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Base Isolation Devices To Reduce the Vulnerability of Structures Subject to Strong Dynamic Events

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Abstract

In this research work a seismic base isolation system is studied. The analysed seismic base isolation system is realized by high damping hybrid seismic isolators. This isolator is obtained by the assembly in series of lead rubber bearing and a friction slider characterized by strong friction coefficient. The nonlinear dynamic behaviour is studied by analyzing the proper hysteretic cycles of the base isolation device. The analyzed base isolation device is intended to be able to work under the effects of strong dynamic and seismic events, whereas strong dynamic events are considered those characterized by high intensity and/or high frequency content. In this regard a nonlinear dynamic analysis is performed, and the structural behaviour of the base isolation device is suitably investigated. The analysis is intended so that the base isolation device can suitably perform under events characterized by high values of peak ground acceleration and events with high energetic content.
The analysis is performed of the different phases of the mathematical behaviour of the base isolation device and the mathematical simulation of the base isolation device is properly illustrated.

Keywords: base isolation devices, nonlinear dynamics, structural analysis, structural vulnerability, strong seismic events, hysteretic cycles.

1 Introduction

In the present work a base isolation device is illustrated for the mitigation of the vulnerability of structures subject to strong dynamic and seismic events. The considered base isolation device is realized by high damping hybrid seismic isolators. The device is obtained by the combination in series of lead rubber bearing and a friction slider characterized by strong friction coefficient.

In the present approach the structure is designed according to the proper seismic codes and the hysteretic effects are mainly designed to occur in the base isolation devices [1, 2, 3]. Accordingly, the hysteretic behaviour of the device considered is properly analyzed and investigated, see also [4-14]. For a dynamic analysis of a base isolated structures with irregularities in plan, see also [15, 16]. For an investigation of the comparative dynamic analysis of base isolated structures and the corresponding fixed base structures see also [17-22].

Typically, in base isolated structures the adopted approach is based on the elongation of the vibration period of the structure. The dynamic behaviour of the base isolated structure is designed by assigning the period of the fundamental vibration mode to be positioned in the low part of the design response spectrum, so that the seismic forces applied to the base isolated structure are reduced with respect to those applied to the fixed base structure. However, this approach can fail in producing beneficial effects for example in case of dynamic events with high energetic content at low frequency, see e.g. [18].

In such cases an approach with the limitation of the shear force applied to the structure can represent a useful alternative. The intent is to limit the shear force transmissible to the structure independently from the intensity and the frequency of the seismic event.

In the present paper this intent is studied by analyzing a seismic base isolation system realized by high damping hybrid seismic isolators. Such isolator is obtained by assembling in series a lead rubber bearing and a friction slider characterized by high friction coefficients. The nonlinear dynamic behaviour of the structure is influenced by the suitable hysteretic cycles of the base isolation device.

The analyzed base isolation device is intended to maximize its beneficial effects under strong dynamic and seismic events, such as dynamic events characterized by high intensity and/or high energetic content at low frequency. The nonlinear dynamic behaviour is studied by considering the hysteretic cycles of the base isolation device. A nonlinear dynamic analysis can be performed based on the structural behaviour of the base isolation devices. The different phases of the mathematical behaviour of the base isolation device are analysed and the mathematical simulation of the base isolation device is properly discussed.

High damping rubber bearing isolators are typically adopted in base isolation techniques for structural analysis, see e.g. [23]. They can be used in series, see e.g. [24], or in parallel with sliding isolators, see also [25]. Linearized modelling of such devices are sometimes adopted to obtain simplified and more robust computational analyses. Conversely, lead rubber bearing isolators are also frequently used, see e.g. [26, 27] and they can also be used in parallel with friction isolators. They provide a greater dissipative capacity with respect to the high damping rubber bearings with more capacity to contrast base displacements.

At variance with the system proposed by [28] in which a high damping rubber bearing isolator is positioned in series with the friction slider, in the present analysis a lead rubber bearing isolator is placed in series with the friction slider isolator. The use of lead rubber bearing isolator instead of the high damping rubber bearing isolator provides a more stable behaviour and more dissipative capacity. This base isolation device is studied to analyse its performance with respect to the constitutive behaviour for the using in base isolation systems suitable for strong seismic events characterized by events with high intensity in terms of peak ground acceleration and events with high energetic content at low frequency.

2 Modelling the constitutive behaviour of the components of the seismic device

In the present section we consider the different components of the considered base isolation device, namely the lead rubber bearing and the friction slider. In fact, the considered base isolation device is composed by the assembling in series of a lead rubber bearing and a friction slider. The friction slider will be characterized by high friction coefficient, so that for low and medium seismic events only the lead rubber bearing will be activated, whereas for strong seismic events both the lead rubber bearing and the friction slider will be activated.
The behaviour of the base isolation device is developed in different phases depending on the part of the base isolation that is activated. In the sequel we will specify the behaviour of the single components of the base isolation device and afterwards we will consider the behaviour of the global device considered as an assembling in series of the lead rubber bearing and the friction slider.

2.1 Constitutive behaviour of the lead rubber bearing isolator

The lead rubber bearing isolator is realized by rubber layers and steel layers. In the internal part there is a lead core. The constitutive model of the isolator is modelled by an hysteretic model described in [23]

$$F = \alpha \frac{F_y}{\gamma_y} \gamma + (1-\alpha) F_y Z \tag{1}$$

In the above expression the reacting force F of the isolator is expressed by a linear term depending on the yielding value of the force F_y and a hysteretic recall term. The shear deformation is γ, the shear deformation corresponding to F_y is γ_y, the ratio between the yielding stiffness and the elastic stiffness is α, and Z is an hysteretic parameter depending on coefficients which define the shape of the hysteretic cycle.
A lead rubber bearing isolator is represented in Fig.1 (left). A typical hysteretic cycle of the constitutive behaviour of the lead rubber bearing isolator is illustrated in Fig. 2 (left).

2.2 Constitutive behaviour of the friction slider isolator

The friction slider isolator is realized by steel plates and teflon bearings, see Fig. 1 (right), and it allows the sliding between the plates. The friction sliders can be characterized by low, medium and high friction coefficients which typically range between 0.05 and 0.20.

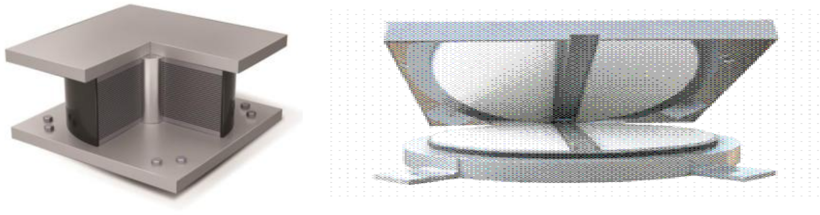

Fig. 1: Lead rubber bearing isolator (left) and friction slider isolator (right).

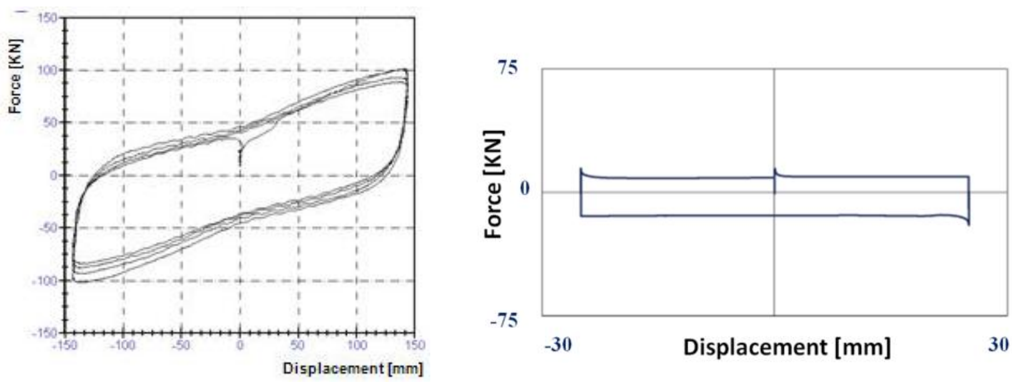

Fig. 2: Hysteretic cycles of the lead rubber bearing isolator (left) and of the friction slider isolator (right).

The friction coefficient depends on the sliding velocity between the plates during the seismic event, the contact pressure between the plates and the temperature. For the constitutive behaviour of the friction slider isolator, the Coulomb law has been assumed in which the expression of the friction coefficient depends on the sliding velocity and on the minimum and maximum values of the friction coefficients during the event, see e.g. [24, 25],

$$\mu = f_{\max} - \left(f_{\max} - f_{\min}\right)e^{-r\left|\dot{d}_b\right|} \tag{2}$$

in which μ represents the friction coefficient, $f_{\max}$ and $f_{\min}$ represent in turn the maximum (minimum) friction coefficient associated with high (low) sliding velocity, r is the inverse of a characteristic sliding velocity, used to model the transition between maximum and minimum friction coefficients. The coefficient r can be determined experimentally and usually it does not exceed 100 s/m.

3 Global modelling the constitutive behaviour of the considered seismic device

In our analysis we consider a seismic base isolator obtained by the assembling in series of a lead rubber bearing, see Fig. 1 (left), and a friction slider characterized by strong friction coefficients, see Fig. 1 (right). The constitutive behaviour of the component represented by the lead rubber bearing has been detailed in section 2.1, see Fig. 2 (left), whereas the constitutive behaviour of the component represented by the friction slider has been detailed in section 2.2, see Fig. 2 (right).
The objective of this analysis is to consider a global seismic isolator which is composed by the two isolators which are placed in series, respectively a lead rubber bearing and a friction slider, which by working together are capable to cope with strong seismic events. In fact, the nonlinear dynamic behaviour of the structure base isolated by the considered global seismic isolator is influenced by the proper hysteretic cycles of the global base isolation device. The objective of this study is to investigate such hysteretic cycles which play an essential role in the isolation of structures when they are subject to strong dynamic events.
For the seismic design of the structure, we consider that for seismic events associated to the Ultimate Limit States, such as Human Life Safeguard Limit State and Collapse Prevention Limit State, see the Italian seismic code NTC 2008 [29] and the Eurocode EC8 [30], only the lead rubber bearing isolator is activated by ensuring a nearly elastic behaviour of the structure above the base isolation (superstructure) so that all the hysteretic phenomena are localized in the isolation devices. For stronger seismic events, for instance those characterized by extremely high intensity values of the peak ground acceleration or high energetic content at low frequency, also the friction slider is activated. The analysis is performed by considering a limitation of the force strategy. Typically, it may be considered a maximum horizontal force between 10-20% of the total structural weight according to the design needs. After the extreme seismic events a recentring operation can be applied.
The mathematical modelling of the global base isolation device can therefore be studied by considering the different phases of the constitutive behaviour of the global base isolation device, in particular fifteen different phases can be considered. For extended details on the mathematical modelling of the different phases of the constitutive behaviour of the global base isolation device see [18].
In this analysis we consider the structure as a single degree of freedom system base isolated by the global base isolation device and subject to an harmonic horizontal force $f(t) = f_0 \sin(\overline{\omega} t)$ where $\overline{\omega}$ is the frequency of the harmonic horizontal force.
The global base isolation device is composed by a lead rubber bearing with a constitutive behaviour described in section 2.1 (characterized by an elastic component, and hysteretic damper and an equivalent viscous damper), and a friction slider placed in series with a constitutive behaviour described in section 2.2 (characterized by a friction component).
The force vs displacements diagram representing the hysteretic cycle of the single lead rubber bearing isolator is illustrated in Fig. 3. The force vs displacements

diagram representing the hysteretic cycle of the single friction slider isolator is illustrated in Fig. 4. The force vs displacements diagram representing the hysteretic cycle of the global base isolation device, composed by the placement in series of the lead rubber bearing and the friction slider, is illustrated in Fig. 5.

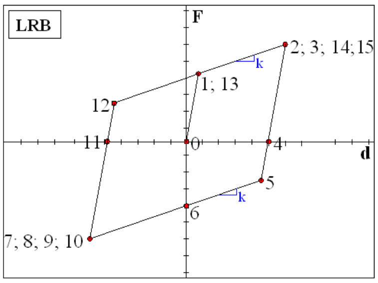

Fig. 3: Hysteretic cycle of the lead rubber bearing isolator.

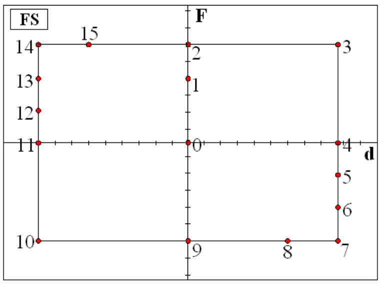

Fig. 4: Hysteretic cycle of the friction slider isolator.

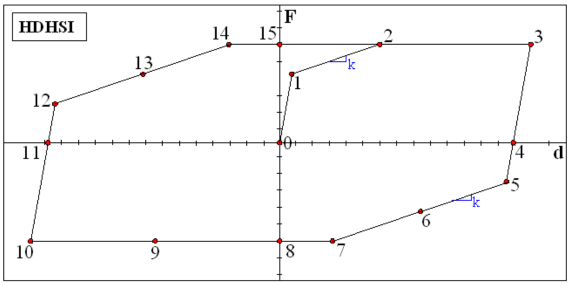

Fig. 5: Hysteretic cycle of the global base isolation device, as composed by the placement in series of a lead rubber bearing and a friction slider.

The force vs displacement diagram illustrated in Fig. 5 shows that the hysteretic cycle of the global base isolation device is characterized by an hysteretic response in which the top branch and the bottom branch are horizontal by providing a suitable limitation of the force which is transmitted to the above superstructure.

This behaviour is an advantageous feature of the considered isolator since the isolator can be considered as an effective isolator in case of earthquakes characterized by particularly high intensity. Accordingly, a subsequent investigation can furtherly be performed for the dynamic behaviour of the considered global base isolation device by a finite element analysis.

4 Conclusions

In the present research work a base isolation system has been analysed. The considered base isolation system is realized by the composition of a lead rubber bearing and by placing in series a friction slider with high friction coefficient. The objective is the research for a base isolation system able to cope with particularly strong seismic events, where strong seismic events are intended as the ones characterized by high intensity in terms of peak ground acceleration and high energetic content at low frequency which are known to be particularly challenging for base isolated structures.

The adopted base isolation device is designed by considering the friction slider characterized by suitably high values of the friction coefficient, so that for seismic events comparable with the ones associated with the Ultimate Limit State, as defined by the seismic codes [29, 30], only the lead rubber bearing is activated. Whereas for stronger seismic events also the friction slider is activated. It is noted that in case of dangerous seismic events a recentring operation may be required, however such operation can be considered as required only for extremely strong earthquakes and it does not require any construction difficulties.

In the work the different constitutive behaviour of the lead rubber bearing and of the friction slider have been illustrated. The considered base isolation device is realized by a composition of the two isolators. Accordingly, the constitutive behaviour of the considered global seismic isolation device has been investigated, and the force vs displacement plot of the hysteretic behaviour has been analysed. It has been shown that the global base isolation device can provide a limitation of the force strategy according to the requested objectives of the analysis.

The considered global base isolation device can be furtherly investigated with a detailed finite element analysis and by considering the nonlinear dynamic behaviour of such device when properly used as a base isolation system for structures also characterized by plan irregularities. This further research work will be the object of a future research program.

References

[1] F. Naeim and J. M. Kelly, Design of Seismic Isolated Structures, John Wiley, New York, 1999.

[2] K. L. Ryan and A .K. Chopra, Estimation of seismic demands on isolators based on nonlinear analysis, J. Struct. Eng., ASCE, 130, pp. 392-402, 2004.

[3] C. Christopoulos, A. Filiatrault, Principles of Passive Supplemental Damping and Seismic Isolation, IUSS Press, Pavia, Italy, 2006.

[4] S. Nagarajaiah, A. M. Reinhorn and M. C. Constantinou, 3D-Basis: Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures: Part II, Technical Report NCEER-91-0005, Nation Center For Earthquake Engineering Research, Buffalo, N.Y., 1991.

[5] De Angelis, F., Taylor, R.L., A Nonlinear Finite Element Plasticity Formulation without Matrix Inversions, Finite Elements in Analysis And Design, Vol. 112, pp. 11-25, 2016.

[6] De Angelis, F., Taylor, R.L., An Efficient Return Mapping Algorithm for Elastoplasticity with Exact Closed Form Solution of the Local Constitutive Problem, Engineering Computations, Vol. 32, Issue 8, pp. 2259 - 2291, 2015.

[7] De Angelis, F., Extended formulations of evolutive laws and constitutive relations in non-smooth plasticity and viscoplasticity, Composite Structures, Vol. 193, pp. 35-41, 1 June 2018.

[8] De Angelis, F., On the structural response of elasto/viscoplastic materials subject to time-dependent loadings, Structural Durability & Health Monitoring, Vol. 8, No. 4, pp. 341-358, 2012.

[9] De Angelis, F., A variationally consistent formulation of nonlocal plasticity, Int. Journal for Multiscale Computational Engineering, Vol. 5, Issue 2, pp. 105-116, Begell House Inc. Publishers, New York, 2007.

[10] De Angelis, F., A comparative analysis of linear and nonlinear kinematic hardening rules in computational elastoplasticity, Technische Mechanik, Vol. 32 (2-5), pp. 164-173, 2012.

[11] De Angelis, F., Computational issues and numerical applications in rate-dependent plasticity, Advanced Science Letters, Vol. 19, Number 8, pp. 2359-2362, American Scientific Publishers, USA, 2013.

[12] De Angelis, F., De Angelis, M., On solutions to a FitzHugh-Rinzel type model, Ricerche di Matematica, Vol. 70, Issue 1, pp. 51-65, 2021.

[13] De Angelis, F., Meola, C., Non-smooth evolutive laws in multisurface elastoplasticity with experimental evidence by infrared thermography, Composite Structures, Vol. 265, Art. n. 113156, pp. 1-9, 2021.

[14] De Angelis, F., A multifield variational formulation of viscoplasticity suitable to deal with singularities and non-smooth functions, Int. Journal of Engineering Science, Vol. 172, Art. 103616, pp. 1-16, 2022.

[15] Cancellara, D., De Angelis, F., Assessment and dynamic nonlinear analysis of different base isolation systems for a multi-storey RC building irregular in plan, Computers and Structures, Vol. 180, pp. 74–88, February 2017.

[16] Cancellara, D., De Angelis, F., Dynamic nonlinear analysis of an hybrid base isolation system with viscous dampers and friction sliders in parallel, Applied Mechanics and Materials, Vol. 234, pp. 96-101, 2012.

[17] Cancellara, D., De Angelis, F., Nonlinear dynamic analysis for multi-storey RC structures with hybrid base isolation systems in presence of bi-directional ground motions, Composite Structures, Vol. 154, pp. 464–492, 2016.

[18] Cancellara, D., De Angelis, F., A base isolation system for structures subject to extreme seismic events characterized by anomalous values of intensity and frequency content, Composite Structures, Vol. 157, pp. 285–302, 2016.

[19] Cancellara, D., De Angelis, F., Dynamic assessment of base isolation systems for irregular in plan structures: Response spectrum analysis vs nonlinear analysis, Composite Structures, Vol. 215, pp. 98-115, 2019.

[20] De Angelis, F., Cancellara, D., Dynamic analysis and vulnerability reduction of asymmetric structures: Fixed base vs base isolated system, Composite Structures, Vol. 219, pp. 203-220, 2019.
[21] Cancellara, D., De Cicco, S., De Angelis, F., Assessment and vulnerability reduction of under-designed existing structures: Traditional vs innovative strategy, Computers and Structures, Vol. 221, pp. 44-64, September 2019.
[22] Cancellara, D., De Angelis, F., Base isolation systems for structures subject to anomalous dynamic events, Lecture Notes in Mechanical Engineering, 24th Conference of the Italian Association of Theoretical and Applied Mechanics, AIMETA2019, Rome, Italy, 15-19 September 2019, Code 238859, pp. 175-187, Springer, 2020.
[23] Wen, Y.K., Method for Random Vibration of Hysteretic Systems, Journal of the Engineering Mechanics Division, ASCE, Vol. 102, No. EM2, pp. 249-263, 1976.
[24] Mokha, A.S., Constantinou, M.C., Reinhorn, A.M., Teflon bearing in base isolation. I: testing, J. Struct. Engrg. (ASCE), Vol. 116 (2), pp. 438-454, 1990.
[25] Constantinou, M.C., Mokha, A.S., and Reinhorn, A.M., Teflon bearing in base isolation. II: modelling, J. Struct. Engrg. ASCE, Vol. 116 (2), pp. 455-474, 1990.
[26] Robinson, W.H., Tucker, A.G., A lead-rubber shear damper, Bull. N. 2, Natl. Soc. Earthquake Eng., Vol. 10, pp. 151-153, 1977.
[27] Robinson, W.H., Lead rubber hysteretic bearings suitable for protecting structures during earthquakes, The Journal of the Anti-Seismic Systems International Society (ASSISi), Seismic Isolation and Protection Systems, vol 2, n. 1, Mathematical Sciences Publishers, pp. 5-19, 2011.
[28] Gueraud, R., Noel-Leroux, J.P., Livolant, M. and Michalopoulos, A.P., Seismic isolation using sliding elastomer bearing pads, Nuclear Engineering and Design, Vol. 84, 3, 363-377, 381-382, 1985.
[29] NTC 2008, Decreto Ministeriale 14/01/2008, Nuove Norme Tecniche per le Costruzioni, (in italian), Gazzetta Ufficiale n. 29 - Suppl. Ordinario n. 30, Roma (Italy), 2008.
[30] EC8, Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General rules, seismic actions and rules for buildings, PrEN1998-1, European Committee for Standardization, TC250/SC8, 2003.