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A New Structural Modification Approach for Seismic Protection using Adaptive Negative Stiffness Device

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ABSTRACT

Column forces, displacements and accelerations experienced by the structure during strong ground motions can be reduced by weakening and (or) softening the structure and adding a supplemental damper. Although this approach proved to be promising analytically, the concept of “structural strength reduction” leads to inelastic behavior and large permanent deformations in the main structural system. In this paper a new concept is developed to emulate weakening in a structural system by adding an “adaptive negative stiffness device” (NSD) and shifting the “yielding” away from the main structural system; leading, to the new idea of “apparent weakening” with reduced inelastic excursions in the main structural system. This is achieved through an adaptive negative stiffness system (ANSS), which is a combination of NSD and a damper. Engaging the NSD at an appropriate displacement (simulated yield displacement), that is well below the actual yield displacement of the structural system, will result in a composite structure-device assembly that 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. Essentially, a yielding-structure is “mimicked” without any, or with minimum yielding and permanent deformation in the main structure. In summary, the main structural system undergoes less acceleration, less displacements and less base shear, while the ANSS “absorbs” them. This paper presents the working principle and details on development and study of the ANSS/NSD. Through numerical simulations, the effectiveness and the superior performance of the ANSS/NSD as compared to a structural system with supplemental passive dampers is presented.

INTRODUCTION

Conventional structures designed for loads specified by codes undergo significant inelastic deformations during severe earthquakes, leading to stiffness and strength degradation, increased inter-storey drifts, and damage with residual drift. These yielding structures however keep the global forces within limited bounds dictated by the yielding levels. The inelastic effects can be reduced to some extent using passive seismic protection systems in the form of supplemental damping devices. This approach has emerged as an efficient way to reduce response and limit damage by shifting the inelastic energy dissipation from the framing system to the dampers (Lobo *et al.*, 1993, Constantinou and Symans, 1993, Spencer and Nagarajaiah, 2003). Examples of few such passive systems are base isolation systems (Nagarajaiah et al. 1991, Nagarajaiah *et al.* 2005, 2006; Narasimhan *et al.*, 2006), fluid dampers (Constantinou and Symans, 1993,1997), adaptive tuned mass dampers (Nagarajaiah 2009), adaptive friction dampers (Fenz and Constantinou, 2008), active and semiactive control (Spencer and Nagarajaiah 2003).

Adaptive systems belong to the category of passive seismic protection systems but they are more sophisticated than the regular passive systems. An adaptive system consists of adaptive stiffness and/or damping devices which are capable of changing the stiffness and/or damping of the device depending on the displacement amplitude (Nagarajaiah 2009, Fenz and Constantinou, 2008). These devices are designed to exhibit a force-displacement behavior which upon the addition of structural properties will result in an adaptive system having superior characteristics compared to the original structure. Adaptive systems can also be classified into variable stiffness devices and variable damping devices (Nagarajaiah 2009, Spencer and Nagarajaiah, 2003).

Recently, Iemura and Pradono (2009) proposed pseudo-negative-stiffness dampers (PNSD) that are hydraulic or semiactive or active devices capable of producing negative-stiffness hysteretic loops. It has been shown in their investigations that by adding negative-stiffness hysteretic loops the total force would be lowered significantly. Common passive dampers that act in parallel with the stiffness of structure add to the total force rendering the shear force larger than that due to stiffness of the base-structure alone. Iemura and Pradono (2009) have also reported the applications of PNSD to the benchmark control problems for seismic response reduction. Effectiveness of the proposed method has been validated on three benchmark structures, cable-stayed bridges, buildings, and highway bridges, subjected to various types of recorded ground motions (Iemura and Pradono, 2009). It must be noted that the passive hydraulic dampers cannot "push" the structure is the same direction as the structural displacement; the adaptive NSD proposed in this paper can. Since the NSD has a precompressed spring, it has the ability to push the structure in the same direction as the structural displacement generating the true negative stiffness, instead of pseudo negative stiffness. A hydraulic device that is fully active or semiactive as in the case of PNSD can generate a pseudo-negative stiffness in which case feedback control would be needed to generate the negative stiffness.

All the methods described in this section thus far suffer from one or other limitation: 1) active control devices require feedback and substantial power; 2) semi-active controllers require feedback but nominal power 3) passive control devices may reduce displacement but lead to larger base shear. Combination of adaptive negative stiffness and damping device can result in reduction in base shear and displacement response of the structure. However, to date truly negative stiffness systems have received relatively little attention as compared to aforementioned semiactive or pseudo negative stiffness systems and thus represent a significant gap. Hence, development of new true negative stiffness devices is necessary to reduce the inelastic behavior excursions in the main structural system. ANSS/NSD can reduce damage in frames by reducing the base shears and deformations and they can also eliminate residual inter-storey drifts.

Reinhorn *et al.* (2005) and Viti *et al.* (2006) introduced the concept of weakening structures (reducing strength and stiffness), while introducing added viscous damping to reduce simultaneously total accelerations and inter-story drifts. Design methodologies for softening the structure (reducing stiffness) and adding damping devices using control theory have been proposed by Cimellaro *et al.* (2009) to determine the locations and the magnitude of weakening and/or softening of structural elements and the added damping while insuring structural stability. A two-stage design procedure was suggested: (i) first using a nonlinear active control algorithm, to determine the new structural parameters while insuring stability, then (ii) determine the properties of equivalent structural parameters of passive system, which can be implemented by removing or weakening some structural elements, or connections, or reduction of stiffness of the main structural elements and by addition of energy dissipation systems. Passive dampers and weakened elements were designed using an optimization algorithm to obtain a response as close as possible to an actively controlled system.

In this study a new concept of ANSS is proposed and the idea of "adaptive weakening." The original stiffness of the main structural system is left unchanged in the proposed ANSS and the "adaptive weakening" occurs due to NSD that mimics the "yielding" thus attracting it away from the main structural system—unlike the weakening concept proposed earlier, wherein the main structural system stiffness itself is reduced.

This paper presents comprehensive details of development and study of the behavior of the ANSS/NSD. The NSD is described in detail and its force-displacement loop is presented. Through numerical simulations it is shown that the concept of ANSS/NSD is very effective in elastic and inelastic structural systems. The effectiveness and the superior performance of the ANSS/NSD as compared to a structural system with supplemental passive dampers when subjected periodic and random input ground motions is demonstrated by numerical results.

PRINCIPLE OF ADAPTIVE NEGATIVE STIFFNESS SYSTEM (ANSS)

From here on adaptive negative stiffness system (ANSS) refers to the assembly of NSD and NPD—damper, unless described otherwise. It can also be simply referred as adaptive system or adaptive stiffness system. The main objective of the adaptive system is to reduce the inelastic excursions of the main structure and reduce the base shear of the structure and at the same time limit the maximum displacement of structure. Adaptive systems belong to the category of passive seismic protection systems but they are more sophisticated than the regular passive systems. The adaptive system that is developed in this work consists of two components that are designed in a two step sequence. First a truly adaptive negative stiffness device, which is capable of changing the stiffness of the device during lateral displacement, is developed based on the properties of the structure. This NSD is designed to exhibit true negative stiffness behavior which upon the addition of structure properties will result in reduction of the stiffness of the structure and NSD assembly or "adaptive weakening" there by resulting in the reduction of the base shear of the assembly. Then a passive damper is added to reduce the displacements that are caused due to the reduction in stiffness. It has been found through simulation studies that the deformations of the structure and NSD assembly can be reduced using a passive damper--there by reducing the base shear and displacement in a two step process. An alternate explanation to justify the need for a NSD is explained in the next part of this section.

NEGATIVE STIFFNESS DEVICE (NSD)

True negative stiffness means that the force must assist motion, not oppose it as it is in the case of a positive stiffness spring. Psuedo negative stiffness can be accomplished using active or semiactive hydraulic device. In this paper the authors develop a new device that is passive, as it does not need any feedback signal or external power supply to generate the desired force. NSD has a precompressed bar, nonlinear springs and nonlinear damper (Nagarajaiah and Reinhorn, 1994). Schematic diagram showing the configuration of ANSS is shown in Figure 1(a) and the actual NSD placed in a base isolated system is shown in Figure 1(b). The properties of precompressed vertical spring and nonlinear horizontal springs are chosen in such a way that the desired force displacement is achieved. Precompressed bar is placed vertically between the beam and the top of the chevron brace. Since this is an unstable equilibrium for the spring, any inter-storey drift will result in a lateral force that assists the motion. For complete details of the device and its experimental validation the reader is referred to Sarlis *et al*. (2011).

Working principle: Assume a perfectly-linear single degree of freedom structure with stiffness, K_e, and no damping, an NSD with stiffness K_n and a passive damper with damping coefficient C. The force displacement plots are shown in Figure 2(a) (green line is structure, magenta is viscous damper and red is negative stiffness device). By adding NSD to the structure, schematically shown in Figure 2(b), the assembly stiffness reduces to K_a=K_e–K_n beyond the displacement x_1 (shown as blue line in Figure 2(b)). If, F_2 and x_2 are the maximum restoring force and maximum displacement of a perfectly-linear system (green line in Figure 2(b)) then for the same load the maximum restoring force and maximum displacement of the assembly are F_3 and x_3 (blue line in Figure 2(b)), respectively. K_n is designed to achieve the desired reduction in base shear. Force exerted by the NSD is shown as red line in Figure 2(b). Although the reduction in base shear is achieved the maximum deformation of adaptive system is increased in the process when compared with an elastic system.

Deformation of this assembly can be reduced by adding a passing damping device in parallel to the NSD. To demonstrate the concept, a linear viscous damper is used for illustration but a nonlinear damper is a more optimal choice. An optimization needs to be performed to find the best suited nonlinear passive damper (NPD). By adding the viscous damper to the structure along with NSD maximum displacement is reduced resulting in $x_3 < x_2$. Since the assembly of structure and NSD acts like a nonlinear elastic system, viscous damper even with a very small damping coefficient can be effective. It should be noted that by adding a damper to structure and NSD assembly, base shear of the assembly is not significantly increased.

From Figure 2(a,b,c) it can be seen that there is an offset displacement, x_1, called as "simulate yield-displacement", before the negative stiffness device is engaged. This is to avoid excessive response for relatively small external excitations. For displacements x such that $|x| < |x_1|$ the NSD assembly provides zero force and the structure behaves like the original linear structure. A provision to create this initial gap can be provided in the actual device using a pair of mechanical springs.

Analytical Model: The force in the NSD is given in Eq. (1) (Nagarajaiah and Reinhorn, 1994; Sarlis *et al.*, 2011). Force displacement characteristics of the vertical spring, horizontal spring and the NSD are shown in Figure 3. When the precompressed vertical spring is displaced to an inclined position at angle θ_s from the vertical, the axial force of the vertical spring, F_s, is given by

$$F_s = \left\{ P_{in}/K_s - \left(l_s - l_p \right) \right\} K_s \tag{1}$$

where K_s is the vertical spring stiffness, l_s is the length of the inclined spring, l_p is the length of vertical spring when u=0, P_{in} is the initial compression force in the vertical spring. The horizontal component of F_s assists the motion creating negative stiffness upto to zero force point beyond which the stiffness turns positive as shown in Figure 1(a). The addition of an horizontal elastoplastic spring ensures that the initial gap occurs before the NSD engages. A force-displacement loop of NSD—for a particular set of parameters—is shown in Figure 3 (red line), in comparison with the elasto-plastic base-structure (green line) and the structure + NSD (blue line).

PASSIVE DAMPING DEVICE

In the previous section a detailed study on the desired characteristics of NSD was described. Since the NSD reduces the effective stiffness of the structure+NSD assembly increased deformations will result. To limit these deformations a nonlinear passive damper has to be used. Assuming that we have the design ground motion for which the adaptive system has to be designed, the first step is to find the active control force exerted by the output feedback controller to satisfy desired performance specifications. Using optimization method proposed by Cimellaro *et al.* (2009), wherein the optimal properties of the damper, that minimizes the error between the active control force and force exerted by the passive devices, can be found. In this study, with the assumed NSD properties, a linear viscous damper with 20% damping ratio is found to be very effective. Force exerted by the passive damper is given by the following equation

$$F_{NPD} = 2\xi \sqrt{K_e m}\, \dot{x} \tag{2}$$

where, F_{NPD} is the force exerted by the damper, is the damping ratio, K_e is the elastic stiffness of structure and m is the mass of the structure. As mentioned in previous section the main objective of the adaptive system is to reduce the base shear of the structure and at the same time limit the maximum displacement of structure. It will be uneconomical and unrealistic to design devices that will retain the structure in elastic state, without any yielding, after a major earthquake. So, all the studies in this paper involves structure whose properties are representative of a real building and the loading cases for which there is yielding in the structure are also considered.

Ultimate goal of this study is to prove the concept and the effectiveness of the proposed ANSS/NSD analytically and experimentally. All the simulation studies presented in this paper are for a 1:3 scale three storey frame structure developed at University at Buffalo for a study of zipper frames. In the initial phase 2^{nd} and 3^{rd} floors of the frame are braced rendering it essentially as a single degree of freedom system, which is considered in this study. Push-over curve for the zipper frame is obtained using the commercial software with the exact detail. Sivaselvan-Reinhorn model (Sivaselvan and Reinhorn, 2001) is used to capture the bi-linear hysteresis characteristics observed in the three-storey frame. Strength degradation and pinching are ignored. Governing equation of motion for the structure is shown in Eq. 3,4. Simple parameters like K_e and ε are obtained from the push-over curve. Mass of the structure, *m*, is measured and the values for remaining parameters are obtained using an optimization algorithm. Description of the variables is given in Table-1.

$$m\ddot{x} + \left(2\xi\omega_n m\right)\dot{x} + \alpha\left(1-\varepsilon\right)z + \varepsilon K_e x = -m\ddot{x}_g \tag{3}$$

$$dz/dx = K_e\left(1 - \left|z/K_eY\right|^{\eta}\left(\gamma\,\mathrm{sgn}\left(z\dot{x}\right) + \beta\right)\right) \tag{4}$$

SIMULATION RESULTS

Periodic Ground Motion: For all the results, for periodic input, presented in this work, 10 cycles of sinusoidal input are considered. Excitation frequency is same as the natural frequency of the base structure, $\omega_n = \sqrt{K_e/m}$.

Elastic Systems**:** For those systems that will remain in elastic region for the design ground motion, NSD is found to be very effective. NSD will reduce the base shear of the structure substantially. To demonstrate this fact, a periodic ground motion is applied to the zipper frame. Amplitude of the ground motion is chosen such that the structure and NSD assembly will remain in elastic region. Adaptive system here refers to the structure and NSD assembly; damper is not used. Response time histories comparing the actual structure and adaptive system (structure + NSD) are shown in Figure 4. It can be seen from results in Figure 4 that all the response characteristics i.e., displacement, velocity and acceleration of the base structure (red curve) are higher that the adaptive system (green curve). Force-displacement behavior of the actual structure and the adaptive system are shown in Figure 5; it is evident from these results that the adaptive system remains in the elastic region whereas the base structure yields. The component forces acting in the adaptive system are shown in Figure 6. “Simulated yield displacement” for the NSD is assumed at a normalized displacement of 0.25. It should be noted that passive damper is not yet included for the results shown in Figures 4, 5 and 6. For the systems that remain in elastic region, NSD alone is effective for reducing base shear without any increased deformations. A passive damper can be added to reduce the deformation of structure along with the base shear.

Inelastic Systems: The performance of the NSD is further verified for higher input amplitudes. Amplitude of input ground motion is increased so that the adaptive system starts yielding. For yielding structures NSD alone will not improve the performance of the adaptive system. Passive damper has to be added to limit the excessive displacements caused due to reduction in the overall stiffness of the structure.

Passive viscous damper with 20% damping ratio is used in the simulations studies presented in the paper. Three systems are compared after the addition of passive viscous damper (1) Bilinear system (referred to as BS), (2) Bilinear system + passive damper (referred to as PS), and (3) Bilinear system + passive damper + NSD (referred to as ANSS).

For the same input amplitude and 10 input cycles it was found that, by adding the passive damper the deformation of the structure is reduced substantially with a slightly higher base shear (Nagarajaiah *et al.*, 2010). In addition, the acceleration of adaptive system is 40 % less--compared to passive system and base structure system. Due to the presence of NSD in adaptive system the base shear is reduced substantially, whereas in the case of passive system base shear is larger than the case with base structure alone.

To study the efficiency of the ANSS/NSD, performance of the aforementioned systems is verified for Kobe ground motion. The response histories and the force-displacement loops for Kobe earthquake excitation are shown in Figures 7 and 8 respectively. The system with NSD and damper reduces both the displacement and base shear significantly, as evident in Figures 7 and 8.

CONCLUSIONS

A novel and new adaptive negative stiffness system (ANSS) and negative stiffness device (NSD) is proposed and developed in detail in this paper along with a new concept of "adaptive weakening". The proposed NSD does not rely on structural-response feedback and external power supply—unlike previously reported pseudo-negative stiffness devices that do depend on active control—hence, is passive, and exhibits true adaptive negative stiffness behavior by possessing predesigned variations of stiffness as a function of structural displacement amplitude. Addition of NSD to the structural system will result in the reduction of stiffness in the combined system or "adaptive weakening" occurs; however, it is important to note that the stiffness of the base-structure remains unchanged in this study—unlike the concept of weakening proposed earlier wherein the stiffness of the base-structure itself is reduced. Addition of the passive damper reduces the displacements that are caused due to the reduction in effective stiffness.

Effectiveness of the proposed ANSS/NSD in elastic and inelastic structural systems has been demonstrated through the simulation studies for periodic and random input ground motions. It has been shown that the main structural system suffers less force, less displacements and less damage, while the ANSS “absorbs” them.

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Table 1: Description of variables

Description	Variable	Variable	Description
Yield displacement	Y	$\ddot{x}_g$	Ground displacement
Mass	m	ξ	Damping ratio
Pre-yielding stiffness	K_e	ω_n	Natural frequency
Yield strength	K_eY	ε	Post yield stiffness ratio
S-R Model parameter-2	γ		S-R Model parameter-3
S-R Model exponent	η		

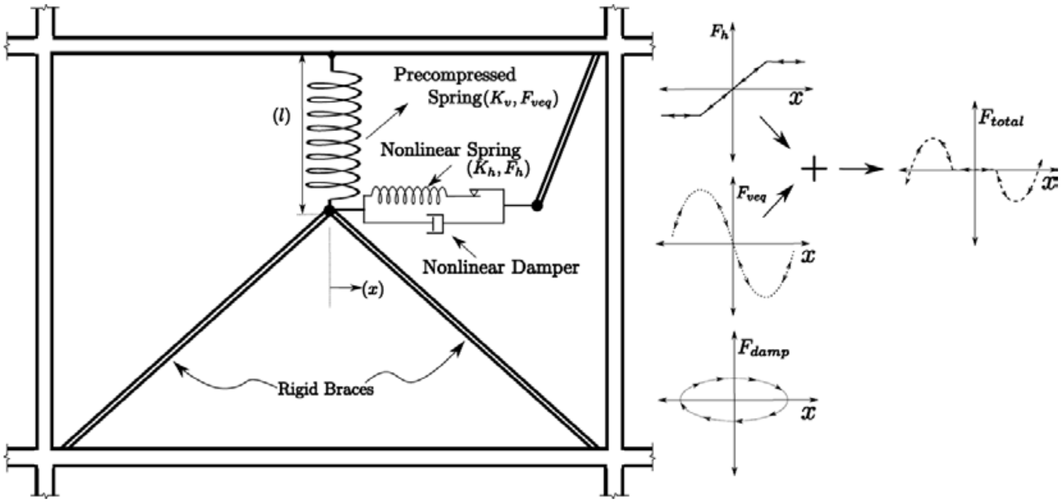


Figure 1(a): The New Concept of ANSS/Negative Stiffness Device—NSD.

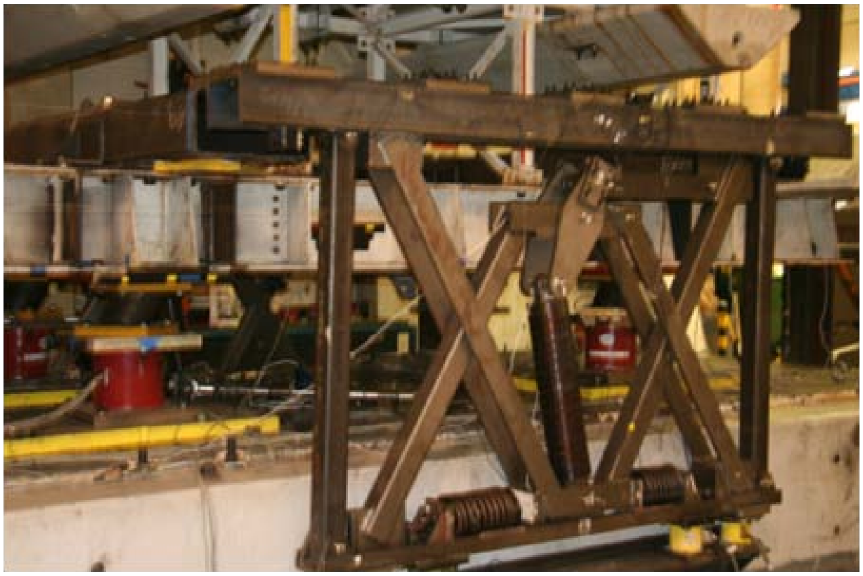
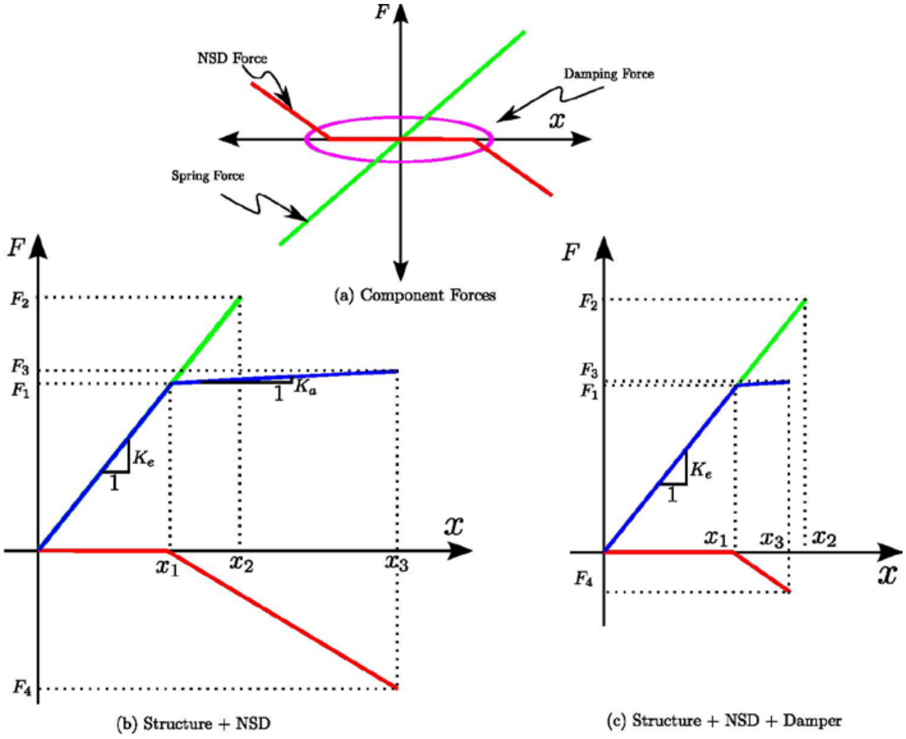


Figure 1(b): NSD placed in a base isolated building tested at SUNY-Buffalo



(a) Component Forces

(b) Structure + NSD

(c) Structure + NSD + Damper

Figure 2: Working principle of ANSS (a) Component F-D plots (b) Linear system with Negative stiffness Device (c) Linear system with Negative stiffness device and Damper [Green- Base-structure, Red- NSD, Blue- Assembly]

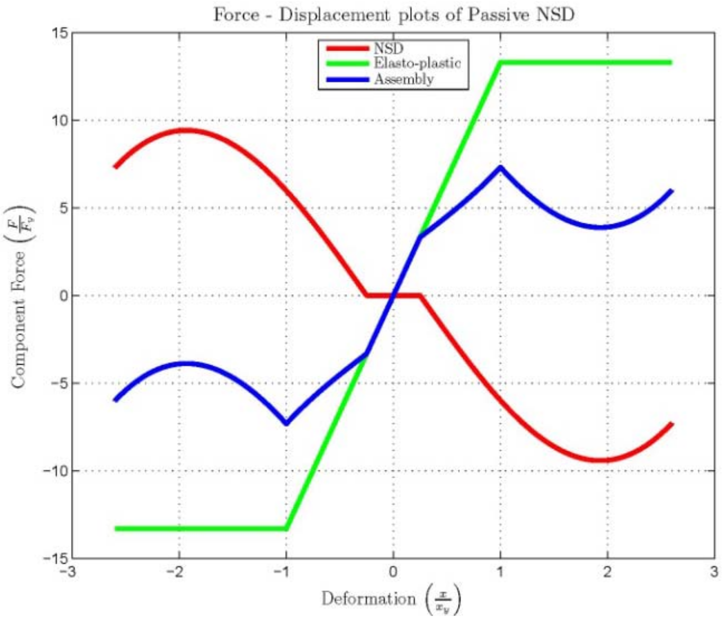


Figure 3: Force-displacement loops of NSD [Green- Base-structure, Red- NSD, Blue- Assembly]

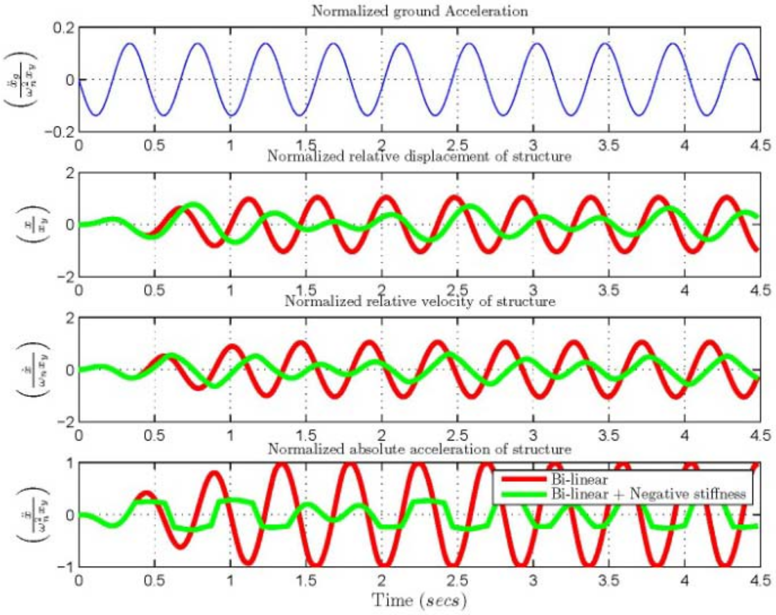
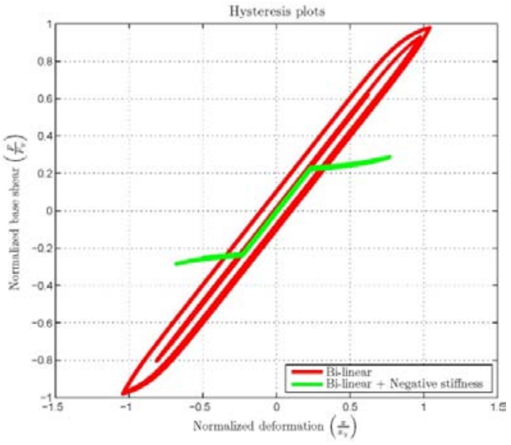


Figure 4: Comparison of responses of system with and without NSD (with the main structure being essentially elastic)



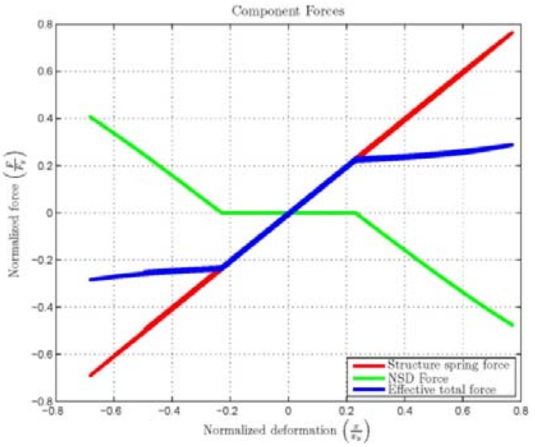


Figure 5: Comparison of hysteresis loops of system with and without NSD (with the main structure being essentially elastic)

Figure 6: Comparison of component spring forces of the adaptive system (with the main structure being essentially elastic)

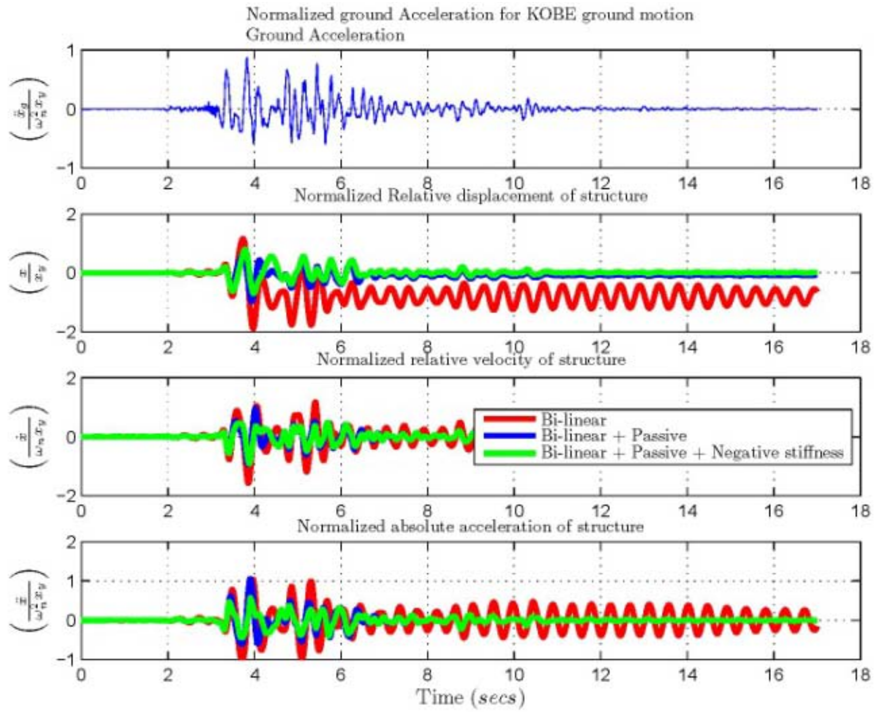


Figure 7: Comparison of responses with and without passive damper/NSD (with structure yielding) under Kobe earthquake excitation.

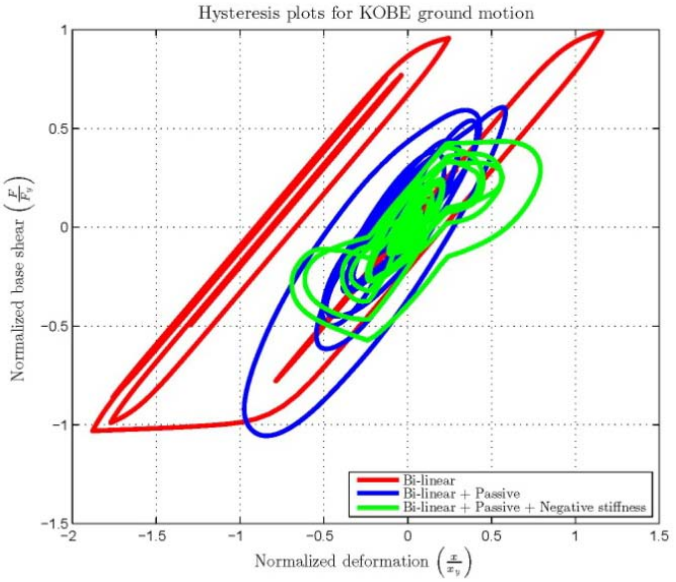


Figure 8: Comparison of hysteresis loops of system with passive damper/NSD (with structure yielding) under Kobe earthquake excitation.