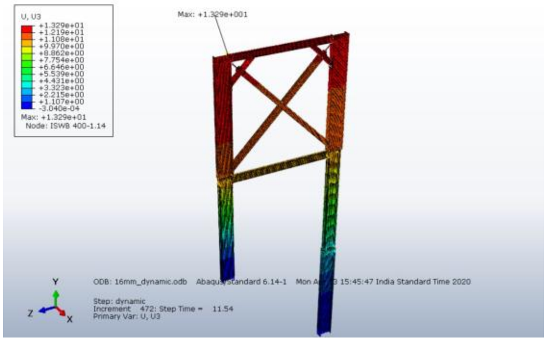
Fig-13: Sinusoidal cyclic load ranges from 20kN to 150 KN

RESULTS AND INFERENCE

Dynamic time history analysis



(a)



(b)

Fig-14: The Maximum storey displacement of Test frame(a) Without equipping SMA bar (b) with equipping SMA bar of mid-sized diameter(16mm)

Table-4: Comparison of maximum absolute and Maximum inter-story drift

Test frame equipped	Maximum absolute displacement (mm)			Maximum inter-story drift (mm)		
	Ground	Floor-1	Floor-2	Ground	Floor-1	Floor-2
KBF	5.48	16.03	20.24	16.03	10.55	4.2
SMA-10mm	4.37	14.07	16.5	14.07	9.7	2.43
SMA-16mm	3.84	11.42	13.29	11.42	7.58	1.87
SMA-22mm	3.028	9	10.32	9	5.972	1.32

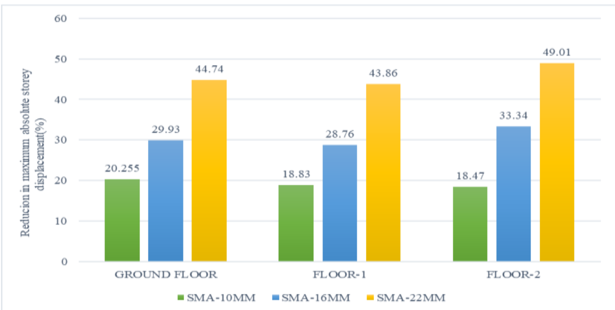


Chart -1: Graphical comparison of percentage reduction in Maximum storey displacement.

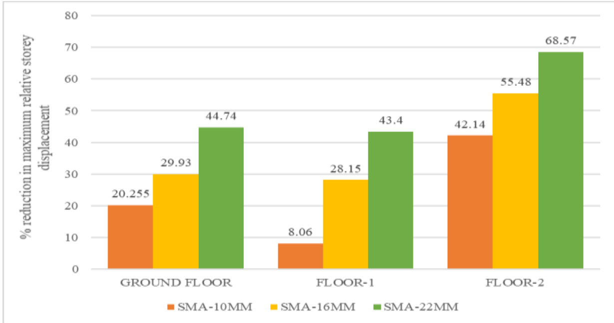
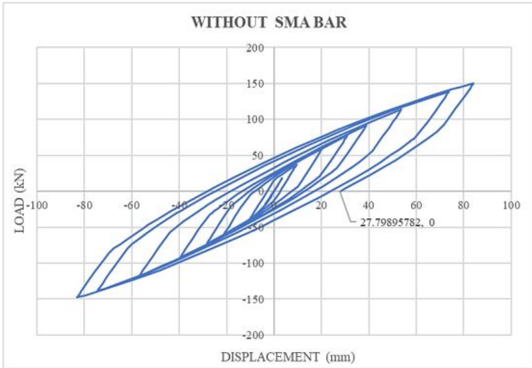


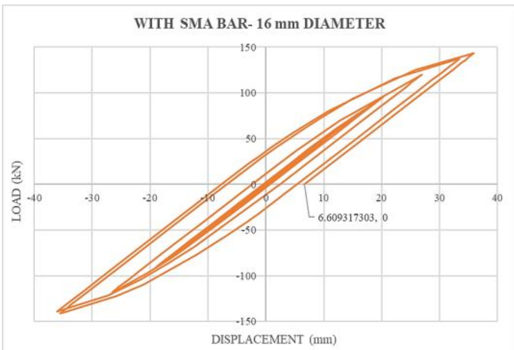
Chart -2: Graphical comparison of percentage reduction in storey drift

By analysing the results which are obtained from the dynamic time history analysis in the view of different comparisons, it is evident that there is not much effective reduction in both Maximum storey displacement and Maximum storey drift in each storey with small sized diameter bars (10mm dimeter). But with the use of a large sized diameter bar (22mm diameter), 68.57% of reduction in top storey drift is possible.

Non-linear static analysis



(a)



(b)

Chart-3: Load-displacement graph (a) without SMA bar (b) with a mid-sized diameter(16mm) SMA bar.

Table-5: Summary of results obtained from the non-linear static analysis in tabular form

Test frame equipped	Residual displacement (mm)	Improvement in recentering property (%)
Without SMA bar	27.8	-
SMA bar-10mm diameter	10.014	63.98
SMA bar-16 mm diameter	6.61	76.22
SMA bar-22 mm diameter	5.145	81.49

By comparing the different residual displacements obtained from the Non-linear static analysis, we can observe that even for small diameter SMA bars (10mm diameter), the reduction in the residual displacement value is satisfactory. In the present study we can reduce the residual displacement, more than 60% by equipping 10 mm diameter SMA bar and the reduction for a 22mm diameter bar is more than 80%.

CONCLUSION

The conclusions obtained can be summarized as follows:

- The employment of SMA bars in a steel framed mid-rise step-back building configuration does not remarkably reduce the storey drift but the permanent roof displacement (residual displacement) of the same is significantly reduced.
- Small diameter SMA bars (10mm) have a very little effect in reducing the storey drift in step-back building configurations. However, with the use of large diameter SMA (22mm) bars, we can reduce the storey drift in each storey about half of the drift which is obtained without equipping SMA bars.
- The employment of a small diameter SMA bars can have a significant effect in reducing the permanent roof displacement (residual displacement). Thus, even with the implementation of a small diameter SMA bars within the X-Knee braced steel framed Step-back building structure, the structural damages during an earthquake in hilly regions can be reduced to an appreciable level.
- The complete removal of residual displacement is not at all possible even with the use of large diameter SMA bars. However, we can reduce the permanent roof displacement up to 80% by the employment of a large diameter SMA bar in the structure.
- The effect of recentering in step-back buildings is almost same as that of a structure which rest on a flat surface. So that, the irregularity in structural configuration of buildings have few or no effect in the unique property; that is, super elasticity of Shape Memory Alloy bars.

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