Negative Stiffness Device for Seismic Resistant Bridge.

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***Abstract*— This paper presents an overview of the experimental study of negative stiffness device of a seismic protective system over base isolation. Response of structure to earthquake disturbance is the prime cause of damage and loss to lives. The dynamic analysis of structure for NSD and isolators are briefly explained. This study mainly aims on the displacement analysis difference and its effects on the bridge structural system.**

***Keywords*— base isolation, negative stiffness device, bridge, earthquake analysis.**

I. INTRODUCTION

The bridges constructed with good construction stechniques and equipment in the recent decades have been impacted severely by earthquake leading to extensive loss of life and acreage and enormous amount of sufferings to the survivors of the affected area. This destruction of property, life and resources has lead the researchers to develop an earthquake protective system, hence giving rise to the concept of active and passive damping solutions. One such solution given by them is base isolation technique.

Earth undergoes continuous changes underneath giving rise to fault lines and higher magnitude earthquakes. The proof of destruction caused by these high intensity seismic waves have been witnessed in the past few years. But in recent years even the base isolation concept is proving insufficient to make a structure more seismic protective. This lead the researchers to develop a new concept of negative stiffness device to save the structure from the damages.

The concept of base isolation is as old as in the year 1923, since then there has been numerous development in the concepts and design of isolating the bridges and buildings from seismic forces. Countries like United States Of America, Japan, New Zealand, India have taken on the utilization of this technique as their part of construction. However in India this concept is still not been adopted by maximum constructed structures, but these days the use of concept can be seen in bridge projects like the metro,

elevated highways and bridges for railway track. The use of base isolation has not yet been seen in residential building and public buildings in India except the Bhuj hospital in Gujarat. The national level guidelines and codes are currently not available for the efficient seismic resistant structure design for the engineers.

The current practice for designing structures to be seismic protective it relies on the ductile performance and allowance of developing an inelastic deformation in higher magnitude seismic activity so as to obtain reduced inertia force. The design of structures according to current design practice gives inelastic response of structure. In way to reduce the design forces, an attempt has to be made by improving ductility behaviour of the structure for allowing structure to yield. Designing conventional structures specified by the provided codes is based on the theory that the structure should defy seismic loads while sustaining an acceptable level of damage. The structures are designed in such a manner so as to be strong and non-collapsible though their serviceability and functionality in the aftermath of strong seismic activity are not taken into consideration. This is achieved by designing buildings and bridges having ductile behaviour which lets them yield when subjected to drifts, and damage with long term drifts, which hampers the structural functioning. The observation is that there considerable increase in the amount of energy distribution generated by earthquake in the structure. Whenever there is an earthquake a limited amount of energy enters the structure as input, this input energy should either be absorbed or dissipated through heat. Although the ability of the structure to somehow inherent the damping and reduce the amplitude of vibration exist all the time. In order to improve the structural performance of the bridge or building against seismic vibrations can be improved by inducing energy absorption mechanism within the structure. Many significant advantages can be drawn with seismic protected structures.

II. BASE ISOALTION

Base isolation is one of the known passive control methods used for maintaining the stability of the structure against earthquake actions. The figure .1 shows the hysteresis behaviour of a rubber base isolator. Weakening of structure and providing dampers have been proved to be an effective method of analysing structure's response. This approach has thus drawn further attention towards the development of NSD.

Usually it is suggested that isolation of base of structures can be achieved by introducing base supports with elastic flexibility of horizontal motion. Such isolation method can be functional for impulsive (type 1) of seismic activity but would permit the cyclic build up of intolerable base translations and loads on the structure during longer earthquakes (type 2 and type 3).

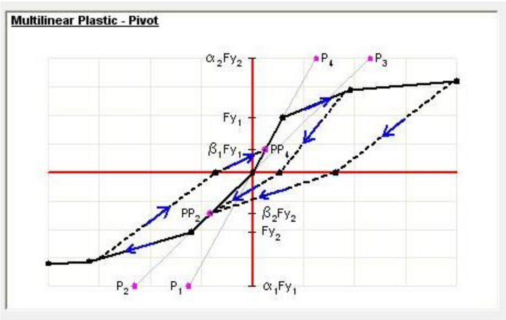

Figure 2 .1 the hysteresis behaviour of a rubber base isolator

Base isolation is flexible device which when provided in structure decreases the seismic forces of a structure. The reason why isolation mechanism is provided at the base of the structure is because it reduces the ground motions induced due to earthquake from transferring it to superstructure above the isolation there is considerable reduction in the response of a typical building and the corresponding loading.

III. NEGAVTIVE STIFFNESS DEVICE

The negative stiffness device is a structural control mechanism which applies force in the direction of external force that is acting on the structure. Negative stiffness device also abbreviated as NSD can be explained as a device in which control force is negatively proportional to the deformation. As compared to other deformation controlling methods this device makes it possible to reduce the stiffness while reducing the response quantities of structure. Large base deformations and permanent drifts is one major limitation in base isolation the structure, however using negative stiffness device this limitation can be overcome as the isolation is achieved.

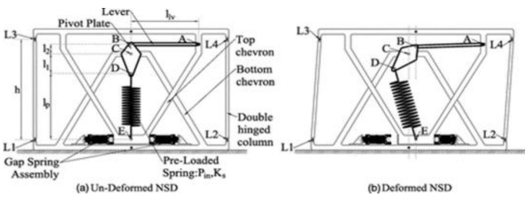

Figure 3.1 diagrammatic representation of NSD.

The concept of negative stiffness for Nagarajaiah et al. (1994,2010) leading to the development of a new NSD that was tested at the device level and then on a base isolated structure by Sarlis et al. (2011a. 2011b). Perilous components of the device and a brief description of the working principle and the governing equations are described in this section.

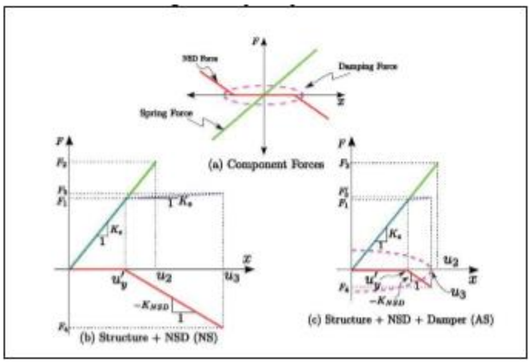

Figure 3.2: working principle of an NSD.

The device comprises of a pre-compressed spring shown in the figure and has two gap spring assembly at the bottom of the arrangement. The vertical spring is connected to a link that transfers horizontal load to the upper and lower part of the frame. When the device undergoes deformation in a particular direction the vertical spring rotates and creates a force that assists motion, generating a stiffness that is not positive. The NSD has the following components and its characteristics:

A. A highly compressed spring that generates force in the direction of motion i.e. negative stiffness, further the magnitude of force reduces with the increase in the displacement so as to ensure the stability of the structure remains intact.

B. A dual chevron self-controlling system to resist the preload on the compressed spring and also to prevent the transfer of the vertical component of the preload to the structure.

C. Gap spring assembly that provides the system with positive stiffness up to a defined displacement such that the combined effect of compressed vertical spring and the two horizontal spring is equivalent to zero up to the predefined displacement. The GSA is essential for the bilinear elastic behaviour with an appropriate yield displacement which is smaller than the actual yield displacement in the structure.

The diagrammatic representation of NSD shown in fig.2. the length of the compressed spring (CS) placed vertically and the force in the undeformed shape are L and P_1, also the stiffness in vertical spring is given by Kv. The length of the lever-arms are L_1 and L_2, force applied by the horizontal spring is F_h . α and β are the angle of rotation of the vertical spring and lever arm. The horizontal force created by the device due to displacement (u) is given by the equations from 1 to 5

$$\beta = \sin^{-1}(\frac{u}{L2}) \qquad (1)$$

$$\alpha = \tan^{-1}(\frac{u(L+(\frac{L1}{L2})}{L+L1(L-\cos\beta))}) \qquad (2)$$

$$Lext = \sqrt{(L+L1(L-\cos\beta))^2 + u^2(L+\frac{L1}{L2})^2} \quad (3)$$

$$Fv = P1 + Kv(\,Lext - L) \qquad (4)$$

$$Fnsd = Fv\ (\sin\alpha + \frac{L1}{L2}\frac{\sin(\alpha+\beta)}{\cos\beta}) + Fh \qquad (5)$$

The magnitude of force exerted by NSD is obtained from the formula for Fnsd. The force displacement behaviour effect of NSD and the modelling of non linear bridge structure is described briefly in the next section.

IV. ANALYTICAL MODEL

The equation 5 described in section III is used for the relation between lateral forces exerted by NSD with respect to the deformation undergone by the structure. In CSibridge software there is provision of providing multi-elastic link which can be capable to exhibit considerable weakening keeping in consideration of the structural stability. For the analysis of bridge, a total length of 200 m is considered with piers placed at an equal interval of 50m with abutments at each end. The soil type considered is type II foundation in seismic zone IV.

The bridge model designed in CSiBridge software for the analysis of seismic effect using an isolator and NSD to understand the displacement behaviour of the bridge under earthquake forces. The foundation condition is considered fixed for analysis purpose. The type of bridge considered for analysis is a simple girder bridge. The study will mainly focus on analysing and finding the difference in displacement with NSD and with a base isolator. The study will focus on finding out displacement, element forces and time history analysis. The model as shown in figure is analysed for El Centro time history, the acceleration vs time data equally spaced at 0.02 seconds as shown in figure.

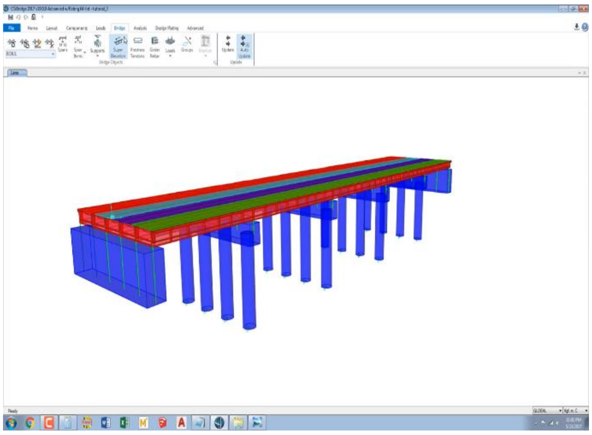

Figure 4.1:- analysis model prepared in CSiBridge.

TABLE I
NEGATIVE STIFFNESS DEVICE PROPERTIES.

Quantity	**Symbol**	**Value**	**units**
Distance from spring pin to fixed pin	L_1	25.4	Cm
Distance from lever pin to fixed pin	L_2	12.7	Cm
Spring length	L_s	76.2	Cm
Spring rate	K_v	1.4	Kn/cm
Preload	P1	16.5	Kn
Double hinged column height	h	124.5	Cm
Lever length	L_Y	67.3	Cm
NSD engagement displacement	U_d	1.65	Cm
Spring stiffness S1	K_1	4.9	KN\cm
Spring stiffness S2	K_2	0.3	Kn\cm
Spring vertical S3	$P1_2$	8.1	KN

V. RESULTS AND DISCUSSIONS.

From the above analytical model analysed and the equations derived for the NSD the following results and discussions were obtained. The seismic action depends on the ductile behaviour and allows the development of inelastic deformations in high magnitude earthquake. Thought the application of NSD is limited to extremely small sensitive devices in automobiles, huge scale application in structures like bridge will need medication of the existing mechanism to reduce the demand for preload forces and to make a device that does not impose any additional load on the structure other than those needed for obtaining seismic protected structural system.

The models generated in the software having the same parameters but the only difference was first model described in figure 5.1 was designed without any isolator or NSD. The second model generated was using an negative stiffness producing device as shown in figure 5.2.

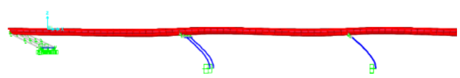

Figure 5.1:- the above model displays the span under displacement without an NSD

Figure 5.2:- the above model displays the span under displacement with and NSD

Increased height of the column decreases the stiffness and decreases the rate of oscillation or frequency.

From the above results obtained it can be said that the use of NSD over base isolation can be beneficial but with certain modification in the device so as to avoid external force application for preload case.

From the analysis and observations it was observed that Negative stiffness produced provided better stability to the structure against the seismic vibrations as compared to a bridge structure without NSD. Though the base isolators used as passive method to control the structural disturbance negative stiffness produced in the structure can prove to be more promising for the structure's stability.

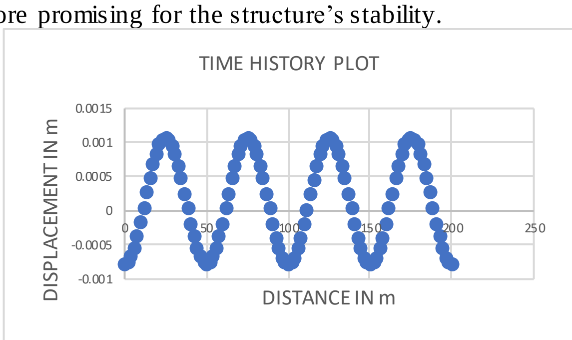

Figure 5.3:- the time history plot for displacement

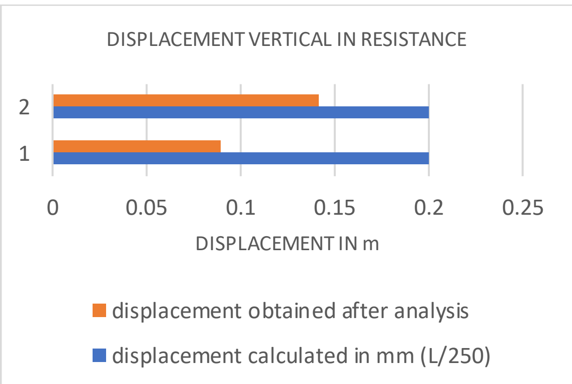

Figure 5.4:- displacement graph analytically obtained and calculated

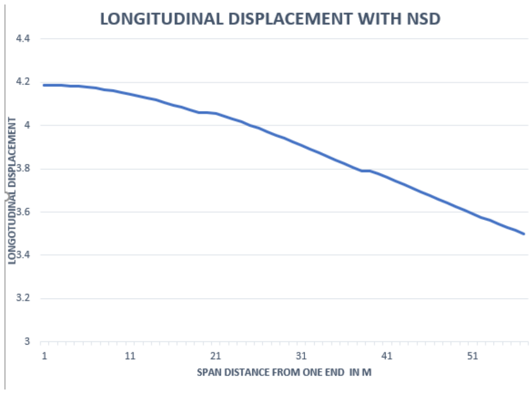

Figure 5.5:- longitudinal displacement with NSD

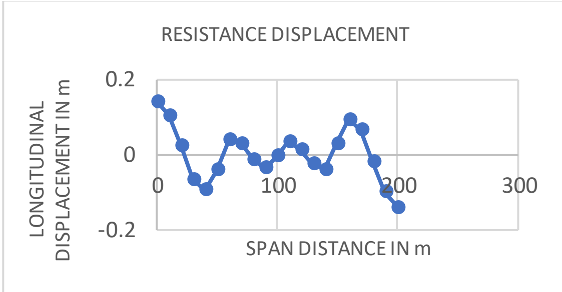

Figure 5.6:- damping effect on the acceleration response spectrum

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