PRESTRESSED BEARINGS IN THE SEISMIC ISOLATION OF STRUCTURES

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ABSTRACT

Base isolation systems should be able to carry tension loads that may occur at the isolation level and transmit them to the foundation in order to control uplift and thus ensure the general stability of the isolated superstructure. Prestressed earthquake isolators result from the combination of common seismic isolation bearings with vertical prestressed tendons which are located in pairs on both sides of the bearing. In this paper, the features of the prestressed bearings are described, some theoretical aspects are outlined, and the software suitable for the three-dimensional non-linear dynamic analysis of seismic isolated structures, incorporating prestressed isolators is presented. The performance of the isolators is demonstrated by a case study of a base isolated structure.

KEYWORDS

Seismic isolation, isolation bearings, prestressed earthquake isolators, PEI, tension restrainer, uplift control, prestressed FPS isolators, prestressed elastomeric isolators, prestressed flat sliding bearings, prestressed roller bearings

INTRODUCTION

Seismic isolation is an earthquake design philosophy based on the concept that a structure can be protected from earthquakes by decoupling the superstructure's motion from that of its foundation. This aims to reduce directly the seismic forces applied on the superstructure during an earthquake excitation. However, the magnitude of the horizontal ground excitation, the structure's lateral resisting system and/or the structure's slenderness and, overturning moments can cause a strong variation of the isolator's axial force. This phenomenon, increased by the vertical ground acceleration, may result in stress on the bearings by substantial tension forces. It has generally been accepted that elastomeric isolators should not be subjected to tension loads, as well as other common seismic isolators, e.g. sliding or roller bearings are not capable to control uplift. This necessitates that some alternative means have to be found to resist the tension loads and uplift phenomenon. The objective of this research was to design a new tension restraint device and to investigate its influence on the dynamic response of the isolated structure. Furthermore, the research work focused on the three following requirements: a) it should be possible to combine the device with several types of earthquake isolators, b) the accommodation of tension forces shall not occur suddenly but progressively in order to prevent impact loads on the isolated superstructure and,

c) permanent capacity to receive tension forces that may occur in the isolators. (Permanent capacity means that the ability of the device to receive tension forces has to be independent of the isolator's shear deformation).

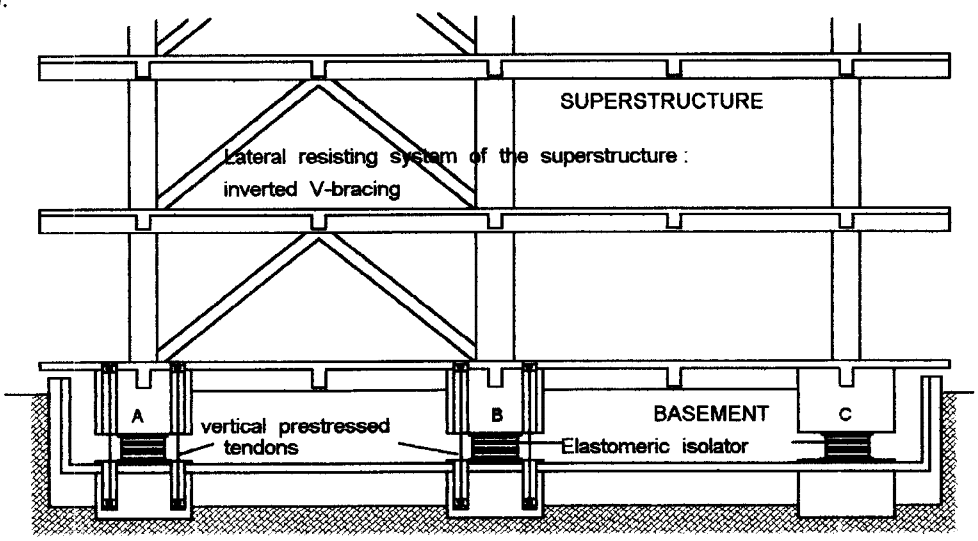

Fig. 1: Arrangement of the vertical prestressed cables on both sides of each bearing that supports the braced frame of the isolated superstructure (isolator A and B only).

DESCRIPTION AND OPERATION OF THE PRESTRESSED BEARINGS

In order to fulfil the aforementioned requirements, vertical prestressed tendons are located in pairs, symmetrically on both sides of each bearing that could be subjected to uplift (Fig. 1). It should be noted here that the tendons are not bonded in the concrete. The symmetrical arrangement of the tendons aims to achieve a uniform application of the prestressing forces on the bearings. The upper end of the tendon is anchored in the superstructure whereas the lower end is anchored in the foundation. The space needed for the unrestricted movement of the cables during the shear deformation of the isolation system is provided by inserting the cables in casings with adequate diameter (Fig. 2) (Logiadis, 1995).

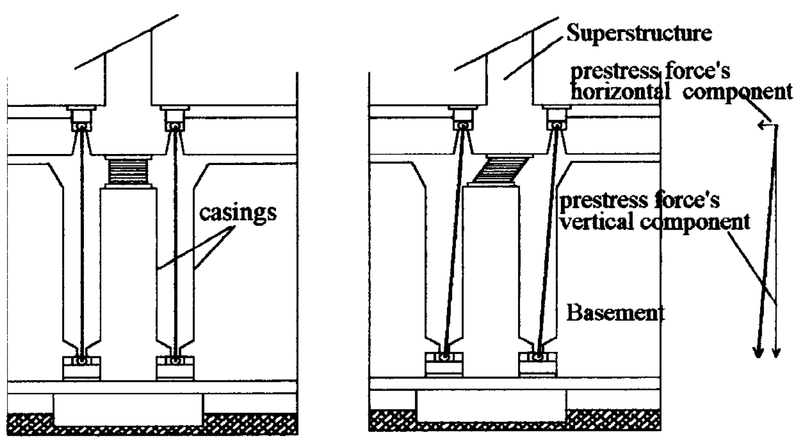

Fig. 2 : Prestressed elastomeric bearing in its undeformed and deformed position.

To avoid bending stresses in the prestressing elements during the shear deformation of the isolator, the tendon's anchorage assembly has to be designed in such a way that allows free rotation at both ends.

During the shear deformation of the isolation system, the tensioning elements change length. This results in a change of the prestressing force. The prestressing force can be decomposed in a horizontal and a vertical part. The horizontal component always acts in the opposite direction of the superstructure's motion as a recentering force. The prestressed earthquake isolators can safely carry both shear and axial forces generated at the isolation interface from the seismic motion. The horizontal load is mainly carried by the bearing and the vertical one, which could be tensile in nature, is carried by the cables. In order to achieve a permanent tension-proof interface between the isolated superstructure and its foundation, the prestress value must be chosen such that during the maximum shear deformation of the isolation system the tendon's strain will remain within the elastic range of the tendon's material.

Prestressing elements can be made of steel or high-strength synthetic material (e.g. Glass fibre Reinforced Plastics, GFRP) (Budelmann, 1991). GFRP tendons consist of glass fibres embedded in a matrix of unsaturated polyester resin. These elements have been extensively investigated and are been used in prestressed concrete structures (Specht, 1992). GFRP tendons were used in the current study because of the following advantages that they exhibit over their steel counterparts (Rostasy, 1992):

1) Possibility of integrating sensors within the tendons in order to achieve "intelligent" tensioning elements, e.g. for monitoring purposes or active assemblies.
2) They exhibit an almost ideal linear elastic behavior in axial tension (elongation at break: 33 ‰). Their maximum permissible prestress value under service loads is approximately 14 ‰ , whereas the corresponding value of steel elements is about 2.3 ‰.
3) Their modulus of elasticity is 51 KN/mm^2 and so approximately 0.25-times the E-modulus of steel elements. Therefore stress loss in the tendon resulting from anchorage slip or other member's shortening is of minor importance in GFRP tendons.
4) High corrosion resistance and electromagnetic neutrality.

DESIGN CONSIDERATIONS

During an earthquake excitation the tensioning elements are dynamically loaded with few cycles of high stress amplitude and many cycles of small stress amplitude. The number of loading cycles that the tendons will be subjected to depends on the nature and number of the earthquake excitations they have to withstand. Designing the tendons requires an estimation of the maximum allowed stress which affects the derivation of the minimum permissible length of the tensioning elements. This stress can be related to the tendons fatigue behavior (Logiadis, 1995). That is, for the maximum stress amplitude (maximum stress amplitude equals maximum allowed stress minus initial tensioning stress) it is reasonable to take the fatigue strength at a stated number of loading cycles modified by a safety factor that accounts for notching, ageing, environmental and scaling effects. In order to specify the tendons fatigue strength, axial load tests at various frequencies and amplitudes were performed on GFRP and steel tendons at Aachen University of Technology (Logiadis, 1995).

Another point that must be considered in order to determine the tendon's minimum permissible length is the effect of deformation in vertical direction during its shear deformation. Regarding the height variation of an isolator unit during its shear deformation, seismic isolators can be classified as follows : a) 'Constant height isolators', e.g.: flat sliding isolators and roller bearings, b) 'Increasing height isolators', e.g.: FPS-isolators and, c) 'Varying height isolators' (height of the bearing depends on its axial load $\pm P$), e.g.: elastomeric bearings.

Within the limitations of this paper, all further descriptions are restricted to prestressed elastomeric isolators and GFRP tensioning elements.

<u>Minimum permissible length of the tensioning elements</u>: The results from the previously mentioned tests at Aachen University of Technology showed that for GFRP tendons a reasonable value for the tendon's maximum stress amplitude is 250 N/mm^2. Using theory of elasticity principles and taking into consideration the height variation of an elastomeric isolator during its shear deformation, the equation giving the minimum allowable length (ℓ) of the GFRP tendons can be written in polynomial form as (Logiadis, 1995):

$$a_4 \cdot \ell^4 + a_3 \cdot \ell^3 + a_2 \cdot \ell^2 + a_1 \cdot \ell + a_0 \geq 0 \quad (1)$$

where : $a_4 = +1{,}0$, $a_3 = +\left(\frac{2 \cdot X \cdot Y - N}{X \cdot K_c}\right)$, $a_2 = +\left(\frac{X \cdot Y^2 + Z - N \cdot Y - u^2 \cdot K_c^2}{X \cdot K_c^2}\right)$,

$a_1 = -\left(\frac{2 \cdot Y \cdot u^2}{X \cdot K_c}\right)$, $a_0 = -\left(\frac{Y^2 \cdot u^2}{X \cdot K_c^2}\right)$ and :

$$N = 4 \cdot \left|F_{V,EL}\right| \cdot \left(\frac{perm.\Delta\sigma}{E} + 1\right), \quad X = \left(\frac{perm.\Delta\sigma}{E} + 1\right)^2 - 1, \quad Y = E \cdot A \cdot \cos^2\alpha, \quad Z = \left(2 \cdot F_{V,EL}\right)^2$$

The symbols in the terms a_0 , a_1 , a_2 and a_3 are defined as follows :

$u = u_{max}$: Maximum shear deformation of the isolator
K_c : Compressive stiffness of the elastomeric isolator at $u = u_{max} / 2$
$F_{V,EL}$: Axial load on the isolator due to earthquake excitation
E , A : Modulus of elasticity and cross-sectional area of the tensioning element
perm.$\Delta\sigma$: Permissible stress amplitude of the tendons. It is equal to the tendon's maximum stress amplitude multiplied by a safety factor, which accounts for uncertainties at the tendon's anchorage assemblies. This factor for GFRP tendons equals 0.6 (Specht, 1992).

From (1) it is evident that the tendon's minimum permissible length is a function of the compressive stiffness of the elastomeric bearing. On the other hand, the elastomeric isolator's design depends on the axial load due to prestressing. As a consequence, the tensioning element's design is coupled with the design of the elastomeric isolator. Hence, to design a prestressed elastomeric isolator an iterative approach should be used: Initially an estimation of the tendons length can be obtained using the following equation:

$$\ell \geq \zeta \cdot \left(u_{max} / 0.0767\right), \text{ where } 1.60 \leq \zeta \leq 1.80 \quad (2)$$

Then the elastomeric bearing can be designed. In the final step (1) is used to ensure that the estimated tendons length is greater than the minimum permissible length. Therefore (1) can be understood as a check of the tendons minimum allowable length.

Force-displacement relationships: The equations that describe the prestressing forces horizontal and vertical components as a function of the isolator shear and vertical deformations are given by (Logiadis, 1995) :

$$F_H = \frac{E \cdot A \cdot u}{\ell} \cdot \left[1 + \left(\varepsilon^{(o)} - 1\right) \Big/ \sqrt{1 + (u/\ell)^2 + (\Delta z/\ell)^2 - 2 \cdot (\pm\Delta z)/\ell}\right] \quad (3)$$

$$F_V = E \cdot A \cdot \left[1 - (\pm\Delta z)/\ell\right] \cdot \left[1 + \left(\varepsilon^{(o)} - 1\right) \Big/ \sqrt{1 + (u/\ell)^2 + (\Delta z/\ell)^2 - 2 \cdot (\pm\Delta z)/\ell}\right] \quad (4)$$

where $\varepsilon^{(o)}$ is the strain due to initial prestress, E, A and ℓ are the tendon's modulus of elasticity, cross-sectional area and initial length, and u and Δz are the isolator actual shear and vertical deformations ($+\Delta z$: height reduction, $-\Delta z$: height increase)

The coupling of the isolator's and tendon's design and performance is also apparent from (3) and (4). The elastomeric isolator's height variation $\pm\Delta z$ affects directly the components of the prestressing force's and conversely, the tendon's force influences the bearing's height variation.

COMPUTER PROGRAM 3D-BASIS-PB

The computer program 3D-BASIS has been specifically developed for the analysis of base isolated structures (Nagarajaiah et al., 1989). Due to the fact that it can analyse seismic isolated structures with great accuracy and execute the analysis with reasonable CPU time demands on personal computers, it has become increasingly popular among researchers and practising designers (Nagarajaiah et al., 1991 and 1993).

The program 3D-BASIS-PB maintains all features of program 3D-BASIS with the following enhancements (Logiadis, 1995):

1) *Overturning moments computation*: Overturning moments due to earthquake excitation including P-Δ effects are computed and their influence on the axial load time history of the isolators is accounted for. Two options are available for modelling the superstructure's lateral resisting system : a) Moment resisting frame and b) shear walls, core elements and/or braced frames. The modelling of the lateral resisting system of the superstructure is crucial since it distributes the overturning moments and the resulting axial loads to the isolation system.

2) *Prestressed earthquake isolators modelling* : Four new elements capable of modelling the behaviour of prestressed isolators have been developed. These four new elements are: a) prestressed cylindrical elastomeric isolators, b) prestressed flat sliding bearings c) prestressed FPS isolators and c) prestressed roller bearings.

3) *Friction coefficient variation*: The coefficient of sliding friction 'μ_s' is a function of the Teflon compound and the pressure at the sliding interface (Constantinou et al., 1990a and 1990b). This dependency of the coefficient of sliding friction is explicitly modelled in the program 3D-BASIS-PB, taking into consideration the experimental results presented by Constantinou (1990b).

4) *Height variation of cylindrical elastomeric isolators*: The time history of the height variation of cylindrical elastomeric isolators is evaluated taking into consideration the isolator's compressive stiffness variation during its shear deformation, the axial load variation due to overturning moments and vertical ground excitation and, the prestressing force variation due to shear and vertical deformation of the elastomeric bearing. Due to the coupling of the design of the elastomeric bearings and tendons, the evaluation of the isolators height variation and the components of the prestressing force is performed iteratively, requiring force equilibrium in vertical direction within each time step of the program's solution algorithm.

5) *Vertical ground acceleration*: The effects of vertical ground acceleration on the behavior of the isolators have been included.

DYNAMIC ANALYSIS OF AN ISOLATED STRUCTURE

In order to demonstrate the applicability of the prestressed earthquake isolators a four story R/C structure with shear walls as lateral resisting system is considered. Figure 3 shows the plan view and the location of the earthquake isolators. The four story superstructure has a total weight (dead load plus half live load) of 13329 KN, which is equally distributed on every floor. The shear stiffnesses at every floor along the X and Y axes are 11000 and 12000 KN/mm respectively. The superstructure's damping ratio is assumed to be 5% of critical at each mode. Accidental eccentricity of 5% in X direction was assumed between the center of mass and the center of resistance at each floor.

The isolation system consists of 16 cylindrical laminated elastomeric bearings (Fig. 3). The yield displacement of each isolator is 0.05 m, the total pre yielding shear stiffness of the isolation system (all isolators combined together) is 40.4 KN/mm and the total post yielding stiffness of the isolation system is 13.1 KN/mm. This system provides an isolation period of 2.0 seconds in both directions. Every shear wall is supported by two isolators.

The building is assumed to be founded on a type 2 soil (stiff clay) in seismic zone 4 according to UBC '91. The ground excitations used in the dynamic analysis are the two horizontal components, N79E and

N11W, of EUREKA 022 (1954) earthquake. The two time histories are appropriately scaled in order to fit the design response spectrum required by the seismicity of the area where the isolated structure is located.

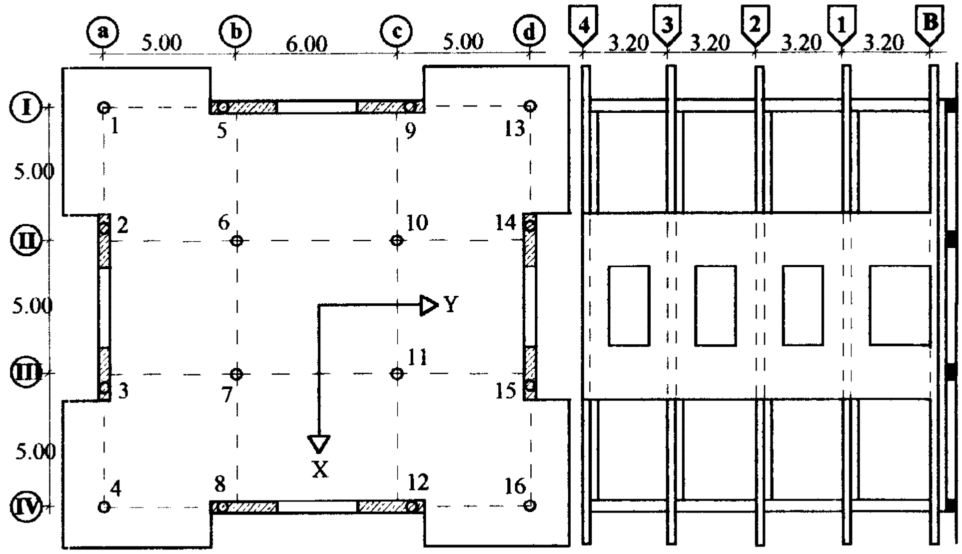

Fig. 3 : Plan and side views of the four story R/C isolated structure.

A preliminary static lateral response analysis indicated that the isolators supporting the shear walls will be subjected to tensile loads of the order of 300 KN. Preliminary time history analysis using program 3D-BASIS-PB verified the results of the static analysis. Figure 4 shows the time history of the axial load of the elastomeric isolator No. 8 and its shear deformation in Y direction. When the shear deformation reaches its maximum value the isolator is subjected to tension.

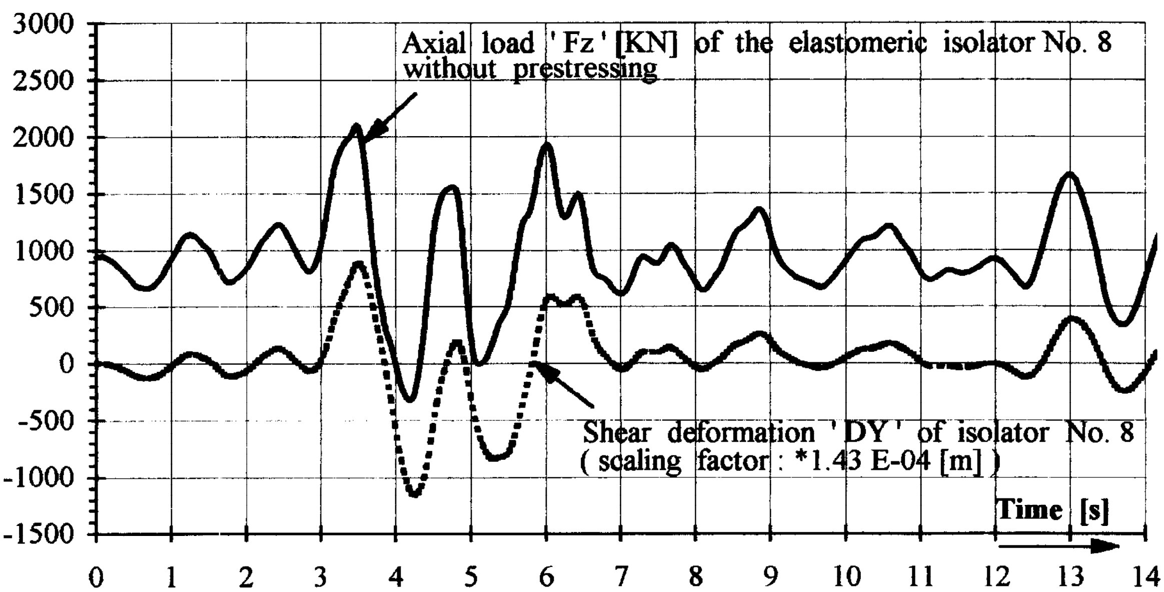

Fig. 4 : Axial load and shear deformation time histories of the elastomeric isolator No. 8.

This unwanted effect can be eliminated by using prestressed elastomeric isolators, that is, providing the GRFP tendons with an initial total prestressing force of 500 KN per isolator. Two tendons are supplied at both sides of each isolator supporting shear walls. Each tendon has a cross sectional area of 530 mm^2, length of 10 m and modulus of elasticity of 51 KN/mm^2.

A detailed model was prepared for the 3D-BASIS-PB and the non-linear dynamic analysis was carried out. Figure 5 presents the time histories of the axial load, vertical displacement and shear deformation in

Y direction of the prestressed elastomeric isolator No. 8. At the time of the maximum shear deformation the isolator still remains under compression. This is a direct result of the use of the prestressing elements. Figure 6 presents the total shear force versus shear deformation relationships of the prestressed isolator in X and Y directions.

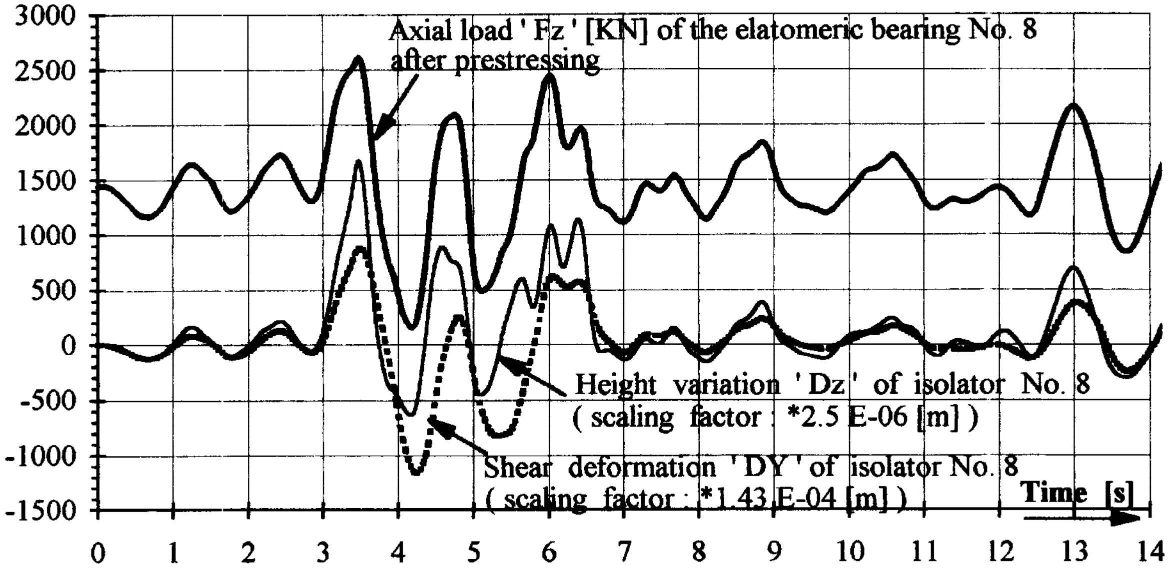

Fig. 5 : Axial load, vertical displacement and shear deformation time histories of the prestressed elastomeric isolator No. 8.

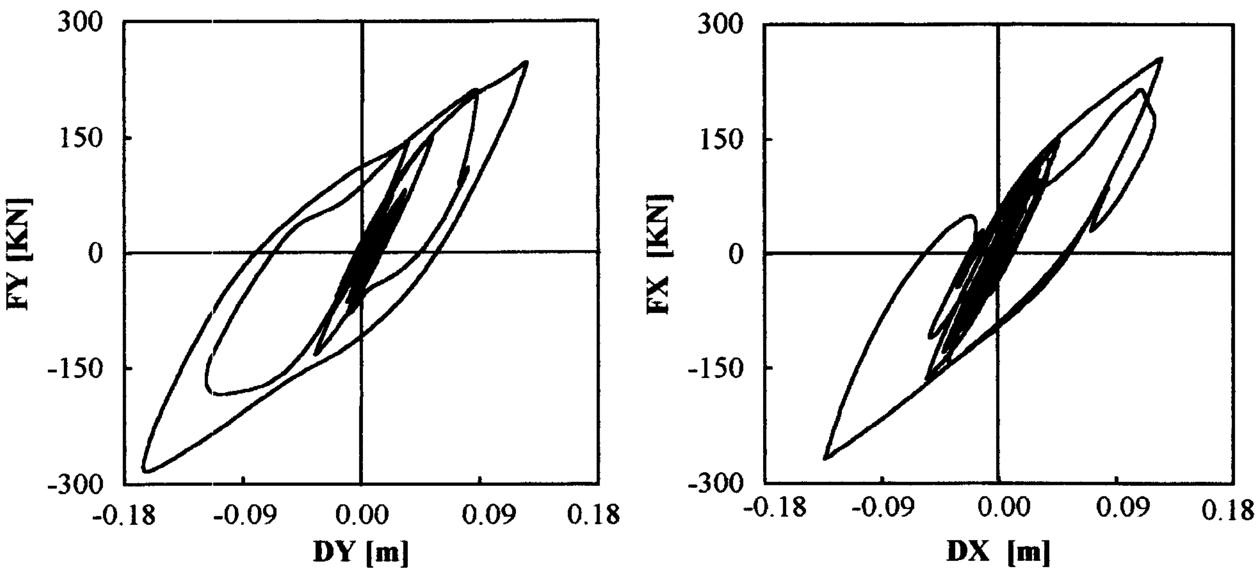

Fig. 6 : Force displacement relationships of the prestressed elastomeric isolator No. 8.

CONCLUSIONS

Summing up, the following concluding remarks can be stated:

1) The properties of the seismic bearings are coupled with the properties of the tendons hence, forming a separate category of bearings for the seismic isolation of structures, namely, prestressed earthquake isolators (PEI).

2) Prestressed earthquake isolators successfully restrain the isolated superstructure against uplift, maintaining its vertical interconnection with the foundation and preventing harmful effects on its lateral resisting system (e.g. cracks on shear walls due to differential vertical displacements at the supporting bearings).
3) PEIs, in contrary to the common isolation systems, provide an additional option to the engineer to modify the properties of the isolation interface at any time even after the completion of the construction. The properties of the common isolation systems (elastomeric, sliding, roller bearings) are a function of geometry and material properties only, while the PEI's properties are in addition a function of the prestressing force. The prestressing force can be changed at any given time.
4) Since the tensioning elements do not engage or disengage abruptly, their force displacement relationships are smooth and continuous without stepping effects (see (3) and (4)) so that they guarantee smooth ride of the isolated superstructure.
5) In the design of the isolation system, the vertical component of the earthquake excitation and the influence of the overturning moments on the axial force of the bearing must be considered.
6) During shear deformation of the isolators, the prestressed cables produce recentering forces, enhancing the safety of the superstructure and contributing to smaller residual displacements in the isolation system.

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