The 2021 World Congress on
Advances in Structural Engineering and Mechanics (ASEM21)
GECE, Seoul, Korea, August 23-26, 2021

Comparison of base isolation systems for reinforced concrete structures with irregularity in plan

*DonatoCancellara[1)]

[1)] *Department of Structures for Engineering and Architecture,*
University of Naples Federico II, 80125 Naples, Italy
[1)] donato.cancellara@unina.it

ABSTRACT

In this paper base isolation systems for reinforced concrete buildings are analyzed in order to compare their seismic behaviour. The analyzed reinforced concrete building is characterized by irregularity in plan and it has been designed according to the European seismic codes. The behaviour of the structure is analyzed and compared when it is subject to strong seismic events. In the analysis two hybrid base isolations systems have been analyzed, namely a high damping rubber bearing actuated in parallel with friction sliders and a lead rubber bearing also actuated in parallel with friction sliders. A dynamic nonlinear analysis has been performed for the three-dimensional structure base isolated by the two considered base isolation systems and the response of the structure to seismic actions is evaluated. The structural behaviour is assessed and the dynamic nonlinear analysis is discussed. A comparative analysis is illustrated for the base isolation systems by considering the structure characterized by irregularity in plan and by evaluating the seismic performance of the base isolated structure with the two considered base isolation systems and the seismic performance of the fixed base structure.

1. INTRODUCTION

The base isolation technique is a strategy for disconnecting the structure from the ground accelerations due to seismic events. We have adopted here the strategy of elongation of the period of vibration of the structure with respect to the case of fixed base structure, see e.g. Naeim and Kelly (1999) and Ryan and Chopra (2004). In the present analysis we considered a multi-storey Reinforced Concrete (RC) structure characterized by irregularity in plan. The behaviour of two different base isolation systems is analyzed. The first one is a hybrid base isolation system realized by High Damping Rubber Bearings (HDRB), see e.g. Wen (1976), actuated in parallel with Friction Sliders (FS) with low friction coefficient, see e.g. Mokha et al. (1990).The

---

[1)] Research Associate

second one is a hybrid base isolation system realized by Lead Rubber Bearings (LRB), see e.g. Robinson and Tucker (1977) and Robinson (1982), actuated in parallel with Friction Sliders (FS) with low friction coefficient. The dynamic nonlinear analysis for the base isolated structure has been performed by adopting bi-directional ground motions and with the recorded accelerograms, see e.g. Park et al. (1986), Nagarajaiah et al. (1991a, 1991b) and Wilson (2002). A fast nonlinear dynamic analysis algorithm has also been considered in the nonlinear dynamic analysis of the structure, see e.g. Wilson (2002). In the dynamic analysis the SAP2000NL code (2014) has been adopted. A modal nonlinear time history analysis is usually considered with explicit or implicit integration algorithms, see e.g. Newmark (1959), Wilson et al. (1973), Hilber et al. (1977), Hughes (1987), Clough and Penzien (1975).

The structural analysis has been performed in accordance with the European codes EC8 (2003) and EC2 (2004) and with the recorded accelerograms as represented in the European Strong-motion Database ESD, see e.g. Luzi et al. (2020).In particular we considered the recorded accelerograms of a seismic event occurred in Montenegro, seismic input record 000199. The present analysis complements the results given by Cancellara and De Angelis (2016a, 2016b, 2017, 2019) and De Angelis and Cancellara (2019). The effectivity of the two base isolation systems is illustrated and compared when the irregular in plan structure is subject to bi-directional ground motions. The results of the dynamic nonlinear analysis are illustrated and compared with the results of the fixed base structure. In the analysis we considered the time history of the base acceleration, the time history of the base displacement of the superstructure, the time history of the base shear and the time history of the inter-storey drift, see also e.g. Park et al. (1986), Nagarajaiah et al. (1991a, 1991b), Christopoulos and Filiatrault (2006), Fenz and Constantinou (2008).

2. THE IRREGULAR IN PLAN STRUCTURE CONSIDERED IN THE ANALYSIS

We analyze a structure placed in Italy and characterized by topographic category T1, soil type B. The structure is of class II and it has a nominal life of 50 years with a reference period of 50 years. With regard to the seismic hazard we refer to the Italian seismic code NTC 2018 (2018) and the Eurocodes EC2 (2004) and EC8 (2003). The building is characterized by a ground floor for commercial purposes, three floors for residential purposes and an attic. The building is characterized by irregularity in plan and it is L-shaped. For more details on the geometry of the structure see e.g. Cancellara and De Angelis (2017). For the dynamic analysis we considered in particular the seismic event occurred in Montenegro, on 15 April 1979, characterized by seismic magnitude 7.03 on a stiff soil, seismic input record 000199, see European Strong-motion Database ESD, Luzi et al. (2020). For assessing the nonlinear dynamic response of the structure we adopted a fast nonlinear dynamic analysis algorithm, see e.g. Wilson (2002), implemented in SAP2000NL code (2014). A modal nonlinear time history analysis has been performed, see e.g. Newmark (1959), Wilson et al. (1973), Hilber et al. (1977), Hughes (1987), Clough and Penzien (1975). The structure of the building has been designed so that beams and columns generally perform in the elastic range, see for instance Park et al. (1986), Nagarajaiah et al. (1991a, 1991b), Fenz and Constantinou (2008).

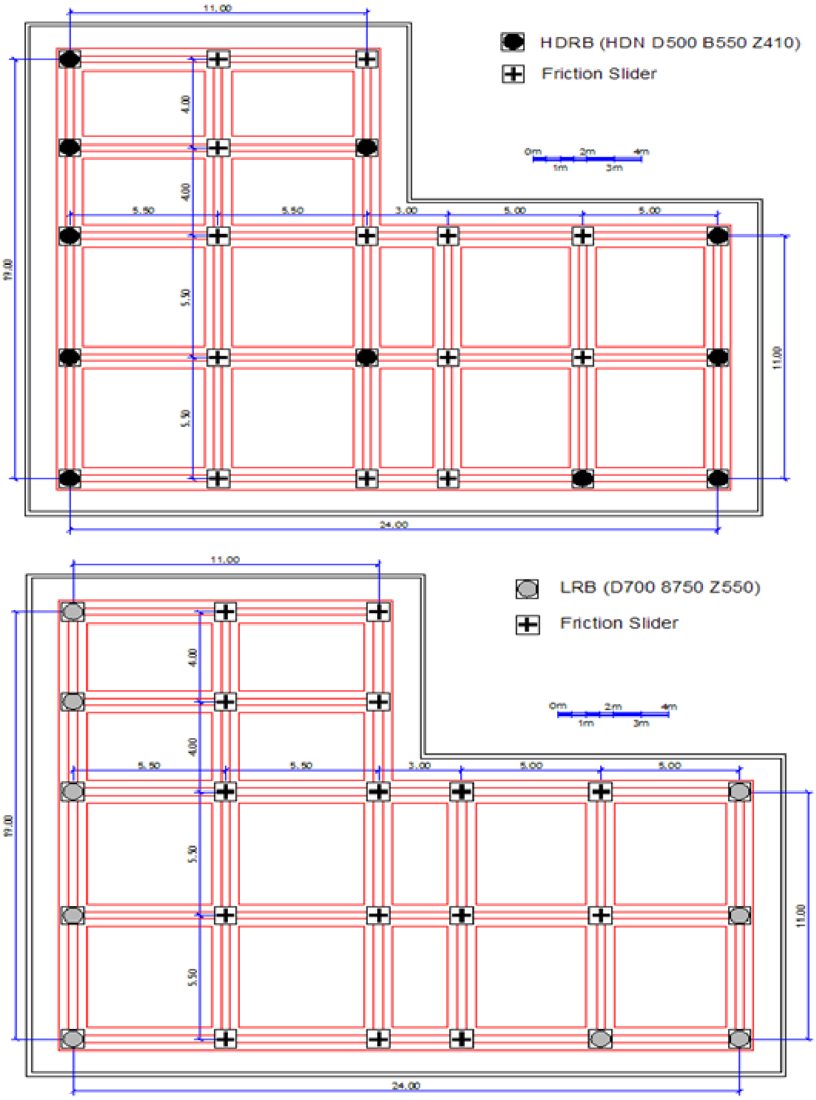

Fig. 1: The structure with the disposition in plan of the different isolators for the base isolation system HDRB+FS (top figure) and the base isolation system LRB+FS (bottom figure). (Integrated with supplemental findings and modified from Cancellara and De Angelis, 2017).

3. THE BASE ISOLATION SYSTEMS ADOPTED IN THE ANALYSIS

In the analysis we have adopted a first base isolation system composed by High Damping Rubber Bearings (HDRB) with equivalent viscous damping of 10% and located in parallel with friction sliders (FS) qualified by a low friction coefficient. For the criteria of the disposition in plan of the isolator devices, see e.g. Cancellara and De Angelis (2017), the aim is to decouple the vibration modes of the structure and thus regularizing the dynamic behaviour of the base isolated structure. The second analyzed base isolation system is composed by Lead Rubber Bearings (LRB) positioned in parallel with friction sliders (FS) qualified by a low friction coefficient. This second base isolation system admits to consider higher damping levels of about 30%.The objective of the isolation system is to increase the fundamental period of vibration of the structure, so that the pseudo-accelerations derived from the design spectrum are lower with respect to the ones in the fixed base structure. In the analysis for the elastomeric components of the isolation devices the hysteretic model proposed by Wen (1976) has been adopted. For alternative dynamic nonlinear analysis of hybrid base isolation systems see, e.g., Cancellara and De Angelis (2012a, 2012b, 2012c, 2016a, 2016b, 2017, 2019) and De Angelis and Cancellara (2019).For nonlinear constitutive models and rate effects in inelastic material behaviour, see e.g. Alfano et al. (2001), De Angelis (2000, 2007a, 2012a, 2012b, 2013, 2015, 2018), De Angelis and Cancellara (2013, 2017), De Angelis and Taylor (2014, 2015, 2016), De Angelis et al. (2018). For applications and investigation to other constitutive models see e.g. De Angelis (2007b, 2018), De Angelis and De Angelis (2021), De Angelis and Meola (2021), De Cicco and De Angelis (2020). For alternative procedure to reduce the structural vulnerability associated to dynamic and seismic events see e.g. Cancellara et al. (2019).

The disposition in plan of the devices, for the first base isolation system HDRB+FS and for the second base isolation system LRB+FS, are illustrated in Fig. 1, see also Cancellara and De Angelis (2017). Stability of the devices can be investigated by referring to De Angelis (2012c) and De Angelis and Cancellara (2012). The design of the base isolation systems was realized by means of a linear analysis. Subsequently, a nonlinear dynamic analysis has been performed by adopting the SAP2000NL (2014) finite element code.

4. COMPARATIVE ANALYSIS OF THE BASE ISOLATION SYSTEMS

The structure have been verified for the different base isolation systems by means of a nonlinear dynamic analysis by assessing the structural behavior of the base isolated structure with the two considered base isolation systems and the fixed base structure.

In Fig. 2 a comparative analysis is reported for the behaviour of the structure base isolated by the HDRB+FS base isolation system, the structure base isolated by the LRB+FS base isolation system and the fixed base structure (FB). In particular, for the seismic record associated to the Montenegro seismic event (code 000199 in x-direction), we report in Fig. 2 the maximum values of the base shear for the structure with the base isolation system HDRB+FS, the structure with the base isolation system LRB+FS and the fixed base structure FB.

We observe that, with respect to the traditional fixed base structure, both base isolation systems HDRB+FS and LRB+FS ensure an effective decrease of the maximum base acceleration and of the maximum base shear of the base isolated structure. The maximum base acceleration and the maximum base shear show a decrease of 1/5 to 1/10 with respect to the values observed in the fixed base structure.

For further investigations on base isolation systems see also Cancellara and De Angelis (2012d, 2012e, 2012f), Cancellara et al. (2013b, 2013c) and Cancellara et al. (2013a).

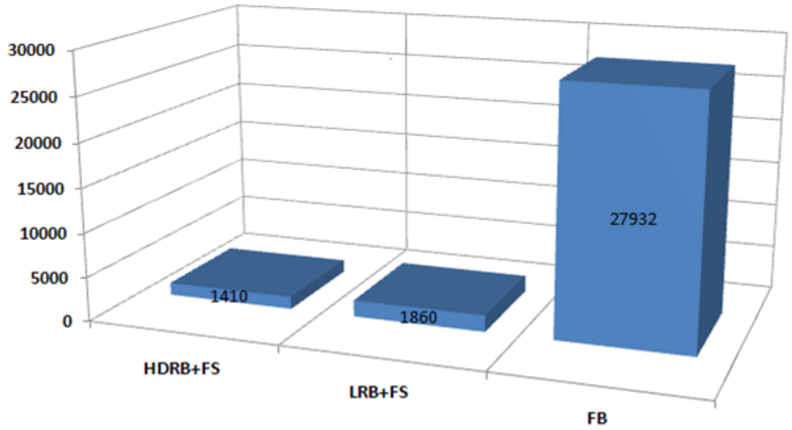

Fig. 2: Maximum values of the base shear (KN) for the structure base isolated by HDRB+FS, the structure base isolated by LRB+FS and the fixed base structure FB. Seismic input: record 000199x, Montenegro. (Integrated with supplemental findings and modified from Cancellara and De Angelis, 2017).

5. CONCLUSIONS

In the present analysis we have considered two base isolation systems: the HDRB+FS base isolation system and the LRB+FS base isolation system.
The present analysis show that friction slider isolators FS can be usefully adopted in parallel with high damping rubber bearings or with lead rubber bearings in order to ensure a suitable base isolation effect for structures characterized by irregularity in plan. The maximum values of the base shear have been reported for the fixed base structure and for the structure base isolated by the two considered base isolation systems, respectively the HDRB+FS base isolation system and the LRB+FS base isolation system. The nonlinear dynamic analysis has shown that the disposition in plan of friction sliders (FS) placed in parallel with elastomeric isolators (LRB or HDRB) is an effective solution for base isolating irregular in plan structures.

REFERENCES

Alfano, G., De Angelis, F., Rosati, L. (2001), General solution procedures in elasto/ viscoplasticity, *Computer Methods in Applied Mechanics and Engineering*, **190**, 5123-5147. (DOI: 10.1016/S0045-7825(00)00370-4)

Cancellara, D., De Angelis, F. (2012a), Hybrid base isolation system with friction sliders and viscous dampers in parallel: Comparative dynamic nonlinear analysis with traditional fixed base structure, *Advanced Materials Research*, **594-597**, 1771-1782. (DOI: 10.4028/www.scientific.net/AMR.594-597.1771)

Cancellara, D., De Angelis, F. (2012b), Steel braces in series with hysteretic dampers for reducing the seismic vulnerability of RC existing buildings: assessment and retrofitting with a non-linear model, *Applied Mechanics and Materials*, **204-208**, 2677-2689. (DOI: 10.4028/www.scientific.net/AMM.204-208.2677)

Cancellara, D., De Angelis, F. (2012c), Dynamic nonlinear analysis of an hybrid base isolation system with viscous dampers and friction sliders in parallel, *Applied Mechanics and Materials*, **234**, 96-101. (DOI: 10.4028/www.scientific.net/AMM.234.96)

Cancellara, D., De Angelis, F. (2012d), Seismical protection properties of high damping rubber bearing and lead rubber bearing base isolation systems for multi-storey RC buildings, *Applied Mechanics and Materials*, **234**, 90-95. DOI: 10.4028/www.scientific.net/AMM.234.90

Cancellara, D., De Angelis, F. (2012e), Seismic analysis and comparison of different base isolation systems for a multi-storey RC building with irregularities in plan, *Advanced Materials Research*, **594-597**, 1788-1799. DOI: 10.4028/www.scientific.net/AMR.594-597.1788

Cancellara, D., De Angelis, F. (2012f), A nonlinear analysis for the retrofitting of a RC existing building by increasing the cross sections of the columns and accounting forthe influence of the confined concrete, *Applied Mechanics and Materials*, **204-208**, 3604-3616. DOI:10.4028/www.scientific.net/AMM.204-208.3604

Cancellara, D., De Angelis, F. (2016a), Nonlinear dynamic analysis for multi-storey RC structures with hybrid base isolation systems in presence of bi-directional ground motions, *Composite Structures*, **154**, 464–492. (DOI: 10.1016/j.compstruct.2016.07.030)

Cancellara, D., De Angelis, F. (2016b), A base isolation system for structures subject to extreme seismic events characterized by anomalous values of intensity and frequency content, *Composite Structures*, **157**, 285–302. (DOI: 10.1016/j.compstruct.2016.09.002)

Cancellara, D., De Angelis, F. (2017), Assessment and dynamic nonlinear analysis of different base isolation systems for a multi-storey RC building irregular in plan, *Computers and Structures*, **180**, 74–88.(DOI: 10.1016/j.compstruc.2016.02.012)

Cancellara, D., De Angelis, F. (2019), Dynamic assessment of base isolation systems for irregular in plan structures: response spectrum analysis vs nonlinear analysis, *Composite Structures*, **215**, 98-115.(DOI: 10.1016/j.compstruct.2019.02.013)

Cancellara, D., De Angelis, F., Modano, M., Pasquino, V. (2013a), Innovative strategy to reduce the seismic vulnerability of a RC existing building: assessment and retrofitting, *Key Engineering Materials*, **569-570**, 191-198.DOI: 10.4028/www.scientific.net/KEM.569-570.191

Cancellara, D., De Angelis, F., Pasquino, M. (2013b), A novel seismic base isolation system consisting of a lead rubber bearing in series with a friction slider. Part I: nonlinear modeling of the system, *Applied Mechanics and Materials*, **256-259**, 2185-2192. DOI:10.4028/www.scientific.net/AMM.256-259.2185

Cancellara, D., De Angelis, F., Pasquino, M. (2013c), A novel seismic base isolation system consisting of a lead rubber bearing in series with a friction slider. Part II: Application to a multi-storey RC building and comparison with traditional systems, *Applied Mechanics and Materials*, **256-259**, 2174-2184.DOI: 10.4028/www.scientific.net/AMM.256-259.2174

Cancellara, D., De Cicco, S., De Angelis, F. (2019), Assessment and vulnerability reduction of under-designed existing structures: traditional vs innovative strategy, *Computers and Structures*, **221**, 44-64. (DOI: 10.1016/j.compstruc.2019.05.016)

Christopoulos C., Filiatrault A. (2006), Principles of Passive Supplemental Damping and Seismic Isolation, IUSS Press, Pavia, Italy.

Clough R.W., Penzien J. (1975), Dynamics of Structures, New York: McGraw-Hill.

De Angelis, F. (2000), An internal variable variational formulation of viscoplasticity, *Computer Methods in Applied Mechanics and Engineering*, **190**(1-2), 35-54. (DOI: 10.1016/S0045-7825(99)00306-0)

De Angelis, F. (2007a), Multifield potentials and derivation of extremum principles in rate plasticity, *Materials Science Forum*, **539-543**, 2625-2630.

De Angelis, F. (2007b), A variationally consistent formulation of nonlocal plasticity, *Int. Journal for Multiscale Computational Engineering*, **5**(2), 105-116, New York. (DOI: 10.1615/IntJMultCompEng.v5.i2.40)

De Angelis, F. (2012a), A comparative analysis of linear and nonlinear kinematic hardening rules in computational elastoplasticity, *Technische Mechanik*, **32** (2-5), 164-173.(http://www15.ovgu.de/ifme/zeitschrift_tm/2012_Heft2_5/07_DeAngelis.pdf)

De Angelis, F. (2012b), On the structural response of elasto/viscoplastic materials subject to time-dependent loadings, *Structural Durability & Health Monitoring*, Tech Science Press, **8** (4), 341-358. (DOI: 10.32604/sdhm.2012.008.341)

De Angelis, F. (2012c), On the stability of discrete models of compressed beams in elastic media, *Applied Mechanics and Materials*, **152-154**, 982-989. DOI:10.4028/www.scientific.net/AMM.152-154.982

De Angelis, F. (2013), Computational issues and numerical applications in rate-dependent plasticity, *Advanced Science Letters*, **19**(8), 2359-2362, American Scientific Publishers, USA. (DOI: 10.1166/asl.2013.4919)

De Angelis, F. (2015), An Effective Computational Approach for the Numerical Simulation of Elasto/Viscoplastic Solid Materials, *Advances in Mechanical Engineering*, **7** (2), Article ID 340726, 1-8. (DOI: 10.1155/2014/340726)

De Angelis, F. (2018), Extended formulations of evolutive laws and constitutive relations in non-smooth plasticity and viscoplasticity, *Composite Structures*, **193**, 35-41. (DOI: 10.1016/j.compstruct.2018.03.032)

De Angelis, F., Cancellara, D. (2012), On the influence of the elastic medium stiffness in the buckling behavior of compressed beams on elastic foundation, *Applied Mechanics and Materials*, **166-169**, 776-783. DOI: 10.4028/www.scientific.net/AMM.166-169.776

De Angelis, F., Cancellara, D. (2013), Seismic vulnerability of existing RC buildings and influence of the decoupling of the effective masonry panels from the structural frames, *Applied Mechanics and Materials*, **268**, Issue Part I, 646-655. DOI: 10.4028/www.scientific.net/AMM.268-270.646

De Angelis, F., Cancellara, D. (2017), Multifield variational principles and computational aspects in rate plasticity, *Computers & Structures*, **180**, 27–39. (DOI: 10.1016/j.compstruc.2016.05.011)

De Angelis, F., Cancellara, D. (2019), Dynamic analysis and vulnerability reduction of asymmetric structures: fixed base vs. base isolated system, *Composite Structures*, **219**, 203-220. (DOI: 10.1016/j.compstruct.2019.03.059)

De Angelis, F., Cancellara, D., Grassia, L., D'Amore, A. (2018), The influence of loading rates on hardening effects in elasto/viscoplastic strain-hardening materials, *Mechanics of Time-Dependent Materials*, **22**(4), 533-551. (DOI: 10.1007/s11043-017-9375-7)

De Angelis, F., De Angelis, M. (2021), On solutions to a Fitz Hugh-Rinzel type model, *Ricerche di Matematica*, **70**(1), 51-65. (DOI: 10.1007/s11587-020-00483-y)

De Angelis, F., Meola, C. (2021), Non-smooth evolutive laws in multisurface elastoplasticity with experimental evidence by infrared thermography, *Composite Structures*, **265**, Art. 113156, 1-9. (DOI: 10.1016/j.compstruct.2020.113156)

De Angelis, F., Taylor, R.L. (2014), Numerical algorithms for plasticity models with nonlinear kinematic hardening. In: 11th World Congress on Computational Mechanics, WCCM XI, and 5th European Conference on Computational Mechanics, ECCM V, Eds.: E. Onate, J. Oliver and A. Huerta, (ISBN 978-84-942844-7-2), EBook Tomo VI, pp. 6560-6570, CIMNE (International Center for Numerical Methods in Engineering), Barcelona, Spain, 20-25 july, 2014.

De Angelis, F., Taylor, R.L. (2015), An Efficient Return Mapping Algorithm for Elastoplasticity with Exact Closed Form Solution of the Local Constitutive Problem, *Engineering Computations*, **32**(8), 2259 - 2291. (DOI:10.1108/EC-06-2014-0138)

De Angelis, F., Taylor, R.L. (2016), A Nonlinear Finite Element Plasticity Formulation without Matrix Inversions, *Finite Elements in Analysis and Design*, **112**, 11-25. (DOI: 10.1016/j.finel.2015.12.007)

De Cicco, S., De Angelis, F. (2020), A plane strain problem in the theory of elastic materials with voids, *Mathematics and Mechanics of Solids*, **25**(1), 46-59. (DOI: 10.1177/1081286519867109)

EC2 (2004), Eurocode 2: Design of concrete structures, UNI EN 1992-1-1, European Committee for Standardization, CEN/TC 250.

EC8 (2003), 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.

Luzi L., Lanzano G., Felicetta C., D'Amico M. C., Russo E., Sgobba S., Pacor, F., & ORFEUS Working Group 5 (2020), Engineering Strong Motion Database (ESM) (Version 2.0), Istituto Nazionale di Geofisica e Vulcanologia (INGV).https://doi.org/10.13127/ESM.2, https://esm-db.eu/ (formerly http://esm.mi.ingv.it).

Fenz D.M., Constantinou M. (2008), Development, implementation and verification of dynamic analysis models for multi-spherical sliding bearings, Report MCEER-08-0018, Buffalo, NY, Multidisciplinary Centre for Earthquake Engineering Research.

Hilber H.M., Hughes T.J.R., Taylor R.L. (1977), Improved numerical dissipation for time integration algorithms in structural dynamics, *Earthquake Engineering and Structural Dynamics*, **5**, 283-292.

Hughes T.J.R. (1987), Finite Element Method - Linear Static and Dynamic Finite Element Analysis. Prentice-Hall, Englewood Cliffs, New Jersey.

Mokha A.S., Constantinou M.C., Reinhorn A.M. (1990), Teflon bearing in base isolation. I: testing, *J. Struct. Engrg. ASCE*, **116**, 240-261.

Naeim F., Kelly J. M. (1999), Design of Seismic Isolated Structures, John Wiley, New York.

Nagarajaiah S., Reinhorn A.M., Constantinou M.C. (1991a), 3D-Basis: Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures: Part 1, Technical

Report NCEER-91-0005, National Center For Earthquake Engineering Research, Buffalo, N.Y.

Nagarajaiah S., Reinhorn A.M., Constantinou M.C.(1991b), Nonlinear dynamic analysis of three-dimensional base isolated structures (3D-BASIS): part 2, Report NCEER-91-0005, National Center for Earthquake Engineering Research, Buffalo, N.Y.

Newmark N.M.(1959), A Method of Computation for Structural Dynamics, *Journal of the Engineering Mechanics Division, ASCE*, **85**(3), 67-94.

NTC 2018 (2018), Decreto Ministeriale 17/01/2018, Aggiornamento delle Norme Tecniche per le Costruzioni, Gazzetta Ufficiale n. 42 del 20 febbraio 2018 - Supplemento Ordinario n. 8, 1-368, Roma, Italy, (in italian).

Park Y.J., Wen Y.K., Ang A.H-S.(1986), Random Vibration of Hysteretic Systems under Bi-Directional Ground Motions, *Earthquake Engineering and Structural Dynamics*, **14**(4), 543-557.

Robinson W.H.(1982), Lead rubber hysteretic bearings suitable for protecting structures during earthquakes, *Earthquake Engineering and Structural Dynamics*, **10** (4), 593-604.

Robinson W.H., Tucker A.G. (1977), A lead-rubber shear damper, Bull. N. 2, *Natl. Soc. Earthquake Eng.*, **10**, 151-153.

Ryan K. L., Chopra A .K. (2004), Estimation of seismic demands on isolators based on nonlinear analysis, *J. Struct. Eng., ASCE*, **130**,392-402.

SAP2000NL (2014), Structural Analysis Programs - Theoretical and User’s Manual, Release No. 16.03, Computers and Structures Inc., Berkeley, CA, USA.

Wen Y.K. (1976), Method for Random Vibration of Hysteretic Systems, *Journal of the Engineering Mechanics Division, ASCE*, **102**, No. EM2, 249-263.

Wilson E.L. (2002), Three-Dimensional Static and Dynamic Analysis of Structures, Computers and Structures Inc., Berkeley, CA, Third Edition.

Wilson E.L., FarhoomandI., BatheK.J. (1973), Nonlinear Dynamic Analysis of Complex Structures, *Earthquake Engineering & Structural Dynamics*, **1**(3), 241-252.