Modelling the Response of Isolation Rubber Bearings with Variable Axial Loading

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ABSTRACT

Seismic base isolation systems protect thousands of structures and infrastructures all over the world. Its effectiveness for seismic protection is widely recognized owing acceleration reduction and minimization of the ‘panic’ effects for the occupants. This aspect has recently recognized of special interests also for strategic structures and facilities for which superior performances expected.
This work deals with the development of a modified model for simulating the horizontal response of rubber bearings, extending the existent procedures to variable axial loading. laboratory tests serve as the target for developing the numerical formulation.

Keywords: *seismic isolation, rubber bearing, biaxial loading, numerical modelling*

1 INTRODUCTION

Passive, anti-seismic, systems have already been used to protect more than 23000 structures such as bridges and buildings, both existing and of new construction, in more than 30 countries. Among others systems, the seismic isolation ones are recognized as the most effective in terms of protecting the structural integrity due to reduction of the absolute accelerations and minimization of the ‘panic’ effects within the design limits they are intended for. Although their still limited introduction for the protection of strategic buildings, seismic base isolation is likely to become a widespread solution in the design of structures and facilities for which superior performances are needed and functionality after an earthquake event is of utmost importance.

Abe et al. [1, 2] proposed differential hysteretic models of laminated rubber bearings, high damping rubber bearings, lead-rubber bearings and natural rubber bearings, under biaxial and tri-axial (axial force and both component of horizontal displacement component) loading conditions on the basis of experimental results. Such models have been proved to perform satisfactorily for complex seismic structural analyses. However, in their current formulation, they reproduce the device response at a fixed value of the axial loading.

The present paper is focused on modelling the response of rubber bearings, extending the existent procedures to variable axial loading. Suitable laboratory experimental tests, available in the existent literature, represent the target for developing the proposed numerical approach.

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2 REFERENCE SPECIMEN AND LABORATORY TESTS

A cyclic shear tests of lead–rubber bearings was conducted (Yamamoto et al. [3]) to identify the mechanical characteristics of the lead-rubber bearing under large deformations at different values of the axial load.

The bearing comprised 24 layers of 2.0 mm thick rubber at 250 mm diameter, with a rubber layer shape factor (ratio between the steel layer area and the lateral surface of a single rubber layer) S_1=31.3 and second shape factor (ratio of the device diameter and the total thickness of the rubber layers) S_2=5.2. The bearing had a 50.0 mm diameter lead plug.

The laboratory tests consisted in applying a sinusoidal horizontal displacement with four cycles of loading at the increasing shear strain amplitudes of 50, 100, 200, 300 and 400 %, while the vertical load applied to the bearing was maintained constant. The tests were repeated at compressive stresses of σ = 0, 5, 10, 20, and 30MPa.

Table 1: Characteristics of the tested isolator

Item	**Value**
Isolator external diameter	250 mm
Steel reinforcing plate diameter, d'	250 mm
Diameter lead plug	50 mm
Number of elastomeric layers, n	24
Thickness of elastomeric layers, t_r	2 mm
First shape factor, $S_1 = d'/4 \cdot t_r$	31.3
Second shape factor, $S_2 = d'/n \cdot t_r$	5.2
Full isolator height, T_b	170.2 mm
Nominal dynamic shear modulus, G	1.44 MPa

3 ABE ET AL. MODEL

The Abe et al. [1, 2] model is herein selected for modelling the response of rubber bearings with variable axial loading.

In the Abe et al model for isolation devices the restoring force **F** is obtained as the sum of three contributions, superimposing an hysteretic component coming from an elastic non-linear spring ($\mathbf{F}^{(1)}$), the force in elastic-plastic spring ($\mathbf{F}^{(2)}$) and, finally, a second elastic non-linear spring for an hardening contribution ($\mathbf{F}^{(3)}$). Such components are defined by the following equations.

$$\mathbf{F} = \mathbf{F}^{(1)} + \mathbf{F}^{(2)} + \mathbf{F}^{(3)} \tag{1}$$

$$\mathbf{F}^{(1)} = K_1 \left\{ \beta + (1-\beta)\exp\left(-\frac{\tilde{U}_{\max}}{\alpha} \right) \right\} \mathbf{U} + \alpha \left\{ 1 - \exp(-\beta |\mathbf{U}|) \right\} \frac{\mathbf{U}}{|\mathbf{U}|} \tag{2}$$

$$\tilde{U}_{\max} = \max_{0<s\leq t} \left\{ |\mathbf{U}(s)| \right\} \tag{3}$$

$$\frac{\dot{\mathbf{F}}^{(2)}}{Y_t} = \frac{\dot{\mathbf{U}}}{U_t} - \frac{|\dot{\mathbf{U}}|}{U_t} \left(\frac{|\mathbf{F}^{(2)}|}{Y_t} \right)^{n-1} \frac{\mathbf{F}^{(2)}}{Y_t} \tag{4}$$

$$Y_t = Y_0 \left(1 + \left| \frac{\mathbf{U}}{U_H} \right|^p \right) \tag{5}$$

$$U_t = U_0\left(1+\frac{\tilde{U}_{\max}}{U_s}\right) \tag{6}$$

$$\mathbf{F}^{(3)} = K_2\left(\frac{|\mathbf{U}|}{U_H}\right)^r \mathbf{U} \tag{7}$$

In the previous equations **U** denotes the horizontal relative displacement across the isolator, K_1, α e β are other required parameters for defining the elastic non-linear spring; Y_t is the yielding force and U_t the corresponding displacement of the elastic-plastic spring (both include a modelling of the increase of the area of the hysteresis loops trough the parameters Y_0 – the initial yielding force – and U_H). The behavior of the third non-linear elastic spring delivering the forces listed in $\mathbf{F}^{(3)}$, called the *hardening spring*, depends on the parameters K_2 and r. This spring, working in parallel to the elastic-plastic spring, expresses the increase of the tangent stiffness.

The vertical response of the device is not directly modelled, and was assumed as uncoupled from the horizontal response. Instead, the horizontal response will be affected by the value of the vertical force carried by the device. To model this aspect, the parameters of the Abe et al model have been identified on a sample isolator for different values of the acting axial force. These values will than be used in computing the numerical response of the device under variable axial loading.

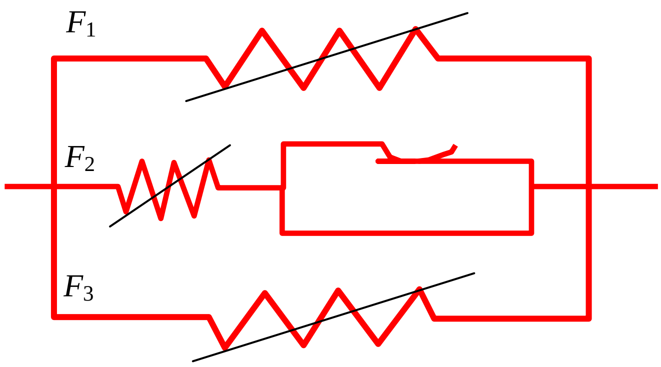


Figure 1 – Schematic representation of the Abe et al. model.

4 ABE ET AL. MODEL PARAMETERS IDENTIFICATION

This section describes the optimization procedure employed in the identification of the Abe et al. model parameters. The target of the optimization procedure is represented by the cyclic shear tests of lead–rubber isolator as described in the literature research paper by Yamamoto et al. [3] under large deformations at different axial loads (0, 5, 10, 20,30 MPa). The optimization procedure herein employed is the *Pattern Search* one, as implemented in Matlab code [4].

For each level of axial force a different set of the parameters for the Abe et al. model has been identified by minimizing the root mean square error (RMSE) between the experimental cyclic response and the one form the numerical model.

Not all the Abe et al. model parameters highlighted essential variation: a preliminary sensitivity analysis allowed to fix constant values for a number of them. Table 1 summarizes all the identified parameters (in bold are highlighted the ones with fixed value). Figures 2-5 depicts the comparison between the experimental responses of the lead-rubber bearing in Yamamoto et al. [3] with the numerical output from the Abe et al. model and the parameters in Table 2.

Table 2: Parameters indentified with method Pattern Search. The parameters in bold are maintained constant as the axial stress increase.

	Axial stress				
	σ =0 Mpa	**σ=5 Mpa**	**σ=10 Mpa**	**σ=20 Mpa**	**σ=30 Mpa**
Parameters					
K_1	**11**	**11**	**11**	**11**	**11**
α	**3**	**3**	**3**	**3**	**3**
β	0.01	0.0021	0.0058	0.002	0.0001
A	19	19	12	12	4
B	0.04	0.04	0.05	0.04	0.04
N	0.3	0.3	0.25	0.3	0.3
Y_0	15	16	15	20.5	22.45
U_H	99	108	110	118	112
P	1.3	0.9	1.5	2.4	3.75
U_0	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
U_S	100	110	200	56	25
K_2	0.105	0.097	0.03	0.0014	-0.135
R	2	2.3	2.5	2.3	2.6

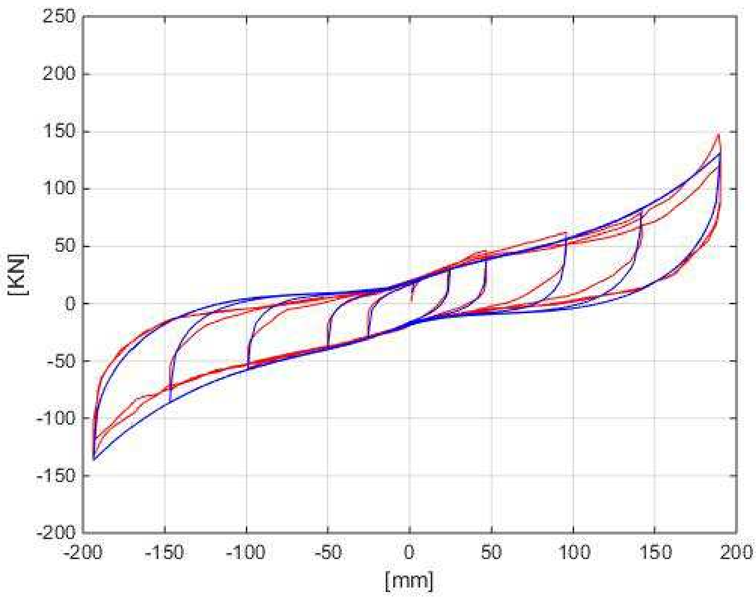


Figure 2 – Cyclic shear test of the tested isolator (50%, 100%,200%, 300% and 400% deformations and 5 MPa constant vertical stress). Red line: experimental test; Blue line: numerical simulation.

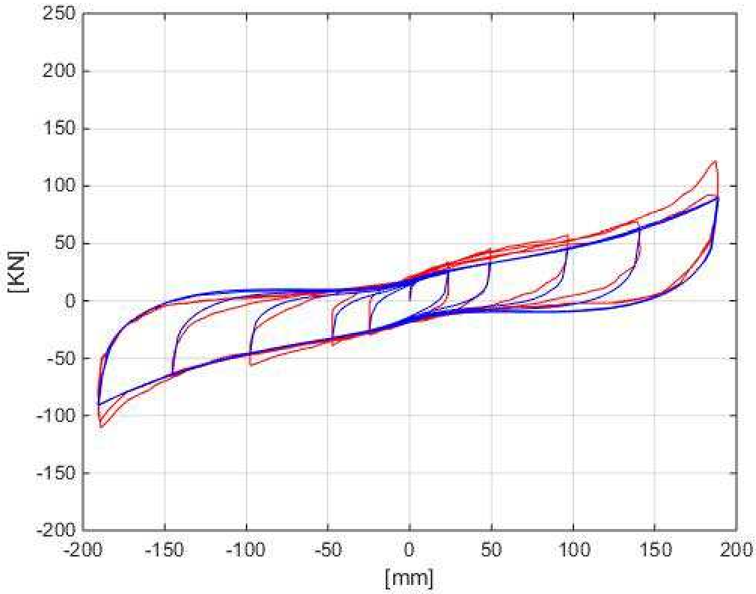


Figure 3 – Cyclic shear test of the tested isolator (50%, 100%,200%, 300% and 400% deformations and 10 MPa constant vertical stress). Red line: experimental test; Blue line: numerical simulation.

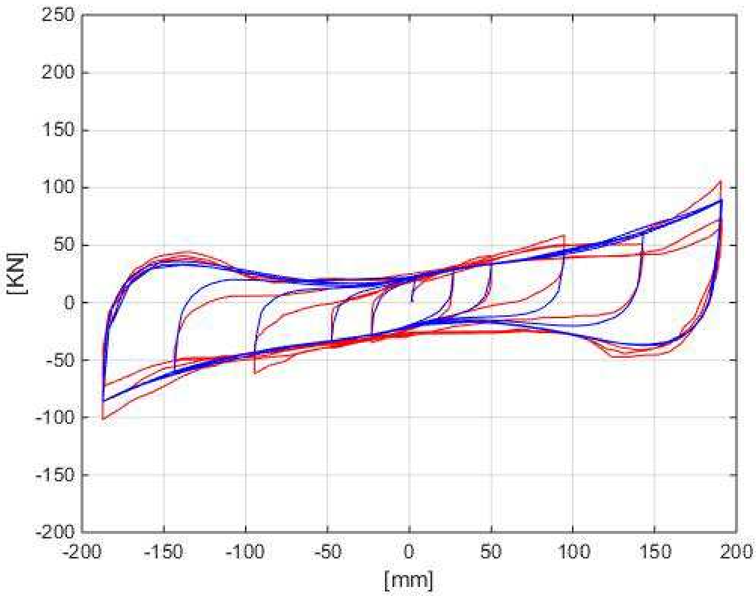


Figure 4 – Cyclic shear test of the tested isolator (50%, 100%,200%, 300% and 400% deformations and 20 MPa constant vertical stress). Red line: experimental test; Blue line: numerical simulation.

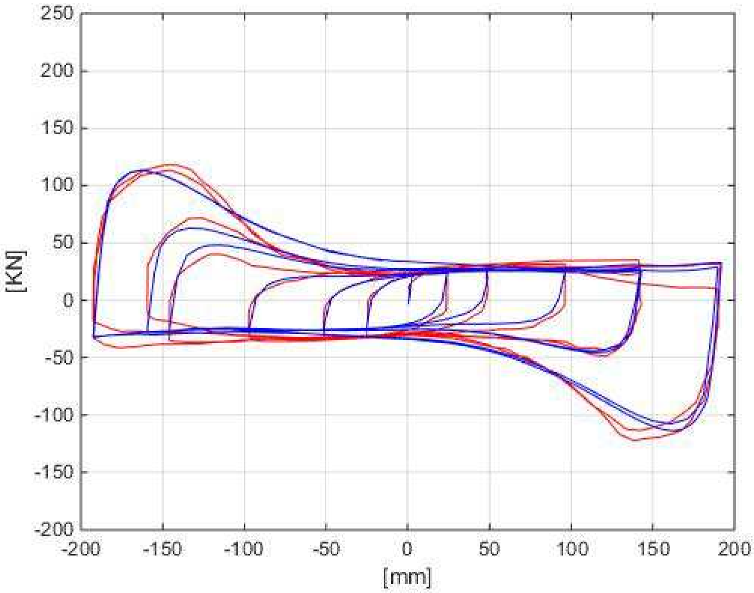
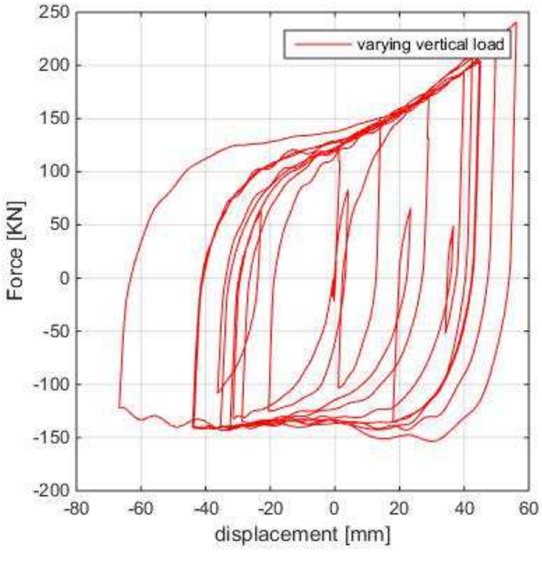


Figure 5 **–** Cyclic shear test of the tested isolator (50%, 100%,200%, 300% and 400% deformations and 30 MPa constant vertical stress). Red line: experimental test; Blue line: numerical simulation.

5 MODEL OUTCOMES FOR MULTICOMPONENT SEISMIC LOADING

Whenever the loading is multicomponent, the horizontal response of the device results affected. Figures 6 and 7 compares the response with and without variation of the axial loading for the identified device. The time histories for the corresponding variation of the axial force and horizontal displacements are reported in Figures 8-11. These time histories were extracted form the response of two isolation devices in the numerical model of a base isolated nuclear power plant presented in [5], which was also studied in [6, 7]. The time histories were scaled to the geometry of the device under study in this work: the axial force was scaled by the area of the cross section in the two devices to impose the same value of axial stress; the displacements were scaled to impose the same value of shear distortion in the rubber layers of the two devices.

In computing the response with the Abe et al. model under constant value of axial force, the peak compression value divided by two was selected.



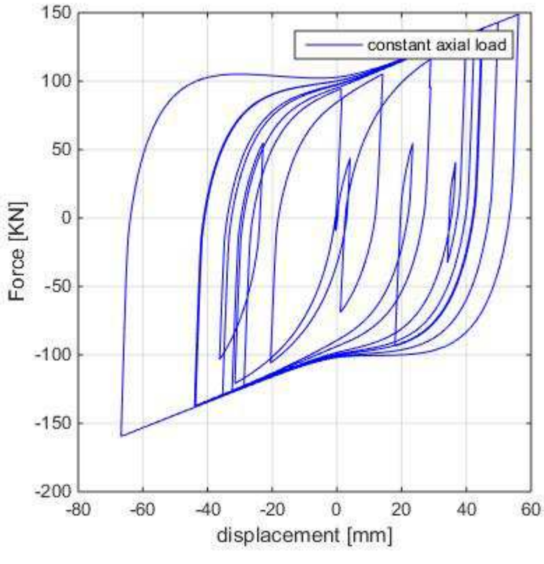


Figure 6 – Lead–rubber bearing shear force–displacement hysteresis loops for cyclic shear tests with: a) varying vertical load , b) 6.5 MPa constant vertical stress.

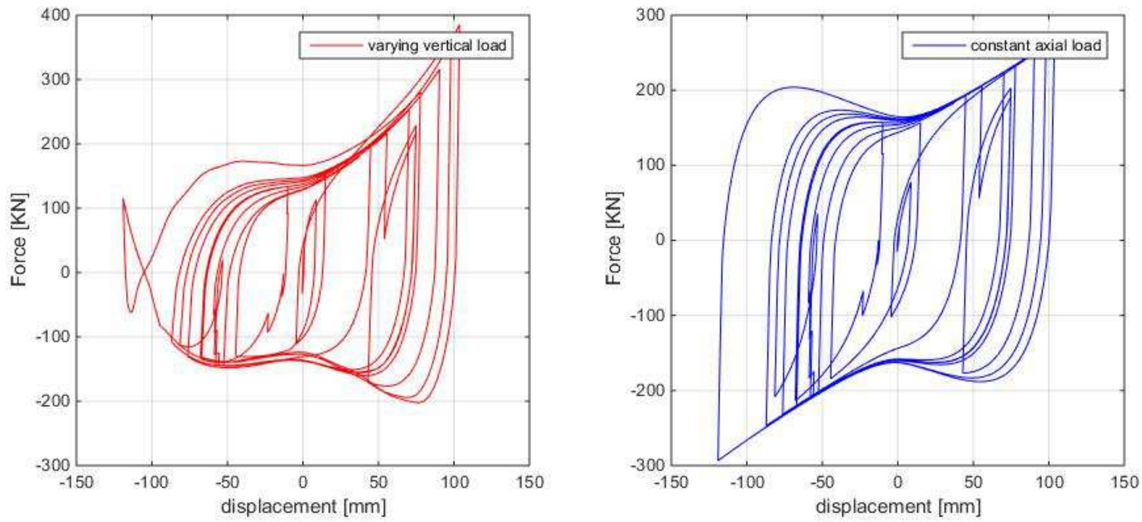


Figure 7 – Lead–rubber bearing shear force–displacement hysteresis loops for cyclic shear tests with: a) varying vertical load , b) 9.5 MPa constant vertical stress.

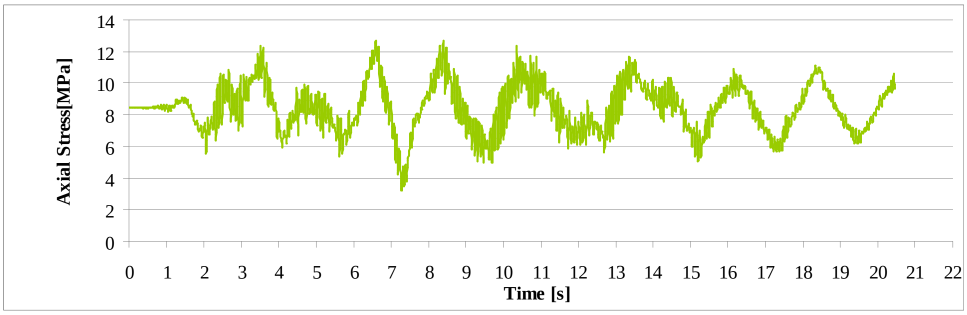


Figure 8 – Time histories of the axial force (in terms of stress) used for the response in Figure 6.

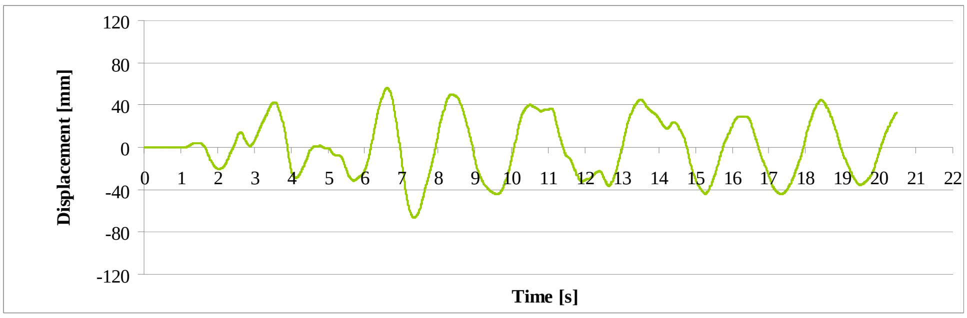


Figure 9 – Time histories of the horizontal displacement used for the response in Figure 6.

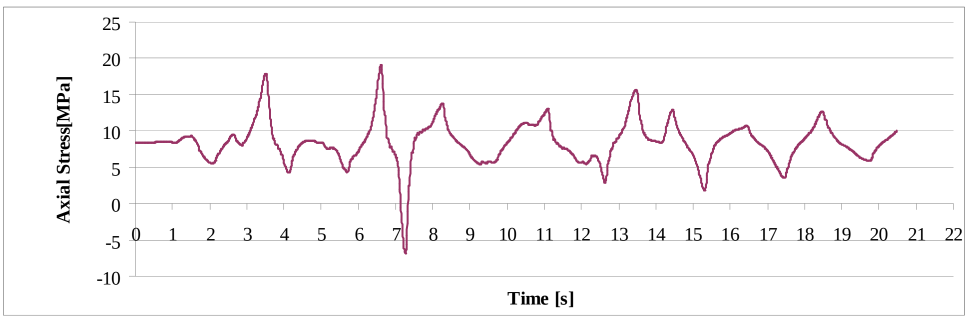


Figure 10 – Time histories of the axial force (in terms of stress) used for the response in Figure 7.

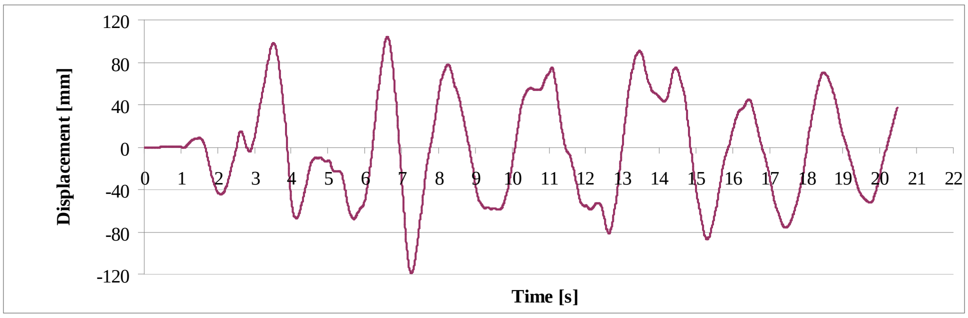


Figure 11 – Time histories of the horizontal displacement used for the response in Figure 7.

6 CONCLUSION

This research work is devoted to the set-up of a numerical model from the Abe et al. class type which is proposed to fit the asymmetric hysteresis response of a lead plug rubber bearing isolation device under variable axial loading.

The physical model of the device has been tested in a laboratory facility for different values of axial loading. These laboratory tests on the cyclic behaviour of the isolation device under different values of axial force are used as the base to identify the parameters of the proposed model.

Preliminary analyses carried out by using the proposed numerical model highlight the effects that the axial load can have on the device horizontal response. For the larger values of the axial load herein considered, this can be substantial.

REFERENCES

[1] M. Abe, J. Yoshida, Y. Fujino (2004), "Multiaxial Behaviors of Laminated Rubber Bearings and Their Modeling. I: Experimental Study", J Struct Eng-ASCE, 130:1119-1132.

[2] M. Abe, J. Yoshida, Y. Fujino (2004), "Multiaxial Behaviors of Laminated Rubber Bearings and Their Modeling. II: Modeling", J Struct Eng-ASCE, 130:1133-1144.

[3] S. Yamamoto, M. Kikuchi, M. Ueda and I.D. Aiken (2009), "A mechanical model for elastomeric seismic isolation bearings including the influence of axial load", Earthquake Engng Struct. Dyn. 38:157–180.

[4] MATLAB. Release R2013a user manual, MATLAB, Natick, Massachusetts, 2013.

[5] M. Domaneschi, L. Martinelli, F. Perotti (2012), "The effect of rocking excitation on the dynamic behaviour of a Nuclear Power Plant reactor building with base isolation", in Proc. of the 15th World Conference on Earthquake Engineering, LISBON (PORTUGAL) 2012, http://www.iitk.ac.in/nicee/wcee/article/WCEE2012_2154.pdf

[6] M. Domaneschi, L. Martinelli, F. Perotti, M. Tomasin, "Assessing the performance of a high damping rubber bearing in beyond-design conditions", Proceedings of the Tenth International Workshop on Structural Health Monitoring, September 1-3, 2015, Stanford, CA-USA. ISBN 978-1-60595-275-8.

[7] F. Perotti, M. Domaneschi, S. De Grandis (2013), "The numerical computation of seismic fragility of base-isolated NPP buildings", Nuclear Engineering and Design, 262:189–200.