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Seismic response of solar energy generation systems

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Abstract

In the last few years, while seeking specific climate change impact mitigation targets, solar energy generation systems have become more and more popular, as one of the main sources of clean energy. However, roof mounted solar panels are often installed without a proper design of the supporting structures, in particular with respect to natural hazards, such as earthquakes. Because solar cells are sensitive to both horizontal and vertical accelerations, neglecting the installation detailing, aimed at reducing the accelerations transferred by the supporting structures to the solar panels, could become an issue even for low seismic intensities, compromising the significant investments made to install the energy generation system. This paper investigates the seismic response of solar energy generation systems mounted on the roof of strategic facilities. A cascading approach is adopted to define the seismic demand to which the solar energy generation systems are prone. To do so, a set of floor acceleration time histories is first generated by analysing a supporting structure located in a medium-high seismic hazard zone in Italy. Then, the seismic response of the energy generation system is investigated to highlight the critical issues found in typical installation practice.

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Keywords: *Solar energy generation systems; non-structural elements; seismic vulnerability; cascading analysis*

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1. Introduction

The widespread deployment of photovoltaic (PV) systems plays an essential role in addressing climate change and promoting sustainable energy. As the cost of PV modules and electronics continues to decrease, the structural supporting systems represent an increasing share of both total costs and system performance, affecting efficiency, durability, and economic viability over time. One of the key challenges surrounding the installation of PV systems is ensuring structural resilience under environmental loads and natural hazards, such as wind action, temperature variation and seismic events. Inadequate structural detailing or poor-quality components, combined with corrosion effects over the lifespan of the system, can lead to premature failures. These issues are even more critical for PV systems integrated within existing infrastructure, such as sound barriers or building facades, as well as for PV systems installed on the roof of strategic buildings that should ensure complete functionality in the aftermath of earthquakes.

Recent research has explored the mechanical and seismic performance of PV mounting systems using different approaches. However, most of these works focused on static or environmental loading over dynamic seismic assessment. For instance, Shen et al. (2023) focused on optimising "fixed-adjustable" PV structures for cost and efficiency, with limited attention to earthquake effects. Zhang et al. (2025) compared design prescriptions for PV supporting systems across various codes, observing that the Chinese design approach exhibited lower reliability and suggesting improvements for bolt and purlin hanger design. Zhang et al. (2014) showed that U-shaped steel-connected PV-shear walls maintain deformation and power generation capacities during simulated seismic events. Kwon et al. (2023) evaluated the earthquake stability of solar module soundproofing structures through 3D numerical analysis, noting that some integrated barriers may require additional detailing for severe earthquakes, since they are prone to significant seismic amplifications, risking the glass panel's integrity. Avci-Karatas (2020) utilised finite element analysis to assess stresses in steel PV support structures under environmental loads, providing design insights based on Turkish codes. Lastly, Iturralde Carrera et al. (2025) reviewed advancements in PV mounting structures, highlighting trends toward modular, lightweight, and adaptive designs while emphasising the importance of integrated structural design and material selection for durability.

Despite this progress, limited attention has been paid to the seismic response of PV mounting systems installed on critical facilities. To bridge such a gap, this study provides insights on the seismic performance of a rooftop-mounted PV system, focusing on immediate serviceability in the post-earthquake emergency phase. A simplified Finite Element Model (FEM) was developed using OpenSeesPy (Zhou & Scott, 2018) to conduct modal and linear time-history analyses. A cascading analysis method has been used to investigate the seismic response of the PV supporting system by adopting as seismic input the results of nonlinear time history analyses carried out on a four-storey reinforced concrete hospital building located in a medium-to-high seismic zone in Italy. The findings provide a better understanding of potential damage states and offer a basis for preliminary vulnerability assessment, contributing to the broader goal of enhancing the seismic resilience of PV supporting systems in critical facilities.

2. Methodology

The seismic performance of the case study PV mounting system was investigated adopting a cascading analysis approach, as illustrated in Figure 1 (Filiatrault and Sullivan, 2014). This method separates the complex interaction between the main structure and the non-structural element into two sequential steps.

First, the main structure was analysed under a set of ground motions selected for the site of interest. A multiple-stripe analysis was conducted to investigate the structural performance, thus, with a different set of conditional ground motions selected for each seismic intensity level or return period. Then, the PV mounting system, treated as a non-structural component rigidly connected to the roof, was analysed independently using the roof-level floor acceleration time-histories recorded during the structural analysis.

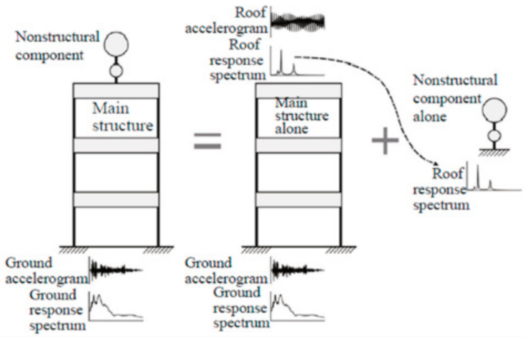


Fig. 1. Cascading approach used to analyse the PV mounting system (Filiatrault and Sullivan, 2014).

Two analyses were conducted: 1. modal analysis to identify the natural frequencies and primary vibration modes of the PV structure; 2. linear time-history (LTH) analysis to quantify displacements at critical points, particularly at anchorage connections. These displacements were used to evaluate both in-plane distortions and out-of-plane deflections of the PV panels. The computed deformation measures were then compared to predefined threshold values to identify potential damage. Three performance limit states were defined, based on engineering judgment and practical experience, as there are no codified criteria available in the literature. The adopted thresholds are listed in Table 1.

Table 1. Definition of performance limit states for the photovoltaic panels.

Limit State	In-plane Distorsion	Out-of-plane Deflection	Description
LS1 – Minor damage	⩾ 5 mm	⩾ 5 mm	Microcracks in cells, slight deformation
LS2 – Severe damage	⩾ 10 mm	⩾ 10 mm	Mechanical detachment, frame damage
LS3 – Collapse	⩾ 15 mm	⩾ 15 mm	Glass breakage, functional collapse

These threshold values are supported by experimental findings reported by Li et al. (2019), who demonstrated that PV panels may experience significant stress and nonlinear deformation under large out-of-plane deflections, especially when mounted with free-edge boundary conditions. Their work reinforces the need for conservative displacement limits to ensure structural and functional integrity.

3. Case study and numerical modelling

The case-study non-structural element analysed in this work is part of a modular energy station designed for autonomous energy generation, storage, and distribution using renewable sources. Engineered for transport via ship, air, rail, or truck, the station is housed in a standard 20-foot container and includes extensible and foldable skids equipped with photovoltaic (PV) panels, batteries, and inverters. Once deployed, the skids can be positioned on diverse surfaces (including rooftops, vehicles, and uneven terrain) and activated to deliver power for various applications, from single outposts to entire compounds. This study focuses on the seismic vulnerability assessment of the foldable skids used as mounting structure for PV panels once installed on the building roof.

The PV mounting system (Figure 2) is optimised for compactness and ease of transport. It features a base frame made of welded CorTen-A steel profiles, with the two central members that serve as forklift pockets. There are five identical aluminium superstructures mounted on the base and hinged to the steel base frame to allow folding during storage. Each aluminium superstructure supports a single PV panel. The superstructures are made of cold-formed aluminium profiles, connected via bolted brackets, with inclined beams and horizontal crossbars acting as panel supports.

Due to the geometric and constructional complexity of the real system, a simplified finite element model of the case study PV mounting system was developed using the open-source software OpenSeesPy (Zhou & Scott, 2018), as illustrated in Figure 3.

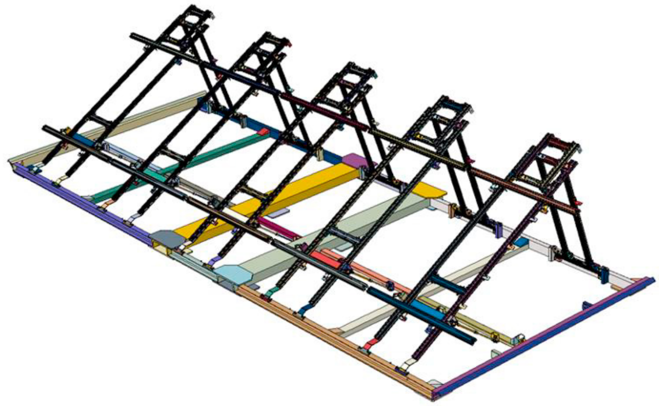


Fig. 2. PV mounting system.

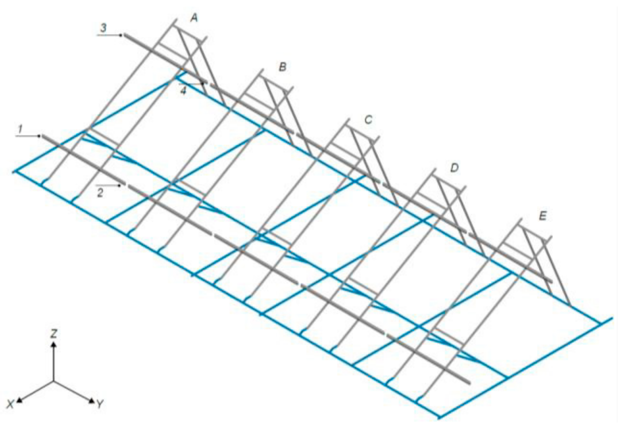


Fig. 3. Simplified FEM model of the PV mounting system.

In this first approach to the seismic response of the PV mounting system, the materials were modelled as elastic-perfectly plastic. As illustrated in Figure 3, the blue structural members are made of CorTen-A steel, while the grey superstructures are composed of aluminium. The mechanical properties of these materials, namely the Young's modulus, E, the Poisson's ratio, υ, and the yielding strength, F_y, are summarised in Table 2.

Table 2. Mechanical properties of the materials used for the PV mounting system.

Material	E (MPa)	υ	F_y (MPa)
Cor-Ten A	210000	0.3	345
Aluminium	70000	0.33	250

The PV supporting system was modelled assuming a simplified geometry. The steel profiles at the base were idealised by omitting minor curved or sloped surfaces, whereas equivalent sections in terms of area and inertia were defined for the aluminium frames.

Given the slender nature of the metallic members, a Eurocode 3 (2004) - based classification of cross-sections was performed to evaluate local buckling susceptibility. Most members were Class 1, except for the short-direction perimeter beams of the base frame, which were classified as Class 3. However, their local buckling risk was mitigated by their fully restrained end conditions. The PV mounting system was modelled with fixed boundary conditions at the four base corners, simulating the real anchorage points on the roof of the host structure. All translational and rotational degrees of freedom were restrained at these nodes. In turn, the aluminium superstructures were hinged to the base to reflect their actual folding function, allowing for rotational movement at their connections.

The PV panels were included in the model through kinematic constraints applied at their support connections, specifically at points 1 to 4 of spans A to E, as indicated in Figure 3, accounting for their in-plane stiffness. This modelling choice allowed the panels to act as stiff diaphragms, improving the overall rigidity and stability of the mounting system under dynamic loads, including seismic excitation. For each aluminium frame, the mass of one 25 kg PV panel was applied as uniformly distributed gravity loads on the supporting crossbars. Additionally, the self-weight of all structural components, both steel and aluminium, was included as distributed loads along each member's length. This simplified yet representative model enabled an effective dynamic evaluation of the PV mounting system under realistic boundary conditions.

4. Evaluation of the seismic demand

The PV mounting system was analysed using a database of floor acceleration time histories obtained from the analysis of a reinforced concrete (RC) frame designed according to the Eurocode 8 (2005) seismic provisions and representative of a hospital building. A site near the city of Cassino (Italy), characterised by a design peak ground acceleration on stiff soil of 0.21 g for a 10% probability of exceedance in 50 years, was selected. The RC frame is characterised by four floors with an inter-storey height of 3.5 m. In terms of material properties, the unconfined concrete compressive stress was assumed as 25 MPa, while the characteristic yielding rebar strength was 375 MPa. Based on the selected site, a set of 20 horizontal ground acceleration records for four return periods (T_R) associated with different performance objectives were selected from the PEER NGA-West database (PEER). These four performance objectives and return periods are as follows: 1) immediate operability (T_R = 100 years), 2) damage limitation (T_R = 140 years), 3) life safety (T_R = 975 years) and 4) collapse prevention (T_R = 2475 years). Hazard-consistent record selection was based on spectral compatibility (matching of the geometric mean) with a conditional mean spectrum determined according to the methodology proposed by Jayaram et al. (2011). The seismic performance of the PV mounting system was thus evaluated through 160 linear time-history analyses using 20 roof-level accelerograms for the selected T_R. Each accelerogram was applied in two directions to account for bidirectional shaking assuming the load combination rule proposed by the Eurocode 8 (2005): 100% in X with 30% in Y, and vice versa.

5. Seismic response of the PV mounting system

5.1. Eigenvalue analysis

An eigenvalue analysis of the PV mounting system was first conducted. Table 3 reports the results of the eigenvalue analysis for the modes associated with the higher modal participating mass ratios (ρ), including also the period (T) and the mode directions.

Table 3. Results from the Eigenvalue analyses of the case study structure.

Mode	Mass Contribution	ρ [%]	T [s]
1	Translational in X	57.08	0.098
4	Rotational	27.95	0.084
15	Translational in Y	99.52	0.024

All the intermediate and higher modes exhibit negligible mass participation, mostly involving local deformations in the lightweight aluminium members. The concentration of mass in just a few modes indicates that the system behaves as a low-degree-of-freedom stiff structure (according to FEMA 461 (2007), a non-structural system can be classified as stiff system if the first period is lower than 0.1s). This behaviour was somewhat expected given the small geometric dimensions and low mass of the structure (slightly more than 500 kg, including the weight of the PV panels).

5.2. Linear Time-History analysis

The seismic response of the PV supporting system was investigated by linear time history (LTH) analysis performed using OpenSeesPy (Zhou & Scott, 2018). Displacement time-histories at the panel anchorage points (1-4 across spans A-E) were recorded. Minimum and maximum displacements were extracted and projected onto the panel's local coordinate system to calculate in-plane distorsions and out-of-plane deflections. For each span, 20 peak values for both distortion and deflection were obtained per T_R and seismic load combinations (Case 1: 100% in X – 30% in Y; Case 2: 30% in X – 100% in Y). These peak values were then subjected to statistical analysis by computing the mean and standard deviation. Figure 4 shows the box plots summarising the LTH results related to the in-plane distorsions for Case 1 (Figure 4a) and Case 2 (Figure 4b), while Figure 5 reports the box plots of the out-of-plane deflections for Case 1 (Figure 5a) and Case 2 (Figure 5b), respectively. The thresholds for first two performance limit states defined in Table 1 are also included in the figures. For each box plot, the mean and standard deviation of the 20 peak distorsion/deflection values are respectively denoted by a cross-sign and a horizontal dash.

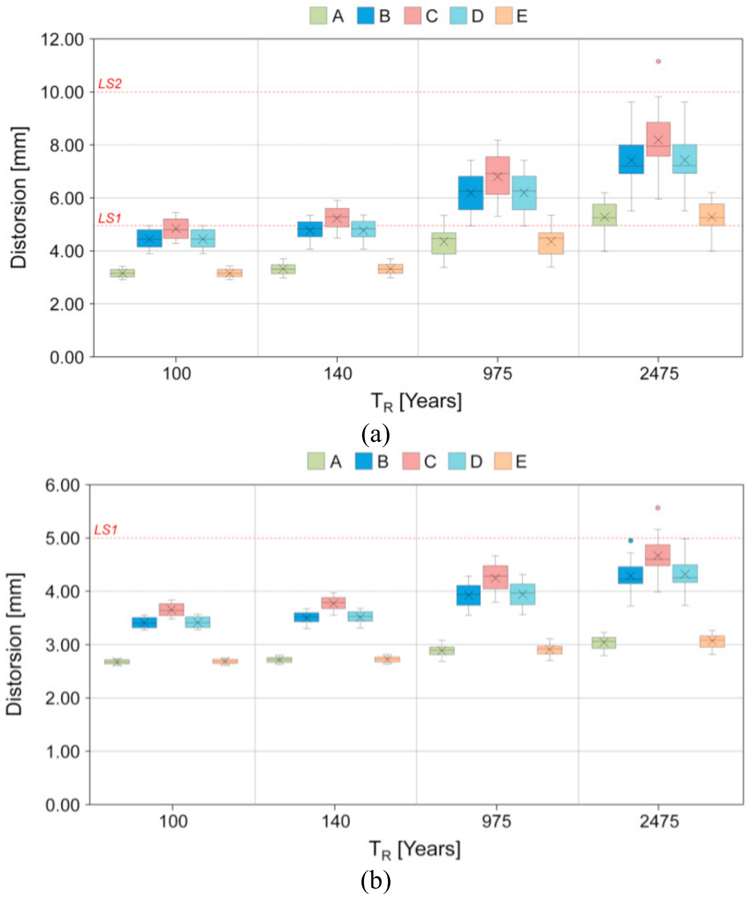
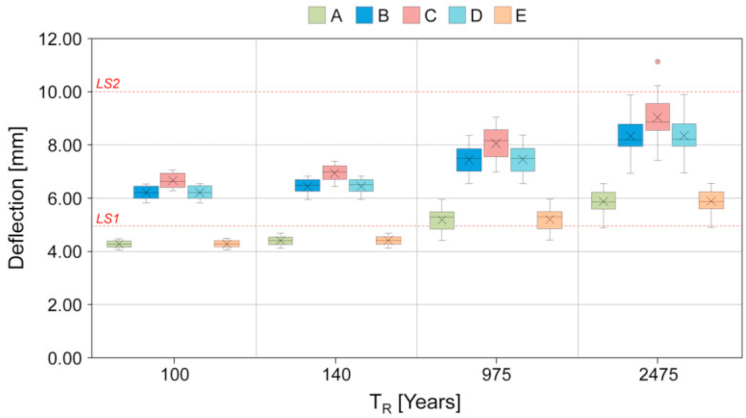
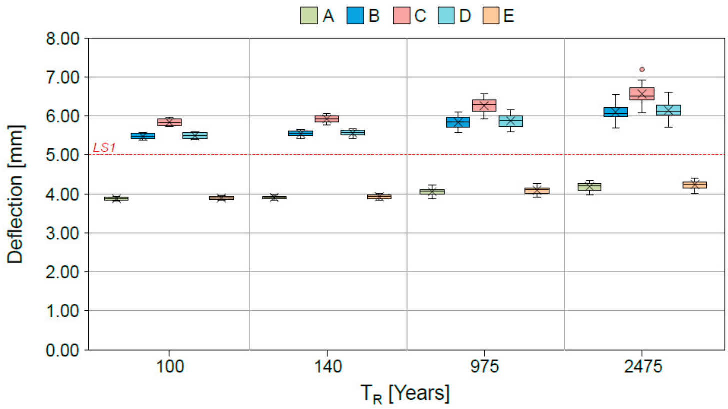


Fig. 4. In-plane distorsions of the photovoltaic panels for (a) Case 1 and (b) Case 2 seismic load combination.



(a)



(b)

Fig. 5. Out-of-plane deflections of the photovoltaic panels for (a) Case 1 and (b) Case 2 seismic load combination.

In general, an apparently non-linear increase in both parameters is observed with increasing T_R, ranging from 100 to 2475 years. Concurrently, the dispersion of the data, illustrated by the box plots, tends to increase with seismic intensity, suggesting greater variability in the PV supporting system response under higher seismic loads. Furthermore, all the spans generally exhibit symmetrical behaviour in their response magnitudes.

Comparing the obtained relative displacements with the displacement thresholds of the performance limit states, a marked directional sensitivity is noted. Both in-plane distorsions (Figure 4a) and out-of-plane deflections (Figure 5a) induced by the Case 1 load combination are systematically larger when compared to those obtained with the Case 2 counterpart (Figures 4b and 5b). Specifically, for T_R values of 975 and 2475 years, the responses deriving from Case 1 frequently exceed LS1 (5 mm) for most spans (A, B, C, D), indicating generation of microcracks in the PV cells. In some cases, upper whiskers and outliers even reach or exceed LS2, suggesting the starting of mechanical detachment or frame damage. In contrast, for Case 2, LS1 exceedance is less frequent, and LS2 is rarely reached. In this case study, LS3 is never achieved, although some extreme outliers for the highest T_R in Case 1 get close to the LS3 threshold. Although further analyses are still required, also investigating other sources of vulnerability, the obtained results point out the possibly induced damage in the PV supporting systems and the susceptibility of their response to the input direction.

6. Conclusions

This study addressed the seismic vulnerability of increasingly widespread roof-mounted solar energy generation systems, often installed without adequate seismic detailing. A cascading analysis methodology was adopted to achieve this goal. It involved the non-linear time history analysis of a multi-storey reinforced concrete frame designed according to the criteria adopted for hospital buildings and, subsequently, the linear time history analysis of a photovoltaic (PV) supporting system using as input the roof-level accelerations time histories recorded in the structural analysis. The selected case-study PV supporting system was a modular unit with foldable components, designed for flexible installation.

The results revealed different responses of the PV supporting system in the two loading directions. In-plane distorsions and out-of-plane deflections induced by seismic action in the transverse direction were systematically larger when compared to those in the longitudinal one. For the higher return periods adopted in the study, the response of the PV supporting system in the transverse direction frequently exceeded the first limit state (LS1), corresponding to immediate operability, indicating the generation of microcracks in photovoltaic cells. In some cases, the second limit state (LS2), associated with damage limitation, was also exceeded, suggesting a risk of mechanical detachment or frame damage. In contrast, when the main seismic action component was in the longitudinal direction, LS1 exceedance was less frequent, and LS2 was rarely reached.

The findings reported in this study highlighted the importance of studying the seismic performance of PV supporting systems in order to introduce adequate seismic detailing to enhance the stiffness and strength of such systems. Future research will focus on improving the numerical models allowing to study further sources of possible vulnerability in the PV supporting systems and on performing extensive multiple-stripe analyses in order to define fragility curves for risk-based assessment frameworks.

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References

Shen, W., Zeng, Y., Zhang, W., Tang, Z., Xie, H., 2023. Structural design and simulation analysis of fixed adjustable photovoltaic support. Journal of Computational Methods in Sciences and Engineering 23(3), 1409–1423.

Zhang, D., Wang, R., Liu, J., Huang, X., 2025. Mechanical performance and stress redistribution mechanisms in photovoltaic support connections: A finite-element-driven design optimization study. Applied Sciences 15(6), 3174.

Zhang, H., Dong, J., Duan, Y., Lu, X., Peng, J., 2014. Seismic and power generation performance of U-shaped steel connected PV-shear wall under lateral cyclic loading. International Journal of Photoenergy 2014(1), 362638.

Kwon, S.Y., Kim, J., Yoo, M., 2023. Evaluating earthquake stability of solar module soundproofing structure by 3D numerical analysis. Buildings 13(12), 3075.

Avci-Karatas, C., 2020. Design and analysis of steel support structures used in photovoltaic (PV) solar panels (SPs): A case study in Turkey. Department of Transportation Engineering, Faculty of Engineering, Yalova University.

Iturralde Carrera, L.A., Díaz-Tato, L., Constantino-Robles, C.D., Garcia-Barajas, M.G., Zapatero-Gutiérrez, A., Álvarez-Alvarado, J.M., Rodríguez-Reséndiz, J., 2025. Advances in mounting structures for photovoltaic systems: Sustainable materials and efficient design. Technologies 13(5), 204.

Zhu, M., McKenna, F., Scott, M.H., 2018. OpenSeesPy: Python library for the OpenSees finite element framework. SoftwareX 7, 6–11.

Filiatrault, A., Sullivan, T., 2014. Performance-based seismic design of nonstructural building components: The next frontier of earthquake engineering. Earthquake Engineering and Engineering Vibration 13(Suppl. 1), 17–46.

Li, Y., Xie, L., Zhang, T., Wu, Y., Sun, Y., Ni, Z., Zhao, P., 2020. Mechanical analysis of photovoltaic panels with various boundary condition. Renewable Energy 145, 242–260.

CEN, 2004. EN 1993-1-1: Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings. Brussels: European Committee for Standardization.

CEN, 2005. EN 1998-1: Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings. Brussels: European Committee for Standardization.

Jayaram, N., Lin, T., Baker, J.W., 2011. A computationally efficient ground-motion selection algorithm for matching a target response spectrum mean and variance. Earthquake Spectra 27(3), 797–815.

Federal Emergency Management Agency, 2007. FEMA 461: Interim testing protocols for determining the seismic performance characteristics of structural and nonstructural components. Washington, DC: FEMA.