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Optimization of Seismic Response of Steel Structure Using Negative Stiffness Damper

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Abstract: *Earthquakes of greater magnitude can cause stark destruction. Seismic protection of structures is one important tool to minimize damages and total collapse of structures. Researchers have made many attempts to achieve this goal with various techniques and one such strategy of seismic response control developed is introducing true negative stiffness in the structure. True negative stiffness is introduced with the help of negative stiffness damper (NSD). The NSD generates force in the direction of the displacement and hence it is called Negative Stiffness. The present study focuses on modelling NSD device in a commercial software tool (ETABS 2016). Further the device is implemented on 2D Steel frame models and seismic parameters like base shear, Storey displacement and Top storey acceleration are studied.*
Keywords– *Negative Stiffness Damper, Seismic response control.*

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I. Introduction

During last two to three decades, the reduction of structural response caused by dynamic effects has become a subject of intensive research. Many structural control concepts have been evolved for this purpose, and quite a few of them have been implemented in practice. They include reduction of undesirable vibrational levels of flexible structures due to unexpected large environmental loads, retrofitting existing structures against environmental hazards, protecting seismic equipment and important secondary systems and provision of new concepts of design of structures against environmental loading. These structural control systems can be broadly classified into Active control, Passive control, Semi-active control and Hybrid control systems. An alternative approach is to "simulate yielding" by introducing true negative stiffness at prescribed displacement leading to the concept of "apparent weakening". This is achieved with Negative Stiffness Devices (NSD).

Reinhorn *et.al* (2005) introduced the concept of "weakening and damping" to reduce Seismic responses of the structure namely base shear, storey acceleration and storey displacements. Acceleration in the structure can be controlled by weakening the structure (reducing strength). However, any passive damper can be added in parallel to control the inter storey drifts.

H.Iemura *et.al* (2008) proposed a new structural control device and showed negative stiffness can be realized in a passive manner. Gisha et al. (2015) studied the performance of true negative stiffness (TNS) and an adaptive negative stiffness system (ANSS) on a five degrees of freedom shear structure. The optimal values of parameters and optimal number of dampers are studied based on the response such as inter storey drifts, accelerations, displacements, and base shear. The conclusions obtained was TNS device is capable of reducing all responses including inter storey drifts and accelerations above the level of its installation in the structure and response control behaviour of the ANSS system changes with the input ground motion.

II. Methodology

The aim of present analysis is to check the effectiveness of Negative Stiffness Damper on 2D steel frames.

2.1 Negative Stiffness Damper

The Negative Stiffness Damper (NSD) is a device that generates force in the direction of impending motion. It can be applied and installed in between the floors or in between the ground floor and isolation level. The NSD is shown in Fig 2.1. The parts of the NSD are as follows:

- A highly compressed machined spring (CS) that develops a force in the direction of motion which gives negative stiffness. The magnitude of the force reduces with increasing displacement so that stability of the system is ensured at large displacements.
- A double chevron self-containing system to resist the preload in the compressed spring.

- A system (called Gap Spring Assembly or GSA) that provides positive stiffness upto a predefined displacement.

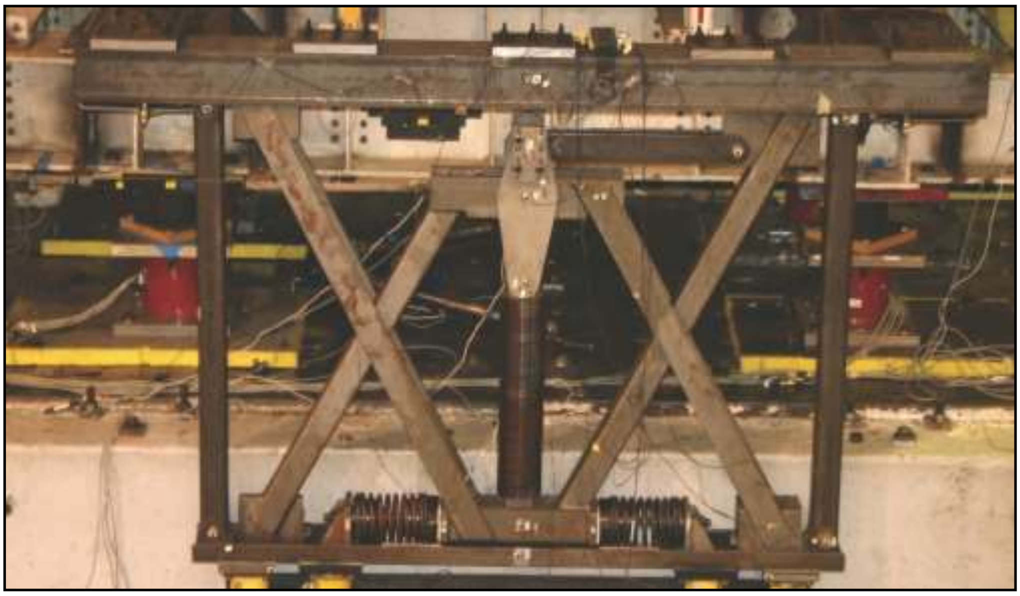


Figure 2.1 A view of Negative Stiffness Damper (Nagarajaiah et al, 2013)

2.2 Operation of NSD

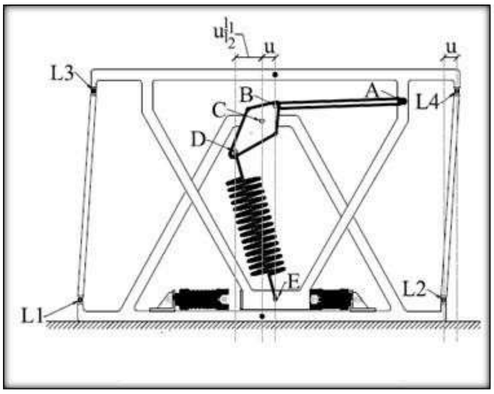


Figure2.2 Deformed Configuration of Negative Stiffness Damper (Nagarajaiah *et al*,2013)

The NSD behavior 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 2.2. 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.

2.3 Data Considered

A G+4 story 2D steel frame fixed at supports, having a bay width of 5 m (X-direction) and story height of 3 m is taken up for study. Beam ISMB 200 and column ISMB 225 with steel grade Fe345. The frame was designed and checked for the following design considerations:

- Live load-5 kN/m
- Self-weight is explicitly captured using steel density of value Fe345 grade steel in ETABS 2016
- Design code- IS1893 (Part 1) : 2016
- Framing type- Special moment resisting frame

- Importance factor - 1
- Seismic zone - zone - III

Following models are considered in the 2D analysis:

1. Model 1 is the 2D frame of column ISMB 225 and beam ISMB 200 fixed at the base and it is considered as reference model without application of NSD (Fig 2.3).
2. Model 2 is the 2D frame of column ISMB 225 and beam ISMB 200 fixed at the base and NSD applied at ground floor level for Bay 1, 2 and 3 (Fig. 2.4).
3. Model 3 is the 2D frame of column ISMB 225 and beam ISMB 200 fixed at the base and NSD applied at first floor level for Bay 1, 2 and 3 (Fig. 2.5).
4. Model 4 is the 2D frame of column ISMB 225 and beam ISMB 200 fixed at the base and NSD applied at second floor level for Bay 1, 2 and 3 (Fig. 2.6).
5. Model 5 is the 2D frame of column ISMB 225 and beam ISMB 200 fixed at the base and NSD applied at third floor level for Bay 1, 2 and 3 (Fig. 2.7).
6. Model 6 is the 2D frame of column ISMB 225 and beam ISMB 200 fixed at the base and NSD applied at fourth floor level. (Fig. 2.8).

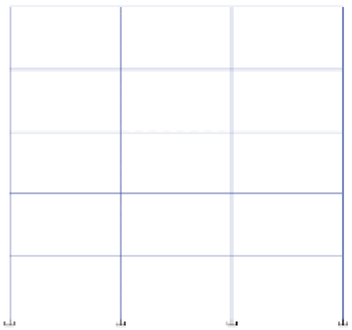
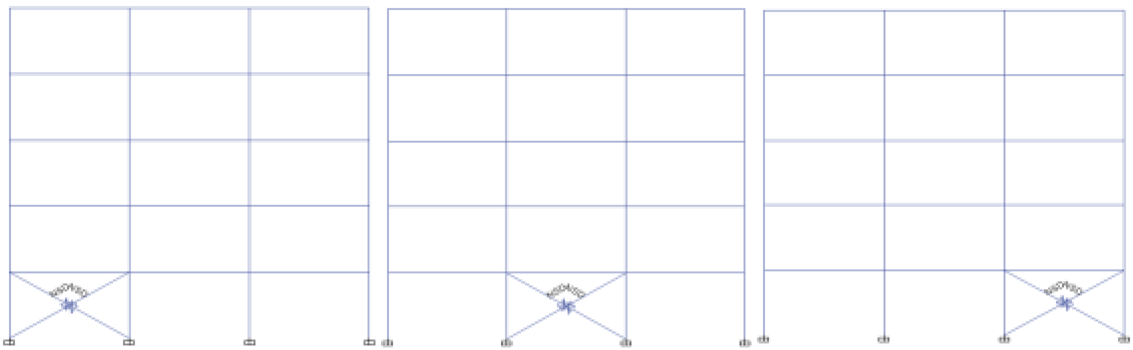
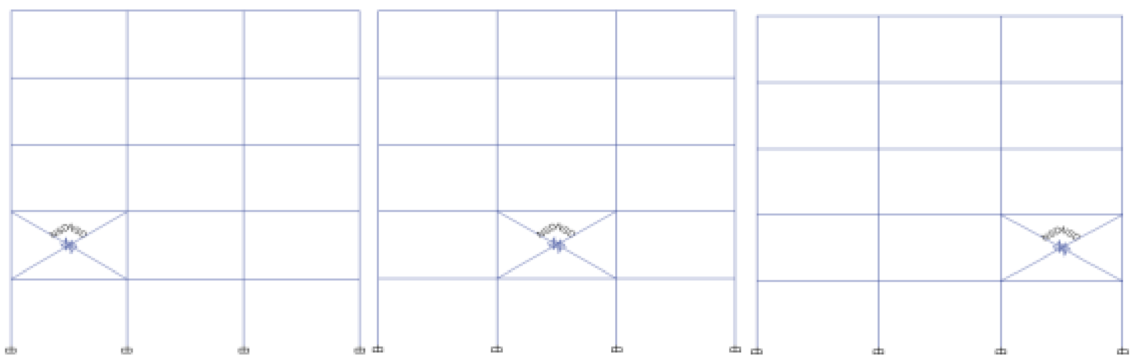


Figure 2.3 Model 1 Frame without NSD



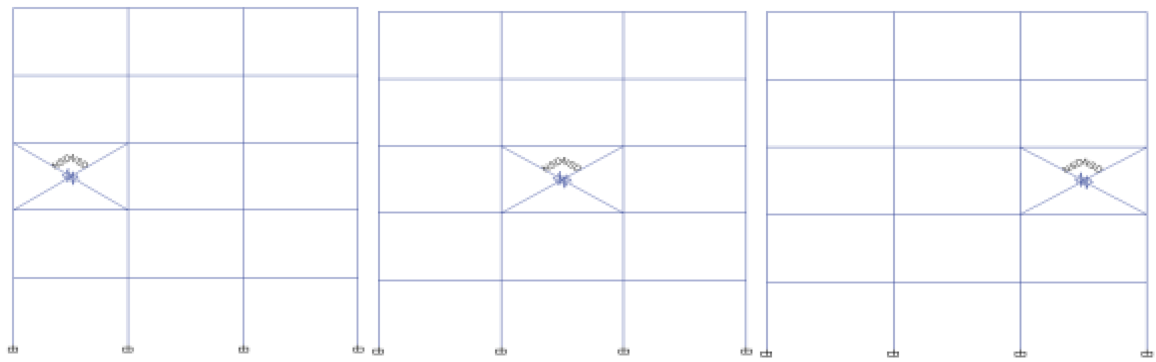
(a) (b) (c)

Figure 2.4 Model 2 Frame with NSD at GF (a) Bay 1 (b) Bay 2 (c) Bay 3



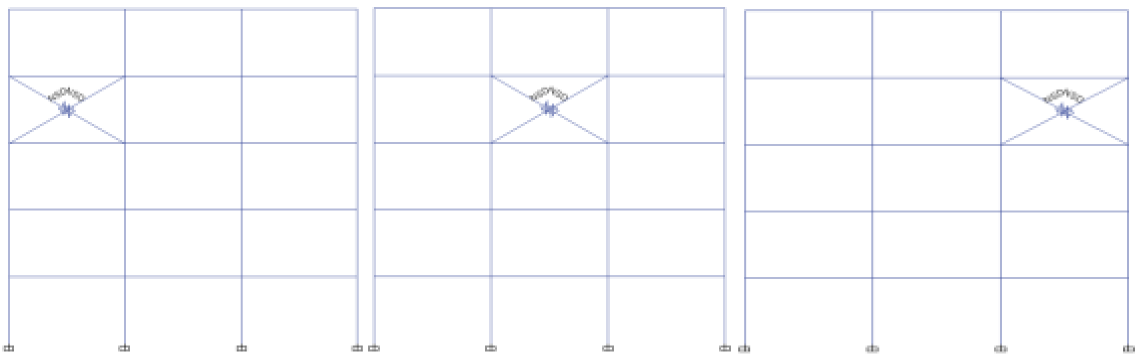
(a) (b) (c)

Figure 2.5 Model 3 Frame with NSD at FF (a) Bay 1 (b) Bay 2 (c) Bay 3



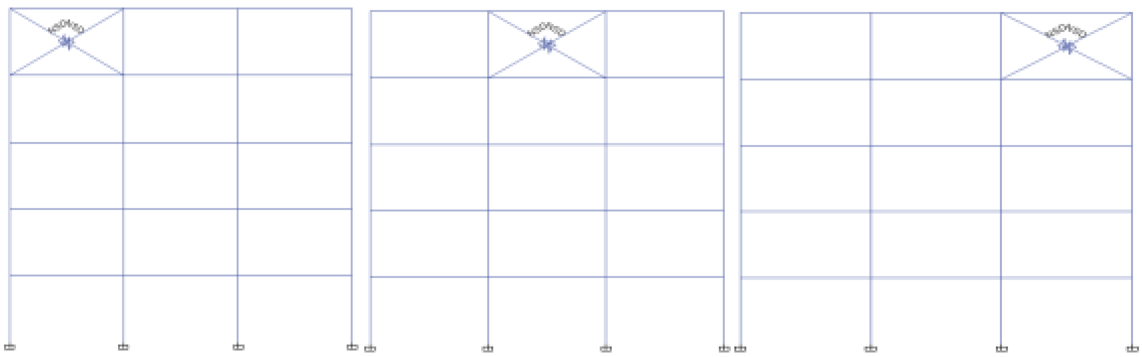
(a) (b) (c)

Figure 2.6 Model 4 Frame with NSD at SF (a) Bay 1 (b) Bay 2 (c) Bay 3



(a) (b) (c)

Figure 2.7 Model 5 Frame with NSD at TF (a) Bay 1 (b) Bay 2 (c) Bay 3



(a) (b) (c)

Figure 2.8 Model 6 Frame with NSD at 4th F (a) Bay 1 (b) Bay 2 (c) Bay 3

III. Method of analysis

3.1 Mathematical Formulation of NSD

By considering equilibrium of Negative Stiffness Damper following relationships are obtained by Nagarajaiah *et al*, 2013.

$$F_{NSD} = -\left(\frac{P_{in} + K_s l_p}{l_s} - K_s \right) \left(\frac{l_1}{l_2} \right) \left(2 + \frac{l_2}{l_1} + \frac{l_p + l_1}{\sqrt{l_2{}^2 - u^2}} \right) u + F_g \qquad (1)$$

$$F_g = \begin{Bmatrix} k_{g1} u, & 0 \le u \le d_{gap} \\ k_{g1} d_{gap} + k_{g2}\left(u - d_{gap}\right) & u > d_{gap} \end{Bmatrix} \qquad (2)$$

$$l_p = \sqrt{l_s^2 - u^2\left(1+\left(\frac{l_1}{l_2}\right)\right)^2} - l_1 + l_1\sqrt{1-\left(\frac{u}{l_2}\right)^2} \qquad (3)$$

Table3.1-Properties of NSD used in the force-displacement expression (Nagarajaiah *et al*, 2013)

Parameter	Value
Distance from spring to fixed pin (l_1)	25.4 cm
Distance from lever pin to fixed pin (l_2)	12.7 cm
Spring length(l_p)	76.2 cm
Gap opening (d $_{gap}$)	1.65 cm
GSA stiffness for spring1 (k_{g1})	4.9 kN/cm
GSA stiffness for spring2 (k_{g2})	0.3 kN/cm
The initial pre-compression force in the spring (P_{in})	16.5 kN
Spring rate (ks)	1.4 kN/cm

3.2 Modelling of NSD in ETABS 2016

Program ETABS2016 contains the “non-linear 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.

Table 3.2 gives the secondary properties of NSD link that need to be given in ETABS 2016.

Table 3.2- Secondary properties of NSD link

	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 PYTHON code is developed for solving equations (1) and (2). The force displacement values obtained from PYTHON results are used as input parameters in ETABS 2016 to model Negative Stiffness Damper.

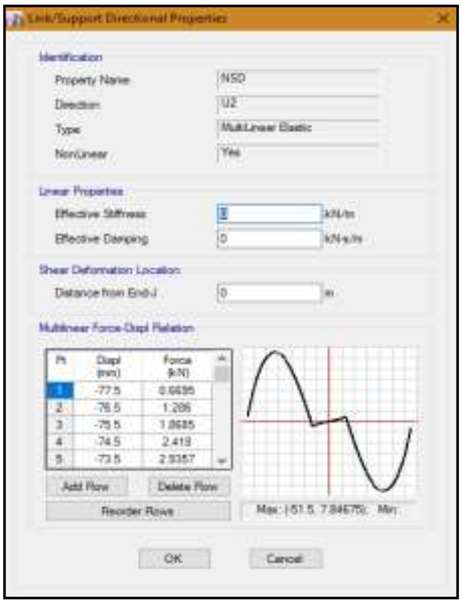


Figure 3.1 NSD properties assigned in ETABS 2016

IV. Results and Discussion

Results are obtained by using Time history analysis in the form of base shear, storey displacement and storey acceleration.

4.1 Base shear of 2D model for Corralit, Holliste and Sylmar earthquake ground motion

Fig 4.1, 4.2 and 4.3 shows a reduction in base shear of **15.96%** when NSD is applied at ground floor of Bay 2 for Corralit time history load case, **37.61 %** when NSD is applied at third floor of Bay 2 for Holliste time history load case and **64.88%** when NSD is applied at first floor of Bay 1 or Bay 3 for Sylmar time history load case.

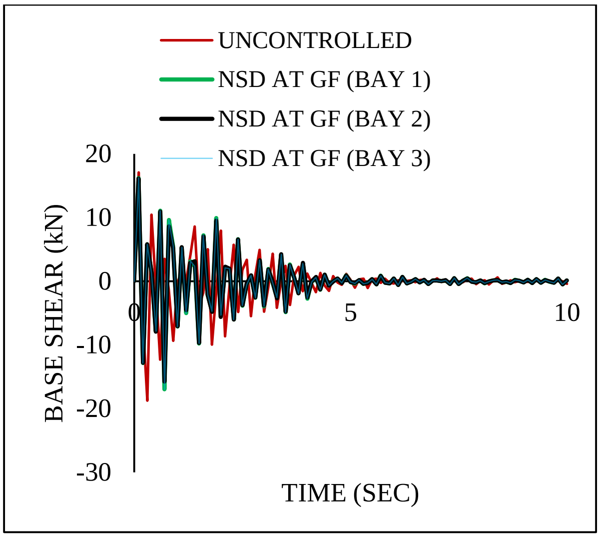


Figure 4.1 Base shear comparison for Corralit TH load case

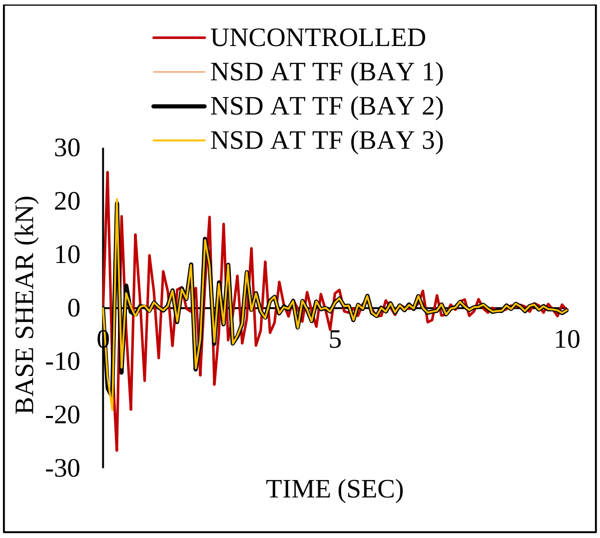


Figure 4.2 Base shear comparison for Holliste TH load case

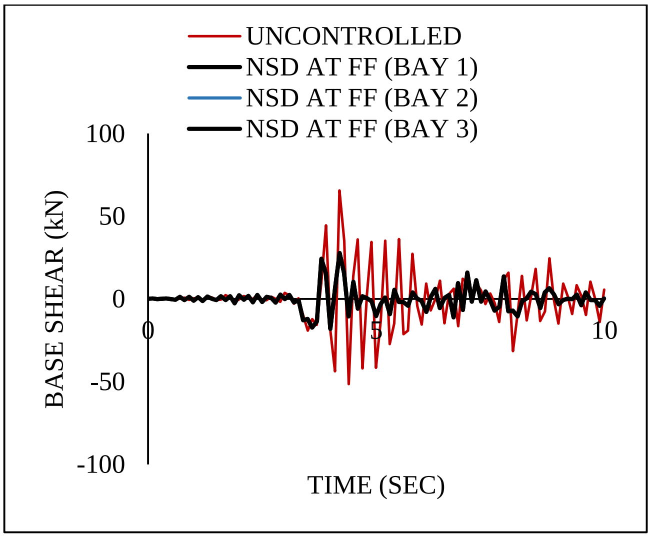


Figure 4.3 Base shear comparison for Sylmar TH load case

4.2 Storey displacement of 2D model for Corralit, Holliste and Sylmar earthquake ground motion

Fig 4.4, 4.5 and 4.6 shows, that the optimum placement of NSD is at second floor of Bay 2 for Corralit, third floor of Bay 2 for Holliste and third floor of Bay 2 for sylmar time history load case respectively when storey displacement is considered. However on the basis of base shear the optimum location decided was at ground floor of Bay 2 for Corralit, third floor of Bay 2 for Holliste and first floor of Bay 1 or Bay 3 (due to symmetry in the structure) for Sylmar time history load case. Thus the response in storey displacement increases with this optimum location. As mentioned earlier in literature review that NSD has to be implemented in structure to reduce the responses for base shear and acceleration. This drawback can be overcomed by adding additional passive dampers with NSD and the assembly is called as Adaptive negative stiffness system (ANSS).

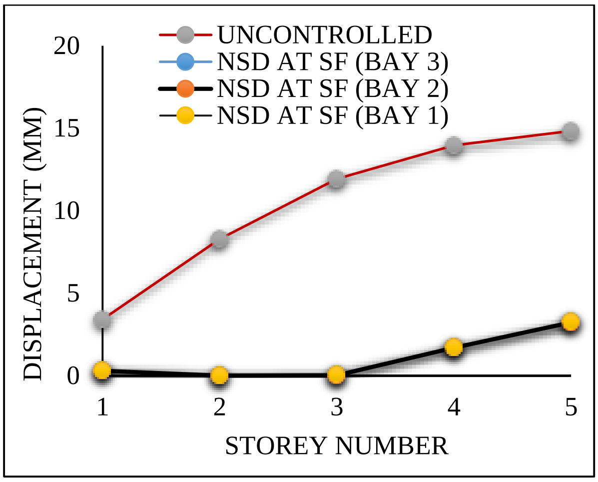


Figure 4.4 Storey displacement comparison for Corralit TH load case

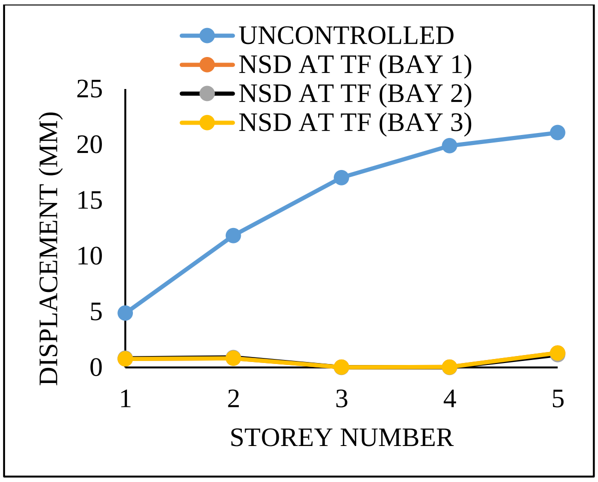


Figure 4.5 Storey displacement comparison for Holliste TH load case

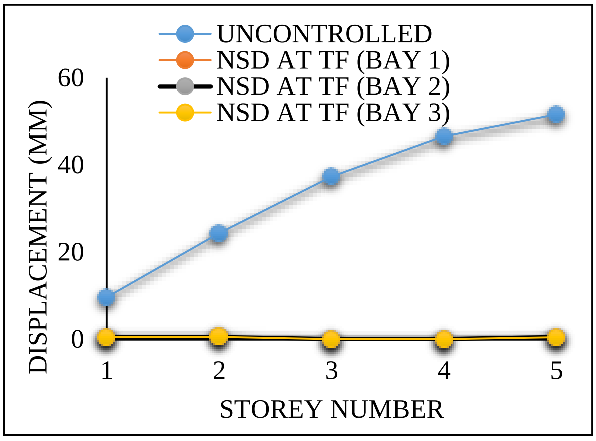


Figure 4.6 Storey displacement comparison for Sylmar TH load case

4.3 Storey acceleration of 2D model for Corralit, Holliste and Sylmar earthquake ground motion

Fig 4.7, 4.8 and 4.9 shows that the optimum placement for NSD is at ground floor of Bay 2 for Corralit, first floor of Bay 2 for Holliste and third floor of Bay 1 or Bay 3 for Sylmar time history (TH) load case. Based upon the seismic response control obtained in base shear and story acceleration it can be concluded that the best possible location of the NSD in 2D model is ground floor of Bay 2 for Corralit, first floor of Bay 2 for Holliste and third floor of Bay 1 or Bay 3 for Sylmar time history load case respectively.

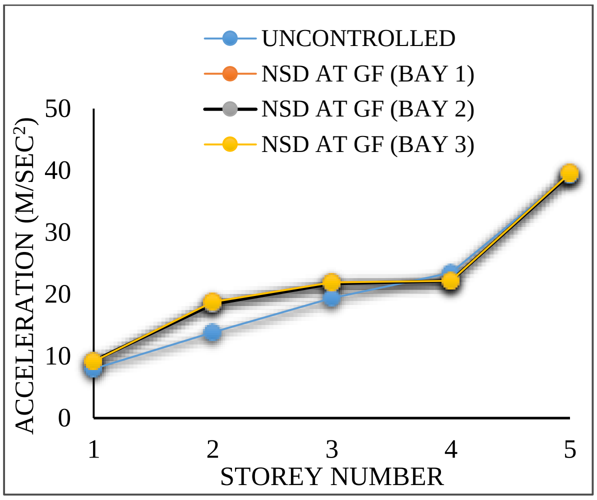


Figure 4.7 Storey acceleration comparison for Corralit TH load case

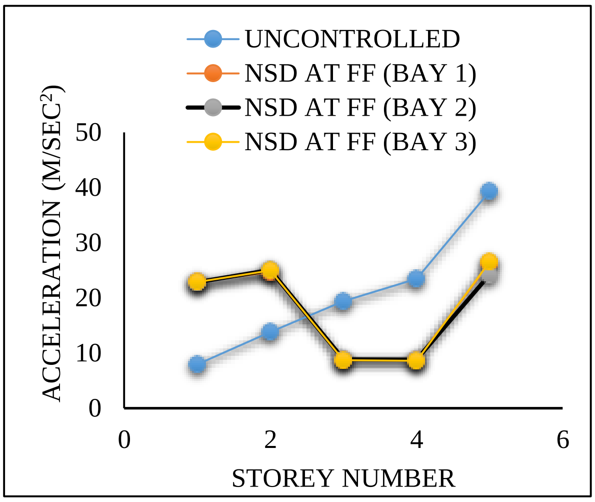


Figure 4.8 Storey acceleration comparison for Holliste TH load case

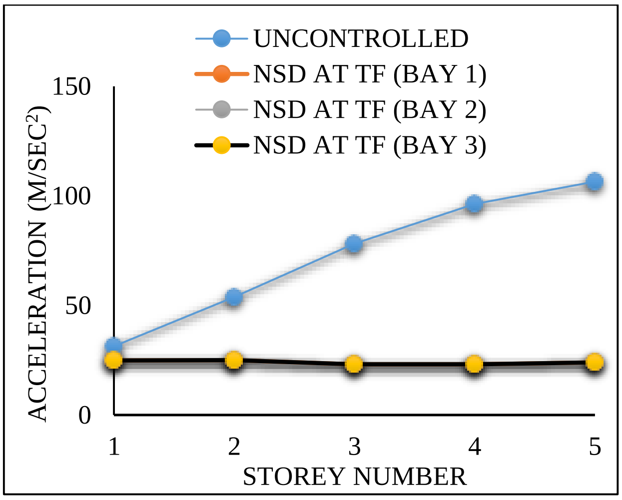


Figure 4.9 Storey acceleration comparison for Sylmar TH load case

V. Conclusions

In the present study analysis of 2D steel frame with and without negative stiffness dampers are carried out using time history analysis in ETABS 2016 software. Three earthquake load histories are used viz, Corralit, Holliste and Sylmar. Based upon the analytical study following conclusions are drawn:

1. Negative Stiffness Damper helps to reduce the base shear and storey acceleration respectively from the results compared with models without Negative Stiffness Damper for all the three considered earthquake load history.
2. Optimal position of Negative Stiffness Damper is decided based upon two seismic parameters namely base shear and storey acceleration.
3. Based on the present study optimal location obtained of 2D model for Corralit earthquake time history is ground floor of Bay 2, Holliste earthquake time history is first floor of Bay 2 and Sylmar earthquake time history is third floor of Bay 1 or Bay 3 respectively.
4. Overall result shows that Negative Stiffness Damper increases the displacement at the level of installation due to apparent weakening introduced by Negative Stiffness Damper. However, it can be controlled by using any passive damper in parallel with NSD.

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