ADAPTIVE NEGATIVE STIFFNESS: A NEW STRUCTURAL MODIFICATION APPROACH FOR SEISMIC PROTECTION

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Abstract

As it is well known in the field of structural dynamics, by designing a ductile structure and letting the structure yield under strong earthquakes, the forces acting on the structure can be reduced to the level dictated by the yield level. However, the structure undergoes permanent displacement. In this study yielding is emulated in a structural system by adding a " ***adaptive negative stiffness device***" and shifting the “yielding” away from the main structural system—leading to the new idea of "***apparent softening and weakening***" that occurs ensuring structural stability at all displacement amplitudes. For this purpose a novel adaptive negative stiffness device, NSD, that is capable of changing the stiffness as a function of device displacement, is developed. By engaging the adaptive negative stiffness device (NSD) at an appropriate displacement (simulated yield displacement), which is well below the actual yield displacement of the structural system, a composite structure-device assembly, behaves like a yielding structure is achieved. The NSD has a re-centering mechanism thereby avoids permanent deformation in the composite structure-device assembly unless, the main structure itself yields. Essentially, a yielding-structure is "mimicked" without any or minimal permanent deformation or yielding in the main structure. Due to the addition of NSD the stiffness of the combined structural system is reduced substantially beyond simulated yield point resulting in increased structural deformations. Addition of a nonlinear passive damper reduces and controls these deformations without any considerable increase in the base shear.

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 adaptive negative stiffness behavior by possessing predesigned variations of stiffness as a function of structural displacement amplitude. The system is called adaptive because it is predesigned to undergo a desired adaptive stiffness changes at various displacement amplitudes. The adaptive negative stiffness system (ANSS) proposed in this paper consists of two elements: 1) a negative stiffness device (NSD) and 2) a passive damper (PD). Upon the addition of NSD to the structural system, predesigned reductions of stiffness occur in the combined system or "***apparent softening and weakening***" occurs; however, it is important to note that the stiffness and the strength of the main structural system remains unchanged in this study (hence, "apparent")—unlike the concept of weakening proposed earlier wherein the strength and implicitly stiffness of the main structural system itself are reduced. In summary, the main structural system suffers less accelerations, less displacements and less base shear or force at the foundation level, while the ANSS "absorbs" them.

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. The corresponding development of an actual NSD device and experimental/analytical study is in progress in the NEESR-Adapt-Struct (www.ruf.rice.edu/~dsg/) project. The results of the experimental/analytical study will be reported upon its completion in the near future.

Introduction

Conventional structures designed for loads specified by codes undergo significant inelastic deformations during severe earthquakes, leading to stiffness and strength degradation, increased interstory 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, Bracci, Shen, Reinhorn and Soong, 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, 2006a,b,c; Narasimhan *et al.*, 2006), fluid dampers (Constantinou and Symans, 1993,1998), adaptive tuned mass dampers (Nagarajaiah 2009), and adaptive friction dampers (Fenz and Constantinou, 2008).

Active-control of structures, wherein the excessive structural response can be attenuated using hydraulic actuators, can also be used to reduce inelastic behavior. The force exerted by the actuator is calculated in real-time using a control algorithm and feedback from sensors. Although this approach is more effective than passive-control, high power requirement and continuous measurement of feedback signal limit it's applications. Semiactive control strategies combine the best features of both passive and active control systems. Semiactive control devices offer the adaptability of active control devices without requiring the associated large power sources (Spencer and Nagarajaiah, 2003). Thus, semiactive systems have received considerable attention in the recent past. Semiactive systems operate on battery power, which is critical during seismic events when the main power source to the structure may fail. Even in semi-active control local feedback is unavoidable.

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).

Variable stiffness devices change the stiffness of the structure adaptively based on the measured feedback signal. Variable stiffness systems first developed by Kobori et al. at Kajima Research Institute, Japan, maintain a non-resonant state under seismic excitation by altering the stiffness, and thus natural frequencies, of a building based on the nature of the earthquake (Kobori et al., 1993). The stiffness is varied by engaging and disengaging the braces in each story of the structural framing system. The hydraulic devices connected between the chevron braces and the floor beams above are used to engage and disengage the bracing system in an on-off manner, thus producing abrupt (discontinuous) changes in stiffness. To overcome the limitations of the variable stiffness system, Nagarajaiah et al. developed a Semi-Active Instantaneously Variable Stiffness (SAIVS) system which varies the structural stiffness continuously and smoothly so as to maintain a non-resonant state (Nagarajaiah and Mate, 1998). The SAIVS device is a mechanical device consisting of four springs arranged in a rhombus configuration. The SAIVS device, which has been experimentally tested and shown to be effective, has been incorporated within a smart variable stiffness tuned mass damper (STMD) (Nagarajaiah 2009) and smart base isolated structures (Nagarajaiah et al. 2005, 2006a,b,c; Narasimhan *et al.*, 2006). Since it requires considerable space, the SAIVS device can only be implemented in an STMD at the top of a fixed-base building or at the base of a base-isolated structure. Due to space constraints, it cannot be implemented within the bracing system of fixed-base structures. Also, Yang et al (2000) have developed and shown the effectiveness of a Resetting Semi-Active Stiffness Device (RSASD).

Variable damping devices change the damping properties of the structure continuously or in multiple stages based on the measured feedback signal. Symans et al. (Symans and Constantinou 1997, Constantinou and Symans 1998) have developed variable damping systems that utilize variable orifice fluid dampers for structural systems and experimentally tested them at both the component level and within multi-story building frames and base isolated structures. The development of Magnetorheological (MR) fluids that are used in controllable fluid dampers represented a significant step forward in changing damping in attenuating the structural response. MR fluids typically consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil. Spencer and Dyke have conducted a number of studies to assess the usefulness of MR dampers for seismic response reduction (Spencer *et al.*, 1997). They also developed and tested a large-scale MR damper suitable for full-scale applications.

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. The passive negative stiffness friction damper—a convex frictional interface or bearing, opposite of the well known frictional pendulum base isolation bearing, that is essentially an unstable friction bearing—proposed by Imeura and Pradono (2009) can generate the pseudo negative stiffness. The pseudo negative stiffness is by virtue of the fact horizontal force at the convex frictional bearing assists the motion in either direction; however, this type of a system is primarily applicable to base isolated structures, wherein such frictional bearings are used. An additional complication of the pseudo negative stiffness friction bearing is that the structure to which it is attached has to accommodate significant vertical motion in additional to the horizontal displacement.

Nagarajaiah et al. (2005, 2006a,b,c) have studied smart base-isolated structures with combined SAIVS device and MR dampers and have shown that significant response reductions are possible by independently varying stiffness and damping. Such systems are called variable stiffness and damping systems. However, in these studies, the SAIVS device has the same physical limitations as previously described.

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 shift the inelastic behavior from the structural system to ANSS/NSD. 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 implicitly stiffness), while introducing supplementary 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 Reinhorn 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, reducing the yield capacity of the structure 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.

The new idea of "***apparent softening and weakening*** " and a new concept of ANSS are proposed in this study, The original stiffness and strength of the main structural system is left unchanged in the proposed ANSS and the "apparent softening and weakening" occurs due to NSD that mimics the "yielding" thus attracting it away from the main structural system—unlike the concept of weakening proposed earlier, wherein the main structural system strength and implicitly stiffness are 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 hereon adaptive negative stiffness system (ANSS) refers to the assembly of NSD and PD—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 shift the inelastic behavior of the structure to the NSD and reduce the base shear (foundation force) of the structure and at the same time limit the maximum displacement and acceleration 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 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 negative stiffness behavior which upon the addition of structure properties will result in reduction of the stiffness of the structure and NSD assembly or "apparent softening and weakening" there by resulting in the reduction of the base shear of the assembly. Then a passive damper is designed, for the assembly designed 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.

Importance of Negative stiffness device: Alternate explanation

Analytically, active control is the most effective, robust way for reducing the response of structure. But, from practical implementation point of view it suffers with two limitations: 1) large external power to drive the actuator and 2) dependency on the structural-response feedback. Recently, researchers have developed algorithms to break down the control force, calculated from any active control algorithm, into a combination of passive forces and the remaining marginal amount as an active force—a concept termed as "Integrated design of inelastic controlled structural systems" by Reinhorn, Cimellaro and Lavan (2009) using the concept "weakening" introduced by Cimellaro, Lavan, and Reinhorn (2009). Due to the limitations and unreliability of the active control devices during extreme events, the objective is to let the passive components take the maximum amount of force, which are more reliable, leaving very little for the actuators that impart active control force.

Consider a linear multi degree of freedom system with mass $\mathbf{M}$, stiffness $\mathbf{K}$ and damping $\mathbf{C}$ subjected to a ground motion $\ddot{\mathbf{x}}_g$. Equation of motion is shown in Eq. 1. $\mathbf{x}$ is the relative displacement vector of the structure and $\mathbf{F}_a$ is the desired active control force required to control the structure. $\mathbf{F}_a$ can be calculated easily using standard LQR control algorithms. Active control force can be represented as shown in Eq. 2. $\mathbf{G}_2$ and $\mathbf{G}_2$ are constant gain matrices. Using optimization, the gain matrices $\mathbf{H}_1$ and $\mathbf{H}_2$ can be found such that the error between $\mathbf{F}_a$ and $\mathbf{F}_p$ is minimized. $\mathbf{H}_1$ and $\mathbf{H}_2$ are the gain matrices that are directly associated to the additional damping and stiffness forces that need to be add to the structure using passive devices. The remaining force $\mathbf{F}_a - \mathbf{F}_p$ is implemented through an active device (Cimellaro *et al.*, 2009).

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = -\mathbf{M}\ddot{\mathbf{x}}_g + \mathbf{F}_a \quad (1)$$

$$\mathbf{F}_a = \mathbf{G}_1\mathbf{x} + \mathbf{G}_2\dot{\mathbf{x}} \quad (2)$$

$$\mathbf{F}_p = \mathbf{H}_1\mathbf{x} + \mathbf{H}_2\dot{\mathbf{x}} \quad (3)$$

The control force $\mathbf{F}_p$ is exerted through four passive components, namely: 1) Positive damping device ($\mathbf{C}_1\dot{\mathbf{x}}$), 2) Negative damping device ($\mathbf{C}_2\dot{\mathbf{x}}$), 3) Positive stiffness device ($\mathbf{C}_3\mathbf{x}$), and 4) Negative stiffness device ($\mathbf{C}_4\mathbf{x}$). The constants $\mathbf{C}_1$, $\mathbf{C}_2$, $\mathbf{C}_3$ and $\mathbf{C}_4$ are representative of properties of the devices. Positive and negative damping force can be implemented using fluid dampers. Positive stiffness can be implemented by additional bracing the only force that is hard to incorporate is the true negative stiffness. In this study a new concept of "apparent softening and weakening" is introduced wherein the "yielding" is shifted to the ANSS/NSD. A mechanism is proposed to develop the true negative stiffness force.

True 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 we develop a new device that is passive, as it does not need any feedback signal or external power supply to generate the desired force. Complete details of the device will be disclosed after the experimental validation which is currently in progress. NSD has a precompressed bar, nonlinear springs and nonlinear damper, similar to the idea proposed earlier by Nagarajaiah and Reinhorn (1994). The configuration of ANSS is shown in Figure 1. 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.

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. All the three elements are shown in Figure 2(a) and the force displacement plots are shown in Figure 3(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 3(b), the assembly stiffness reduces to $K_a = K_e - K_n$ beyond the displacement x_1 (shown as blue line in Figure 3(b)). If, F_2 and x_2 are the maximum restoring force and maximum displacement of a perfectly-linear system (green line in Figure 3(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 3(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 3(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, schematically shown in Figure 2(c). 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 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.

At this stage, there is one important constraint that is imposed on the NSD. From Figure 3(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. Another important constraint on NSD comes into picture when the structural system starts yielding. Assume an elastic-purely-plastic structure and NSD assembly, schematically shown in Figure 4(a). Force displacement plot of the base structure is shown as green line in Figure 4(b), and NSD as red line in Figure 4(b). If the structure is subjected to loads that will take it beyond the yield displacement, x_y, there are two limitations (refer to Figure 4(c)). First, the effective-stiffness of the adaptive system becomes negative i.e., for displacements greater than x_y the slope of blue line is negative, as shown in Figure 4(c). Which signifies an unstable condition and this behavior is not desired as it would result in the collapse of structure.

The second limitation is the increased base shear. In Figure 4 The structure yields first in the positive direction then after the first load reversal, when the structure yields in the negative direction, the base shear of the structure, F_o, and NSD assembly is greater than the base shear that is targeted, F_t, i.e. $|F_t| < |F_o|$. So the negative stiffness of the NSD has to be altered, once the structure starts yielding, to avoid this condition. Similar behavior is observed in case of bilinear system if the post-elastic stiffness of the base structure is less than the negative stiffness of the NSD. Three possible ways of altering the negative stiffness are (1) keeping the force exerted by the NSD constant beyond x_y (shown in 5(b) & Figure 6(b)), (2) disengaging NSD beyond x_y (shown in Figure 5(c)), (3) stiffening the NSD beyond x_y (shown in Figure 5(d)).

Three curves, shown in Figure 5 for each approach, are base-structure (green line), NSD (red line) and the structure + NSD assembly (blue line). Figure 5(a) is the response of an NSD without any constraints on the NSD, Figure 5(b),5(c),5(d) are the responses for 1^{st},2^{nd} and 3^{rd} approaches, respectively. From Figure 5, clearly 1^{st} and 3^{rd} approaches i.e., saturating or stiffening of the NSD after the structure undergoes deformation beyond yield point, are practical adaptive passive or semiactive approaches, respectively. Where as the second approach of disengaging the NSD after a certain displacement is not suitable, since, the base shear is same as uncontrolled system and there is sudden change in stiffness that leads to sharp jumps in acceleration that is undesirable.

Impact of the 1^{st} approach is shown more clearly in Figure 6. Schematic diagram of an elastic-purely-plastic structure and NSD assembly is shown in Figure 6(a). Force displacement plot of the base structure is shown as green line in Figure 6(b), and NSD as red line in Figure 6(b). Force-displacement of the structure + NSD assembly is shown in Figure 6(c). 1^{st} approach is an ideal case and is hard to develop a passive device that is capable of exhibiting this force-displacement behavior. Coincidentally, the NSD developed in this work is based on the 3^{rd} approach that is capable of exhibiting the hardening behavior beyond a certain displacement (after the precompressed bar looses its precompression) by adjusting the geometrical and mechanical properties of the elements in NSD. A semi-active approach has been developed to achieve the 1^{st} approach force-displacement behavior, however, this is beyond the scope of this paper.

Analytical model

For all the simulations in this paper the 3^{rd} approach—with initial zero stiffness, followed with negative stiffness, and later with stiffening at larger displacements—is assumed for the NSD. Equation for the NSD (Nagarajaiah and Reinhorn 1994) is given in Eq. (4).

$$F_{NSD} = 2K_h x + K_v x \left[\frac{\left(\sqrt{1+\left(\frac{x}{l}\right)^2} - \left(\frac{\Delta}{l}\right)\right)}{\sqrt{1+\left(\frac{x}{l}\right)^2}} \right] \quad (4)$$

F_{NSD} is the force exerted by the NSD device. x is the horizontal displacement of the structure. K_h and K_v are the stiffneeses of the horizontal and vertical springs, respectively. l is the length of the precompressed spring in the initial position and Δ is the precompression in the vertical spring. By changing the parameters K_h, K_v, l and Δ, shown in Figure 1, any desired force-displacement curve can be obtained. Complete details of the device will be disclosed in the near future after the experimental studies are completed. Force-displacement loops of NSD—for a particular set of parameters—is shown in Figure 7 (red line), in comparison with the elasto-plastic base-structure (green line) and the structure + NSF(blue line).

Passive Damping Device (PD)

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 PD is given by the following equation

$$F_{PD} = 2\xi\sqrt{K_e m}\dot{x} \quad (5)$$

where, F_{PD} is the force exerted by the damper, ξ 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 (foundation force) of the structure and at the same time limit the maximum displacement and acceleration of structure. It will be uneconomical and unrealistic to design control 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 project is to experimentally prove the effectiveness of the proposed ANSS/NSD. All the simulation studies presented in this paper are for a 1/3rd scale three storey zipper frame developed at University at Buffalo, SUNY. In the initial phase 2^{nd} and 3^{rd} floors of the zipper 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 softwares with the exact detail. Sivaselvan-Reinhorn model (Sivaselvan-Reinhorn,1997) 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. 6. Simple parameters like K_e and ε are obtained from the push-over curve. Mass of the structure, m, is measured and parameters like ξ are assumed. The values for remaining parameters are obtained using an optimization algorithm. Description of the variables is given in Table-1.

$$m\ddot{x} + (2\xi\omega_n m)\dot{x} + \alpha(1-\varepsilon)z + \varepsilon K_e x = -m\ddot{x}_g \quad (6)$$

$$dz = K_e\left(1 - \left|\frac{z}{K_e Y}\right|^{\eta}(\gamma sgn(z\dot{x}) + \beta)\right)\, dx \quad (7)$$

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	$K_e \times Y$	ε	Post yield stiffness ratio
S-R Model parameter-2	γ	β	S-R Model parameter-3
S-R Model exponent	η		

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, $\omega_n = \sqrt{Ke/_m}$.

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 8. It can be seen from results in Figure 8 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 is shown in Figure 9; 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 10, “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 8, 9 and 10. NSD alone is effective for reducing base shear, without any increased deformations, in elastic structures. A passive damper can be added to reduce the deformation of structure along with the base shear, which is considered next.

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. Response time histories comparing the actual structure and adaptive system (structure + NSD) are shown in Figure 11. Force-displacement characteristics are shown in Figure 12 and the component forces acting in the adaptive system are shown in Figure 13. It is evident from Figure 12 that with NSD alone the performance of the adaptive system deteriorates as NSD starts producing positive stiffness which occurs at larger displacements. So, for yielding structures NSD alone will not improve the performance of the adaptive system.

For slightly higher input amplitudes, the displacement response of adaptive system (base-structure + NSD) starts drifting with permanent displacement as shown in Figure 11. But, for fewer number of input cycles the adaptive system may still be effective. It can be seen from Figure 11 the adaptive system without damper will be effective till 3 seconds (approximately 6 cycles). After the normalized deformation of the adaptive system crossed 1.5, as shown in Figures 12 and 13, the NSD starts stiffening. So for normalized deformations higher than 1.5 adaptive system without passive damper will result in large permanent deformations and it is not effective.

Passive viscous damper with 20% damping ratio is used to produce an improved performance. 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 all three systems response time histories are shown in Figure 14, hysteresis loops and component forces are shown in Figures 15 and 16 respectively.

For the same input amplitude and 10 input cycles, by adding the passive damper the deformation of the structure is reduced substantially with a slightly higher base shear. Figure 14 shows the reduction in all the responses of an adaptive system (base-structure + NSD + passive damper). To further justify the requirement of NSD in adaptive system, results are compared with passive system (base structure + passive damper). Deformation characteristics of adaptive system and passive system are very similar, shown in Figure 14, but the acceleration of adaptive system is 40 % less--compared to passive system and base structure system. Same trend is observed in Figures 15 and 16. Component forces in an adaptive system are shown in Figure 16. In the case with ANSS/NSD the base shear (forces experienced by the foundation) is reduced substantially, whereas in the PS case the base shear is larger than the BS case. The shear forces experienced by the columns in the two cases of ANSS and PS is approximately the same, but substantial reduction in accelerations occur in ANSS case as compared to both BS and PS cases—which a signficant benefit as the secondary systems can be protected preventing sever post earthquake losses. From Figure 15 it can be said that the three main objectives of the adaptive system are clearly achieved (1) Base shear of the structural system has been reduced substantially. In case of passively damped system the base shear is greater than the base structure, the column shears remain approximately the same in ANSS and PS as both experience approximately the same displacement, (2) the accelerations are substantially reduced in the case of ANSS as compared to BS and PS cases and (3) deformation of the ANSS case is also reduced when compared to the BS case and is of similar magnitude as the PS case.

Simulation results: Random input ground motion

To study the proposed ANSS/NSD system efficiency for scaled random input ground motions six performance criteria, a slightly modified version of the standard criteria used for benchmark structures (Ohtori et al. 2004), are used to evaluate and compare the performance of developed NSD device, all three aforementioned cases are evaluated. Performance functions are shown in Table 2. These criteria are used to evaluate the performance of various cases. Norm, $||\cdot||$, stands for $||\cdot|| = \sqrt{\frac{1}{t_f}\int_0^{t_f}[\cdot]^2\,dt}$.

Table 2: Performance criteria used for evaluating ANSS for recorded ground motion data

Name	Evaluation Parameter	Formula
J_1	Inter-storey drift ratio	$\max_t \frac{\lvert x(t)\rvert}{x_y}$
J_2	Absolute acceleration	$\max_t \frac{\lvert \ddot{x}(t)+\ddot{x}_g(t)\rvert}{max(\lvert\ddot{x}_g\rvert)}$
J_3	Total storey force (Base Shear)	$\max_t \frac{\lvert F_{TF}\rvert}{K_{ep}Y}$
J_5	Normed inter-storey drift ratio	$\frac{\lvert\lvert x(t)\rvert\rvert}{\lvert\lvert\delta\rvert\rvert_{BS}}$
J_6	Normed absolute acceleration	$\frac{\lvert\lvert\ddot{x}(t)+\ddot{x}_g(t)\rvert\rvert}{\lVert\ddot{x}(t)+\ddot{x}_g(t)\rVert_{BS}}$
J_7	Normed total storey force (Base Shear)	$\frac{\lvert\lvert F_{TF}\rvert\rvert}{\lvert\lvert F_{TF}\rvert\rvert_{BS}}$

Six scaled ground motions are used to evaluate the performance of the ANSS/NSD developed in this work. The performance indices of all the three systems for six ground motions are listed in Table 3. From the results in Table 3, it can be seen that absolute accelerations (J_2) and base shear (J_3) of ANSS is significantly lower than the other two cases of base structure and base structure + passive damper. It should be noted that a simple viscous damper is adopted in these simulations. Better displacement reduction in ANSS can be achieved by finding the optimal nonlinear damper properties for the given NSD properties. The response histories and the force-displacement loops for the three cases, under Kobe earthquake excitation, are shown in Figure 17 & 18.

Table 3: Performance criteria used for evaluating ANSS for recorded ground motion data

PI	System	Chi-Chi	Kobe	Newhall No. 24279	Northridge Sepulveda	Pacoima	Sylmar No.24514
J_1	BS	1.4567	1.9421	1.4192	1.2443	0.6961	1.4951
	PS	0.8208	1.0474	1.0681	0.7434	0.5912	0.7864
	ANSS	0.9379	0.9455	1.1514	1.0033	1.0035	1.0668
J_2	BS	0.5568	1.1933	1.3765	1.3128	0.5146	0.9006
	PS	0.4976	1.2565	1.5061	1.0618	0.4736	0.8123
	ANSS	0.2785	0.7662	0.8904	0.6567	0.3617	0.5213
J_3	BS	1.0102	1.0336	1.0134	1.0075	0.6950	1.0170
	PS	0.8101	0.9530	0.9651	0.7420	0.5908	0.7799
	ANSS	0.3016	0.3258	0.4500	0.3017	0.3336	0.4037
J_4	BS	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	PS	0.2454	0.3973	0.4678	0.2622	0.4160	0.2041
	ANSS	0.3064	0.3586	0.7951	0.3422	0.7981	0.3476
J_5	BS	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	PS	0.4382	0.5592	0.6352	0.3642	0.4530	0.3374
	ANSS	0.3830	0.3641	0.4100	0.2317	0.4024	0.2768
J_6	BS	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	PS	0.3926	0.5083	0.5758	0.3336	0.4160	0.3108
	ANSS	0.3295	0.3015	0.3309	0.1954	0.3434	0.2363

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 main objective of ANSS/NSD to reduce the base shear demands on the main structure and limit the structural deformations and accelerations during extreme loading conditions. 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.

The adaptive negative stiffness system proposed in this paper consists of two elements: 1) a true negative stiffness device (NSD) and 2) a passive damper (PD). Upon the addition of NSD to the structural system, predesigned reductions of stiffness occur in the combined system or "apparent softening and weakening" occurs; however, it is important to note that the stiffness and the strength of the main structural system remains unchanged in this study (hence, "apparent")—unlike the concept of weakening proposed earlier wherein the strength and implicitly stiffness of the main structural system itself are 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. Key conlcusions of these simulation results are (1) for structures that remain in the elastic range NSD reduces the base shear substantially, (2) if reduction in deformation is also a criteria then adding a passive damper with nominal damping coefficient achieves the goal, and (3) for yielding structures, appropriate combination of NSD and passive damper significantly reduces deformations, accelerations, and base shear. In the case with ANSS/NSD the base shear (forces experienced by the foundation) is reduced substantially, whereas in the PS case the base shear is larger than the BS case. The shear forces experienced by the columns in the two cases of ANSS and PS is approximately the same, but substantial reduction in accelerations occur in ANSS case as compared to both BS and PS cases—which a signficant benefit as the secondary systems can be protected preventing sever post earthquake losses. In summary, the main structural system suffers less accelerations, less displacements and less base shear or force at the foundation level, while the ANSS "absorbs" them. The corresponding development of an actual NSD device and experimental/analytical study is in progress in the NEESR-Adapt-Struct (www.ruf.rice.edu/~dsg/) project. The results of the experimental/analytical study will be reported upon its completion in the near future.

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References

Cimellaro G.P., Lavan O. and Reinhorn A.M. (2009), “Design of passive systems for control of inelastic structures,” *Earthquake Engineering & Structural Dynamics*, **38** (6), 783-804.

Constantinou M.C. and Symans M.D. (1993), “Experimental study of seismic response of buildings with supplemental fluid dampers,” *Struct. Des. Tall Build.*, **2**, 93-132.

Cuesta I. and Aschheim M.A. (2001), “Isoductile strengths and strength reduction factors of elasto-plastic SDOF systems subjected to simple waveforms,” *Earthquake Engineering & Structural Dynamics*, **30** (7), 1043-1059.

Fenz D.M. and Constantinou M.C. (2008), “Spherical sliding isolation bearings with adaptive behavior: Experimental verification,” *Earthquake Engineering & Structural Dynamics*, **37**(2),185-205.

Iemura H. and Pradono M.H. (2009), “Advances in the development of pseudo-negative-stiffness dampers for seismic response control,” *Structural Control and Health Monitoring,* **16**(7-8), 1545-2255.

Kobori T., Takahashi M., Nasu T., Niwa N. and Ogasawara K. (1993), “Seismic response controlled structure with active variable stiffness system,” *Earthquake Engineering & Structural Dynamics,* **22** (11), 925-941.

Lobo, R.F., Bracci, J.M., Shen, K., Reinhorn, A.M., and Soong, T.T.,(1993), "Inelastic Response of R/C Structures with Viscoelastic Braces", *Earthquake Spectra*, **9**(3), 419-446

Nagarajaiah, S., Reinhorn, A.M., and Constantinou, M.C., (1991) "Nonlinear Dynamic Analysis of 3D-Base Isolated Structures," *Journal of Structural Engineering, ASCE* , Vol. **117** (7**)**, 2035-2054.

Nagarajaiah S. and Reinhorn A.M. (1994), “Applicability of pseudo-force method to highly nonlinear dynamic problems,” *ASCE*: *Proceedings Structures Congress ’94*, 165-172.

Nagarajaiah S. and Mate D. (1998), “Semi-active Control of Continuously Variable Stiffness System,” *Proceedings Second World Conference on Structural Control*, **1**, 397--406.

Nagarajaiah S. and Sahasrabudhe S. (2005), “Experimental study of sliding base-isolated buildings with magnetorheological dampers in near-fault earthquakes,”*Journal of Structural Engineering, ASCE,* **131** (7), 1025-1034.

Nagarajaiah S. and Sahasrabudhe S. (2006a), “Seismic response control of smart sliding isolated buildings using variable stiffness systems: an experimental and numerical study,” *Earthquake Engrg. & Structural Dyn.*, **35** (2):177-197.

Narasimhan S., Nagarajaiah S., Gavin H. and Johnson E.A. (2006b), “Smart Base Isolated Benchmark Building Part I: Problem definition,” *Structural Control and Health Monitoring*, **13** (2-3), 573-588.

Nagarajaiah S., Mao, Y. Q. and Sahasrabudhe, S. (2006c) “Nonlinear, seismic response spectra of smart sliding isolated structures with independently variable MR dampers and variable stiffness SAIVS system” *Structural Engineering and Mechanics*, 24 (3), 375-393.

Nagarajaiah, S. (2009) "Adaptive Passive, Semiactive, Smart Tuned Mass Dampers: Identification and Control using Empirical Mode Decomposition, Hilbert transform, and Short-Term Fourier transform," *Structural Control and Health Monitoring*, **16**(7-8), 800-841.

NEESR-Adapt-Struct, http://www.ruf.rice.edu/dsg/ [30 May 2009].

Ohtori Y., Christenson R.E., Spencer B.F. and Dyke S.J. (2004), “Benchmark control problems for seismically excited nonlinear buildings,” ASCE: *Journal of Engineering Mechanics*, **130** (4), 366-385.

Reinhorn A, M, Viti S, Cimellaro G. P. (2005) "Retrofit of structures: strength reduction with damping enhancement. *Proceedings of the 37th UJNR Panel Meeting on Wind and Seismic Effects*, Tsukuba, Japan.

Reinhorn, A.M., Lavan, O, and Cimellaro, G.P (2009), “Design of Controlled Elastic and Inelastic Structures” in *Journal of Earthquake Engineering and Engineering Vibration*-Special issue on “*Advances in Seismic Response Control of Structures*”, Special Issue dedicated to Prof. Emeritus T. T. Soong, **8** (4), 469-479

Viti S, Cimellaro G. P, Reinhorn A. M. "Retrofit of a hospital through strength reduction and enhanced damping" *Smart Structures and Systems* 2006; **2** (4):339–355.

Sivaselvan M.V. and Reinhorn A.M. (1997), “Hysteretic models for deteriorating inelastic structures,” ASCE: *Journal of Engineering Mechanics*, **126** (6), 633-640.

Spencer B.F., Dyke S.J., Sain M.K. and Carlson J.D. (1997), “Phenomenological model of a magneto rheological damper,” ASCE: *Journal of Engineering Mechanics*, **123** (3), 230-238.

Spencer B.F. and Nagarajaiah S. (2003), “State of the art of structural control,” ASCE: *Journal of Structural Engineering*, **129** (7), 845-856.

Symans M.D. and Constantinou M.C. (1997), “Seismic testing of a building structure with a semiactive fluid damper control system,” *Earthquake Engineering and Structural Dynamics*, **26** (7), 759-777.

Yang J.N., Kim J.H. and Agrawal A.K. (2000), “Resetting semiactive stiffness damper for seismic response control,” ASCE: *Journal of Structural Engineering*, **126** (12), 1427-1433.

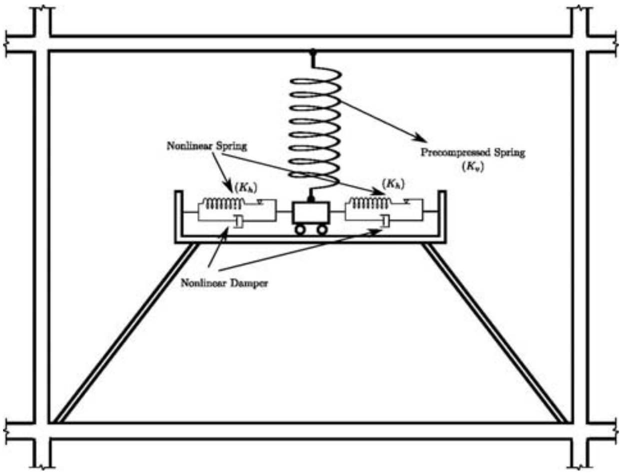

Figure 1: The New Concept of ANSS/Negative Stiffness Device--NSD

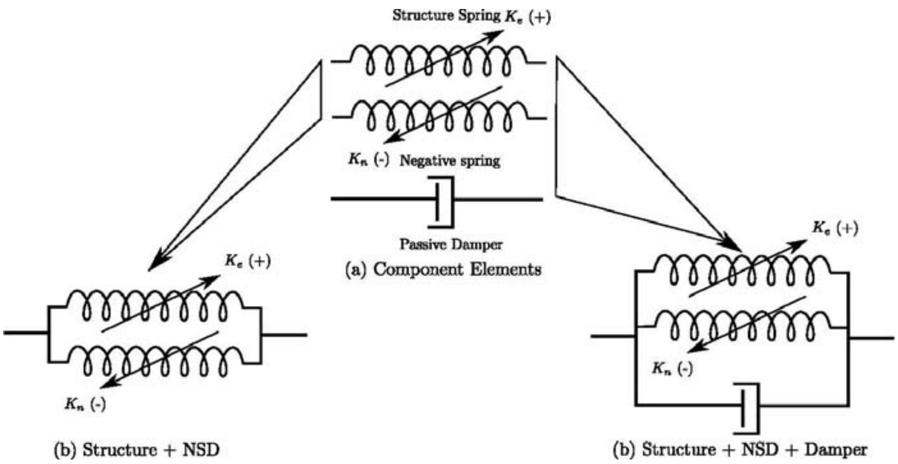

Figure 2: (a) Component elements (b) Linear system + Negative stiffness Device (c) Linear system + Negative stiffness device + Damper

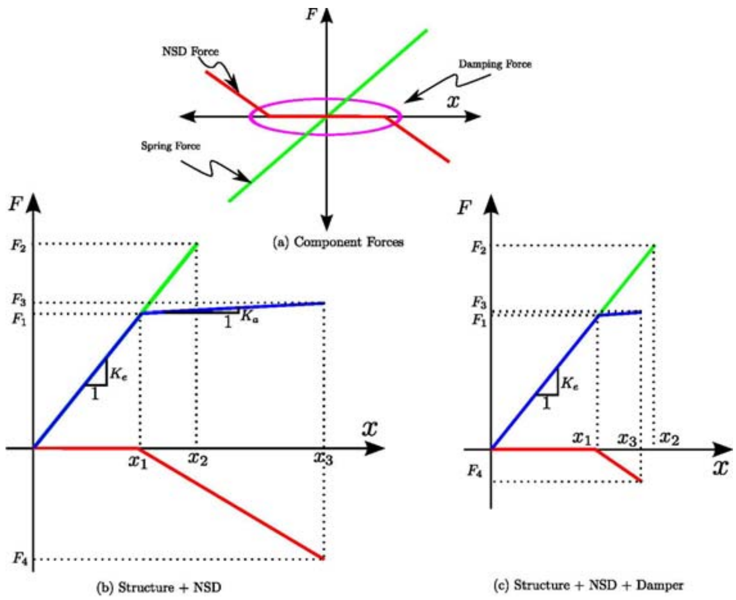

Figure 3: Working principle of ANSS (a) Component F-D plots (b) Linear system with Negative stiffness Device (c) Linear system with Negative stiffness device and Damper [Green-Base-structure, Red- NSD, Blue- Assembly]

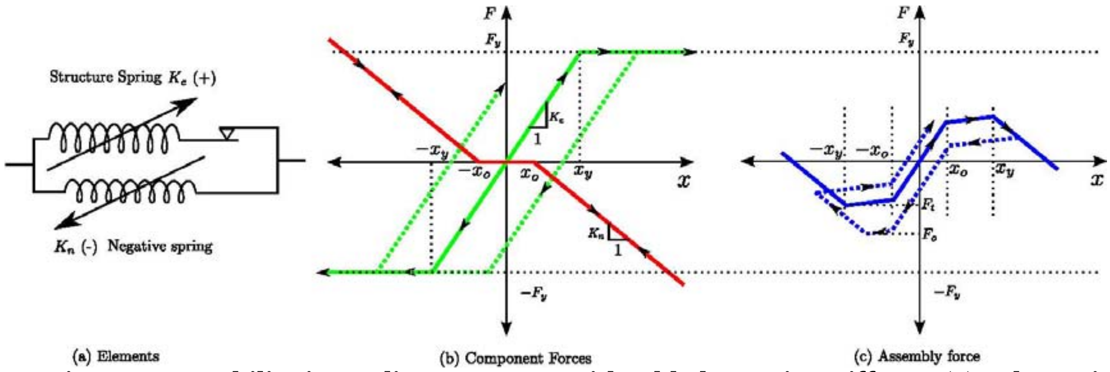

Figure 4: Instability in nonlinear systems with added negative stiffness. (a) Schematic representation (b) F-D characteristics of elasto-plastic system and NSD (c) Structure + NSD [Green- Base-structure, Red- NSD, Blue- Assembly]

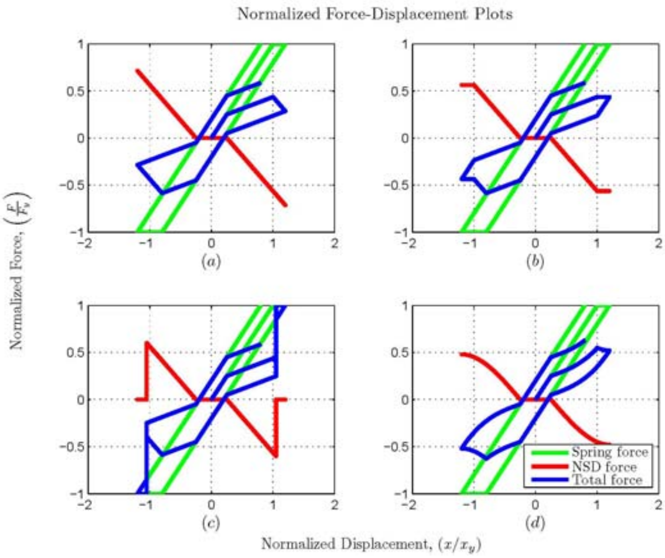

Figure 5: Different feasible force-displacement loops of structure-device assembly for yielding systems (a) no constraints on the force exerted by NSD (b) keeping the force exerted by the NSD constant beyond x_y (c) disengaging NSD beyond x_y (d) stiffening the NSD beyond x_y

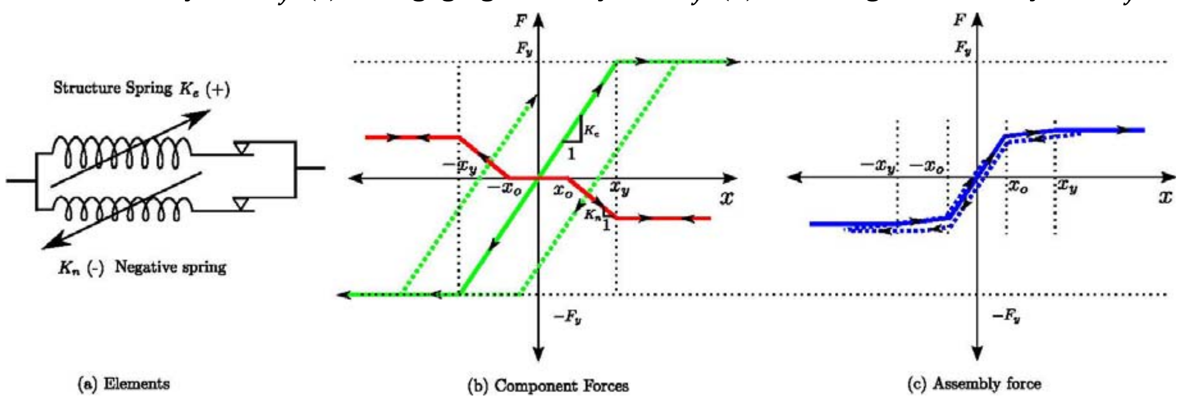

Figure 6: Nonlinear systems with desired negative stiffness. (a) Schematic representation (b) Force displacement characteristics of elasto-plastic system and NSD (c) Structure + NSD [Green- Base-structure, Red- NSD, Blue- Assembly]

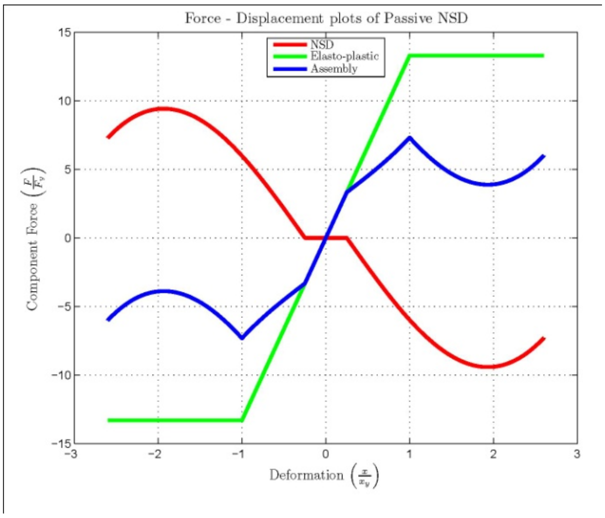

Figure 7: Force-displacement loops of NSD [Green-Base-structure, Red- NSD, Blue- Assembly]

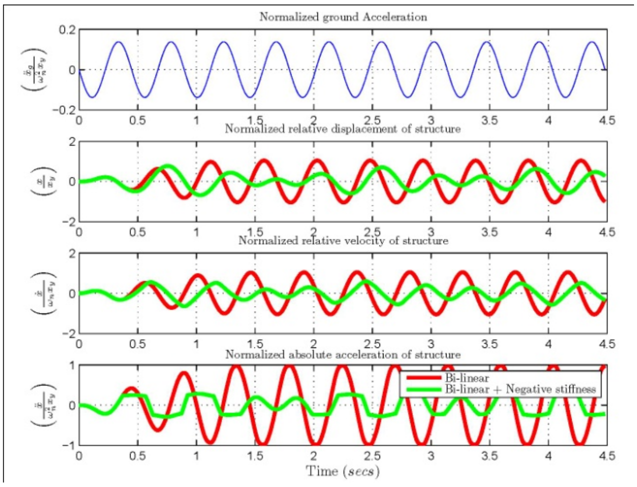

Figure 8: Comparison of responses of system with and without NSD (with the main structure being essentially elastic)

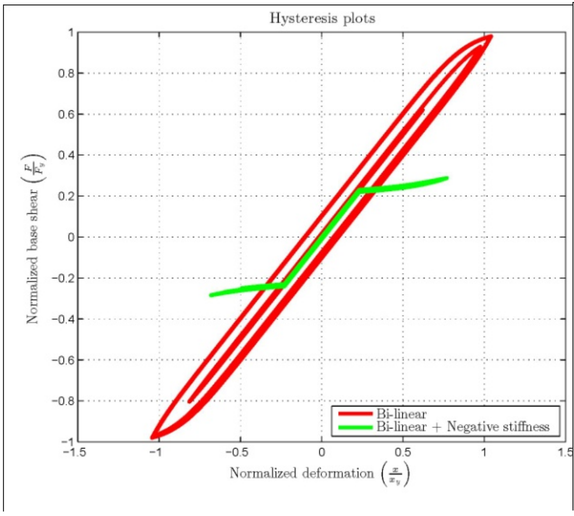

Figure 9: Comparison of hysteresis loops of system with and without NSD (with the main structure being essentially elastic)

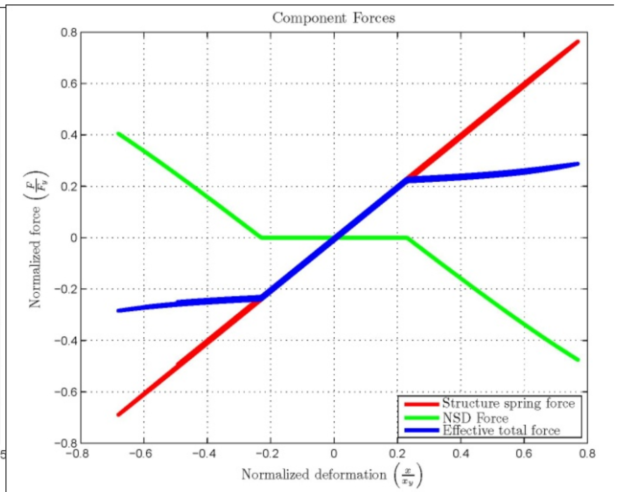

Figure 10: Comparison of component spring forces of system with and without NSD (with the main structure being essentially elastic)

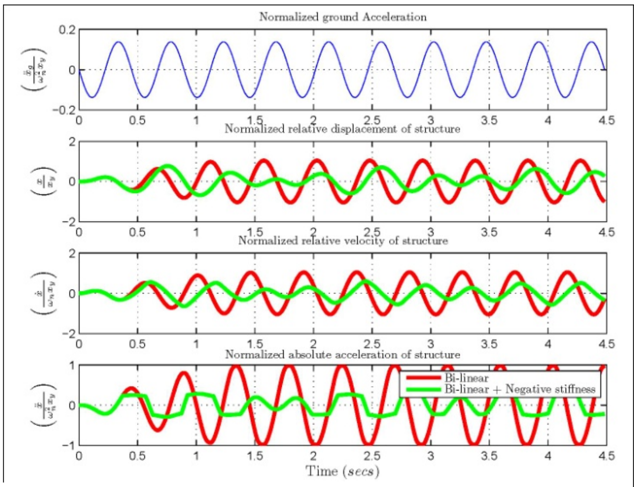

Figure 11: Comparison of responses of Bi-linear system with and without NSD (with structure yielding)

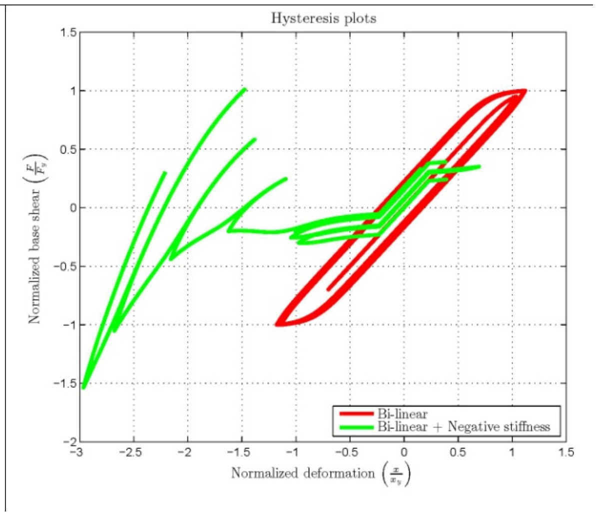

Figure 12: Comparison of hysteresis loops of Bi-linear system with and without NSD (with structure yielding)

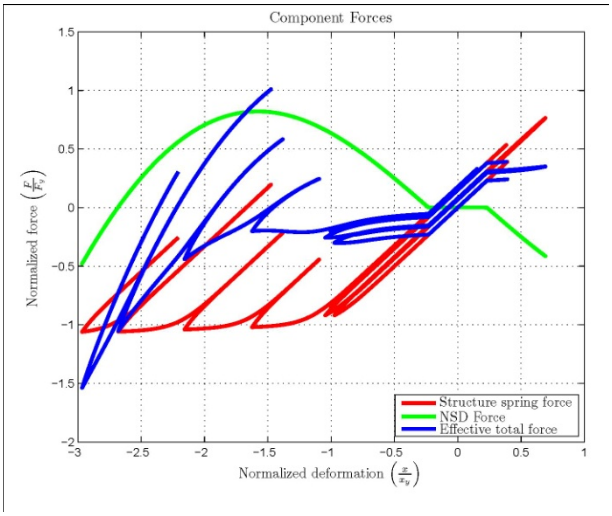

Figure 13: Comparison of component spring forces of Bilinear system with NSD (with structure yielding)

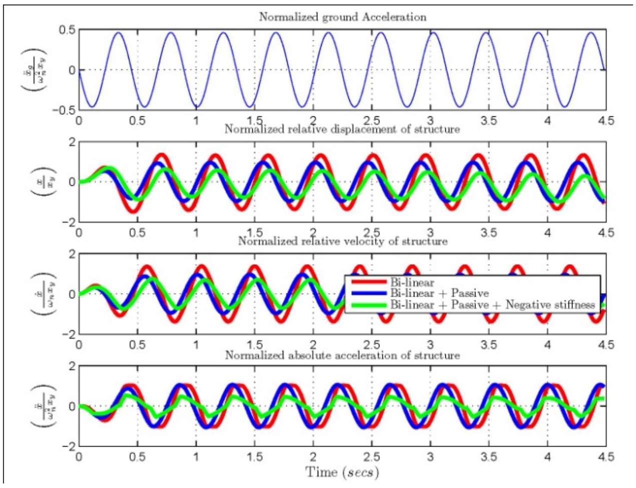

Figure 14: Comparison of responses with and without passive damper/NSD (with structure yielding)

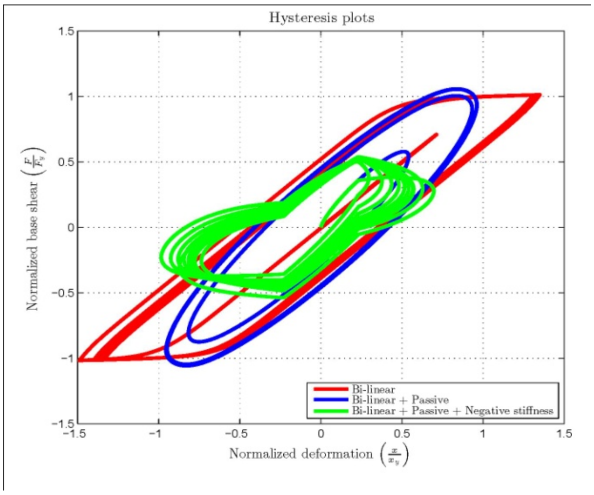

Figure 15: Comparison of hysteresis loops of system with and without passive damper/NSD (with structure yielding)

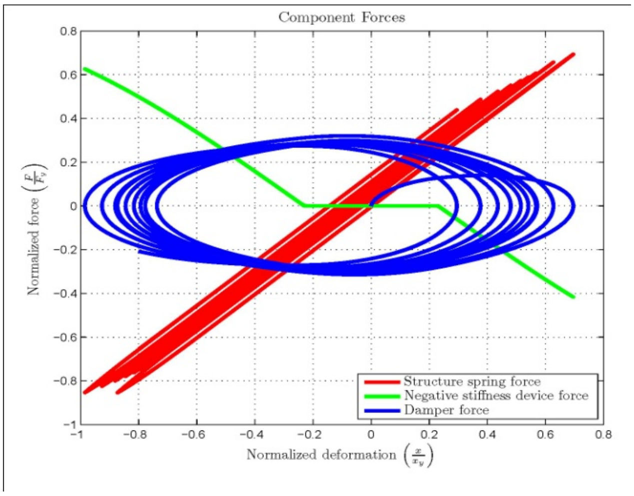

Figure 16: Comparison of component forces of system with passive damper /NSD (with structure yielding)

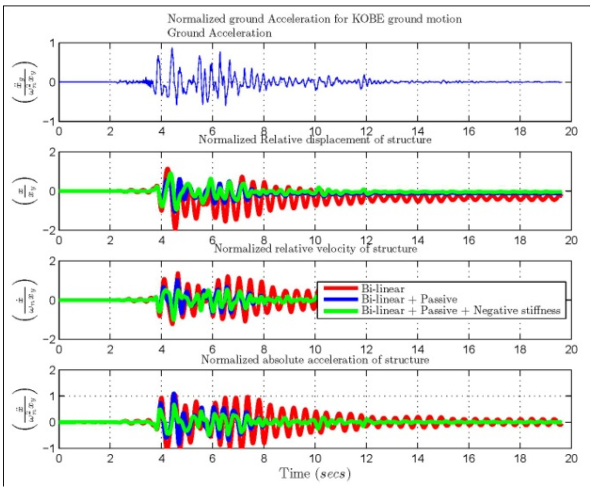

Figure 17: Comparison of reponses with and without passive damper/NSD (with structure yielding) under Kobe earthquake excitation.

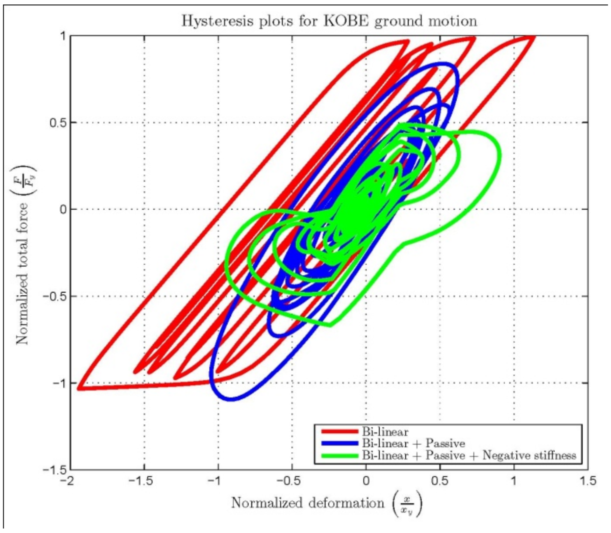

Figure 18: Comparison of hysteresis loops of system with passive damper/NSD (with structure yielding) under Kobe earthquake excitation.