

Behavior assessment of asymmetrical building with concrete damage plasticity (CDP) under seismic load

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Abstract. According to the research conducted, the asymmetric multi-storey buildings are complex and suffer from severe damage caused by increased torsional response. This paper addresses the behavior assessment of setback building with irregularity in the plan under severe seismic event such as *Kobe* earthquake. Using three-dimensional model, the structure is subjected to seismic waves in the three directions through ground accelerations. Nonlinear dynamic procedures have been used by means time-history analysis method. The mechanical model describes physical nonlinear behavior with damage and plasticity showing the regions of cracking propagation, mainly the columns-beams connections and the whole column as well, corroborating the weak column and strong beam concept. The slabs did not present significant failures despite indicating damage regions on the borders of the first floors.

Keywords: dynamic nonlinear analysis, ABAQUS, asymmetric building structure, physical nonlinear behavior, earthquake.

1 Introduction

Real structures are almost always asymmetrical due the imperfections during execution process, architectonics design and innovation. Regarding buildings, the lack of symmetry tends to reduce the performance of structures subjected to seismic loads, thereby, leading to an increase in stresses of certain elements that consequently results in a significant destruction [1].

Buildings with elevation irregularities, e.g., setbacks, it is not uncommon to find considering that in large urban areas the space limitation is required, adequate ventilation and lighting to the lower floors and circulation areas. A lot of this buildings are irregular in the plane as well, i.e., slab discontinuity and reentrant corners. Nevertheless, in contrast, major seismic codes distinguish between irregularity in the plan and in elevation [2].

The consideration of vertical seismic waves on the ground are required in irregular elevated buildings and with large spans due the significant change of the mass and e stiffness over the height of the building [3].

Torsion effect in asymmetric buildings in the plan are presented due the eccentricity of the mass and stiffness, therefore, the problem becomes more complex for multi-story structures [4].

This paper addresses the response of irregular setback building in the plane by means seismic loading to the three directions. The dynamic analysis of spatial frame under *Kobe* earthquake is developed through finite element method with ABAQUS CAE®.

A refined constitutive model of damage coupled with plasticity (i.e. Concrete Damage Plasticity) is used to represent the behavior of the concrete in the structure. Solid 3D finite elements were used to represent the concrete material, steel reinforcements were totally embedded in concrete. Due the complexity of soil-structure interaction, the foundations and soils have not been modeled, hence, earthquake ground accelerations were applied to the base of columns in order to simulate a more realistic seismic event.

2 Concrete damage plasticity

The physical nonlinear behavior of concrete was represented by CDP already implemented in ABAQUS CAE® [5] involving the plasticity concepts with damage approached by Johnson [6], Wahalathantri et al [7], Jankowiak e Lodygowski [8]. The model admits two failure mechanisms observed in Figure 1.

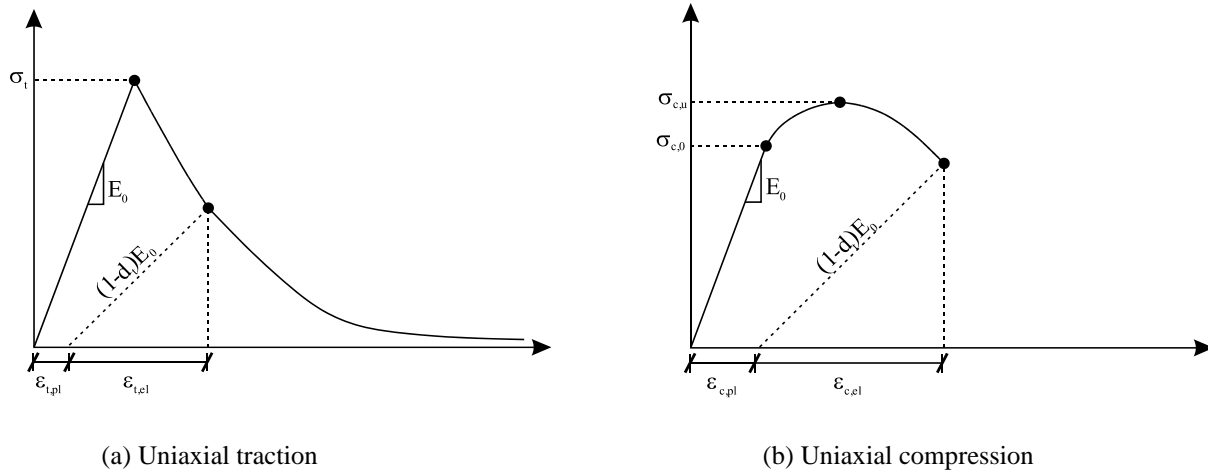


Figure 1. Uniaxial stress-strain response of concrete.

ε_t^{pl} and ε_c^{pl} are the plastic strains in traction and compression respectively; ε_t^{el} and ε_c^{el} are the elastic strains in traction and compression respectively; E_0 is the initial elasticity modulus; d_t and d_c the respective damages in traction and compression with values between [0,1] ; σ_{t0} is the maxim traction stress and its respective elasticity limit; σ_{c0} is the limit of elasticity for uniaxial compression and $\sigma_{c,u}$ is the maxim compressive stress. This elastoplastic model allows the change from the uniaxial stress-strain curve to the plastic stress-strain curve accord with the equations below:

$$\sigma_t = (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{pl}). \quad (1)$$

$$\sigma_c = (1 - d_c)E_0(\varepsilon_c - \varepsilon_c^{pl}). \quad (2)$$

Correlating with *Cauchy* tensor of stress, it is possible to generalize to the multiaxial case:

$$\sigma = E_{el} : (\varepsilon - \varepsilon^{pl}). \quad (3)$$

Where, d is the damage index; ε is the tensor of total strains; ε^{pl} is the tensor of plastic strains; E_{el} is the damaged elastic stiffness, given by: $E_{el} = (1 - d)E_0$; $(\varepsilon - \varepsilon^{pl})$ are defined as the inelastic strain.

3 Nonlinear dynamic analysis

In according to Deierlein et. al [9] the nonlinear dynamic analysis in contrast to nonlinear static analysis provides more accurate response of the structure when subjected to a strong earthquake, furthermore the nonlinear dynamic analysis is most suitable due the building test model being complex, i.e., asymmetrical in plane and elevation.

The enforced analysis was based on the temporal response, where the time-history of ground acceleration was selected from the Pacific Earthquake Engineering Research center (PEER) database.

Japan's famous 1995 earthquake was chosen regarding to its high moment of magnitude and peak ground accelerations purposing to get a better view of damage spread and structure behavior.

The earthquake characteristics are shown in the Table 1.

Table 1. Characteristics of input motion data

Earthquake	Magnitude (Mw)	Hypocenter depth (Km)	Direction	PGA (m/s ²)	T (s)
Kobe, Japan (1995)	6.9	17.9	X (plan)	-2.72	7.55
			Y (up)	4.52	6.40
			Z (plan)	3.12	6.95

It is observed that the greatest acceleration on the ground is in the vertical direction, in addition the peak ground accelerations to the three directions are in close periods.

4 Studied case

The structure is a simplification of four-story building with irregularity in the plan and the elevation disregarding sealing masonry. The test building with 14 meters maximum high has been subjected to *Kobe* earthquake ground accelerations. The density of concrete and steel are 2400 kg/m³ and 7500 kg/m³, in order. An overview of test model and the member dimensions are presented in Figure 1 and 2 respectively.

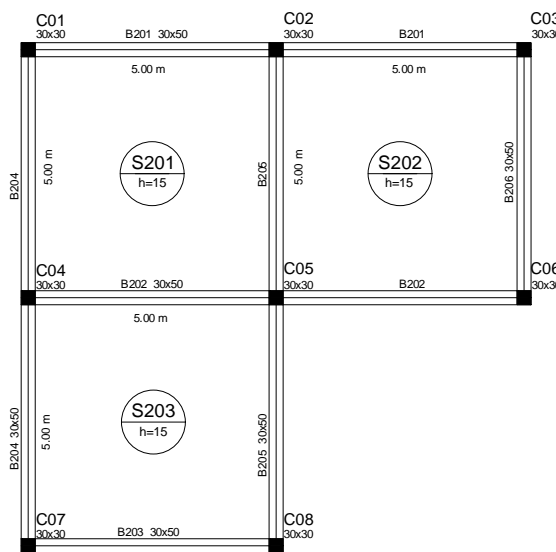


Figure 1. Plan of the test model.

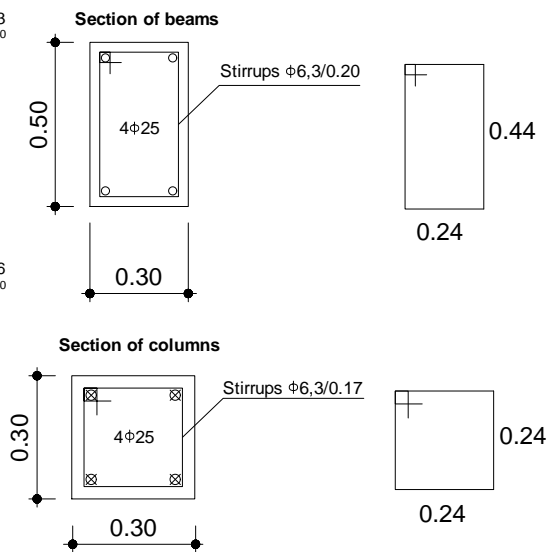


Figure 2. Member dimensions and reinforcement.

The slab was modeled as a deformable diaphragm with concrete damage plasticity model as well, in addition, the slabs reinforcements were not considered just as the discontinuity of the diaphragm was also not considered in order to simplify the analysis. The structure beam-column and slab were discretized with solid C3D8 elements. The beam-column are reinforced with longitudinal and transversal by steel bars. The reinforcements are modelled with B31 beam elements as illustrated in Figure 3. The mesh was divided each 0.1 meters for concrete, longitudinal bars and stirrups.

The concrete structure was modeled in separate parts (i.e., beams, slabs, columns and reinforcements), generating a 3D concrete frame. Then, the reinforcement was embedded into the concrete frame, through the "embedded region" interaction.

Dead loads are considered for all elements (with $g = -9,81\text{m/s}^2$). The building is subjected Kobe earthquake acceleration during 20 seconds. Loads were applied to the underside of the columns, thereby, seismic loading was propagated in the three directions, as shown the Figure 4.

It is relevant to emphasize that the computation costs of this type of analysis can be demanding in the study. For the analysis of this structure under 20 seconds of earthquake, about 48 hours processing were spent, using three processors in parallel.

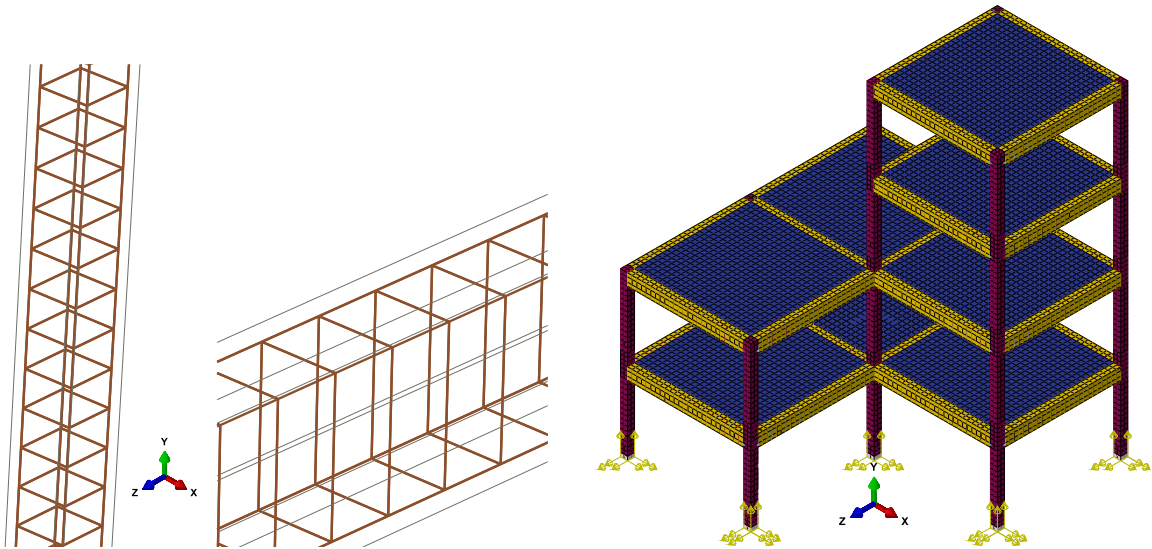


Figure 3. Steel reinforcements embedded in concrete. Figure 4. Displacements application point (meshed).

The properties of materials and parameters of the constitutive models in the elastic and plastic regime are observed in Table 2 and Table 3 respectively. The constitutive model of steel was considered perfectly plastic with yield stress equal 500 MPa. The average tensile strength of the concrete considered was 2.10 MPa.

Table 2. Elastic properties of materials

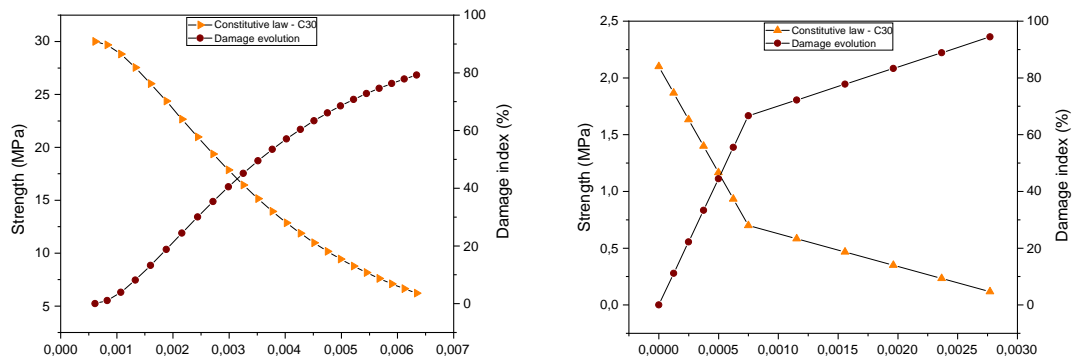
Material	E_0 (GPa)	Compressive Strength (MPa)	Tensile Strength (MPa)
Concrete	21.5	30.0	0.20
Steel CA50	200.0	-*	0.30

*the rupture of reinforcements was not considered in the model.

Table 3. Plastic properties of concrete

Material	Dilation angle ($^\circ$)	Eccentricity	f_{b0}/f_{c0}	K	Viscosity
C30	45	0.10	1.05	0.667	0.0001

The representation of the constitutive relation to compression (a) and traction (b) are shown in the Figure 5, obtained by analytical indications [10].



(a) Compression.

(b) Traction.

Figure 5. Constitutive law and damage evolution of C30.

5 Results

Figures 6 and 7 present the tensile damage in the concrete, where the beginning of the damage in 3.89 seconds may be observed. It is possible to verify that the damage is going to spreading throughout the whole structure at the first few seconds of analysis.

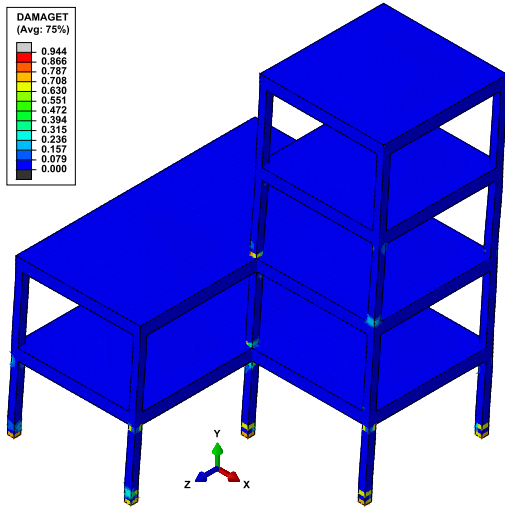


Figure 6. Tensile Damage at 3.89 seconds.

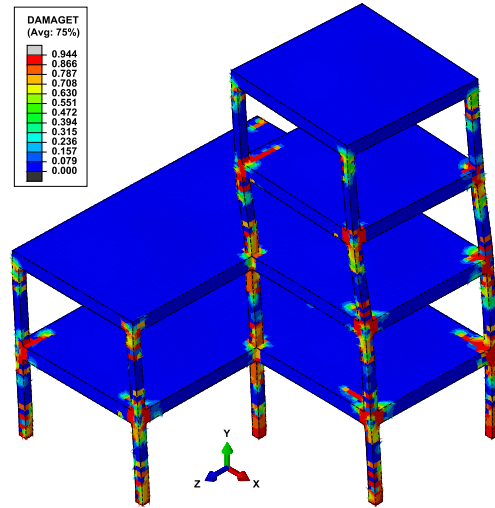


Figure 7. Tensile Damage at 5.51 seconds.

Figures 8 and 9 showed the high concentration of damaged zones in the beam-column connections indicating the formation of plastic hinges, as expected. Moreover, widespread damage to the columns occurs, thus proving the need for strong column and weak beam configuration recommended by literature and codes [11].

It is possible to observe damages located at the diaphragm and the elements linked mainly on the first floor, and high concentrations of stresses in the corners of the floors, in which the collapse mechanism at the edges can be seen. Nevertheless, the slab did not present damage and failure in the middle of the span.

In addition, the torsion effect is evident mainly on the corner columns due the asymmetry of the model building.

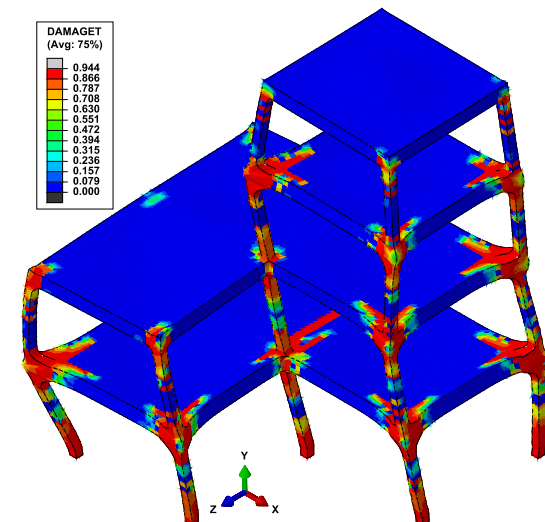
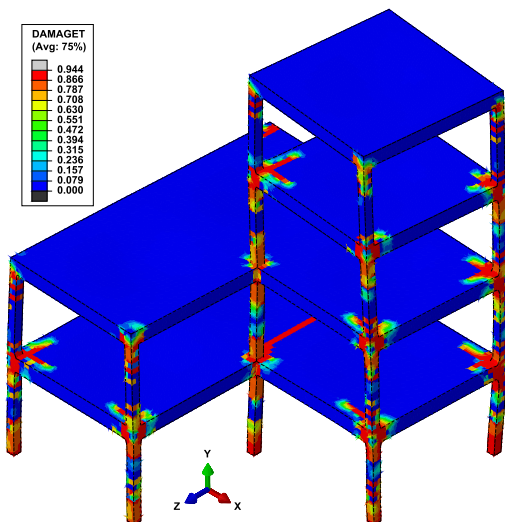


Figure 8. Tensile Damage at 7.03 seconds.

Figure 9. Tensile Damage at 20.00 seconds.

Figure 10 present the compression damage of the third-floor column-beam connection for the frame composed by C30 at 20.00 seconds of analysis.

Figure 11 present the stress of steel reinforcements of the last-floor column-beam connection for the frame, where the maximum stress in structure reached values of 500 MPa, the yield stress for CA50 steel.

The plastic strain in corners reinforcements can be observed in the Figure 12 due de beam-column connections.

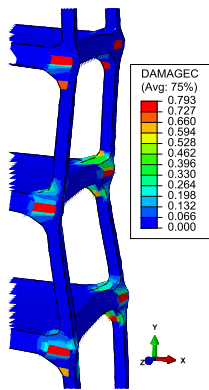


Figure 10. Compression Damage at 20.00 seconds.

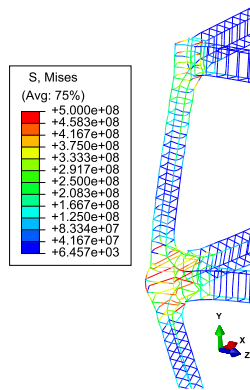


Figure 11. Strength in the reinforcements.

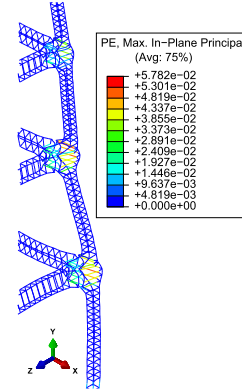


Figure 12. Plastic strain in the reinforcements.

6 Conclusions

The paper focused in the dynamic response of irregular setback building in the plane composed by C30 with steel reinforcements, subjected to *Kobe* earthquake in the three directions. Nonlinear analysis was used with plasticity and coupled damage for concrete and plasticity for reinforcement.

Following were the major concluding drawn from the study:

- 1) Despite the complex structure being subjected to earthquakes in the three directions, it was possible to evaluate the propagation of tensile damage in concrete in beam-column connections, at the edges of the diaphragm and the whole column due the due to its low stiffness in relation to the beams.
- 2) For the purpose to most accurate model it is suggested to model the slab with reinforcements, even if for this analysis the slab has not indicated damage in the middle of the span.
- 3) The results indicate that the structure collapsed, even though the chosen earthquake is considered strong, it is possible to get a higher performance of the structure improving the level of detailing of the reinforcements, e.g., increasing the number of reinforcements, improving the concrete confinement zone, increasing the number of stirrups in the critical zone, i.e., admitting a more ductile structure recommended by Eurocode [12] and American Concrete Institute [13] codes. It is important to emphasize that the Brazilian seismic code [14] does not address the detailing of structures, thereby, it is suggested its review and adequacy with other codes.
- 4) In order to avoid the pathology generated due the reentrant corners, the recommendation given by Federal Emergency Management Agency [15], i.e., employ of wide expansion joints between the connected slabs, increased stiffness in the corners or launch of rigidity core over the structure seeking symmetry whenever possible.
- 5) The responses cannot be concluding for the reason that the building was subjected a unique earthquake due the high computational cost, whereas to provide a greater reliability it should use seven records at least as recommended by ASCE/SEI [16] code.

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Authorship statement

The authors are the only responsible for the printed material included in this paper.

References

- [1] Mahdi T, and Soltangharaie V., Static and Dynamic Analyses of Asymmetric Reinforced Concrete Frame” in Lisboa: the 15th World Conference on Earthquake Engineering, 2012.
- [2] De Stefano, M., Pintucchi, B. A review of research on seismic behavior of irregular building structures since 2002. *Bull Earthquake Eng* 6, 285–308 (2008). <https://doi.org/10.1007/s10518-007-9052-3>.
- [3] Varadharajan S, Sehgal VK, Saini B. Seismic behavior of multistory RC building frames with vertical setback irregularity. *Struct Des Tall Special Build* 2014;23:1345–80.
- [4] Fernández-Dávila, V. I., & Cruz, E. F. (2006). Parametric study of the non-linear seismic response of three-dimensional building models. *Engineering Structures*, 28(5), 756–770.
- [5] Abaqus, (2013), User’s Manual, Version 6.13, Hibbitt Karlsson & Sorensen, Inc., USA.
- [6] Johnson, S. 2006. Comparison of Nonlinear Finite Element Modeling Tools for Structural Concrete. University of Illinois.
- [7] Wahalathantri, B.L.D; Thambiratnam, T.C; Fawzia, S. 2011. A Material Model for Flexural Crack Simulation in Reinforced Concrete Elements Using ABAQUS. Proceedings of the First International Conference on Engineering, Designing and Developing the Built Environment for Sustainable Wellbeing.
- [8] Jankowiak, T; Lodygowski, T. 2005. Identification of Parameters of Concrete Damage Plasticity Constitutive Model. *Foundations of civil and environmental ...* (6): 53-69.
- [9] Deierlein, G.G., Reinhorn, A. M. and Willford, M.R. (2010). Nonlinear structural analysis for seismic design, a guide for practicing engineers, NEHRP Seismic Design Technical Brief No. 4, NIST GCR 10-917-5.
- [10] CEB FIB, 2010 – “Model Code 2010”.
- [11] Moehle, J. P. Hooper, J. D. and Lubke, C. D. (2008). Seismic Design of Reinforced Concrete Special Moment Frames: A Guide for Practicing Engineering, NEHRP Seismic Design Technical Brief No. 1, NIST GCR 8-917-1.
- [12] Eurocode 08. Seismic Design of Buildings Worked Examples. European Committee for Standardization, Lisbon. 2011.
- [13] American Concrete Institute 318 (ACI), 2005, Building Code Requirements for Structural Concrete, American Concrete Institute, Farmington Hills, MI.
- [14] Associação Brasileira de Normas Técnicas. NBR 15421: Projeto de estruturas resistentes a sismos: Procedimento. Rio de Janeiro, 2006.
- [15] FEMA 454, 2004, National Earthquake Hazard Reduction Program Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Building Seismic Safety Council, Washington, DC.
- [16] American Society of Civil Engineers. (2016). Minimum design loads and associated criteria for buildings and other structures. ASCE/SEI 7, Reston, VA.