CHEMICAL ENGINEERING TRANSACTIONS

VOL. 114, 2024

A publication of
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114131

Seismic Performance and Sustainability of Reinforced Concrete Buildings: a Comprehensive Assessment

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Recent earthquakes such as the 2023 Türkiye-Syria, Morocco, and Afghanistan, 2015 Gorkha Nepal, and 2009 Indonesia earthquakes have demonstrated the vulnerability of existing building stock. Throughout Europe, many existing buildings were constructed considering low or moderate standards or without considering them. This study investigates the seismic performance of reinforced concrete (RC) buildings, exemplified as a six-story RC dormitory building, focusing on various support and foundation conditions, soil characteristics, and site seismicity scenarios representing the seismicity of Europe. The research aims to assess the potential effects of exceeding anticipated site seismic intensities, potentially leading to safer communities and infrastructure in the face of impending earthquakes. Robot Structural Analysis Professional software is used for structural analysis and design throughout soil-structure interactions and site seismicity considerations. Moreover, this study investigates the environmental implications of RC buildings, which represent the future building inventory in Europe. It examines the varying material usage required to design structures compliant with Eurocode standards through a life cycle analysis. The methodology employed in this investigation aligns with the core principles of practical design encompassing economic and environmental sustainability. The study's key findings indicate that increasing member size can enhance performance at lower intensities, but this may not be a sufficient strategy at higher intensities, where shear walls may be necessary in high seismic zones. Sustainable design necessitates a balance between material use, performance, and environmental impact.

1. Introduction

Earthquakes have shaped the world's physical and cultural landscapes, from ancient ruins to recent tremors like Kathmandu (2015), Bam (2003), Tangshan (1976), Yogyakarta (2006), Baghdad (2017), and Ancona-Fano (1930). Europe, often seen as stable, is actively shaped by earthquakes. Recent data collection in Italy on earthquake damage to buildings fuels research in seismic risk assessment for existing structures (Tatangelo et al., 2023). Analysing past damage helps researchers understand building vulnerabilities and develop mitigation strategies. The 2009 L'Aquila earthquake in Italy (6.1 magnitude) devastated the Abruzzo region, with L'Aquila bearing the brunt (300 deaths) (Moro et al., 2013). The psychological trauma and recovery were immense. The February 2023 earthquake in southeastern Türkiye (Figure 1) and northern Syria claimed over 50,000 lives and caused widespread damage, marking the deadliest earthquake in Turkey since 1939. Disaster experts like Earthquake Engineering Field Investigation Team (EEFIT) and Earthquake Engineering Research Institute deployed a team to assess the damage and recommend vulnerability reduction strategies (Aktas et al., 2023).

Figure 1: Damaged buildings after the 6 February 2023 Türkiye-Syria Earthquake

Paper Received: 11 June 2024; Revised: 20 October 2024; Accepted: 14 November 2024
Please cite this article as: Silitonga S.A., Bektaş N., 2024, Seismic Performance and Sustainability of Reinforced Concrete Buildings: A Comprehensive Assessment, Chemical Engineering Transactions, 114, 781-786 DOI:10.3303/CET24114131

In Hungary, the 1763 Komárom earthquake, the strongest recorded in the Pannonian Basin in the past millennium, provides valuable data for studying seismic activity. Extensive documentation from Hungarian towns details building damage, aftershocks, and economic impacts (Varga et al., 2021). This earthquake highlights the region's vulnerability and the need for preparedness. Following such a major earthquake, assessing building damage is crucial for managing the crisis and recovery. Post-earthquake surveys serve two key purposes, which include determining building functionality and damage assessment for financial assistance. Many buildings in Europe are earthquake-prone due to their age and outdated design standards. They were constructed without modern seismic considerations, making them vulnerable (Palermo et al., 2018). Residential buildings are particularly at risk. Despite comprising 90% of existing structures, they account for roughly half of earthquake-related losses. This emphasises the critical need to prioritise seismic design and construction practices in the residential sector. Over time, buildings experience wear and tear, compromising their original energy efficiency and seismic safety features. Insulation materials deteriorate, and structural components weaken, reducing their ability to withstand earthquakes (Menna et al., 2013). As a result, older buildings become less energy-efficient and more susceptible to earthquake damage as they age. Some buildings have simply reached the end of their design life, further increasing their vulnerability. These factors combine to create a significant seismic risk for many European structures, highlighting the need for evaluation and potential upgrades.

The unpredictable nature of earthquakes necessitates exceeding current seismic design standards. Eurocode regulations are a good start, but inherent earthquake uncertainty requires structures resistant to stronger shaking. Incorporating additional safety margins and advanced seismic technologies protects the infrastructure from unforeseen seismic activity. During earthquakes, soil composition significantly impacts ground motion. Key soil characteristics influence earthquake effects such as soil type (soft, saturated soils like loose sand amplify ground motion, while stiffer soils like rock dampen shaking intensity), density (denser soils transmit seismic waves more efficiently leading to stronger ground motions, while loose soils can absorb some wave energy reducing intensity), water content (saturated soils are more susceptible to liquefaction, where soil loses strength and behaves like a liquid, causing severe damage to foundations), and topography (hillsides and slopes with loose soils are more prone to earthquake-triggered landslides). These soil characteristics directly influence how earthquake-induced ground motions behave, including amplification (soft, saturated soils can amplify seismic waves, significantly increasing ground motion intensity at the surface), attenuation (denser soils attenuate seismic waves, meaning the wave energy is absorbed or scattered, reducing ground motion reaching the surface), and site response (the combined effect of soil properties on a specific location is known as site response which significantly affects the amount of ground shaking experienced during an earthquake). Seismicity, the frequency and intensity of earthquakes in a region, presents challenges and opportunities for sustainable development. Earthquakes can devastate infrastructure, disrupting daily life, hindering economic activity, and limiting access to essential services. Rebuilding requires significant resources, potentially exceeding 40 % of the initial cost (Gonzalez et al., 2023), diverting funds from other sustainability initiatives.

This study investigates the seismic performance of RC buildings in Hungary, a moderately seismically active country, focusing on structures connected by fixed supports. It aims to understand how this configuration affects stability and failure modes compared to isolated buildings. The research will use a specific soil type to isolate the effect of building configuration on seismic response. It will consider multiple earthquake intensities exceeding Eurocode standards to evaluate the safety margins in current design approaches. This comprehensive analysis will identify potential vulnerabilities in existing structures for enhancing future design and retrofit strategies. Ultimately, it aims to create safer and more resilient communities in earthquake-prone regions. This analysis using AutoCAD (architectural drawing) and Autodesk Robot Structural Analysis (structural analysis) will provide a comprehensive understanding of the structural behaviour under diverse seismic loading conditions by considering Peak Ground Acceleration (PGA) values from 0.1g to 0.6g and soil interactions utilising soil type C (clay), leading to an optimised design for safety, efficiency, and resilience.

2. Soil Properties

Eurocode 8 (EC8) classifies soil based on its influence on earthquake effects. It defines five standard types (A-E) based on shear wave velocity (Vs), a measure of how fast earthquake shaking travels through the ground. Rock (Type A) is the most stable foundation with minimal vibration amplification. Very dense soil (Type B) is a very good foundation material with good drainage and high bearing capacity. Moderately dense soil (Type C) may require more detailed investigation for seismic design than A and B. Loose soil (Type D) is most susceptible to shaking amplification, requiring careful design considerations. Very soft soil (Type E) is the most challenging for seismic engineering, often requiring special foundations. EC8 also recognises two special site conditions (S1 and S2). Rock with shallow overburden (S1) experiences minimal amplification. Lastly, other site conditions (S2) include a wider range of soil profiles with potential for amplification. Understanding soil properties is crucial for earthquake engineering, including seismic design parameters (soil type and site classification influence the design response spectrum used for structural analysis), foundation design (soil properties determine the selection of foundation types (shallow vs. deep) and their design parameters), and structural design (understanding soil behaviour allows engineers to design structures that efficiently channel seismic forces). In this case study, the research utilises soil type C.

3. Seismicity

Earthquake Hazard Maps are vital tools for assessing seismic risk and guiding mitigation efforts in Europe. These maps depict the expected level of ground shaking as a unit of PGA at various locations due to potential earthquakes. PGA values, expressed as a percentage of Earth's gravity (g), are derived from advanced models like the European Seismic Hazard Model 2020 (ESHM20) (EFEHR, 2020). ESHM20 analyses historical earthquake data, geology, and active faults across Europe. It estimates earthquake probabilities and magnitudes in different regions and then simulates ground shaking intensity at various points. The map in Figure 2 (a) uses a colour scheme to communicate shaking intensity, including white to green as low hazard (minimal shaking), yellow to orange as moderate hazard (greater shaking potential), and red to purple as high hazard (potential for significant shaking). These zones correlate with building design codes. Many regions require earthquake-resistant structures to withstand a specific shaking level, typically corresponding to a 10 % probability of occurrence in 50 y (Design Basis Earthquake). This translates to a shaking intensity expected to be exceeded only once every 475 y, on average. The maps show PGA values for different return periods, providing valuable insights into areas likely to experience stronger or weaker shaking during future earthquakes. PGA, measured in units of g, quantifies earthquake ground shaking intensity. Higher PGA signifies stronger shaking and greater damage potential. PGA has two key applications in earthquake engineering, including structural design. Engineers use PGA to calculate seismic forces acting on structures. This information is crucial for designing earthquake-resistant buildings and infrastructure. Building codes specify design PGA values based on seismic risk assessments, and correspondingly usage PGA helps to estimate potential earthquake induced damage to existing structures. This aids post-earthquake response by prioritising buildings for inspection and repair. EC8 incorporates importance factors (γi) to account for varying seismic vulnerability of buildings. These factors are assigned based on a building's societal importance, potential life loss, and economic consequences in an earthquake. Higher factors are assigned to critical structures like hospitals (γi = 1.4) compared to warehouses (γi = 0.8). This prioritises life safety and critical infrastructure by classifying buildings into four categories which are lesser importance (γi = 0.8), ordinary buildings (baseline: γi = 1.0), important for seismic resistance (γi = 1.2), and important for disaster response (γi = 1.4). This system ensures buildings are designed to withstand earthquakes based on their societal importance. Seismic hazard map of Hungary, in Figure 2 (b), shows color-coded five seismic hazard zones with PGA values ranging from 0.08 g (blue) to 0.15 g (orange). A north-south zone of heightened seismic activity is evident west of Győr, aligning with historical data of major earthquakes impacting both Komárom and Győr.

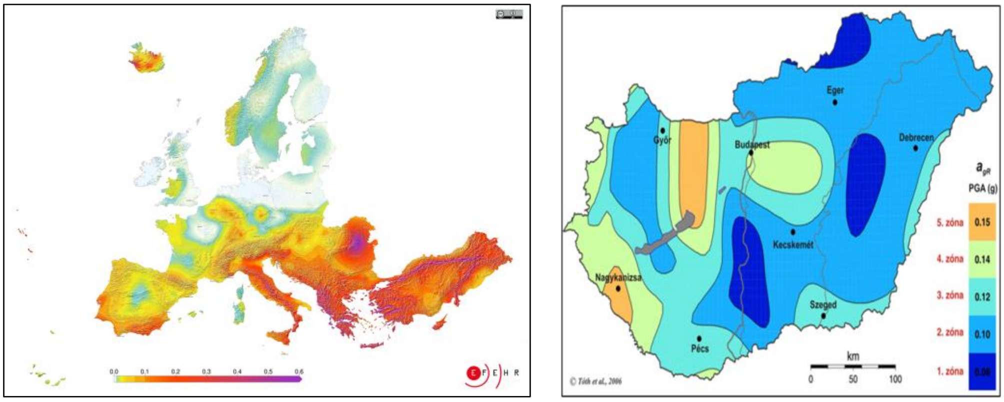

Figure 2: (a) Earthquake Hazard map of Europe 2020 (EFEHR, 2020), (b) Seismic Hazard map of Hungary and Fault line map of Hungary (GeoRisk Earthquake Engineering Ltd., 2006)

In this study, the response spectrum analysis considered a PGA range from 0.1 g to 0.6 g, importance factor of 1.2 (increased seismic design requirements), damping of 5 % (typical for reinforced concrete), and soil type of C (consistent with the case study site). Figure 3 shows the corresponding design response spectra.

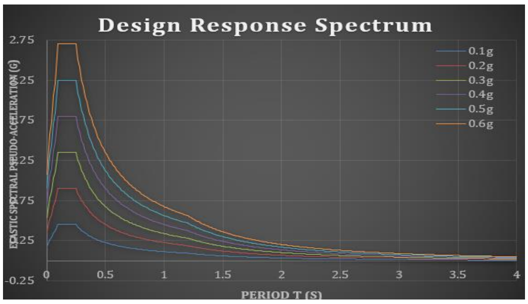

Figure 3: 0.1 g to 0.6 g design response spectrum

4. Structural Modelling and Analysis

To illustrate the seismic performance of Hungarian RC buildings, this research utilises a six-story RC dormitory building as a case study. Inspired by a similar building at Széchenyi István University in Győr, the model features a total height of 21 m and a footprint of 14.5 m x 43 m (rectangular). This CAD model (Figure 4) avoids vertical irregularities but has a plan irregularity due to the significant difference between its short and long sides.

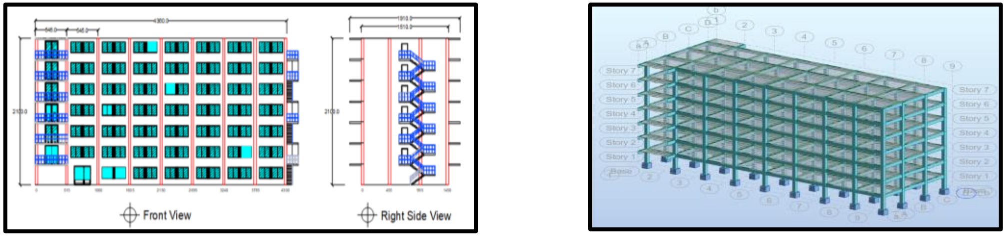

Figure 4: Front and right side view of RC dormitory structure

This table (Figure 6) summarises findings from a scientific study on building performance under various stress levels. It categorises building functionality based on five levels, which are “Operational Performance” meaning building remains fully functional, “Immediate Occupancy” meaning minor to moderate damage, safe for immediate occupancy, “Damage Control” meaning repairable structural damage, “Life Safety” meaning significant or severe damage, may require evacuation, “Collapse Prevention” meaning building on the verge of collapse. Each level corresponds to a specific inter-story drift ratio, indicating how much floors move relative to each other. This data helps emergency responders assess building safety and guides engineers in designing structures that can withstand urban stresses.

Table 1: Performance level of built structures

Performance Level	Abbreviation	EMS-98 (1998) damage states	Inter-story Drift Ratio (%)
Operational Performance	OP	No / Slight	0.5
Immediate Occupancy	IO	Slight / Moderate	1
Damage Control	DC	Moderate / Heavy	1.5
Life Safety	LS	Heavy / Very Heavy	2
Collapse Prevention	CP	Destruction	2.5

5. Environmental Impact Assessment

Life Cycle Assessment (LCA) is a tool to assess a product or service's environmental impact throughout its lifespan, from material extraction to disposal. It helps identify areas for sustainability improvement. Life Cycle Cost Analysis (LCCA) is crucial for sustainable construction projects, particularly when considering concrete, a common building material. LCCA considers the costs of material acquisition, processing, and disposal throughout the concrete lifecycle. This study uses IdematLightLCA to perform a life cycle assessment and calculate the environmental impact of the materials utilised in each building configuration that is built surrounding certain PGA values in order to withstand different magnitudes of earthquakes. With regard to the unit, the LCCA will assess the unit eco-costs, which represent the environmental damage associated with the material, and the carbon footprint, which measures the greenhouse gas emissions during material production.

6. Results and Discussion

A structural analysis was performed for a 7-story building with a fixed support system. The analysis considered seismic performance (deflection) and material usage for sustainability. The building model had 252 columns (3 m tall), 413 Beams (5 m), 28 cantilevers (2 m), column spacing of 5 m, and floor slab thickness of 15 cm. The seismic analysis input includes ground response acceleration (ag) of 0.12g to 0.72g (considering PGA, importance factor, and unit conversion), soil type C, spectrum type using design spectrum, analysis direction of horizontal, and behaviour factor of 1.5 (constant). The analysis explored how member dimensions and PGA values affect a building's seismic performance. Performance is measured by inter-story drift ratio, indicating deflection under load. Lower PGA values (0.1g and 0.2g) had all member configurations achieved good performance (OP to IO) with minimal to moderate damage expected. Moderate PGA values (0.3g) had initial configurations that fell under damage control (DC), and increasing member sizes improved performance in terms of immediate occupancy (IO). As for higher PGA (0.4 g to 0.6 g), even with member size adjustments, performance remained between immediate occupancy and damage control. This suggests the limitations of relying solely on member size at higher seismic intensities. The study recommends investigating the use of shear walls in future analyses, as they can significantly improve seismic performance.

Table 2: Combined Eco-costs and Carbon footprint in each case for each PGA value & Life Cycle Cost Analysis for Concrete and Steel used in each case for each PGA value

PGA	Config	Column Dimensions (cm)	Beam Dimensions (cm)	Combined Eco-Costs (€)	Deflection (cm)	Inter-story Drift Ratio (%)	Combined Carbon Footprint (kg)
0.1g	a	50x50	30x60	103,177.666	9.1	0.4333	517,964.4
	b	45x45	25x40	67,450.428	6.9	0.3285	337,358.2
	c	45x45	25x60	86,284.559	7.7	0.3666	432,292.6
0.2g	a	60x60	30x60	135,915.886	11.6	0.5523	668,082.2
	b	45x45	25x40	79,013.342	18.3	0.8577	386,237.8
	c	50x50	30x50	107,825.564	14.8	0.7047	528,419.4
0.3g	a	50x50	35x60	141,314.16	20.7	0.9857	688,367.4
	b	45x45	30x40	95,004.02	27.1	1.2904	459,963.4
	c	50x50	35x45	119,325.9	23.2	1.1047	579,332.7
0.4g	a	50x50	50x70	214,955.64	27.1	1.2904	1,042,574
	b	45x45	40x60	160,615.64	31	1.4761	774,093.6
	c	50x50	50x50	170,782.4	29	1.3809	823,084.7

Table 2 presents the analysis of the trade-off between material usage and deflection (seismic performance) for PGA values of 0.1g to 0.4g. PGA values of 0.5g and 0.6g were found to have dangerous values of deflection. So, LCA was not conducted, and it is recommended that shear walls be used in this case. Lower deflections under a specific PGA value require more material but lead to better performance (less damage) under seismic loads. Finding a balance between these factors is crucial for sustainable design (minimal material, good performance). For each PGA value, configurations with minimum, maximum, and intermediate deflection were compared. At 0.1g, configuration “a” used the most material but had the least deflection. Configuration “b” used the least material but had the most deflection, and configuration “c” offered a compromise. Similar trends were observed for higher PGA values. The configurations based on performance and sustainability find that 0.1g configuration “a” is the best option due to lower material use with minimal performance compromise. For 0.2g, configuration “c” might be the most reasonable option as it balances material usage and deflection while maintaining good performance. For 0.3g, configuration “c” provides the best performance despite high material use. For 0.4g, all configurations fall within the same performance range; selecting the most sustainable option depends on project priorities (minimising material use vs slightly lower deflection) and configurations “a”, “b”, or “c” could all be potential candidates. The choice depends on project-specific priorities and constraints, such as the relative weight, minimising material usage versus achieving a slightly lower deflection.

The analysis revealed a significant increase in material usage as the PGA increased. For RC structures designed for a PGA of 0.1g to be modified to meet the performance requirements of 0.2g, the quantities increased approximately 28 % for concrete and 61 % for steel. This trend continued at higher seismic intensities. Transitioning from a 0.2g design to a 0.3g design required increases in concrete & steel of 20 % & 31 %. Similarly, from a 0.3g design to a 0.4g design resulted in an additional 32 % & 38 % increase in concrete & steel consumption. In essence, these results suggest that constructing an RC structure designed for a 0.1g PGA in a location with a 0.4g PGA would require approximately 60 % more concrete and 83 % more steel. This highlights the significant impact of seismic intensity on the material requirements for RC structures. Building in earthquake-prone areas (higher PGA) requires stricter designs to ensure safety. This often leads to increased material use, which has a negative environmental impact. The study found that a structure designed for low PGA (0.1g) would need 52 % more eco-cost and 51 % more carbon footprint to meet safety standards in a high PGA (0.4g) location. While minimising material use is ideal for sustainability at low PGA levels, prioritising performance at higher intensities becomes more important. Lastly, a higher-performing structure is less likely to suffer damage, reducing risk to human life, earthquake waste, and the need for reconstruction (saving resources)

7. Conclusions

This study investigated the seismic performance of RC buildings in Europe. A 6-story building model was analysed under various earthquake intensities (PGA: 0.1g to 0.6g) and soil conditions (dense sand/gravel, stiff clay) using software incorporating soil-structure interaction and site seismicity. LCA considered the environmental impact of material usage. The key findings include member size vs. seismic performance: (increasing member size improved performance at lower PGA of 0.1g & 0.2g but had diminishing returns at higher intensities of 0.3g & 0.4g, where shear walls may be necessary for high seismic zones of 0.5g & 0.6g). Regarding performance levels, lower PGAs of 0.1g & 0.2g achieved operational and immediate occupancy performance, while higher PGAs of 0.3g & 0.4g remained in damage control even with member size adjustments. In terms of material use vs. deflection, lower deflection (achieved with more material) resulted in less seismic damage, indicating that sustainable design requires a balance between these factors. For material use vs. seismic zone, lower seismic zones of 0.1g & 0.2g allowed prioritising minimal material use configurations, while higher zones of 0.3g may require slightly more material for significantly better performance and lower maintenance costs. The environmental impact analysis showed that stricter building codes in high seismic zones lead to increased material use and higher environmental costs, with eco-cost rising by 52 % and the carbon footprint increasing by 51 % from 0.1g to 0.4g PGA values. Finally, LCA can balance environmental impact with safety, prioritising higher-performance structures in high seismicity zones, which can reduce waste and long-term environmental impact by reducing the need for reconstruction. To further enhance this research, incorporating shear walls into the structural model is recommended. Analysing the influence of shear walls on building performance under different seismic scenarios can provide valuable insights into improving structural efficiency and seismic resistance in RC buildings.

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