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Optimal use of Negative Stiffness Damper for Seismic Resistant Frames

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Abstract :*The seismic protection of the structures is one of the most important goals of structural engineers in order to save lives and minimize damages to structures in case of high intensity earthquakes. Many attempts are being made to meet this goal.One such attempt is made by the researchers by introducing a negative stiffness damper (NSD). The NSD is a device that produces a force which is in the same direction as the imposed displacement thus the name "negative stiffness". NSD is capable of dissipating seismic forces within the structure without affecting the strength serviceability and functionality of main structure. Negative stiffness devices emulate weakening of the structural system without inelastic excursions and permanent deformations. This study focuses on modelling the device in a commercial software tool. Further the device is implemented on 2D and 3D frame models.For various ground motions the parameters such as base shear, story acceleration andmaximum displacement are studied.*

Keywords : *Apparent yielding, Negative stiffnessdamper, Seismic response control.*

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I. Introduction

Strong ground motion can cause excessive structural deflection and damage or even collapse in structures. Various means of enhancing structural seismic performance have been studied by researchers. These include base isolation, passive control by adding energy absorbing devices to structures and modification of structural dynamic characteristics. Design of conventional structures specified by the codes is based on the philosophy that the structure should withstand seismic load while sustaining an acceptable level of damage. At present, structures are designed to prevent collapse but their serviceability and functionality in the aftermath of strong ground motion are not taken into consideration

Reinhorn*et.al.*[11] (2005) introduced the concept of "weakening and damping" to reduce the acceleration, base shear and deformations of the structure. Acceleration experienced by the structure can be reduced by weakening the structure (reducing strength) and by introducing the additional supplementary viscous damping, the inter-story drifts can also be reduced simultaneously. Although this method is capable of reducing both forces and deformations, it may lead to early yielding of the structural systems, resulting in damage to the structure. H. Iemura1 *et.al.*[5] (2008) proposed a new structural control device that realizes a negative stiffness in a passive manner. The developed device is a typical slide bearing, except that the inverted convex curve is introduced on the sliding plate to generate the negative stiffness. The principle of this damper is illustrated in Figure1.

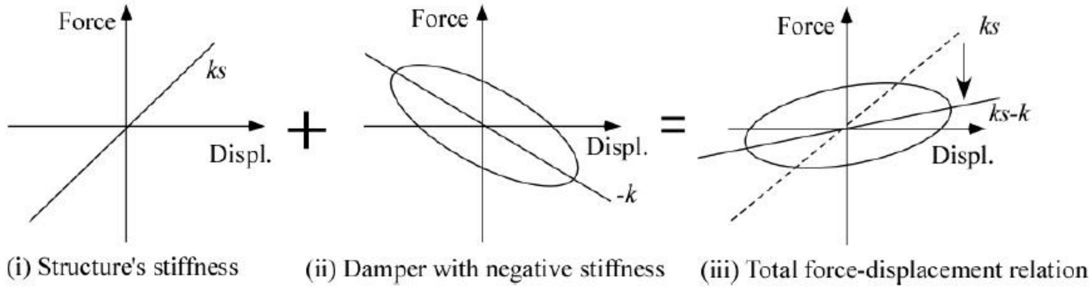


Figure 1 Basic principle of the negative stiffness damper (H. Iemura*et al*, 2008)

Nagarajaiah*et.al*. [9] (2013) were the first to introduce the concept of true negative stiffness for structural applications .True negative stiffness means the force must assist motion, not oppose it as it is in the case of a positive stiffness spring. Pseudo negative stiffness can be accomplished using active or semi-active hydraulic devices. True negative stiffness needs no external power supply. The Negative Stiffness Device (NSD) presented by them is entirely composed of springs and generates an elastic nonlinear true negative stiffness. By engaging the NSD at an appropriate displacement (simulated yield displacement), which is well below the actual yield displacement of the structural system, the composite structure-device assembly, behaves like a yielding structure. The NSD has a re-centering mechanism thereby avoiding permanent deformation in the composite structure-device assembly unless, the main structure itself yields. However, the combined structural system with just the NSD develops increased structural deformations. Addition of passive dampers reduces and controls these deformations without any considerable increase in the base shear.

Gisha M.M *et.al*[3] (2015) have presented the work on true negative stiffness system and adaptive negative stiffness system on a lumped mass five storied shear building. The floors of the structure are assumed to be linear and torsion effects are ignored. A single degree of freedom is considered at each floor level. The optimal values of parameters and optimal number of dampers were found based on base shear, acceleration, displacement, for different ground motions.

II. Negative Stiffness Damper

The Negative Stiffness Damper (NSD) is a device that produces a force which is in the same direction as the imposed displacement thus the name “negative stiffness.” It can be installed in an isolated structure between the ground and the isolation level or in between the floors of any fixed and/or isolated structure. The NSD is shown in Figure 2. The parts of the NSD are as follows:

1. A highly compressed machined spring (CS) that develops a force in the direction of motion (thus, negative stiffness).The magnitude of the force reduces with increasing displacement so that stability of the system is ensured at large displacements.
2. A double chevron self-containing system is provided to resist the preload in the compressed spring and also to prevent the transfer of the vertical component of the preload to the structure.
3. A double negative stiffness magnification mechanism that substantially reduces the requirement for preload so that a practical system is achieved.
4. A system (called Gap Spring Assembly or GSA) that provides positive stiffness up to a predefined displacement such that the combined effective stiffness of NSD and GSA is almost zero until a predefined displacement is reached. The GSA is essential to simulate a bi-linear elastic behaviour with an apparent-yield displacement which is smaller than the actual yield displacement of the structure.

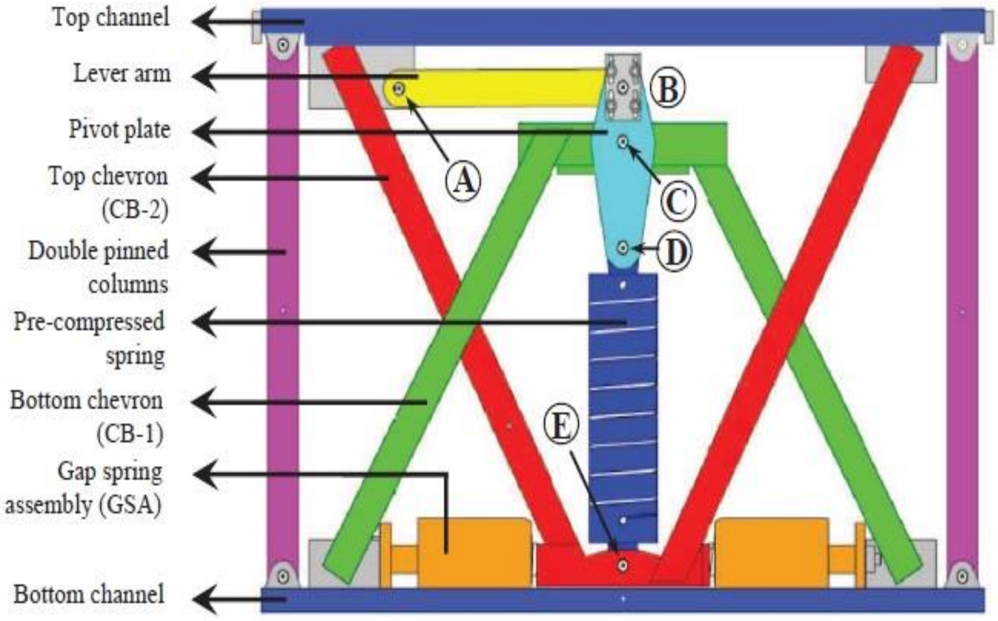


Figure 2 Schematic diagram of Negative stiffness damper

III. Operation OFNSD

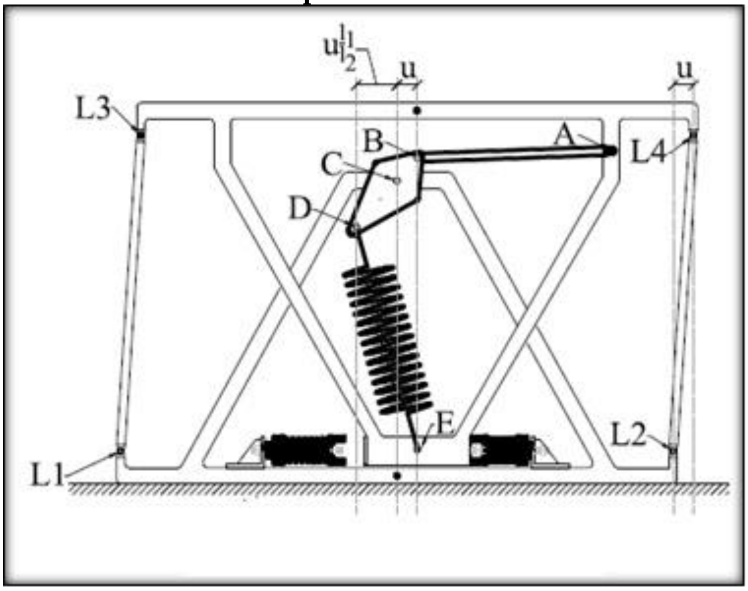


Figure 3Deformed Configuration of Negative Stiffness Damper (Nagarajaiah*et al*, 2013)

The NSD behaviour is determined by the motion of the pivot plate and pre-loaded spring (thus, the motion of points A, B, C, D, E) and by the spring properties of initial length DE, pre-load $P_{in}$and stiffness k_s. Consider the motion of the top of the NSD by displacement *u* towards right as shown in Figure 3. The lever imposes a displacement on the top of the pivot plate (point B) making the pivot plate to rotate about point C. Due to the axial rigidity of the lever and its negligible rigid body rotation, the imposed displacement and the displacement of point B are essentially equal. Since the pivot plate rotates about C, point D moves in the opposite direction from the imposed displacement. It should be noted that the bottom pin of the pre-compressed spring (point E) is rigidly connected to the top of the device via the top chevron brace and therefore has a displacement equal to the one imposed on the top. The kinematics of the spring's top and bottom pins cause the pre-compressed spring to rotate. Since the spring is pre-compressed and rotated in the direction opposite to the imposed displacement, it facilitates the motion rather than opposing it. This gives rise to negative stiffness.

IV. Mathematical Formulation OFNSD

By considering equilibrium of Negative Stiffness Damper following relationships are obtained by Nagarajaiah*et al*

$$F_{NSD} = -\left(\frac{P_{in}+K_s l_p}{l_s} - K_s\right)\left(\frac{l_1}{l_2}\right)\left(2+\frac{l_2}{l_1}+\frac{l_p+l_1}{\sqrt{{l_2}^2-u^2}}\right)u+F_g$$

(1)

Where, $F_g = \begin{Bmatrix} k_{g1}u, & 0 \le u \le d_{gap} \\ k_{g1}d_{gap}+k_{g2}\left(u-d_{gap}\right) & u > d_{gap} \end{Bmatrix}$

(2)

$$l_s = \sqrt{\left(l_p+l_1-l_1\sqrt{1-\left(\frac{u}{l_2}\right)^2}\right)^2 + u^2\left(1+\frac{l_1}{l_2}\right)^2}$$

(3)

Rearranging the above equation one gets,

$$l_p = \sqrt{l_s^2 - u^2\left(1+\left(\frac{u}{l_2}\right)\right)^2} - l_1 + l_1\sqrt{1-\left(\frac{u}{l_2}\right)^2} \tag{4}$$

Table 1 gives the properties of the NDS used for solving the above equations to obtain the force displacement relation of the NSD.

Table 1 Properties of NSD used in the force-displacement expression (Gisha M.M *et al*[4] (2015))

Parameter	Value
Distance from spring to fixed pin (l_1)	0.5842 m
Distance from lever pin to fixed pin (l_2)	0.2921 m
Spring length (l_s)	1.7526 m
Gap opening d_{gap}	0.01651 m
GSA stiffness for spring 1 k_{g1}	1050.72 kN
GSA stiffness for spring 2 k_{g2}	28.02 kN
The initial pre-compression force in the spring P_{in}	95 kN

l_pLength of the spring when the NSD is undeformed.
k_s *is* the stiffness of the pre-compressed spring.
Different k_s value is to be selected for different frames and for different positions. The strategy adopted for selecting the appropriate value of k_s is illustrated by means of the Figure 4.

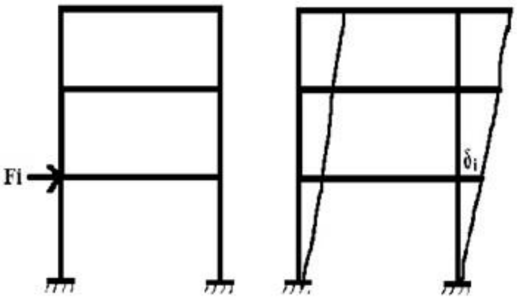


Figure 4 Deformation of laterally loaded frame

R_i is the ratio of force F_i ati^{th} storey to the corresponding displacement δ_i as shown in the Figure 4, $k_s$value is taken as some percentage of $R_i$say between 15% to 30%

V. Modelling OFNSD In Sap2000

The NSD can be modelled in general purpose dynamic analysis programs by (a) direct modelling of the geometry of the device and its components and performing large displacement analysis or (b) activating user-defined elements that emulate the force-displacement relations described by Equations (1) and (2) without the need for large displacement analysis. Program SAP2000 contains the “nonlinear elastic link” element that can replicate any random elastic behaviour. The element requires data on force and displacement without any restriction other than the behaviour has to be elastic.

The NSD model in program SAP2000 requires the use of two elements sharing two nodes in a parallel arrangement as shown in Figure 5.

These elements are:

- A nonlinear elastic element ML1 representing the NSD without the Gap Spring Assembly (GSA) and having a force-displacement relation given by Equation (1) with $F_g=0$.
- A nonlinear elastic element ML2 representing the GSA and having a force-displacement relation given by Equation (2).

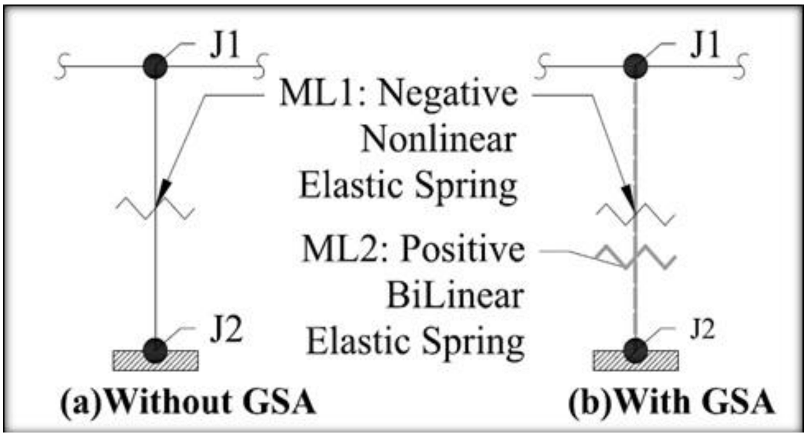


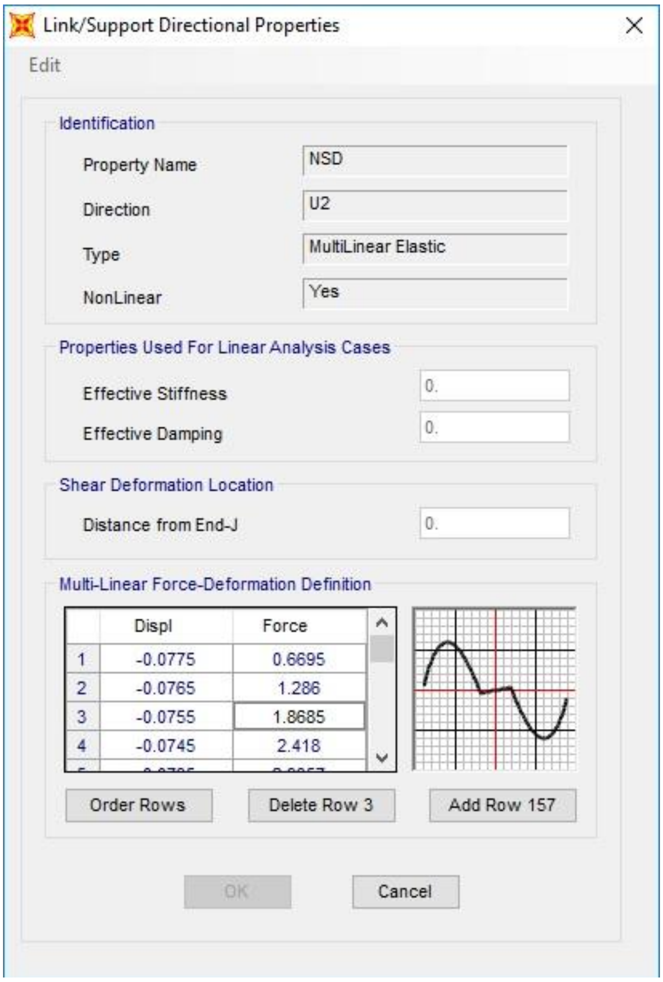
Figure 5 SAP2000 NSD element with and without GSA

The two elements, ML1 and ML2, overlap and share the same joints on top (J1) and bottom (J2) in order to avoid any additional moments that might be introduced if they were to be placed apart. Table 2 gives the secondary properties of NSD link that need to be given in SAP2000.

Table 2Secondary properties of NSD link that need to be used in SAP2000

	ML1	**ML2**
Non-Linear (U2)	Eq (1)	Eq (2)
Rotational Stiffness(R1,R2,R3)	0	0
Effective Stiffness	0	0
Vertical Stiffness (U1)	0	0

A MATLAB code is developed for solving Equations (1) and (2) .The force displacement obtained is inserted in SAP2000 as a multi linear elastic link as shown in the figure 6.



Identification

Property Name: NSD

Direction: U2

Type: MultiLinear Elastic

NonLinear: Yes

Properties Used For Linear Analysis Cases

Effective Stiffness: 0.

Effective Damping: 0.

Shear Deformation Location

Distance from End-J: 0.

Multi-Linear Force-Deformation Definition

	Displ	Force
1	-0.0775	0.6695
2	-0.0765	1.286
3	-0.0755	1.8685
4	-0.0745	2.418

Figure 6 NSD properties assigned in SAP2000

VI. Implementation Of NSD On Frames

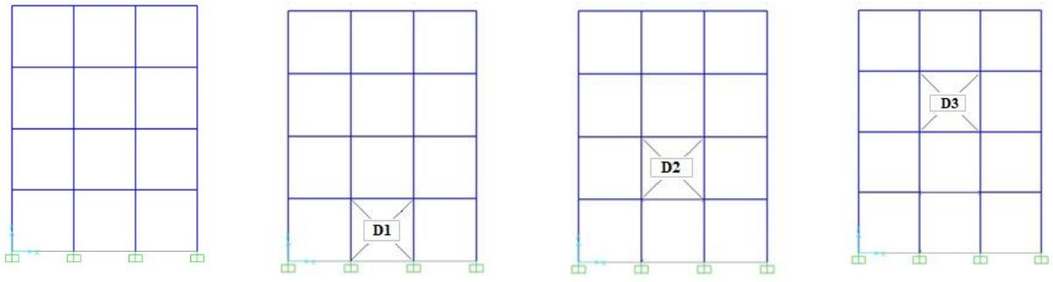
A. 2D model description:

A four storied 2D steel frame fixed at supports, having a bay width of 3 m and story height of 3 m is taken up for study. All beamsare ISMB 200 and all columns are ISMB 225 with steel grade of Fe345.

a. Live load is 5 kN/m on beam element.
b. Self-weight is explicitly captured using steel density of value Fe345 grade steel in SAP200.
c. Design code used is IS1893:2007.
d. Framing type is Special moment resisting frame.
e. Importance factor is 1.
f. Seismic zone is Zone III.
g. Type of analysis is Fast Nonlinear Analysis (FNA)
h. Ground motions considered are Newhall (0.59g), Corrolitos (0.63g).

Three models of the frame were prepared with different positions of NSD and one model was without the damper. The details of the models are described in the following and are illustrated in Figure 7.

1. Model 1 is the 2D frame of column ISMB 225 and beam ISMB 200 fixed at the base.
2. Model 2 is the 2D frame of column ISMB225 and beam ISMB 200 fixed at the base and NSD damper D1 applied at ground floor level.
3. Model 3 is the 2D frame of column ISMB225 and beam ISMB 200 fixed at the base and NSD damper D2 applied at first floor level.
4. Model 4 is the 2D frame of column ISMB225 and beam ISMB 200 fixed at the base and NSD damper D3 applied at second floor level.



Model 1 Model 2 Model 3 Model 4

Figure 7 Description of 2D Models

The Table 3 gives the final values of the R_i and the $K_{si}$of the dampers on all the i floors.

Table 3 Selection of appropriate K_s values

Floor	Damper	R_i	K_{si}
Ground floor	D1	8673 kN/m	17% of 8673 = 1474 kN/m
First floor	D2	2837 kN/m	28% of 2837 = 790 kN/m
Second floor	D3	1622 kN/m	22% of 1622 = 354 kN/m

2D model Results:

Base shear:

Base shear obtained from the FNA of different Models and under the two representative ground motions are given in Table 4,

Table 4 Base Shear Comparison

	Newhall	Corralitos
Model 1	116 kN	149 kN
Model 2	81 kN(30.2%)	103 kN (30.9%)
Model 3	85 kN(26.7%)	109 kN (26.8%)
Model 4	111kN (4.3%)	144 kN (3.4%)

Story acceleration:

The Figure 8 shows the acceleration time histories of the topmost node of models 1 and 2 respectively for the Newhall earthquake. It can be observed that the absolute acceleration of top storey of model 2 (with NSD) is lesser as compared to that of model 1 (without NSD).

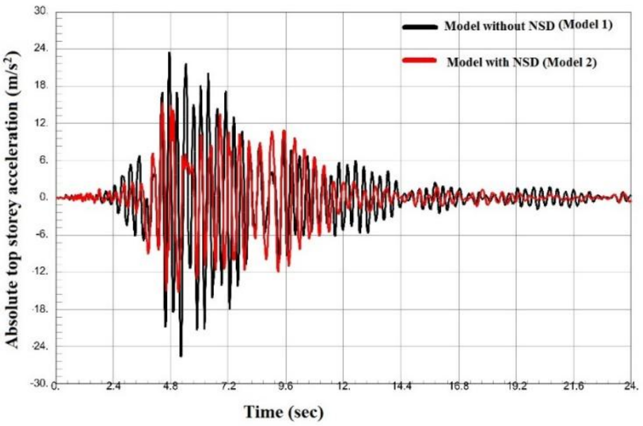


Figure 8Comparison of Absolute top storey acceleration for Newhall TH case

In Table 5, the storey accelerations for Newhall ground motion and for Corrolitos ground motion are presented. From the above comparison and from the table 5 one can observe that the top storey acceleration decreases when NSD is implemented on the structure.

Table 5 storey acceleration for different ground motion

	Newhall ground motion				**Corrolitos ground motion**			
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 1**	**Model 2**	**Model 3**	**Model 4**
X4 (m/s^2)	23.53	15.41	15.25	23.36	34.94	18.20	18.41	33.04
X3 (m/s^2)	20.61	13.09	15.21	19.45	27.98	18.10	18.58	27.76
X2 (m/s^2)	16.57	14.78	13.46	14.70	19.18	16.73	15.12	19.26
X1 (m/s^2)	10.38	10.74	7.08	9.67	9.63	18.20	7.78	8.89

Story displacement:

The story displacement at the level of installation of the device and its comparison to the bare frame is presented in the
Figure 9.

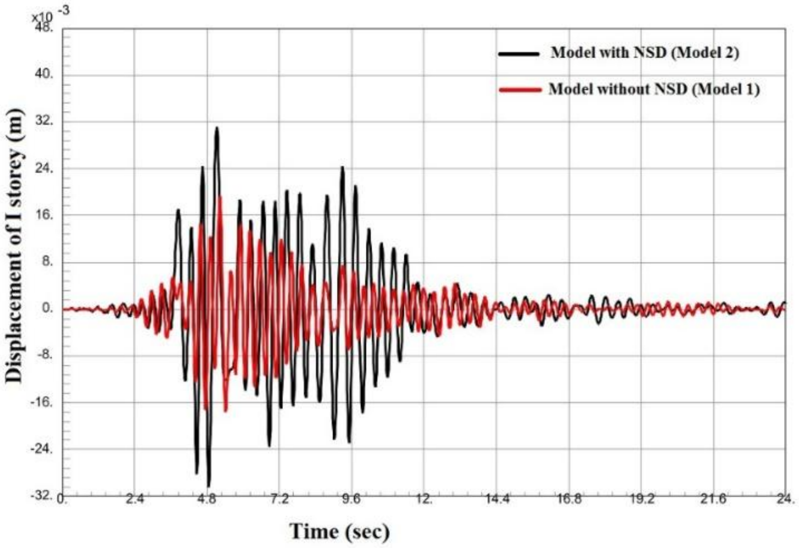


Figure 9 Comparison ofstorey displacement for Newhall TH case

Table 6 gives the story displacements under the two representative ground motions for the four models analysed.

Table 6 Storey displacement for different ground motions

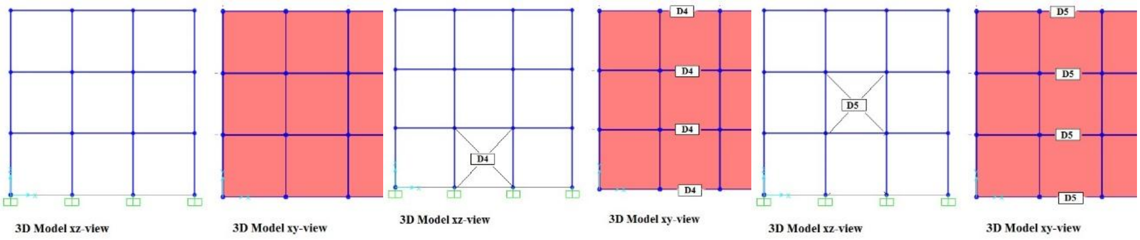
	Newhall ground motion				**Corrolitos ground motion**			
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 1**	**Model 2**	**Model 3**	**Model 4**
X4 (cm)	7.7	7.32	7.82	8..04	9.73	9.47	9.5	10
X3 (cm)	6.56	6.62	7.05	**6.77**	8.2	8.69	8.61	**8.3**
X2 (cm)	4.53	5.31	**5.35**	4.65	5.57	7.09	**6.56**	5.33
X1 (cm)	1.92	**3.11**	1.85	1.97	2.32	**4.18**	2.19	2.2

From the Figure 9 and from the Table 6one can observe that the storey displacement at the level of installation increases when NSD is implemented on the structure.

B. 3D model description:

3D model is of steel frame of beam ISMB 250 and column ISMB 400 with steel grade Fe345, frames are 3m in x-axis, y-axis and z-axis. Slab is modelled as a thin membrane member of thickness 150mm and a concrete grade of M25.The modelled is fixed at the base. The self-weight of the frame is explicitly captured using the steel density value for the material in SAP2000.Live load of 2 kN/m^2 is applied directly on slab. Negative stiffness damper is implemented at different positions describe below.

1) Model 5 is the bared 3D frame fixed at the base, no negative stiffness damper is implemented.
2) Model 6 is the 3D steel frame fixed at the base and the device (D4) is implemented at the ground floor level.
3) Model 7 is the 3D steel frame fixed at the base and the device (D5) is implemented at the first floor level.



Model 5 Model 6 Model 7

Figure 10 Description of 3D Models

3D model Results:

Base shear:

Base shear obtained from the FNA of different Models and under the two representative ground motions are given in Table 7,

Table 7 Base shear for 3D models

	Newhall	**Corralitos**
Model 5	2015 kN	2325 kN
Model 6	1777 kN (11.8%)	1795 kN (22.7%)
Model 7	1444 kN(28.3%)	1742 kN(25.1%)

1) Story acceleration:

In Table 8, the storey accelerations for Newhall ground motion and for Corrolitos ground motion are presented. From table it can be observed that the top storey acceleration decreases when NSD is implemented on the structure.

Table 8Story acceleration for 3D models

	Newhall ground motion			**Corrolitos ground motion**		
	Model 5	**Model 6**	**Model 7**	**Model 5**	**Model 6**	**Model 7**
X3 (m/s^2)	23.55	20.23	17.06	30.15	21.25	22.83
X2 (m/s^2)	17.57	16.20	11.94	19.96	16.43	14.01
X1 (m/s^2)	10.41	8.84	8.10	8.91	7.33	7.20

Story displacement:

Table 9 gives the story displacements under the two representative ground motions for the four models analysed.

Table 9 Storey Displacement for 3D Models

	Newhall ground motion			**Corrolitos ground motion**		
	Model 5	**Model 6**	**Model 7**	**Model 5**	**Model 6**	**Model 7**
X3 (cm)	8.14	10.78	8.56	10.16	10.76	10.45
X2 (cm)	5.59	8.03	**6.04**	6.85	8.00	**7.20**
X1 (cm)	2.22	**3.85**	2.2	2.65	**3.83**	2.50

VII. Conclusions

Following conclusions can be drawn from the analytical investigations carried out in this work.

1) Negative Stiffness Damper helps to reduce the base shear of 2D and 3D frames upto 30% compared to the one with no negative stiffness damper.

2) The absolute top storey acceleration of the structure decreases when a Negative Stiffness Damper is used on the structure.

3) Negative Stiffness Damper increases the displacement at the level of installation of the device.
4) Different Negative Stiffness Dampershave to be modelled for different structures and for different locations of installations in order to arrive at the optimal arrangements of NSDs.

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