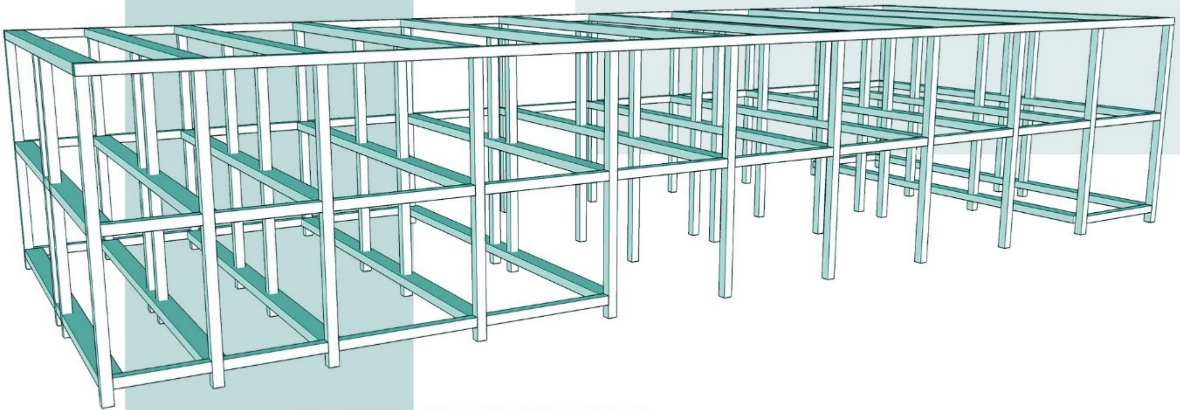
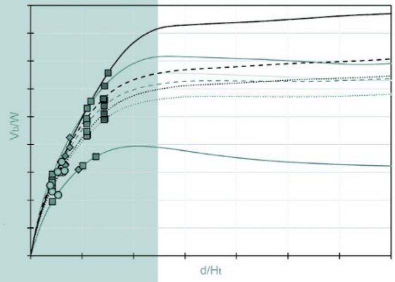
Seismic vulnerability assessment of reinforced concrete buildings. Analysis of primary schools' buildings of the southwestern Iberian Peninsula

Evaluación de la vulnerabilidad sísmica de edificios de hormigón armado. Análisis de los colegios de educación primaria del suroeste de la Península Ibérica

PhD dissertation. Architectural PhD programme

Tesis Doctoral. Programa de doctorado en Arquitectura





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Sevilla, 2021

This PhD thesis has been supported by / Esta tesis ha sido financiada por:

VI Research Plan (PPI) of the University of Seville by the granting of a predoctoral contract.
VI Plan Propio de Investigación (PPI) de la Universidad de Sevilla mediante un contrato de personal predoctoral en formación (PIF).

INTERREG-POCTEP Spain-Portugal programme and the European Regional Development Fund through the project entitled *Projetos de Escolas Resilientes aos Sismos no Território do Algarve e de Huelva*” (0313_PERSISTAH_5_P).
Programa INTERREG-POCTEP España-Portugal mediante la financiación del proyecto 0313_PERSISTAH_5_P.

University Institute of Architecture and Construction Sciences. University of Seville.
Instituto Universitario de Arquitectura y Ciencias de la Construcción. Universidad de Sevilla.

Agradecimientos

Este trabajo, realizado a lo largo de cuatro años en el Departamento de Estructuras de Edificación e Ingeniería del Terreno de la Escuela Técnica Superior de Arquitectura de Sevilla, no habría sido posible sin la colaboración de algunas personas a las que, por medio de estas líneas, quiero expresarles mi agradecimiento.

A los Drs. Antonio Morales-Esteban y Don Percy Durand-Neyra, directores de esta tesis. Su profesionalidad, su pasión por la investigación y sus consejos me han servido de constante guía. Gracias por creer en mí y por ayudarme en todo lo que he necesitado.

Agradezco particularmente la estrecha colaboración de la Dra. Doña Rita Bento. Sus conocimientos sobre ingeniería y vulnerabilidad sísmica han sido fundamentales para el desarrollo de esta tesis. Gracias por acogerme.

A Don Francisco Duarte, profesor del Departamento de Estructuras de Edificación e Ingeniería del Terreno, por fomentar las bases de mi conocimiento estructural desde su aplicación práctica en el mundo laboral.

A los miembros del grupo TEP-107 “Estructuras y Geotecnia”, donde se enmarca este trabajo de investigación, por su ayuda y ánimos durante todo este periodo.

A mis compañeros de la Sala de Investigadores, Elizabeth Contreras y Álvaro Sánchez, por los buenos ratos tan necesarios para seguir trabajando. A todos los compañeros del proyecto PERSISTAH: gracias Beatriz Zapico por tu ayuda; gracias Emilio Romero por tu estrecha colaboración y amistad; gracias Jaime de Miguel por tus ánimos, risas y sobre todo por tu sabiduría; y gracias Marisa Segovia por tus consejos y compañía que me fue de gran ayuda al inicio de este trabajo de investigación.

A Carmen Calama, por tu disponibilidad siempre para intercambiar experiencias e impresiones investigadoras y por su ayuda tan valiosa.

A mis compañeros del Instituto Superior Técnico de Lisboa, hoy mis amigos. Gracias Madalena Ponte por hacerme sentir como una más del grupo. Gracias Rita Couto, mi compañera de investigación, por tu inestimable ayuda para el desarrollo de este trabajo. Gracias Vieri Cardinalli por tu apoyo incondicional y amistad.

A todas aquellas personas que me han apoyado y ayudado directa o indirectamente. Gracias a mis amigos arquitectos: Andrés Lara, David Rivera, Soledad Moreno, Manuel López, Natalia Rodríguez y Víctor González, porque formáis parte de mi vida desde nuestro inicio en el mundo de la Arquitectura. A Alberto Ruiz-Berdejo y José Gracia por vuestra comprensión y amistad. Gracias Christina Apostolidou, por tu interés en mi durante todo el tiempo que estuve en Lisboa. A Inma Valverde por estar siempre a mi lado.

Por último, y de modo muy especial a mi familia, a mi tía Auxi y a mis padres por creer siempre en mí. A Macarena, mi hermana, por tu ayuda siempre. A Alejandro por apreciar y valorar mi trabajo y por tu apoyo absoluto.

Organización

Esta tesis doctoral se presenta mediante la **modalidad de entrega basada en el compendio de artículos**. Por tanto, ha sido sometida a procesos de revisión de la calidad científica necesarios para su publicación y difusión internacional. Las aportaciones cumplen con los requisitos establecidos en la normativa de la Universidad de Sevilla (BOUS de 24 de febrero de 2020), ya que han sido publicadas en medios que cumplen con los criterios de evaluación publicados por la Comisión Nacional Evaluadora de la Actividad Investigadora (CNEAI) en relación al campo científico de la Ingeniería y Arquitectura.

La tesis se presenta como un documento conjunto que recopila los trabajos publicados directamente relacionados con el tema de investigación. Se presentan **tres artículos** publicados en revistas científicas indexadas en el primer (una) y segundo (dos) cuartil del indicador “Journal Citation Report” (JCR) y todas indexadas en el primer cuartil del “Scimago Journal Report” (SJR). Estos son considerados como los principales indicadores de calidad de la producción científica según los organismos de evaluación de la actividad investigadora en el área de la Ingeniería y la Arquitectura. Los artículos se incluyen en el apartado de resultados del documento.

Además de estas publicaciones, durante la etapa predoctoral, se han publicado varias contribuciones clasificadas como: publicaciones producidas por la tesis y publicaciones en colaboración con otros investigadores internacionales y nacionales. En el primer grupo, se incluyen **dos capítulos de libro** y **dos contribuciones a congresos internacionales**. En el segundo grupo, **tres aportaciones a congresos internacionales**, **un libro** publicado en una editorial en el primer cuartil del ranking Scholarly Publishers Indicatos (SPI) y **tres artículos indexados** en el primer y segundo cuartil del **JCR y SJR**. Los avances que han supuesto estos trabajos se han incluido como referencias en las diferentes secciones para conformar el cuerpo del documento. Estas secciones describen las distintas fases llevadas a cabo durante el trabajo de investigación.

Para finalizar, en el documento de tesis se han incluido los apartados de introducción, resumen global de los resultados, conclusiones finales y futuras líneas de investigación.

Organization

This **article-based thesis** is presented by the **compendium of publications**. Therefore, it has been submitted to review processes that guarantee the required scientific quality for its publishing and international diffusion. These publications comply with the requirements established in the regulations of the University of Seville (BOUS, February 24th 2020). They have been published in scientific journals indexed in international databases. Furthermore, they comply with the criteria established by the Spanish National Commission of Research Activity (CNEAI) for the Engineering and Architecture scientific field.

This document compiles all the publications directly related to the research work. **Three articles** are presented. They have been published in scientific journals indexed in the first (one) and the second (two) quartile of the “Journal Citation Report” (JCR) index and all in the first quartile of the “Scimago Journal Report” (SJR) index. These indexes are used to evaluate the quality of the research production according to the Spanish organisms for the evaluation of the research activity in the field of Engineering and Architecture. These articles are included in the “Results” section of this document.

In addition to these publications, several contributions have been published during the pre-doctoral period, which have been classified as: publications produced by the thesis and publications in collaboration with other international and national researchers. In the first group, **two book chapters** and **two contributions to international congresses** have been included. In the second group, **three contributions to international congresses**, **one book** published in an editorial ranked in the first quartile of Scholarly Publishers Indicators (SPI) and **three papers** ranked in the first and second quartile of **JCR and SJR** have been included. The scientific contributions of these publications have been cited in different sections of this document. These sections describe the different phases developed during the research work.

Finally, an introduction to the background and motivation of the thesis, a global summary of the results and a section of conclusions and future research works have been included in this document.

Mención Doctorado Internacional

Esta tesis se presenta para la obtención de la Mención de Doctorado Internacional. La tesis cumple con los requisitos establecidos en la normativa de la Universidad de Sevilla (BOUS de 24 de febrero de 2020) para tal efecto. Durante el periodo de formación predoctoral, se han realizado estancias de investigación de 3 meses de duración en el Instituto Superior Técnico de Lisboa (Portugal) en 2019 y 2021, siendo la supervisora Dr. Rita Bento, profesora Titular del *Departamento de Engenharia Civil, Arquitectura e Geo-recursos del Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal*.

La tesis ha sido informada por dos expertos doctores pertenecientes a instituciones de investigación internacional. El tribunal que evalúa la tesis es de carácter internacional. Además, se adjunta lista de contribuciones científicas publicadas en medios internacionales.

En cuanto al idioma de redacción, las publicaciones elaboradas durante el periodo predoctoral han sido redactadas y publicadas en inglés para su internacionalización. Por tanto, dada la vocación internacional del trabajo, el cuerpo de la tesis ha sido redactado en inglés. Sin embargo, los apartados previos, el resumen y las conclusiones se han presentado en español para garantizar su difusión a nivel nacional.

International PhD mention

This thesis is submitted for the International PhD mention. It complies with all the requirements established by the regulations of the University of Seville (BOUS, February 24th 2020). During the predoctoral period, 3-month research stays have been carried out at the *Instituto Superior Técnico de Lisboa* (Portugal) in 2019 and 2021, under the supervision of Dr. Rita Bento, professor of the Department of Civil Engineering, Architecture and Geo-Resources, *Universidade Técnica de Lisboa, Portugal.*

The thesis has been reviewed by two PhD expert researchers from international scientific institutions. Moreover, the committee that evaluates this thesis is international. The list of the international publications developed during the predoctoral period is listed.

Regarding the language of this document, all the predoctoral publications have been written and published in English to improve the internationalisation of the research work. Therefore, given the international diffusion of the work, this document has been written in English. Nevertheless, some previous chapters, as well as the abstract and the conclusions have been presented in Spanish to guarantee its national diffusion.

List of publications

In this section, the publications derived from the research work are listed. In total, during the predoctoral period, **the scientific production related to the research topic** has been: six scientific articles which have been published in JCR/SJR indexed journals, two book chapters, one book and five congress presentations.

Publications considered in the thesis by compendium

Publications considered in the thesis for the compendium of articles. They comply with the requirements established in the regulation of the University of Seville.

- ARTICLE 1: **Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra, João M. C. Estêvão (2019). *An index-based method for evaluating seismic retrofitting techniques. Application to a reinforced concrete primary school in Huelva*. PLoS ONE 14(4): e0215120. PLos. DOI:10.1371/journal.pone.0215120.

  Database: WOS (JCR). Q2. 5 cites.

  Database: SCOPUS (SJR). Q1. 6 cites.

  Relevant: Honour award. IUACC quarterly award for the best scientific publication in architecture and construction sciences. *Instituto universitario de arquitectura y ciencias de la construcción.* University of Seville. Indexed in WOS, Scopus, Google Scholar.

- ARTICLE 2: **Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra, Beatriz Zapico Blanco (2021). *Influence of the constructive features of RC existing buildings in their ductility and seismic performance*. Bulletin of Earthquake Engineering 19: 377-401. Springer. DOI: 10.1007/s10518-020-00984-z

  Database: WOS (JCR). Q2. 1 cite.

  Database: SCOPUS (SJR). Q1. 1 cite.

  Relevant: Indexed in WOS, Scopus, Google Scholar.

- ARTICLE 3: **Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra. (2021). *Optimal ductility enhancement of RC framed buildings considering different non-invasive retrofitting techniques*. Engineering Structures 242(1): 112572. DOI: 10.1016/j.engstruct.2021.112572

  Database: WOS (JCR). Q1.

  Database: SCOPUS (SJR). Q1.

  Relevant: Indexed in WOS, Scopus, Google Scholar.

Additionally, an article has been submitted to a first quartile journal. Currently, it is under its first supervision.

- ARTICLE: **Maria Victoria Requena-Garcia-Cruz**, Rita Bento, Percy Durand-Neyra, Antonio Morales-Esteban (Under first revision). *Effects of soil-structure interaction in the seismic vulnerability analyses of RC buildings. Methodology and application to a case study in Lisbon*. Journal of Building Engineering.

Additional publications produced by the thesis

Publications derived from the work carried out in the thesis. These are also included in certain parts of this document. The PhD student is the first author in all of them. They are mainly contributions submitted to international congresses known worldwide in the research field.

- **BOOK CHAPTER 1: Maria Victoria Requena-Garcia-Cruz**, Luis Fazendeiro Sa, Antonio Morales-Esteban, João M. C. Estêvão, Mónica Ferreira, Percy Durand-Neyra, Carlos Sousa Oliveira (2017). *Study and assessment of the seismic vulnerability of primary school buildings located at Algarve and Huelva: state of the art*. IDA: Advanced Doctoral Research in Architecture: 193-203.Universidad de Sevilla. ISBN 978-84-16784-99-8.

  Prestigious editorial: **Q1** SPI ranking.

  Relevant: Indexed in Google Scholar. Open Access.

- **BOOK CHAPTER 2: Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Maria Luisa Segovia Verjel, Emilio Romero Sánchez, Jaime de Miguel Rodríguez, João MC Estevão (2019). *Seismic Performance Comparison Between Structure-Improvement Techniques and Ground-Improvement Techniques: Application to a Reinforced Concrete School Building*. WIT Transactions on The Built Environment (185): 99-108. WIT Press. DOI: 10.2495/ERES190081.

  Prestigious editorial: **Q4** SPI ranking.

  Relevant: Indexed in WOS, Scopus and Google Scholar. Open Access.

- **CONGRESS 1: Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Maria Luisa Segovia Verjel, Emilio Romero Sánchez, Jaime de Miguel Rodríguez, João MC Estevão (2019). *Comparative analysis between the Spanish and Portuguese seismic codes. Application to a border RC primary*. 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN19). Vol. 3: 4816-4827. Eccomas Proceedia. DOI: 10.7712/120119.7280.19419.

  Relevant: Indexed in Scopus and Google Scholar. Open Access. International worldwide conference recognised among earthquake engineering researchers.

- **CONGRESS 2: Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra, Emilio Romero Sánchez (2021). *Soil-structure interaction in the seismic vulnerability analysis of RC buildings. Application to a case study building located in southwestern Spain*. 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN21). Eccomas Proceedia.

  Relevant: Indexed in Scopus and Google Scholar. Open Access. International worldwide conference recognised among earthquake engineering researchers.

Additional publications in collaboration with international and national researchers

Publications related to the research work carried out during the predoctoral period in collaboration with international and national researchers:

- **ARTICLE 4:** Maria Luisa Segovia Verjel, **Maria Victoria Requena-Garcia-Cruz**, Enrique de Justo Moscardó, Antonio Morales-Esteban (2020). *Optimal seismic retrofitting techniques for URM school buildings located in the southwestern Iberian Peninsula*. PLoS ONE 14(10): 1-18. PLos. DOI: 10.1371/journal.pone.0223491.

  Database: WOS (JCR). **Q2**. 3 cites.

  Database: SCOPUS (SJR). **Q1**. 3 cites.

  Relevant: Indexed in WOS, Scopus, Google Scholar.

- **ARTICLE 5:** Emilio Romero Sánchez, Antonio Morales-Esteban, **Maria Victoria Requena-Garcia-Cruz**, Beatriz Zapico-Blanco, Beatriz, Jaime de Miguel Rodríguez

(2020). *Specific seismic retrofitting of a compact reinforced concrete building with X-bracings and steel jackets. Application to a primary school in Huelva*. PLoS ONE 15(9): e0238505. PLos. DOI: 10.1371/ journal.pone.0238505.

Database: WOS (JCR). **Q2**.

Database: SCOPUS (SJR). **Q1**.

Relevant: Indexed in WOS, Scopus, Google Scholar.

- **ARTICLE 6:** Rita Couto, **Maria Victoria Requena-Garcia-Cruz**, Rita Bento, Antonio Morales-Esteban (2020). *Seismic capacity and vulnerability assessment considering ageing effects: case study-three local Portuguese RC buildings*. Bulletin of Earthquake Engineering. S.I.: Recent Advanc. Springer.

  Database: WOS (JCR). **Q2**. 1 cite.

  Database: SCOPUS (SJR). **Q1**. 1 cite.

  Relevant: Indexed in WOS, Scopus, Google Scholar.

- **BOOK:** Antonio Morales-Esteban, Emilio Romero-Sánchez, Beatriz Zapico Blanco, **Maria Victoria Requena-Garcia-Cruz**, Jaime de Miguel Rodríguez, João MC Estevão (2020). *Rehabilitación sísmica estructural de colegios de educación primaria*. 1-166. Universidad de Sevilla.

  Prestigious editorial: **Q1** SPI ranking.

  Relevant: Indexed in Google Scholar. Open Access.

- **CONGRESS 3:** Maria Luisa Segovia Verjel, **Maria Victoria Requena-Garcia-Cruz**, Enrique de Justo Moscardó, Antonio Morales-Esteban (2019). *A cost-effective retrofitting technique for URM buildings based on steel encirclements in openings: a case study*. 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN19). Vol. 3: 4955-4967. Eccomas Proceedia. DOI: 10.7712/120119.7280.19419.

  Relevant: Indexed in Scopus and Google Scholar. Open Access. International worldwide conference recognised among earthquake engineering researchers.

- **CONGRESS 4:** Beatriz Zapico Blanco, **Maria Victoria Requena-Garcia-Cruz**, Emilio Romero-Sánchez, Jaime de Miguel Rodríguez, Antonio Morales-Esteban (2020). *Classification of primary school buildings: influence of in-plan irregularities.* 9th European Workshop on the Seismic Behaviour of Irregular and Complex Structures (EWICS).

  Relevant: International worldwide conference recognised among earthquake engineering researchers

- **CONGRESS 5:** **Maria Victoria Requena-Garcia-Cruz**, Rita Couto, Rita Bento, Antonio Morales-Esteban (2020). *Influence of vertical irregularities on the seismic assessment of RC framed and wall-frame buildings*. 9th European Workshop on the Seismic Behaviour of Irregular and Complex Structures (EWICS).

  Relevant: International worldwide conference recognised among earthquake engineering researchers

Resumen

Los terremotos se encuentran entre los desastres naturales que han producido históricamente mayores daños y pérdidas de vidas humanas. La **capacidad destructiva de un terremoto depende de su magnitud, la vulnerabilidad de las construcciones y la capacidad de recuperación de la población**. Por tanto, para minimizar sus consecuencias, **se debe mejorar la prevención y la resiliencia**. De hecho, la minimización de los riesgos geológicos y geotécnicos debidos asociados a desastres naturales se ha convertido en uno de los principales retos de diversas políticas europeas y nacionales. Este interés se ha acrecentado debido a los efectos catastróficos de recientes terremotos sufridos en Europa. En este contexto, los análisis de vulnerabilidad sísmica rigurosos permiten mejorar el comportamiento de los edificios para así reducir el daño sísmico, las pérdidas humanas y el impacto económico de futuros eventos sísmicos.

Esta tesis pretende dar respuesta a este problema centrándose en dos objetivos: i) **evaluar la vulnerabilidad sísmica** de los colegios de educación primaria de hormigón armado (HA) localizados en el suroeste de la península Ibérica, en particular, en la región Algarve-Huelva; ii) desarrollar **métodos específicos de refuerzo sísmico** para que los colegios mejoren su comportamiento sísmico y se reduzca el daño sísmico esperado. Este trabajo se ha centrado en estos edificios debido a su vulnerabilidad: i) una gran parte se construyó con estructura de HA antes de la entrada en vigor de códigos sísmicos restrictivos (presentan un diseño asísmico, materiales estructurales de baja calidad o bajos porcentajes de armadura, entre otros); ii) la considerable peligrosidad sísmica del área, caracterizada por terremotos lejanos de largo período de retorno y magnitud grande-muy grande; iii) la baja proporción de niños/adultos y el estrés postraumático y los trastornos que pueden sufrir los niños tras un terremoto.

Para ello, en primer lugar, se ha analizado la peligrosidad sísmica de la zona Algarve-Huelva. Este estudio ha revelado que **los códigos sísmicos de España y Portugal son considerablemente diferentes**, sobre todo en el proceso de definición del espectro de respuesta. A continuación, se ha llevado a cabo la caracterización de los colegios de educación primaria ubicados en Huelva, trabajo que hasta la fecha no se había realizado. Posteriormente, se ha evaluado el comportamiento sísmico de los edificios mediante el método *performance-based*. La capacidad de las estructuras se ha obtenido mediante análisis estáticos no lineales. La seguridad sísmica se ha analizado a través de dos procedimientos: i) la obtención del daño local siguiendo el proceso establecido en el código sísmico europeo; y, ii) la definición del daño global mediante curvas de fragilidad. Según los resultados, una gran parte de los colegios fueron construidos con estructuras de HA y no cumplen con los requisitos de seguridad sísmica, siendo **sísmicamente vulnerables**.

Para mejorar el comportamiento sísmico de los edificios, se han evaluado varias estrategias de refuerzo sísmico. Estas han sido seleccionados según el análisis del estado del arte. Se ha propuesto un **método basado en un índice** para seleccionar la solución más adecuada según **la eficiencia, el coste económico y el impacto arquitectónico**. Los resultados muestran que las estrategias basadas en la implementación cruces y diagonales de acero son las más rentables. Además, debido a la falta de información en los códigos sísmicos, se ha presentado un **método para evaluar la ductilidad de las edificaciones existentes en España**. Los análisis concluyen que los modelos con **vigas de canto tienen un comportamiento sísmico mejor** que el resto. Además, se concluyó que **al mejorar la ductilidad se obtiene una mayor reducción del daño, obteniendo soluciones más óptimas**. Por tanto, se ha evaluado la mejora de la ductilidad de los edificios considerando **técnicas de refuerzo sísmico**. Diferentes soluciones **no invasivas** se han considerado para no interferir con el uso normal de los mismos. Estas han sido comparadas mediante una ratio coste-beneficio. Finalmente, se han analizado los efectos de la interacción suelo-estructura. Se ha concluido que el suelo puede emporar el comportamiento sísmico de los edificios. Por tanto, deberían ser incluidos en futuros análisis de vulnerabilidad sísmica.

Palabras clave

Evaluación de la vulnerabilidad sísmica: Edificios de hormigón armado; Rehabilitación sísmica, Ductilidad; Análisis estáticos no lineales.

Abstract

Among existing natural disasters, earthquakes have historically caused the most outstanding damage and human losses. **The destructive impact of an earthquake depends on its magnitude, and the vulnerability and the resilience of the population**. Therefore, in order to minimise its consequences, **prevention and resilience should be improved**. In fact, the minimisation of the geological and geotechnical risks associated with natural disasters has become one of the main challenges of European and national policies, especially after the damage caused by recent earthquakes in Europe. Rigorous seismic vulnerability analyses to enhance the behaviour of buildings can help to reduce the seismic damage, the human losses and the economic impact due to future seismic events

This thesis addresses this challenge by establishing two main objectives: i) to **assess the seismic vulnerability** of RC buildings focusing on primary school buildings located in the southwestern Iberian Peninsula, particularly the *Algarve-Huelva* region; and ii) to develop **specific seismic retrofitting methods** for the schools to improve their seismic behaviour and to reduce their expected seismic damage. It has focused on the study of RC primary school buildings in southwestern Spain due to their vulnerability: i) a major part of them was constructed with RC structures prior to restrictive seismic codes (i.e., aseismic design, low-quality structural materials, reinforcement ratios, among others); ii) the considerable seismic hazard of the area, characterised by far away earthquakes of a long-return period and large-very large magnitude; iii) the low/adult child ratio and the post-traumatic stress and depressive disorders that children can suffer from after surviving an earthquake.

To do so, first, the seismic hazard of the Algarve-Huelva area has been analysed. This study has revealed **considerable differences in the seismic codes of Spain and Portugal,** particularly in the definition of the response spectra. Then, the characterisation of the primary school buildings located in *Huelva* has been carried out, which has not been performed to date. Later, the seismic performance of the buildings has been assessed by means of the performance-based method. The capacity of the structures has been obtained through nonlinear static analyses. The seismic safety has been analysed by means of two procedures: i) obtaining the local damage following the European seismic code procedure; and ii) defining the global damage by means of fragility curves. According to the results, a major part of them were built with an RC system and do not comply with the seismic safety requirements, being **seismically vulnerable**.

In order to enhance the seismic performance of the buildings, several seismic retrofitting strategies have been assessed. They have been selected according to the analysis of the state of the art. **An index-based method** has been proposed to select the most suitable solution according to **efficiency, the construction cost and the architectural impact**. The results showed that the steel X-bracings and the single braces retrofitting strategies were the most profitable. In addition, due to the lack of guidance in the seismic codes, **a procedure to assess the ductility of existing Spanish buildings** has been presented. The analyses concluded that **the deep-beams models outperformed the rest**. Furthermore, it was found out that **enhancing the ductility leads to higher damage reduction, resulting in configurations that are more beneficial**. Therefore, the enhancement of the ductile behaviour of RC framed buildings considering **retrofitting techniques** has been assessed. Different **non-invasive** solutions have been considered in order not to disrupt the normal use of the buildings. They have been compared in terms of a benefit-cost ratio. Finally, the effects of soil-structure interaction haven analysed. It has been concluded that they can worsen the seismic performance of buildings. They should be included in future seismic vulnerability analyses.

Keywords

Seismic vulnerability assessment; RC buildings; Seismic retrofitting; Ductility; Nonlinear static analysis

Table of contents

Introduction

In this section, the motivation and background of the research are presented. The key points that the thesis addresses and the aims, divided into main and specific, are described. Finally, the outline of this document is shown. This corresponds to the different phases followed during the research work.

I.1. Motivation and background

I.1.1. International policies on the seismic risk reduction

Among existing natural disasters, earthquakes have historically caused the most outstanding damage and human losses. During the 20th century, earthquakes have cost around 1,000,000 million dollars and have caused 1.5 million casualties worldwide. In the case of Europe, the earthquakes which have occurred during this past century have cost around 20,000 million euros and have caused 19,000 casualties (Battarra et al., 2018).

The destructive impact of an earthquake depends on its magnitude, and the vulnerability and the resilience of the population. Therefore, in order to minimise its consequences, **prevention and resilience should be improved**. The mitigation of geological and geotechnical risks associated with natural disasters to enhance the security of society has become one of the main European concerns. In fact, it has been defined as one of the Societal Challenges of the Horizon 2020 (European Commission, 2014) and the Spanish *Agenda 2030* (Spanish Ministry of Economy and Competitiveness [Ministerio de Economía y Fomento de España], 2017). Among the priorities of these challenges, building resilient communities and reducing disaster risks are core initiatives. Moreover, Spain signed the Hyogo 2005-2015 (United Nations, 2007) and the Sendai 2015-2030 (United Nations, 2015) agreements on disaster risk reduction.

The interest in the studies on the **minimisation of the seismic vulnerability of buildings** has even increased in the past decades, especially after the damage caused by recent earthquakes such as the *L'Aquila* earthquake in 2019 (Italy), the *Lorca* earthquake in 2011 (Spain) and the *Amatrice* earthquake in 2016 (Italy) (Del Gaudio et al., 2017; Fiorentino et al., 2016; Ruiz-Pinilla et al., 2016). A large part of the buildings in these cities was severely damaged during these events. Therefore, analysing and enhancing the seismic performance of buildings has become a major concern (Mazzoni et al., 2018).

I.1.2. International studies on the seismic vulnerability of buildings

There are numerous studies focused on the seismic risk and vulnerability of buildings. Some of them are based on analysing the risk on an urban scale. These mainly consider macroseismic approaches and, to some extent, mechanical methods. Such is the case of the well-known Risk-UE project (Mouroux and Le Brun, 2008). This was mainly based on the seismic risk assessment of different European cities from a macroseismic approach and, to a certain extent, mechanical methods. This methodology was applied to the city of Barcelona (Barbat et al., 2010) and to some Portuguese cities (Fiore et al., 2018). However, few studies were focused on Spain during the development of this project. In fact, few studies can be found on the seismic risk of Spain. In (Martínez-Cuevas and Gaspar-Escribano, 2016), the vulnerability of Lorca's buildings was analysed according to the 2011 earthquake. In (Rivas-Medina et al., 2013), a georeferenced tool was implemented in urban seismic risk studies. In (Gaspar-Escribano et al., 2010), the seismic hazard of southern Spain was analysed. In (Molina et al., 2019, 2018; Rivas-Medina et al., 2014; Salgado-Gálvez et al., 2016) a seismic risk simulator for the Spanish cities of *Adra*, *Elche*, *Alicante* and *Lorca* was developed. In most of them, the buildings´ behaviour was estimated by defining capacity curves based on different structural typologies and construction dates using the HAZUS and Risk-UE methodologies (macroseismic approach).

Nevertheless, the **seismic behaviour of the buildings play a key role in the destructive potential of an earthquake**. Therefore, rigorous studies are needed to properly assess their behaviour in order to specifically reduce the seismic damage and losses. There is currently a growing concern for studying seismic vulnerability at the building scale. These works are based on following or developing mechanical methods, instead of macroseismic approaches, to exhaustively assess and determine the expected seismic performance and damage of buildings. They are characterised by similar working methods. They perform analyses considering case study buildings which are representative of a typology (Barbieri et al., 2013; Candia et al., 2016; Valente and Milani, 2016). Also, they carry out studies on aspects that affect the seismic performance by means of sensitivity or parametric analyses (Milosevic et al., 2019; Simões et al., 2014). Most of these works, whether on an urban or building scale, conclude that **the major part of existing buildings is seismically vulnerable** (Lamego et al., 2017). In this sense, **rigorous seismic vulnerability analyses of existing buildings** and the addition of **appropriate retrofitting** strategies can help **to reduce the seismic damage, human losses and the economic impact due to future seismic events**.

In this context, the **European research project** named **PERSISTAH** (2016-2020) (*Projetos de Escolas Resilientes aos SISmos no Território do Algarve e de Huelva*, in Portuguese) aims to cooperatively analyse and minimise the seismic vulnerability of primary school buildings located in the *Algarve* (Portugal) and *Huelva* (Spain). This project highly increased the risk awareness among the education community of the regions and promoted efficient seismic retrofitting. Several institutions collaborated on this project: the *Autoridade Nacional de Proteçao Civil* of Portugal and the *Dirección General de interior, emergencias y Protección Civil* from Spain at the National and Andalusian level. This reveals the interest that the emergency corps and governments have in this type of studies.

I.1.3. The case study area

The ***Algarve-Huelva* region** is established as one of the most seismic areas of the Iberian Peninsula (Martín Martín, 1989) since it is close to the Eurasian-African tectonic plates boundary (Amaro-Mellado et al., 2017). This results in a **considerable seismic hazard** for the southwestern Iberian Peninsula. In fact, this area is affected by far away earthquakes of a long-return period and large-very large magnitude (Amaro-Mellado et al., 2017). Owing to this, the population is not aware of the relatively high seismic hazard. Buildings in this area have been severely damaged in the past by relevant events such as the 1344, 1531, 1722, 1755, 1859, 1909 and 1969 earthquakes (Sá et al., 2018). Some of these earthquakes are widely known due to their effects, such as the 1755 Lisbon earthquake (M_w=8.5) and the 1969 earthquake (M_w=8) (Sá et al., 2018). Despite the considerable seismic hazard, there is a lack of studies on the area concerning the seismic risk and vulnerability of these buildings. In fact, most of this type of analyses were focused on the east and southern Iberian Peninsula. Furthermore, the area is characterised by the presence of soft surface layers which can amplify the effects of earthquakes.

A few works on the seismic vulnerability of the buildings of the area can be found, which are mainly based on macroseismic approaches. Such is the case of the SIRCO risk simulator (*Simulador de Risco sísmiCO*) (Fazendeiro Sá et al., 2016) or the ERSTA study (*Estudio do Risco Sísmico e de Tsunamis do Algarve*) on the reduction of the seismic and tsunami risk in the Algarve (Portugal) (Autoridade Nacional de Protecção Civil (ANPC), 2010). Both works concluded that the existing buildings present a high seismic risk, which can be reduced by improving the prevention (enhancing the performance of buildings and the awareness of the population) and the emergency planning (before and after the seismic event).

I.1.4. The case study buildings

School buildings have been chosen as the subject of study. The total number of primary schools identified in the *Algarve-Huelva* region is 276 and more than 400 buildings (Morales Esteban et al., 2020). In Huelva, there are 138 schools and 269 buildings.

This building typology is widely known for its relevance in the case of an earthquake. In fact, several studies can be found on the seismic vulnerabilities of schools as in (Augenti et al., 2004; O'Reilly et al., 2018). They have all concluded that **schools are one of the buildings most vulnerable to earthquakes**. This is due to fact that their occupants are mostly children, the low adult/child ratio and the high occupation, making the evacuation of the building during an emergency complicated. Moreover, many studies reported the post-traumatic stress and depressive disorders that children can suffer from after surviving an earthquake (Xu et al., 2018). In addition to this, due to their public nature, schools can also be used as shelters after a disaster. All this makes it **essential to check and guarantee their structural stability in the event of an earthquake**.

Most of the school buildings were constructed in Spain during the 1970s and 1980s. In the case of the Spanish *Huelva* province, most of the schools are low-rise reinforced concrete (RC) framed buildings, which were constructed during this period. They share similar constructive and structural characteristics and were designed with **typical seismic RC structures vulnerabilities**: soft-storey mechanisms, wide beams and irregularities in plan and in height. These elements are known to be some of the main causes of building damage during earthquakes (Rodgers, 2012). In fact, earthquakes have shown that these RC structures are not prepared for moderate-to-strong earthquakes (Valente and Milani, 2018).

Buildings built prior to the seismic codes are those most likely to be damaged by an earthquake (Kam et al., 2011). This is due to the fact that they have only been designed considering the gravity loads, omitting the required lateral load resistance. In Spain, some seismic regulations were available during the 70s. However, they were not very restrictive and were usually omitted by the designers. The first Spanish seismic code which was carefully considered in the design of buildings was the NCSE94 (Spanish Ministry of Public Works [Ministerio de Fomento de España], 1994). This was introduced in 1994, so **most of the schools in the area did not implement seismic considerations in their design procedure** since they were constructed prior to the seismic code (Manfredi and Masi, 2017). Hence, they present smooth rebar, low-quality structural and constructive materials and insufficient reinforcement rebar, especially in the beam-column joints. All these characteristics increase their seismic vulnerability.

I.1.5. The thesis framework

This thesis is part of the PERSISTAH project, developed in collaboration between the University of Algarve and the University of Seville. The main researcher from the University of Seville is one of the supervisors of this thesis. The project was funded with 525,759.32 euros, granting the University of Seville with 325,760.00 euros.

The thesis considers the case study area of the *Algarve-Huelva*, owing to the considerable seismic hazard, focusing on the province of *Huelva*. The RC primary school buildings have been selected as case study buildings due to their seismic vulnerability (construction date, building configuration, structural and constructive characteristics and social aspects). This work has also been extended to include the research carried out in collaboration with the *Instituto Superior Técnico de Lisboa* (Portugal) on the seismic performance assessment of RC buildings.

I.2. Objectives

Due to the situation described previously, several **key points** have been defined, which are related to the drawbacks identified. This thesis addresses the following key points:

- The enhancement of the security of society is a main priority of different international, European and national organisations and institutions.
- The impact of an earthquake depends on the magnitude of the event, and the vulnerability and the resilience of the population.
- There is a lack of studies on the seismic hazard of the *Algarve-Huelva* area and the vulnerability of the buildings located in it.

- Southwestern Spain is characterised by a significantly high seismic hazard. Most of the existing buildings of the area were constructed without seismic considerations.
- Schools are one of the most vulnerable building typologies to earthquakes due to social and structural/constructive aspects.
- The major part of schools in the area was designed with RC structures and present typical seismic vulnerabilities that increase their seismic vulnerability.
- The addition of appropriate retrofitting strategies can help to reduce the seismic damage, human losses and the economic impact due to future seismic events.

Given these key points, the **main objectives** of this thesis are established:

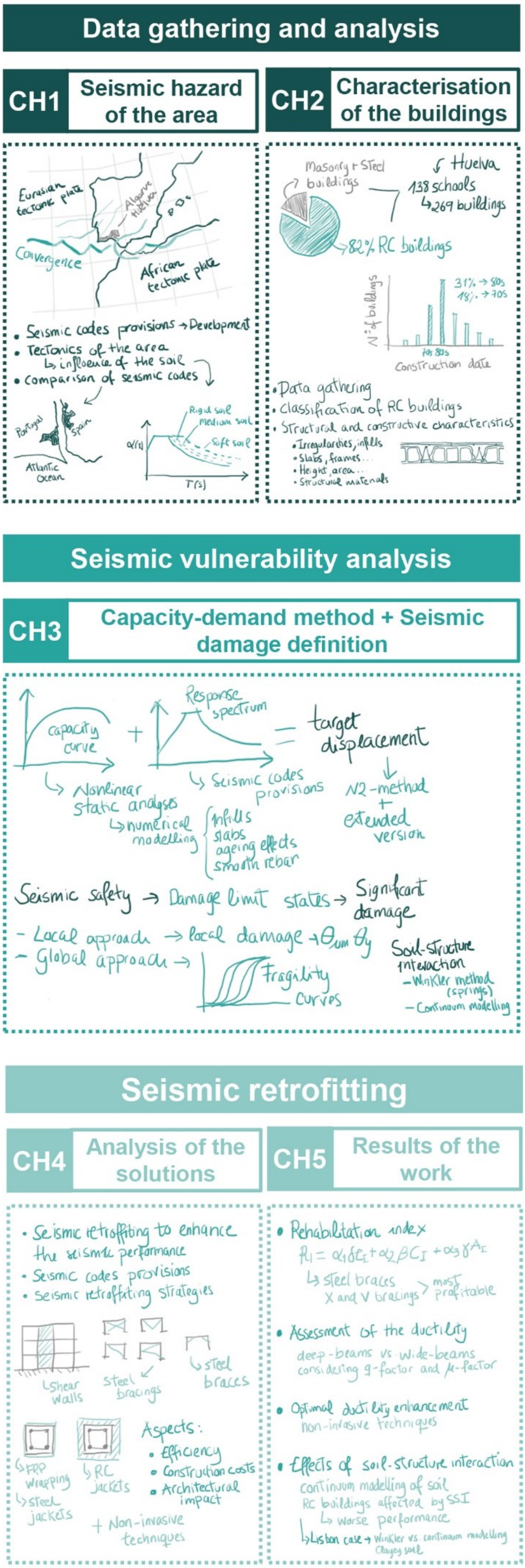
- **Assessing the seismic vulnerability** of RC buildings focusing on the primary school buildings located in the southwestern Iberian Peninsula.
- Developing a specific **seismic retrofitting** method for the schools according to their seismic vulnerability to improve their seismic behaviour and **to help to reduce the expected seismic damage**.

These main objectives have been achieved by establishing the following **specific objectives**:

- Analysing the seismic hazard of the area in order to obtain the seismic action.
- Characterising the primary school buildings according to their constructive, structural and geotechnical characteristics.
- Analysing thoroughly the seismic vulnerability of buildings by means of analytical procedures, considering different seismic safety levels.
- Analysing the effects of each seismic retrofitting solution to obtain its effectiveness by means of numerical analyses.
- Minimising the economic costs, the time consumed, the architectural impact and the construction efforts of the seismic rehabilitation of buildings.

I.3.Outline

This thesis is structured in five chapters showed in Fig. 1, which corresponds to the different phases followed during the research work. Additionally, it includes some other chapters: an introduction to the framework and background of the thesis and the objectives pursued and a section that presents the conclusions drawn from the work carried out.



Chapter 1 contains the analysis of the seismic hazard of the *Algarve* and *Huelva* area. It includes a description of the region considering past earthquakes and the soil characteristics. The seismic hazard in both Spain and Portugal is addressed by defining the seismic codes criteria. Finally, a comparison of both seismic codes is presented.

Chapter 2 deals with the characterization of the buildings for the subsequent seismic analysis. A classification of the buildings according to their structural system, year of construction and geometry and volumetry is presented. The characteristics of the RC buildings are listed.

Chapter 3 briefly details the methodology and the seismic regulations concerning the seismic safety applied in the seismic performance analyses. Different modelling considerations have been listed.

Chapter 4 analyses the different seismic retrofitting techniques for RC buildings available in the literature and seismic codes.

Chapter 5 compiles the articles considered for the compendium, one contribution to a conference and a paper submitted to an indexed journal. The first presents an index-based method to evaluate the seismic retrofitting measures. It takes into account the efficiency, the economic costs and the architectural suitability. The second publication analyses the influence of the constructive characteristics in the ductility of RC buildings. It also proposes a method to evaluate the ductility due to the lack of guidance in the seismic codes. The third contribution studies the optimal ductility enhancement of RC buildings by means of non-invasive retrofitting techniques. The contribution to the congress analyses the effects of the soil-structure interaction (SSI) in the RC buildings of *Huelva*. The paper submitted to the journal assesses the effects of SSI in a case study RC building in Lisbon considering different soil modelling approaches. Additionally, a global summary of the results is included.

Fig. 1. Flowchart of the research work.

Chapter 1

Seismic hazard of the *Algarve-Huelva* region

In this chapter, the seismic hazard of the *Algarve-Huelva* region is analysed. In Section 1.2, the configuration of the region is described. In Section 1.2, the influence of the soil is presented. In Sections 1.3 and 1.4, the requirements established by the seismic codes of Spain and Portugal are presented. In Section 1.5, a comparison between both seismic codes is performed. It should be noted that, in the case of an earthquake, both areas would be equally affected.

This chapter contains part of the following publications:

- **CONGRESS: Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Maria Luisa Segovia Verjel, Emilio Romero Sánchez, Jaime de Miguel Rodríguez, João MC Estevão (2019). *Comparative analysis between the Spanish and Portuguese seismic codes. Application to a border RC primary school*. 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN19). Vol. 3: 4816-4827. Eccomas Proceedia.
- **BOOK CHAPTER: Maria Victoria Requena-Garcia-Cruz**, Luis Fazendeiro Sa, Antonio Morales-Esteban, João M. C. Estêvão, Mónica Ferreira, Percy Durand-Neyra, Carlos Sousa Oliveira (2017). *Study and assessment of the seismic vulnerability of primary school buildings located at de Algarve and Huelva: state of the art*. IDA: Advanced Doctoral Research in Architecture: 193-203.Universidad de Sevilla.
- **BOOK:** Antonio Morales-Esteban, Emilio Romero-Sánchez, Beatriz Zapico Blanco, **Maria Victoria Requena-Garcia-Cruz**, Jaime de Miguel Rodríguez, João MC Estevão (2020). *Rehabilitación sísmica estructural de colegios de educación primaria*. 1-64. Universidad de Sevilla.

1.1. The *Algarve-Huelva* region

The Iberian Peninsula is characterised by a moderate seismic activity compared to other regions of the world (Carreño Herrero and Valero Zornoza, 2011). However, there is a significant seismic activity in the south of the peninsula. This is due to the convergence of the Eurasian and African tectonic plates. As shown in Fig. 2, this convergence is extended throughout the Mediterranean, the Straits of Gibraltar and the Azores Islands.

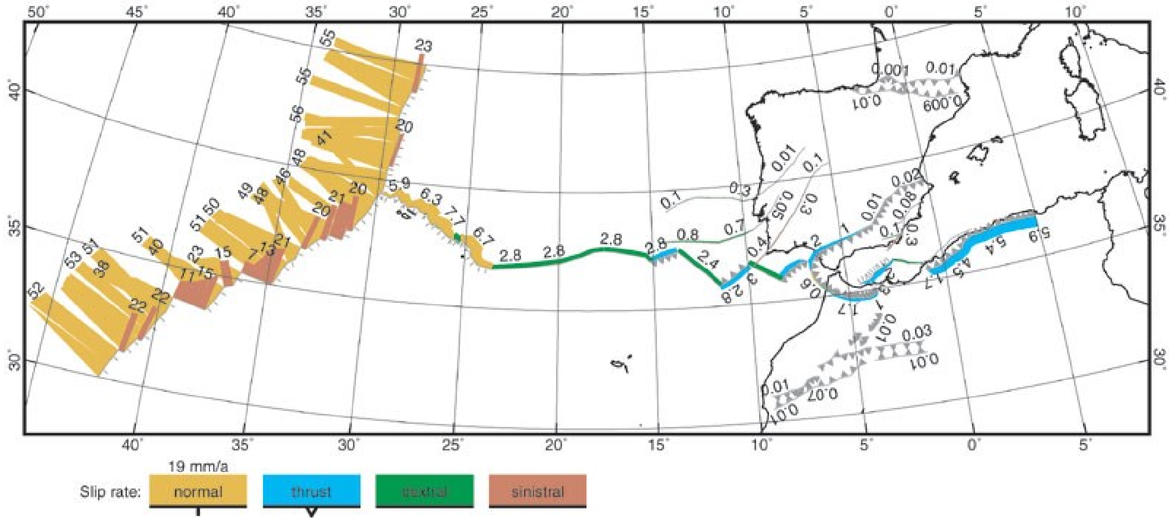


Fig. 2. The Eurasian-African tectonic plates convergence (Gràcia et al., 2010).

Owing to this convergence, the Iberian Peninsula has suffered from numerous high-magnitude earthquakes of catastrophic consequences. According to Table 1, the earthquakes that stand out due to their effects, which are widely-known, are the 1755 Lisbon earthquake (M_w=8.5) and the 1969 earthquake (M_w=8) (Sá et al., 2018). In fact, the Lisbon 1755 earthquake-tsunami is considered as one of the most devastating seismic events worldwide. It has been the most catastrophic natural disaster ever suffered in Europe (Morales Esteban et al., 2020).

Table 1. List of historical earthquakes of the Iberian Peninsula (Silva and Rodriguez Pascua, 2014).

YEAR	PLACE	MAG.	CONSEQUENCES
1522	Alboran Sea	6.5	Total destruction of *Almería* and towns in *Granada*
1531	Lisbon	7.0	Around 30,000 deaths in the city of Lisbon
1680	*Alahaurín el Grande (Málaga)*	6.8	Various towns affected causing minor damage
1722	Gulf of *Cádiz*	6.5	Serious human and material damage from Cape St. Vincent to *Castro Marim*. It caused a local tsunami in *Tavira*
1755	SW of Cape St. Vincent	8.5	Destruction of most of Lisbon. Tsunami of almost 15m in height. Between 10,000 and 90,000 deaths caused by both disasters
1804	Alboran Sea	6.7	Serious damage in *Motril* (Spain)
1829	*Torrevieja (Alicante)*	6.6	Destruction of a large number of houses in various towns in the district. Around 400 deaths
1884	*Arenas del Rey (Granada)*	6.7	Almost one thousand deaths
1969	Cape St. Vincent	8.0	Several deaths and minor damage
2007	SW of Cape St. Vincent	6.1	Minor damage
2009	*Isla Cristina (Huelva)*	6.3	Minor damage. Cracks in buildings. Factory walls collapsed
2011	*Lorca (Murcia)*	5.1	Significant damage and victims. Collapses of highly important buildings
2016	Alboran Sea	6.3	Detachment of façades, cracks and minor injuries. Small tsunami in the Balearic Islands (Spain)

The region with the highest seismic hazard is the southeast of Spain, mainly the Alboran Sea and *Murcia*. This area is characterised by frequent moderate- and low-magnitude earthquakes. Therefore, the vast majority of the studies on the seismic risk, hazard and vulnerability are based on this area. The 2011 *Lorca* earthquake has been the most devastating seismic event recently felt in the Iberian Peninsula. Its hypocentre was located very superficially, around 1 km from the surface. Therefore, and despite its moderate magnitude, the acceleration was 0.36g, leading to devastating effects: it caused more than 300 injuries, casualties and the relocation of more than 10,000 people (Salgado-Gálvez *et al.*, 2016).

Contrariwise, the *Algarve-Huelva* region is affected by far away earthquakes of a long-return period and large-very large magnitude ($M_w \geq 6$) (Amaro-Mellado et al., 2017), such as the 1755 Lisbon earthquake or the 1969 earthquake. Owing to this, the population is not aware of the relatively high seismic hazard of the area. Furthermore, recent studies have identified faults in the southwest region of the *Algarve*. These are the *Herradura* fault, the *Marqués de Pombal* fault or the fault of *San Vicente* (Gràcia et al., 2010) (Fig. 3). These faults caused some of the most damaging earthquakes in the Peninsula, such as the *Marqués de Pombal* fault and the Lisbon earthquake. Moreover, buildings in this area have been severely damaged in the past by relevant events such as the 1344, 1531, 1722, 1755, 1859, 1909 and 1969 earthquakes (Sá et al., 2018). **Despite the considerable seismic hazard, there is a lack of studies on the area on the seismic risk and vulnerability of these buildings.**

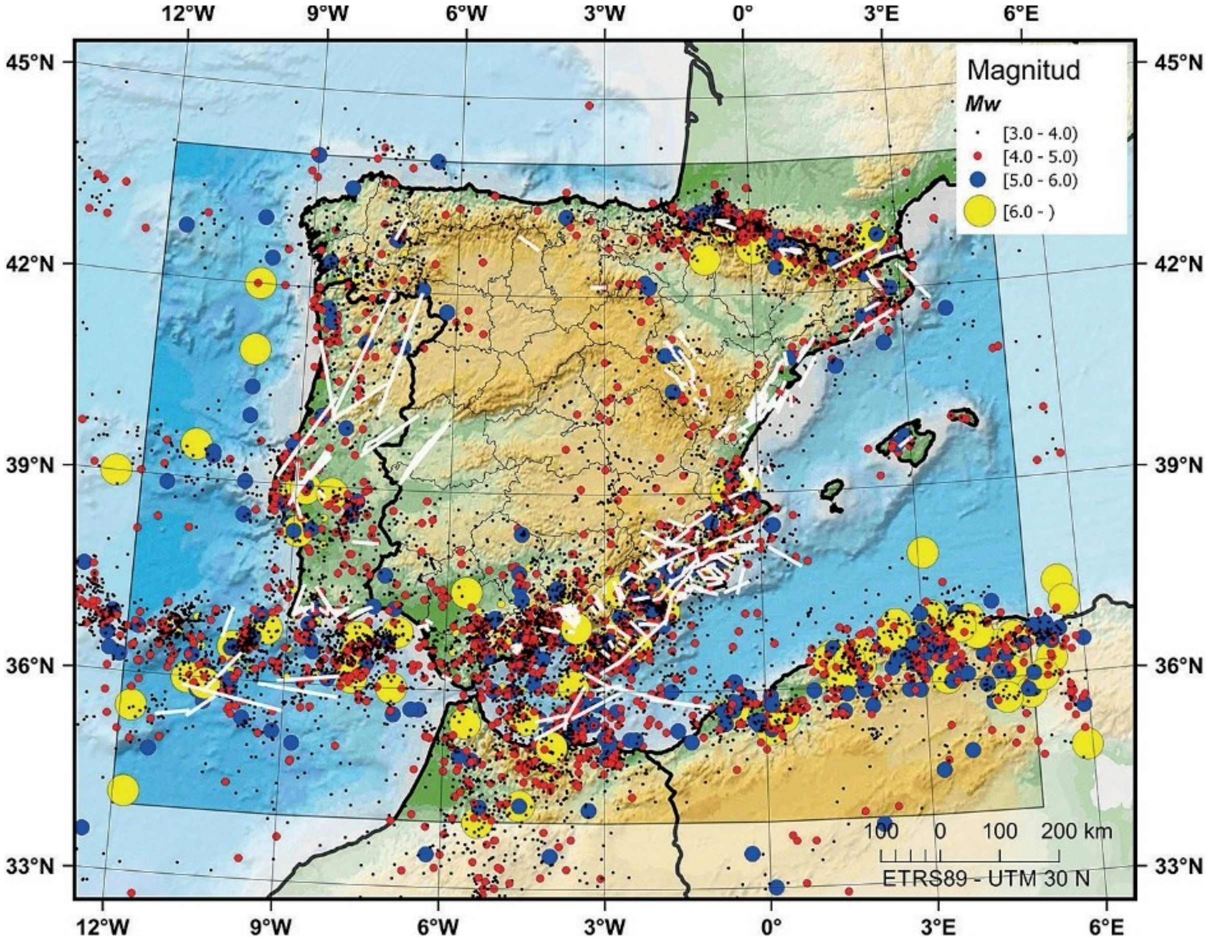


Fig. 3. Active quaternary faults of the Iberian Peninsula and magnitude of the earthquakes defined by (Amaro-Mellado et al., 2017).

1.2. The tectonics of the area

The region of the *Algarve* and *Huelva* is characterised by a similar geological profile with certain nuances (Requena-Garcia-Cruz et al., 2017). This can be observed in the geological map of Spain and Portugal created by the Geological and Mining Institute of Spain (IGM) and

Portugal's National Laboratory of Energy and Geology (LNEG) (Geological and Mining Institute of Spain [Instituto Geológico y Minero de España], 2015).

According to this map, *Huelva* is characterised by the presence of tertiary and quaternary materials of the *Guadalquivir* basin. It has been observed that it has maritime influences and extensive marshland areas (Meijninger, 2006). The main geological materials that can be identified from the shallowest to the deepest are: fluvial deposits, fluvial terraces, basal sandstones and sandy marlstones. The *Algarve* bay is basically characterised by tertiary materials, with a high presence of calcareous materials, clays and sands with some magmatic material (Terrinha et al., 2013).

The characteristics of the soil affect the seismic activity of a region. In fact, according to the Spanish seismic code, **the presence of soft soil can amplify the effects of seismic events**. This is due to the incapability of soft soils to dissipate the seismic waves. Contrariwise, rocky ground can absorb the energy of the earthquakes due to its inertia (Udías and Mézcua, 1986). In the *Algarve*, soft soils can be found at the coast (where most of the population lives), in some valleys and near rivers. In the case of *Huelva*, most of the area near the cost is characterised by the presence of clayey soils. Inversely, the southeastern area of Andalusia is not affected by this amplification since the soil profile is mainly composed of rocky ground.

The effects of the soil are taken into account in seismic codes through a soil behaviour factor. This factor is listed for each type of soil, varying from rock to very soft soils, such as slurries or sludge.

1.3. Evolution of the seismic codes in Spain

Several seismic regulations have been developed over time in Spain. The first seismic code was the PGS-1, published in 1969 (Spanish Ministry of Planning and Development [Ministerio de Planificación del Desarrollo], 1968). This code proposed a classification of buildings according to their importance. In this case, schools were included in the "ordinary buildings" group. For this group, the consideration of this regulation was optional. In addition, this code proposed different seismic areas, actions and a method to seismically design buildings.

The next code was the PSD-1, published in 1974 (Spanish Ministry of Planning and Development [Ministerio de Planificación del Desarrollo], 1974). It proposed a classification of buildings according to the structural system to estimate the seismic damage, including seismic zones and a similar designing method to the previous regulation.

The *Norma de Construcción Sismorresistente* (Seismic Building Code) (NCSE94) (Spanish Ministry of Public Works [Ministerio de Fomento de España], 1994) was published in 1994. It established new probabilistic seismic hazard analyses and maps, including more complex methods of designing and analysing. It can be considered as the first restrictive seismic code in Spain.

Currently, the *Normativa de Construcción Sismorresistente Española* (Spanish Seismic Building Code) (NCSE02) has been applied since 2002 (Spanish Ministry of Public Works [Ministerio de Fomento de España], 2002). It compiles the criteria for the determination of the seismic action and seismic requirements for the design of new buildings and rehabilitation of existing ones. **This code provides only requirements to prevent the collapse of buildings. Therefore, only static analyses are allowed and no damage thresholds are considered**. Recently, there has been an update of the seismic hazard analyses carried out by the IGN, which are recommended to be used (Spanish Ministry of Public Works [Ministerio de Fomento de España], 2012).

The Eurocode 8 (EC8) (European Union, 2004) is a European code whose application has only been recommended in Spain. Its aim is to standardise the seismic criteria among

European countries. In addition, National Annexes for each country can be developed, which include specific parameters considered by each country.

1.4. Comparison between the seismic codes of Spain and Portugal

In the case of an earthquake, the areas of the *Algarve* and *Huelva* would be affected equally. However, the seismic codes of each country differ considerably (Estêvão et al., 2019). In Portugal, the *Decreto Lei 235/83* (RSAEEP) (Imprensa Nacional-Casa da Moeda, 1983) and the EC8 are mandatory. Whereas in Spain, only the NCSE02 must be fulfilled. The main difference is the value of seismic action due to the different approaches used in the probabilistic seismic hazard analyses. Contrariwise, no significant differences have been found regarding other seismic aspects such as the ductility assessment or the constructive criteria.

As previously mentioned, **the European Union promoted a homogenisation of the design rules for earthquake resistant structures through the EC8. However, the determination of basic seismic parameters, such as the seismic action, must be provided by the National Annexes**. As pointed out in (García-Mayordomo et al., 2004), the main differences in the seismic parameters and their values are outlined in Table 2. These authors concluded that inter-country cooperation would improve the earthquake catalogue and the criteria defining the seismogenic zones. In (Hachem et al., 2010), the seismic design criteria and ground motion selection methods from five different world regions were compared. They demonstrated that despite the incentive for harmonisation, obvious differences could be mainly found in the response spectra definitions.

Table 2. Basic characteristics of the ground acceleration and response spectra according to each seismic code.

Parameter	Decree-law RSAEEP	EC8	NCSE02	Spanish maps update	Spanish annex to EC8	Portuguese annex to EC8
Date	1983	1998	2002	2012	2010	2010
Seismic scale	Magnitude	-	Intensity	Magnitude	-	-
Seismic estimation	Historical Parameters Attenuation laws Gumbel III	-	Historical Parameters	Historical Parameters Attenuation laws	-	-
Attenuation functions	Acceleration	-	Macroseismic	Acceleration	-	-
Hazard analysis	Gumbel I	-	Poisson	Poisson	-	-
Hazard descriptor	PGA	$a_g=a_{gR}\cdot\gamma_I$	$a_c=S\cdot\rho\cdot a_b$	PGA	$a_{gR}=0.8\cdot a_b$	a_{gR}
Importance factor	-	$\gamma_I=1$	$\rho=1$	$\rho=1$	$\gamma_I=1.3$	γ_I-T_1=1.45 γ_I-T_2=1.25
Type of spectrum	Type 1 and 2	Type 1 and 2	Type 1	Type 1	Type 1 and 2	Type 1 and 2
No-collapse limitation values	T_{NCR}=1000 years	T_{NCR}=475 years P_{NCR}=10%	T_{NCR}=500 years P_{NCR}=2 ‰	T_{NCR}=475 years P_{NCR}=10%	T_{NCR}=475 years P_{NCR}=10%	T_{NCR}=475 years P_{NCR}=10%
Severe damage limitation values	-	T_{DLR}=95 years P_{DLR}=10%	T_{DLR}=95 years P_{DLR}=10%	T_{DLR}=95 years P_{DLR}=10%	TDLR=95 years PDLR=10%	TDLR=95 years PDLR=10%
Ground acceleration value (m/s^2)	-	-	*Ayamonte* a_c=1.597 a_g=1.428	*Ayamonte* a_c=1.763 a_g=1.5	-	Vila Real $a_{g\text{-}T1}$=2.2 $a_{g\text{-}T2}$=2.1

Both in the Spanish NCSE02 and in the values update of 2012, the probabilistic seismic hazard analysis was based on a Poissonian distribution. Therefore, it used mean values of seismic acceleration. However, the Portuguese code considered a Gumbel I distribution, which bore in mind the maximum values of acceleration. Therefore, owing to the different approaches and other factors (Estêvão and Oliveira, 2001), **the acceleration values obtained for Portugal and Spain are rather different, even for locations at the border**.

Among these other factors, considerable differences can be found in the assessment of the return periods. The NCSE02 used a value of 500 years while the EC8 and the Spanish and Portuguese updates and annexes considered 475 years. This is important when compared to the return period considered in the *Decreto-Lei*, which took into account a return period of 1,000 years. Therefore, the seismic action is considerably higher than the provisions established in the NCSE02 or its values update of 2012.

Furthermore, the ground accelerations are expressed for different types of soil. The NCSE02 determines the acceleration for a type II or B while the rest consider a type I or A. Therefore, the acceleration values established in the NCSE02 must be modified by a reduction factor, defined in the update of 2012 in order to use the EC8 response spectrum. Moreover, only one type of response spectrum (distant earthquake) is presented in the NCSE02, while both the EC8 and the Portuguese establish two types for nearby and distant earthquakes.

Regarding the importance factor, used in the definition of the response spectrum, the Spanish code establishes this as 1.0 for school buildings. However, this differs from the values considered by both the EC8 and the National Annexes of both countries. The first considers a value of 1.3 while the other two establish this as 1.45, leading to higher values of ground acceleration.

In order to compare the seismic provisions regarding the definition of the response spectrum, a comparison has been carried out considering each seismic code. The ground acceleration of two towns located on the border between Spain and Portugal has been borne in mind. The municipalities selected for the analysis were *Vila Real de Santo António* and *Ayamonte* (Fig. 4). They are separated by the *Guadiana* River and are characterised by soft soils with similar properties.

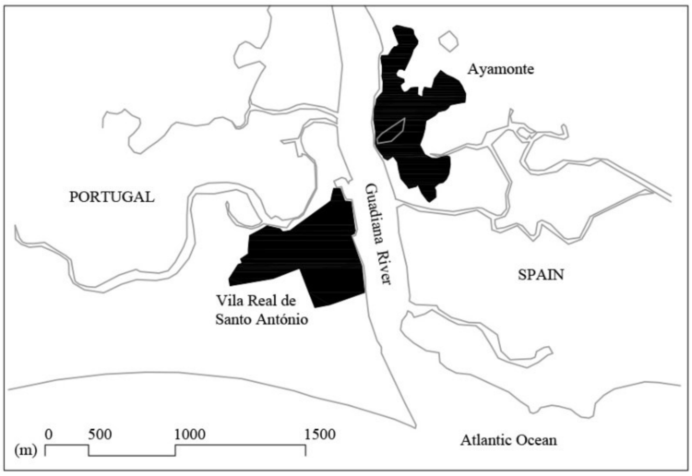
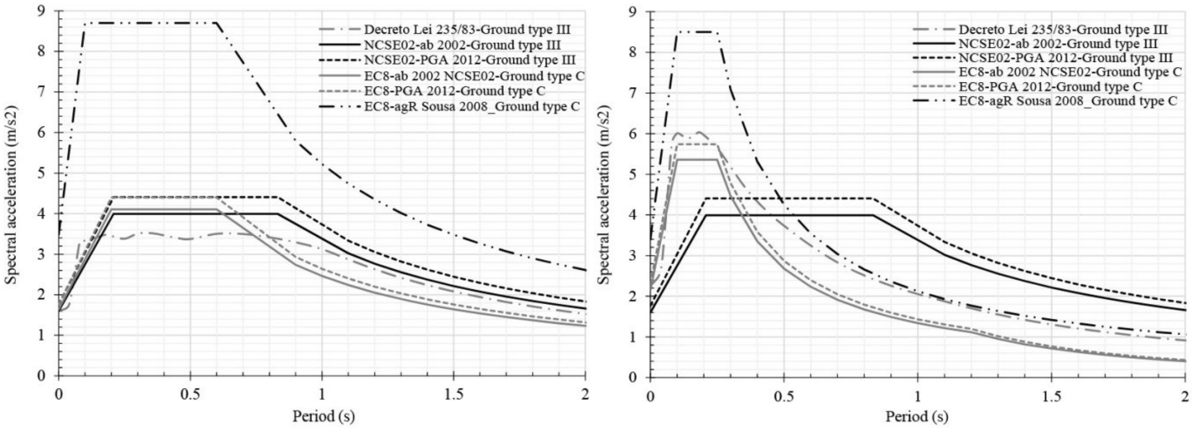


Fig. 4. Localization of towns considered in the analysis.

The response spectra were determined according to each seismic code provision: the Portuguese *Decreto Lei*; the NCSE02 response spectrum considering *Ayamonte* and the values obtained by the 2012 update; and the EC8 response spectrum considering these former values and the Portuguese seismic action provisions for *Vila Real* established in the National Annex and in (Campos Costa et al., 2008). The soil type selected has been type III in the case of the Spanish code and C in the European codes, respectively. The comparison between response spectra is shown in Fig. 5.



(a) (b)

Fig. 5. Comparison of the response spectra for each seismic code for a distant earthquake scenario (type 1) (a) and a nearby earthquake scenario (type 2) (b).

It can be observed that there are considerable differences in terms of the value of seismic action, differing by up to 60% (M.V. Requena-Garcia-Cruz et al., 2019). Moreover, the seismic hazard analyses implemented in these seismic codes are outdated. In fact, as pointed out in (Oliveira et al., 2000), further research must be performed on the definition of the ground motions including attenuation laws and scenario features.

Chapter 2

Characterisation of RC primary school buildings

In this chapter, the characterisation of the RC primary school buildings is presented. In Section 2.1, the data gathering procedure is described. In Section 2.2, the classification of the school buildings is presented, focusing on the RC structures. In Section 2.3, the structural and constructive characteristics of the RC buildings identified are listed.

This chapter contains part of the following publications:

- **BOOK:** Antonio Morales-Esteban, Emilio Romero-Sánchez, Beatriz Zapico Blanco, **Maria Victoria Requena-Garcia-Cruz**, Jaime de Miguel Rodríguez, João MC Estevão (2020). *Rehabilitación sísmica estructural de colegios de educación primaria*. 1-64. Universidad de Sevilla.
- **CONGRESS:** Beatriz Zapico Blanco, **Maria Victoria Requena-Garcia-Cruz**, Emilio Romero-Sánchez, Jaime de Miguel Rodríguez, Antonio Morales-Esteban (2020). *Classification of primary school buildings: influence of in-plan irregularities*. 9th European Workshop on the Seismic Behaviour of Irregular and Complex Structures (EWICS).

The first step to assess the vulnerability of the school buildings is to properly classify the population under study. Several groups which could potentially share a similar seismic behaviour have been identified. Within each group, a representative building was selected as an index of the typology and was assessed in detail. The conclusions of the analysis, as well as the prescribed retrofitting schemes can, in this way, be conceived at a typology level and then slightly adapted to each individual building.

2.1. Data gathering

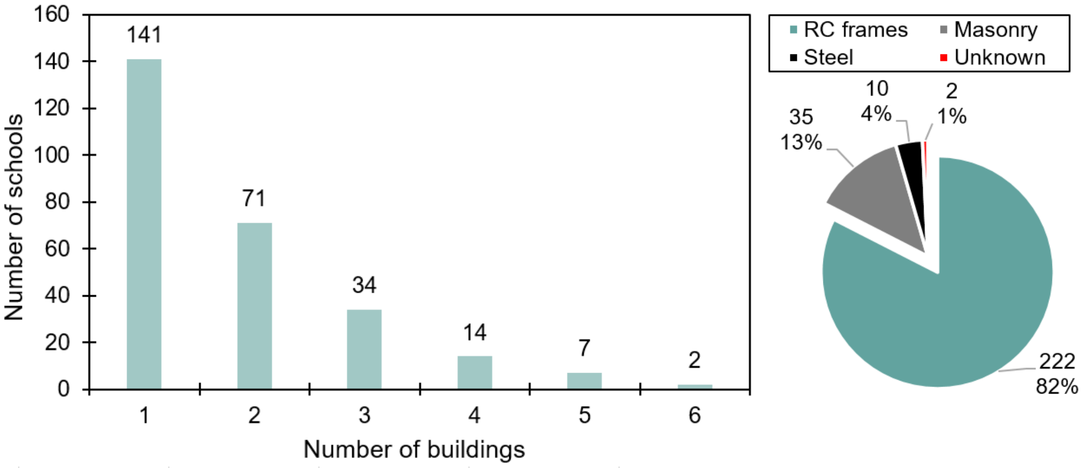
The buildings have been characterised according to the information available: aerial images, on-site visits, surveys and original and refurbishment projects (including both descriptive and graphic reports) obtained from different municipal archives of *Huelva*, the College of Architects of *Huelva* and the Ministry of Education of the Andalusian Government.

A database was created that considered different sections such as: the school identification, the services, the type of construction, the structural and constructive characteristics, the existence of damage or maintenance of the building… Specific spreadsheets were designed for those buildings for which specific information was available. These were completed for 23% of the schools.

In addition, online questionnaires were sent to each school. The questionnaires required information related to the maintenance, possible damage to the buildings, the existence of rehabilitation works and extensions. The main goal was to verify the data gathered. Information of 33% of the schools was collected using this tool.

2.2. Classification of the school buildings

There was a total of 138 primary schools identified in *Huelva* (Morales Esteban et al., 2020). The school complexes are composed of 1 to 6 individual buildings, adding up to a total of 269 buildings (Fig. 6 (a)). Data about buildings have been gathered employing the available information in each case: original and rehabilitation projects, aerial images, visits, adhoc surveys sent to the schools, etc. Then, the information has been processed. A general classification based on the structural type has been carried out. As shown in Fig. 6 (b), **the RC structures are the most representative type**, being 82% of the total number of buildings. On this basis, this thesis has been focused on the study of this group.



(a) (b)

Fig. 6. Number of schools according to the number of buildings (a) and number of buildings according to the structural system (b).

The schools were also analysed according to their construction date (Fig. 7). 31% of the buildings were constructed in the 1980s, 18% during the 1970s (18%) and 15% in the 1990s. It is important to highlight the relationship between the date of construction and the structural system. Most of the masonry buildings were constructed before 1970, while **most of the buildings that were built during the 1970s to 90s are RC buildings**.

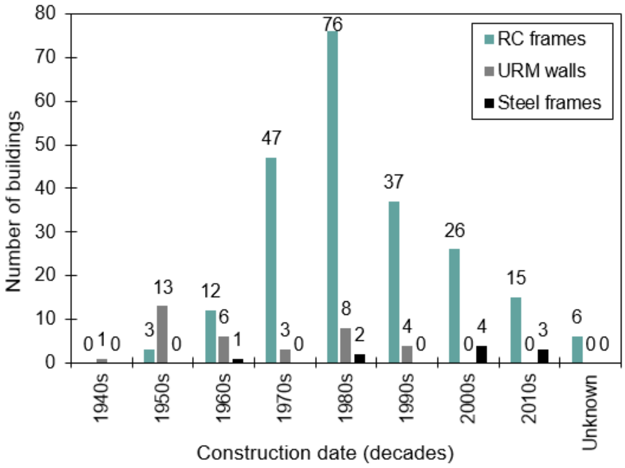
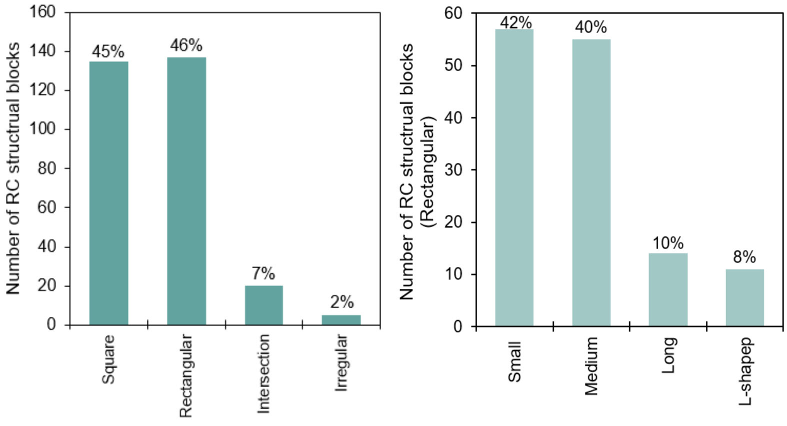


Fig. 7. Buildings according to their construction date and structural system (buildings for which the structural system is unknown have not been considered).

The RC structures studied present structural joints which divide the buildings in different structural blocks that need to be analysed separately. A total of 297 blocks have been identified (Zapico Blanco et al., 2020). The RC blocks have been divided into groups depending on their geometrical shapes: *square*, *rectangular*, *intersection* and *irregular* (Fig. 8 (a)). *Square* blocks are the most regular, with similar dimensions in both directions. *Rectangular* blocks are characterised by a predominant dimension which is at least twice as large as the orthogonal one. *Square* and *rectangular* are the predominant types, with 45% and 46% of the total population respectively. The other two groups are not representative (<10% of the population). This research work has mainly focused on the *square* ones, given their comparatively higher asymmetry. Blocks in this group are quite regular in volume, however, they can be divided into four subgroups: *small*, *medium*, *long* and *L-shaped* (Fig. 8 (b)). Again, the first two groups are the most representative ones, being 42% and 40% of the population, respectively. *Small rectangular* blocks are very regular both in plan and elevation, and present one single storey. *Medium rectangular* blocks are similar to them but are larger in plan and have two to three storeys, which makes them potentially more vulnerable to seismic action. The index buildings selected for the present work belong to this sub-group.



(a) (b)

Fig. 8. RC structural blocks based on their general geometry (a) and *rectangular* group classification (b).

2.3. Structural and constructive characteristics of the RC buildings identified

As previously shown, 222 buildings with an RC system have been identified. Different aspects that characterise these buildings are presented as follows.

2.2.1. Construction date and regulations

RC school buildings started to be constructed from around the 1950s and have continued to be built until the present day, the major part of them being built during the 70s-80s. During this period, the structural and construction codes have been developed and updated considerably. The changes in the mechanical properties and design regulations of each RC construction code have been listed in Table 3.

Table 3. Mechanical properties and design regulations established in each Spanish construction code for RC buildings.

	Regulations	**EH-68**	**EH-73**	**EH-80**	**EH-88**	**EH-91**	**EH-98**	**EHE-08**
	Date	1968	1973	1980	1988	1991	1998	2008
Concrete	f_{ckmin} (N/mm^2)	12	12.5	15	15	15	20	25
	E (N/mm^2)	No	No	$\sqrt{1900 f_{ck}}$	$\sqrt{1900 f_{ck}}$	$\sqrt{1900 f_{ck}}$	$\sqrt[3]{1000 f_{cm}}$	$\sqrt[3]{8500 f_{cm}}$
Steel	f_y (N/mm^2)	230	220	410 (CS-400)	410 (CS-400)	410 (CS-400)	400 (B400S)	400 (B400S)
	Diameter (Φ_{min}) (mm)	5	6	4	no	4	6	6
	Types bars	smooth	smooth and corrugated	smooth and corrugated	smooth and corrugated	smooth and corrugated	corrugated	corrugated
Other	Provision	No	No	On hanger	On hanger	On hanger	On hanger	On hanger
	Actions	No	No	Yes	Yes	Yes	Yes	Yes
	Coat.	No	No	No	Yes	Yes	Yes	Yes
	Coefficient security S: steel C: concrete	No	No	S:1.15 C: 1.5	S: 1.15 C: 1.5	S: 1.15 C: 1.5	S: 1.15 C: 1.5	S: 1.15 C: 1.5

According to the available information, the mechanical properties identified for the RC buildings have been listed in Table 4. It should be noted that no information regarding the structural and constructive parameters has been collected from several schools. Therefore, when assessing their seismic vulnerability, these parameters will be taken according to their construction date.

Table 4. Mechanical properties of RC buildings obtained from the available information.

Parameter	**Units**	**Concrete (H-175)**	**Steel (CS-400)**
Weight by volume (W/V)	kN/m^3	24.51	76.47
Strain modulus (E_c)	kN/m^2	According to regulation	210
Poisson's ratio (U)		0.2	0.3
Coef. Thermal expansion (A)	1/C	10E-05	1.2E-05
Concrete strength (f'_c)	MPa	17.5	
Elastic limit (F_y)	kN/m^2		420
Minimum tensile strength (F_u)	kN/m^2		Fy·1.10

2.2.2. Height and area

The floor area of these buildings ranges from 125 m^2 to 4,700 m^2. 36% (80) have only one storey while the rest (125) have two storeys. 6% of them have three storeys of higher area values varying between 2,000 and 3,000 m^2. In addition, 13 of them have a similar geometric shape (H-shape) and characteristics, which can be identified as an own typology.

The height of a standard storey ranges from 3.00 m to 3.45 m. Although most of the RC buildings are regular in height, they present sanitary slabs. This type of slab is characterised by the presence of short columns on the ground floor. This is a typical constructive configuration that can be commonly found in most RC buildings of the 1970s-80s. In this case, short columns are created due to the elevation of the ground floor from the soil surface to avoid humidity and water problems. This ground-floor construction often leads to isolated footings (superficial or deep). The elevation ranges from 0.35 m to 0.80 m. The presence of short columns is one of the most typical seismic vulnerabilities of RC buildings. Shear forces are concentrated on these columns, leading to worse seismic behaviour.

2.2.3. Slabs

Most of the slabs of these buildings are one-way and, in a few cases, two-way or reticular (Fig. 9). The latter are used when supporting higher spans. In any case, for the numerical analyses both configurations can be considered as a rigid diaphragm. The thickness of both types of slabs varies from 0.25 m to 0.30 m.

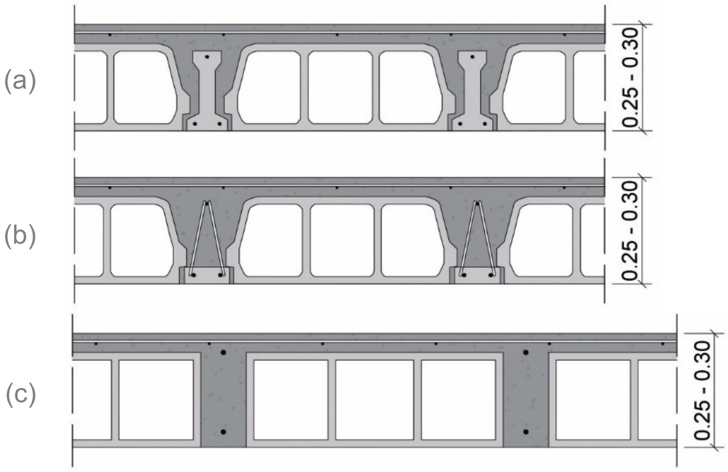


Fig. 9. Sections of the sanitary (a), one-way (b) and two-way (c) RC slabs.

The slabs present the following characteristics:

- Slabs in standard floors: a one-way concrete slab with reinforced beams, ceramic or lightweight concrete vaults and compression layer in standard floors; or two-way with lost panels of lightweight or ceramic concrete.
- Sanitary slab on the ground floor: one-way concrete slab with pre-stressed beams, ceramic or lightweight concrete vaults and compression layer on the ground floor.

2.2.4. Columns and beams

It has been identified that these structures do not present bracing systems. Therefore, the horizontal loads are only supported by the frames, i.e., the beams and the columns. These elements will transmit the shear forces and the bending moments.

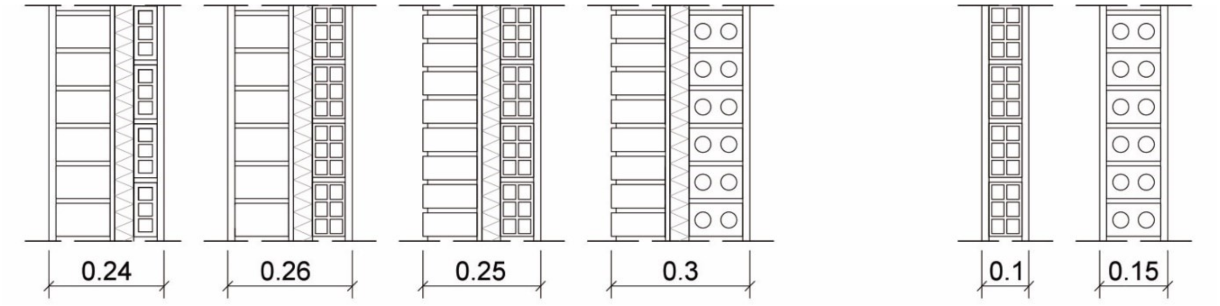
Buildings with one-way slabs were mainly built with wide-beams rather than with deep-beams. The dimensions of these beams can differ considerably. In the case of the tie beams, these are usually wide beams with the same width of the column. The columns are mainly similar in all of the buildings analysed. They vary in size from being rectangular instead of square and supporting higher spans or number of storeys. The characteristics of the RC frames are listed in Table 5. It should be pointed out that these buildings were built before the application of seismic codes. Therefore, the beam-column joints might be weak and their seismic behaviour will be worse.

Table 5. Characteristics of the RC frames.

Aspect		Columns	Deep-beams	Wide-beams	Tie beams	Rebar position
Dimensions	Min	25x25cm	25x25cm	25x40cm	25x25cm	
	Max	30x45 cm	80x30cm	30x60cm	30x30cm	
Longitudinal reinforcement	Min		2Ø12mm	2Ø12mm	2Ø12mm	High
	Max	4Ø12mm	5Ø16mm	4Ø16mm	2Ø16mm	
	Min	8Ø16mm	4Ø12mm	2Ø12mm	2Ø12mm	Low
	Max		5Ø20mm	5Ø20mm	3Ø16mm	
Transverse reinforcement	Min	Ø6mm/30cm	Ø6mm/30cm	Ø6mm/30cm	Ø6mm/30cm	
	Max	Ø8mm/15cm	Ø8mm/15cm	Ø6mm/15cm	Ø6mm/15cm	

2.2.5. Infills and partitions

The infills of these buildings are mainly composed of a perforated ceramic half-brick wall (11.5 cm), an air chamber (4-5 cm), a simple hollow ceramic brick partition (5 cm) and their respective interior and exterior layers (Fig. 10). Therefore, the total thickness of the infills is around 24.5 cm. However, different configurations have been identified. The outer layer can be made up of ½ foot of solid or perforated facing ceramic brick or double hollow ceramic brick with a water-repellent cement mortar rendering on both sides. The air chamber generally has 4-5 cm thick fibreglass thermal insulation. The inner sheet can also be made up of a double hollow ceramic brick or glass-type partition.



(a) (b)

Fig. 10. Different types of exterior infills (a) and internal partitions (b).

The interior partitions are not structural; therefore, they are not linked to the RC system. It has been found out that some of the interior partitions do not reach the ceiling, leading to the generation of short columns.

2.2.6. Irregularities

Irregularities in plan and in height are one of the main drawbacks of these buildings. The RC structure is completed by perimeter infills. Infills can improve the seismic behaviour of buildings if they are regularly distributed. If not, they can produce negative effects and can cause earlier shear failures of columns (Dolšek and Fajfar, 2008). This is especially important when they are not regular in height since they can create soft-storey mechanisms. A recurrent characteristic of the population studied is the presence of atriums. Where an atrium is present, infill walls are removed, and an irregularity is created, potentially impairing the seismic performance of the building**.**

Only in the case of the *rectangular* blocks, atriums can be found in 39% of them. This percentage could be higher, given that in 33% of the cases, the presence of an atrium has not been verified. Atriums can be found in two different positions: in corners or in middle bays.

Also, they have been found in just one floor or in two floors and symmetrically or asymmetrically distributed.

In addition, these buildings are characterised by the presence of sanitary slabs that create short columns on the ground floor. This is another irregularity that leads to worse seismic behaviour.

Chapter 3

Seismic vulnerability assessment

In this chapter, the seismic vulnerability assessment has been briefly presented. In Section 3.1, the method to analyse the seismic capacity of the buildings subject of study is described. In Section 3.2, some of the assumptions considered in the analyses are presented. In Section 3.3, the seismic performance assessment is briefly described, defining the seismic safety considerations.

This chapter contains part of the following publications:

- **ARTICLE: Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra, João M. C. Estêvão (2019). *An index-based method for evaluating seismic retrofitting techniques. Application to a reinforced concrete primary school in Huelva*. PLoS ONE 14(4): e0215120. PLos. DOI:10.1371/journal.pone.0215120.
- **ARTICLE: Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra, Beatriz Zapico Blanco (2021). *Influence of the constructive features of RC existing buildings in their ductility and seismic performance*. Bulletin of Earthquake Engineering 19: 377-401. Springer. DOI: 10.1007/s10518-020-00984-z
- **ARTICLE: Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra. (2021). *Optimal ductility enhancement of RC framed buildings considering different non-invasive retrofitting techniques*. Engineering Structures 242(1): 112572. DOI: 10.1016/j.engstruct.2021.112572
- **BOOK:** Antonio Morales-Esteban, Emilio Romero-Sánchez, Beatriz Zapico Blanco, **Maria Victoria Requena-Garcia-Cruz**, Jaime de Miguel Rodríguez, João MC Estevão (2020). *Rehabilitación sísmica estructural de colegios de educación primaria*. 1-64. Universidad de Sevilla.
- **ARTICLE:** Rita Couto, **Maria Victoria Requena-Garcia-Cruz**, Rita Bento, Antonio Morales-Esteban (2020). *Seismic capacity and vulnerability assessment considering ageing effects: case study-three local Portuguese RC buildings*. Bulletin of Earthquake Engineering. S.I.: Recent Advanc. Springer.
- **CONGRESS: Maria Victoria Requena-Garcia-Cruz**, Rita Couto, Rita Bento, Antonio Morales-Esteban (2020). *Influence of vertical irregularities on the seismic assessment of RC framed and wall-frame buildings*. 9th European Workshop on the Seismic Behaviour of Irregular and Complex Structures (EWICS).

In this section, a general approximation to the methodology is presented. However, specific description of the modelling of the structures and procedure followed is included in each published contribution.

3.1. The seismic capacity of the buildings

The seismic performance of the buildings has been analysed by means of the performance-based method. This is based on the determination of the seismic capacity and the demand of the structures (Maio et al., 2017). According to these parameters, the so-called performance point of the building (displacement vs. basal shear force) is obtained. The performance point, or target displacement, is determined by the intersection of the capacity curve of the building and the inelastic response spectrum (Morales Esteban et al., 2020). This intersection can be carried out by two methods: the capacity-demand spectrum method from the ACT-40 (Applied Technology Council (ATC), 1998) and the N2-method (Fajfar, 1999). In this work, the N2-method has been taken into account, which is the procedure implemented in the EC8-1 Part 1 (European Union, 2004) to determine the target displacement.

The capacity of the buildings is obtained by means of nonlinear static analyses. It is expressed in capacity curves, which represent the non-linear relationship between the basal shear and the displacement of the control node. This control node is generally located at the centre of masses of the rooftop. Nonlinear static analyses can reasonably obtain the capacity of low- and mid-rise buildings (Inel and Ozmen, 2006). Therefore, since the schools subject of study are of one to three storeys high, this method can be applied to obtain their capacity. Nevertheless, the analyses heavily depend on an adequate modelling of the structures and rigorous selectin of the horizontal load pattern to be applied (Mwafy and Elnashai, 2001).

In this case, the capacity curves have been obtained for the two orthogonal directions of the models (X and Y). Two steps have been defined: the gravitational and the horizontal. In the former, the gravitational loads are control-load applied incrementally. In the latter, the loads are also incrementally applied controlling the displacement of the control node. In this work, several softwares have been used to model the structures and to obtain the capacity, such as SAP v.2000 (Computers and Structures INC, 2014), Abaqus (Dassault Simulia, 2014) and OpenSees (McKenna et al., 2000). A pre- and post-processor for OpenSees, called STKO software, has been implemented (Petracca et al., 2017). As established in the EC8, two load patterns have been considered, uniform and modal. The first is defined considering the masses of each of the master nodes at each storey multiplied by the height. The second is proportional to the fundamental vibration mode behaviour for each direction of the building.

The seismic demand has been obtained according to the seismic codes considered. The response spectrum is used, which has been defined following the corresponding procedure. The ground acceleration has been selected according to the localisation of the buildings analysed and the values established in the seismic codes.

3.2. Assumptions considered for the numerical analyses

Different parameters have been considered for the numerical analyses to determine the seismic capacity of the buildings. As previously mentioned, the RC buildings have masonry infills. In the cases under study, these are slightly heterogeneously distributed in the plan and elevation. During the research stay at IST, the influence of the irregularities of RC buildings was analysed (Requena-Garcia-Cruz et al., 2020a). It was concluded that infills could worsen the seismic behaviour of buildings if they are not regularly distributed. They can lead to the generation of soft-storey mechanisms due to the vertical discontinuity of masonry infills. This is likely to occur if the global ductility of the RC buildings is low (as well as the ductility of the structural elements), and if the infills are relatively weak and brittle. Therefore, special attention has been paid to the modelling of irregularities in the buildings due to the infills distribution and the configuration of the RC structure itself. The infill panels have been considered and modelled by assuming the two-diagonal truss approach established in (Celarec et al., 2012).

The major part of the RC buildings subject of study was built before the introduction of modern seismic codes. Hence, they present smooth rebar, low-quality structural and constructive materials and insufficient reinforcement rebar, especially in the beam-column joints. In this study, a simple approach to consider the effects of the smooth rebar was performed by modifying the steel constitutive law. Moreover, these buildings are reaching the end of their nominal life. During the research stay at the IST, the influence of the ageing effects on RC buildings was analysed, concluding that they affect their seismic behaviour, increasing their vulnerability (Couto et al., 2020). Ageing effects have therefore been taken into account. Also, since the concrete slabs present significant stiffness in all the buildings, their effects have been simulated by connecting the RC beams by a rigid diaphragm at each floor level.

3.3. The seismic performance assessment

3.3.1. The N2-method

The N2-method is established in the Annex B of the EC8-1 to determine the target displacement of the buildings considered. It is based on the determination of the intersection between the capacity curves of the models and the response spectrum defined. There are several approaches to define the bilinear curve as analysed by (Park, 1998). The N2-method establishes a procedure based on the equivalent elasto-plastic energy absorption. It should also be pointed out that in order to apply this method, the multi-degree of freedom (MDOF) capacity curve should be converted to a single-degree of freedom (SDOF) system. This can be performed by calculating a transformation factor (Γ) according to the equivalent masses of the system and the normalised displacements of the master nodes of each storey of the structure.

The extended version of the N2-method has also been considered to determine the target displacement. This version allows accounting for the influence of the infills in the determination of the SDOF idealised curve. This is carried out by idealising a multi-linear force-displacement relation that includes the point at which the infills fail completely (Dolšek and Fajfar, 2005)

3.3.2. The seismic safety considerations

The seismic safety assessment can be carried out by means of two procedures: local and global damage assessment. The first is used for exhaustive analyses and, normally, only for single buildings. The second is used when conducting an analysis of massive buildings and takes into account the use of fragility curves.

In this work, for the first approach, the EC8 part 3 (EC8-3) (European Union, 2005) procedure has been borne in mind. It estimates the seismic safety of the buildings by means of the demand/capacity ratio (DCR) for each vertical structural element (columns and walls). It defines three damage states: damage limitation (DL), significant damage (SD) and near collapse (NC). In addition, a limit state associated with operation (OP) has been added, as this damage limit will be considered in future European regulations. These are calculated considering two types of failure: fragile and ductile. The NC limit is calculated considering both types of failures: a) for the fragile one, the shear resistant; and b) for the ductile one, the ultimate chord rotation. SD is only calculated for the ductile failure, considering 75% of the NC. Finally, DL is calculated with the yielding chord rotation. The SD LS has been used for the seismic safety assessment, as established in the EC8-3. It has been assumed that the most critical vertical element, considering a ductile or fragile failure, controls the state of the structure.

For the fragility assessment, the simplified method developed in (Milutinovic and Goran S. Trendafiloski, 2003) has been followed. Fragility curves define the probability of reaching or exceeding a specific damage state, given a specific structural response and a seismic action. They describe a lognormal cumulative distribution function which needs some statistical parameters, such as the standard deviation and the median value. These parameters have not been specifically defined for the RC buildings subject of study. Therefore, they have been obtained from other research works on similar RC building configurations.

3.3.3. Soil-structure interaction

The soil-structure interaction effects on the case study buildings' seismic performance has been analysed by means of several approaches. Particularly, in (Requena-Garcia-Cruz et al., 2021b), the 3D continuum model of the soil has been carried out to simulate its nonlinear behaviour. The most probable soil profile has been defined considering several nearby geotechnical studies. Further details can be found in the paper.

The paper submitted for an indexed journal focuses on quantifying the SSI effects in RC buildings seismic vulnerability analyses by means of two approaches: the Beam on Nonlinear Winker method (BNWM) and the soil continuum modelling. The aim of this paper is to propose a method to practically include the SSI effects and to thoroughly characterise the soil behaviour. The method has been applied to a case study RC mid-rise building located at Lisbon. 3D finite elements procedures have been proposed to reproduce the complex soil nonlinear constitutive law. This have been done in order to represent the behaviour of the entire system (soil + foundation + structure) as realistically as possible.

Chapter 4

Seismic retrofitting strategies for RC buildings

In this chapter, the analysis of the seismic retrofitting strategies for RC buildings is presented. In Section 4.1, the importance of retrofitting the case study buildings is briefly described. In Section 4.2, the different strategies are analysed considering the seismic codes provisions and studies on the seismic retrofitting of RC buildings.

This chapter contains part of the following publications:

- **ARTICLE:** **Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Percy Durand-Neyra, João M. C. Estêvão (2019). *An index-based method for evaluating seismic retrofitting techniques. Application to a reinforced concrete primary school in Huelva*. PLoS ONE 14(4): e0215120. PLos. DOI:10.1371/journal.pone.0215120.
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- **BOOK CHAPTER:** **Maria Victoria Requena-Garcia-Cruz**, Antonio Morales-Esteban, Maria Luisa Segovia Verjel, Emilio Romero Sánchez, Jaime de Miguel Rodríguez, João MC Estevão (2019). *Seismic Performance Comparison Between Structure-Improvement Techniques and Ground-Improvement Techniques: Application to a Reinforced Concrete School Building*. WIT Transactions on The Built Environment (185): 99-108. WIT Press. DOI: 10.2495/ERES190081.
- **BOOK:** Antonio Morales-Esteban, Emilio Romero-Sánchez, Beatriz Zapico Blanco, **Maria Victoria Requena-Garcia-Cruz**, Jaime de Miguel Rodríguez, João MC Estevão (2020). *Rehabilitación sísmica estructural de colegios de educación primaria*. 1-64. Universidad de Sevilla.

4.1. Retrofitting to enhance the seismic performance

The major part of the buildings under study were built before the application of current and restrictive seismic codes. Therefore, they were just designed to withstand gravitational loads and not horizontal ones. For this reason, as shown in the results section, they present a high seismic vulnerability, not complying with the seismic safety restrictions. Consequently, in order to enhance their performance, they must be seismically retrofitted.

Several retrofitting strategies have been widely implemented in RC buildings. They must be appropriately selected considering different aspects such as the efficiency, the construction costs or the architectural impact. In this work, an exhaustive revision of the state of the art on seismic retrofitting strategies has been carried out. They have been analysed according to their feasibility of implementation in the school buildings studied. However, these strategies can also be applied to other buildings with similar structural systems.

4.2. Analysis of the available seismic retrofitting solutions

5.2.1. Seismic codes provisions on the retrofitting of RC buildings

International seismic codes propose different seismic retrofitting strategies. They describe each solution and define the aspects that they might improve. In Europe, the EC8-3 presents a series of general criteria on the retrofitting of buildings, providing information on the different possible interventions. Several approaches are presented to enhance the seismic performance of buildings, such as the increase of the reinforcement of the structure and its foundation (Maria Victoria Requena-Garcia-Cruz et al., 2019), the improvement of the ductility, the reduction of masses, the addition of seismic isolation or damping.

Nevertheless, the most famous classifications of the seismic retrofitting strategies are those proposed by the American seismic codes: the standard FEMA-356 (American Society of Civil Engineers (ASCE), 2000) and the ATC-40 (Applied Technology Council (ATC), 1996). FEMA-356 proposes different intervention strategies based on the deficiency to be corrected: the local modification of components, the minimisation of irregularities, the increase of the global ductility, the global retrofit of the structure, the reduction of masses or the addition of seismic isolation. This classification is similar to the one developed by the EC8-3. However, the most widely used classification is the one proposed by the ATC-40 (Fig. 11). This proposes four general strategies to retrofit structures. Among them, those most implemented are the system's strengthening and stiffening, the enhancing of the deformation capacity and the reduction of the earthquake demand.

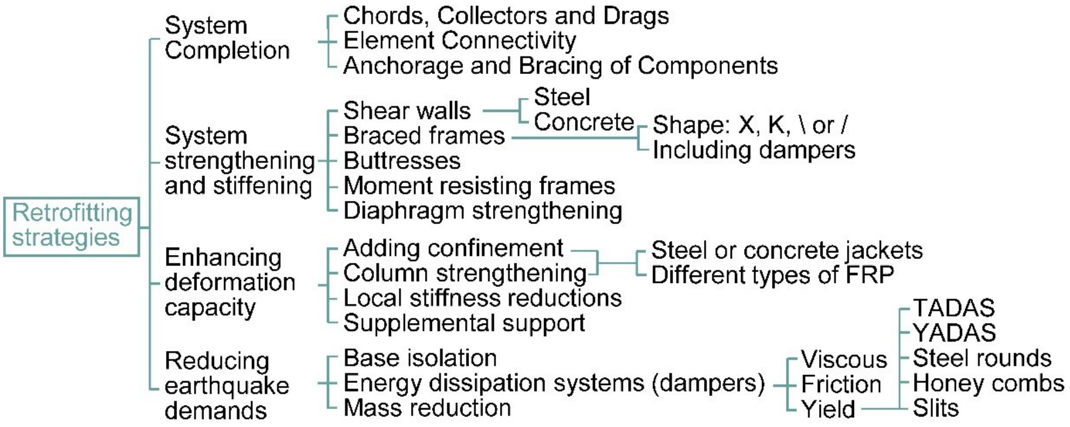

Fig. 11. Classification of the retrofitting strategies proposed by the ATC-40.

5.2.2. Studies on the seismic retrofitting of RC buildings

Strengthening and stiffening strategies are the most common approaches implemented in the seismic retrofitting of RC buildings. They are based on the addition of shear walls, steel bracings and internal frames, among other configurations (Fig. 12). The effects of adding shear walls in RC buildings have been analysed in (Fardis et al., 2013). In this work, structural bays were converted into RC walls. It was concluded that it was difficult to build the walls and that there was the additional construction cost of their foundation. In (Pincheira and Jirsa, 1995), a comparison between the effects of implementing shear walls and bracings was performed. The results revealed that higher values of capacity were obtained for the models adding bracings compared to the models with shear walls.

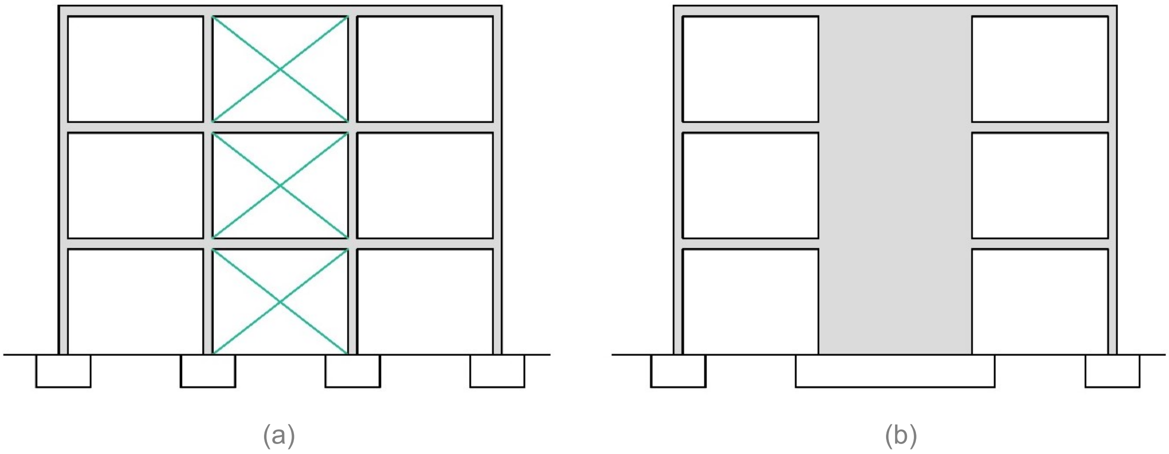

Fig. 12. X-bracings (a) and shear walls (b) retrofitting techniques.

Shear walls can be built using reinforced concrete or steel elements, such as rolled steel plates (Fig. 13). They can be added in one or more storeys and they must be rigidly anchored to the original structure. This strategy leads to higher values of architectural impact and disruption on the use of the building.

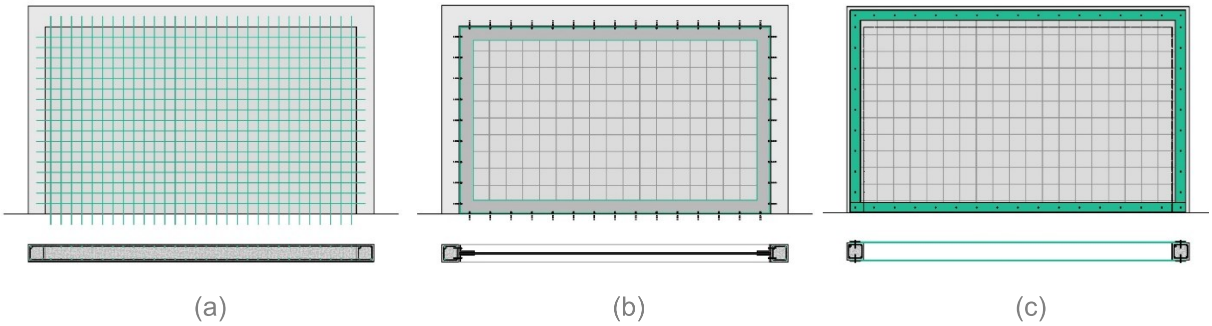

Fig. 13. Some configurations of shear walls using reinforced concrete (a) and different steel elements (b) and (c).

Another seismic retrofitting strategy based on the increasing of the system stiffness is the reinforcement of slabs (Fig. 14). However, this scheme has not been widely used in the retrofitting of RC buildings, not even in schools. It requires high construction costs and working hours. This type of technique is more often implemented in the retrofitting of masonry buildings. Another strategy that is quite expensive but results in higher efficiency ratios is the addition of moment resisting frames or additional buttresses (Fig. 15). Neither of these solutions is usually implemented in low- to mid-rise RC buildings.

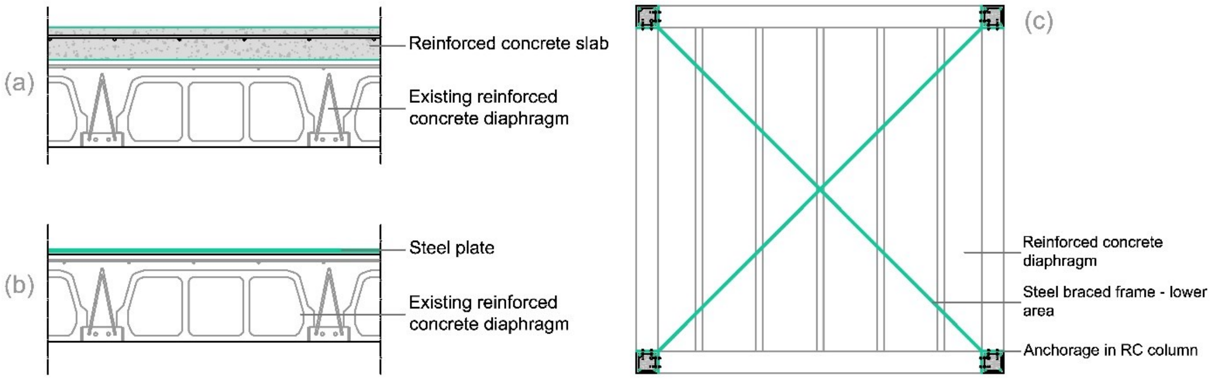

Fig. 14. Different configurations for the stiffening of RC slabs: (a) RC slab on existing RC slab; (b) Steel plate on existing RC slab; (c) Steel braces under existing RC slab.

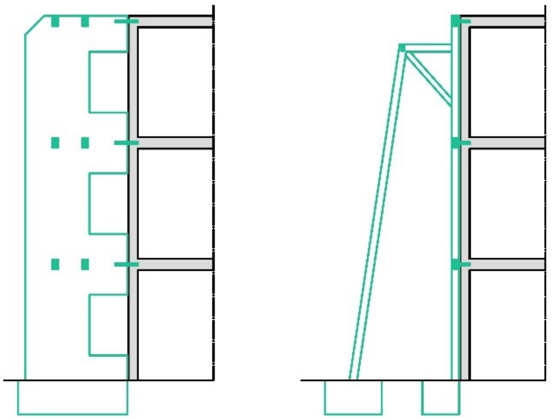
(a) (b)

Fig. 15. Stiffening systems using buttresses of RC walls (a) and steel beams (b).

Adding steel bracings in RC frames buildings is one of the most widely used systems for seismic reinforcement. This type of system increases the strength and rigidity of the structure. There are numerous configurations based on the position and configuration of the retrofitting elements (Fig. 16). In (TahamouliRoudsari et al., 2017), it was concluded that retrofitting RC frames with different steel braces always increases the stiffness and strength of the structure. This was also tested in (Ozcelik et al., 2013, 2012) in which chevron braces were included in the buildings to analyse their effects. Adding steel bracings is relatively cheap and easy to implement in existing structures. Also, this solution can be easily removed. Nevertheless, its architectural impact is high, and this can disrupt the use of the building.

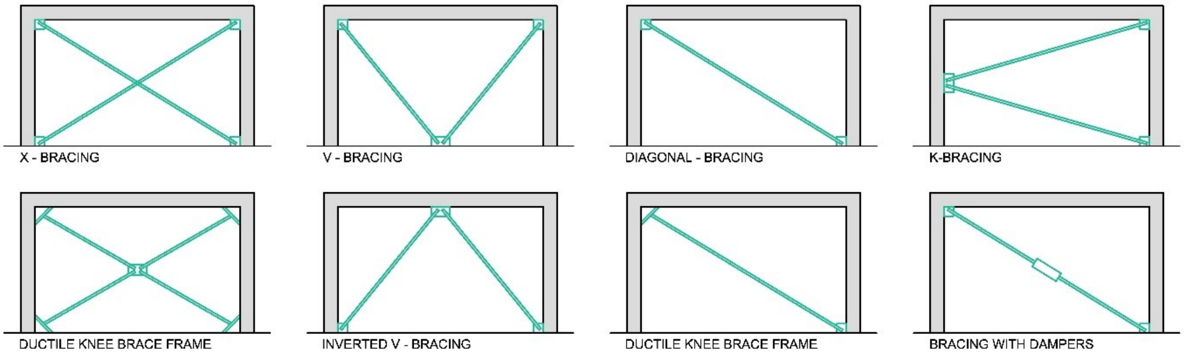

Fig. 16. Different stiffening systems using steel bracings.

The enhancing of the deformation capacity of RC structures has been also widely analysed. This strategy is focused on the addition of different elements such as the confinement in the beam-column joints, the steel or RC jackets or the carbon fibre strips (Fig. 17). These methods can increase the vertical structural elements' capacity to resist horizontal forces. In addition, they can improve the ductility of the structure due to the increase of the confinement of the columns. Moreover, these solutions can be fully integrated into the structure, not affecting the normal use of the building.

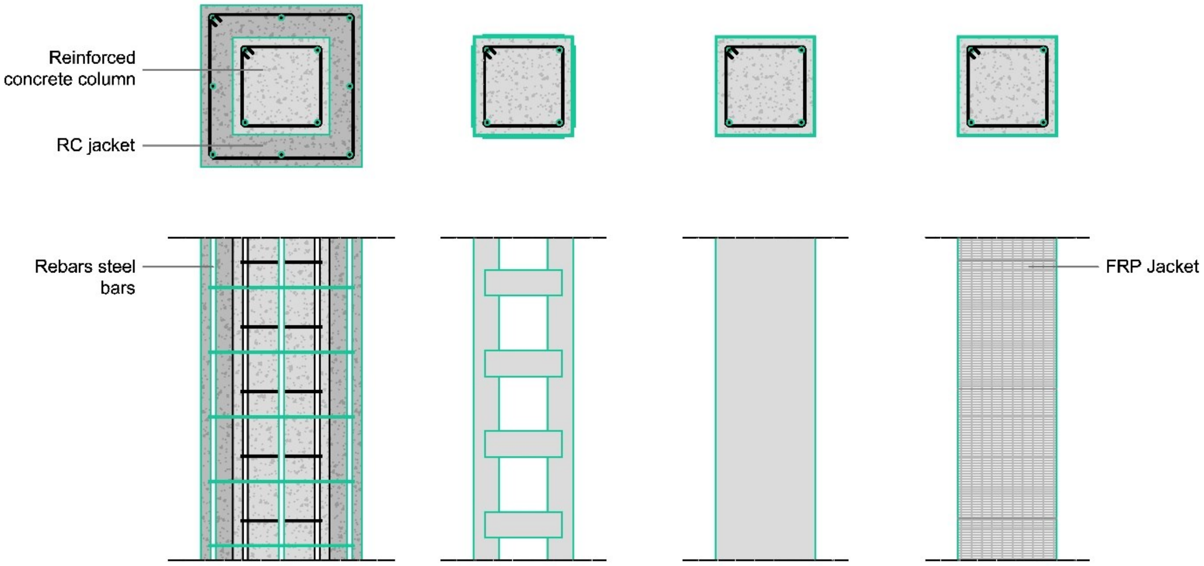

Fig. 17. Strategies to improve the deformation capacity of the RC structures: (a) RC jacket; b) Steel jacket; c) Continuous steel jacket; d) FRP-wrapping.

The addition of RC jacketing and Fibre Reinforced Polymer (FRP) wrapping in columns was analysed in (Valente and Milani, 2018) among other strategies. It was highlighted that the position of these measures is outstanding in order not to generate unfavourable torsional effects. This conclusion was also pointed out in (Colomb et al., 2008; Di Ludovico et al., 2008). Solutions can be added by varying the position and ratio of the retrofitting material.

The reduction of the earthquake demand is based on the addition of base isolation systems or energy dissipation system (dampers). The former configuration is more recent than the latter. In most studies, the dampers are included within the bracings. However, they can also added to the RC structure itself. The effects of the different types of dampers have been analysed in different studies: fluid viscous in (Sorace and Terenzi, 2008), friction in (Kim and Shin, 2017) or yield. The latter type of dampers can be divided according to the dissipation element. They can be steel plates named TADAS and YADAS (Oh et al., 2009), steel rounds, honeycombs or slits (Oh et al., 2009). Moreover, these systems were added to different internal and vertical steel frames. Such is the case of the work developed in (Ozcelik et al., 2011), which included yield damper devices in RC structures. It was concluded that the strength can be increased by the seismic upgrade, but it may be limited by the horizontal shear strength of the RC beam-column joints. Nevertheless, the addition of this type of device is recommended for buildings of considerable height and volume (Pampanin et al., 2006). In fact, they are not very useful in small buildings.

The seismic retrofitting of schools has been also analysed. In (Seo et al., 2018), a new algorithm was presented to obtain the amount and the position in which the retrofitting material is needed. Also in (Sorace and Terenzi, 2012, 2009), a fluid viscous damper bracing system was incorporated in a school resulting in an improvement of the seismic behaviour by up to 30%.

One of the main goals of this thesis is the analysis of seismic retrofitting strategies to improve the seismic behaviour of schools. Owing to the configuration and use of the buildings, the architectural impact of the schemes has been borne in mind. Therefore, non-invasive retrofitting strategies have been particularly studied. In (Sasmal and Nath, 2017), the effectiveness of non-invasive inclined single steel braces was analysed. It was concluded that the position angle is outstanding in the seismic behaviour of the structures. In (Kanchana Devi et al., 2018), different types of steel haunches were implemented in a building, concluding that the number of anchorages increases the seismic performance. In (Pampanin et al., 2006; Truong et al., 2017), experimental tests were performed to validate a steel haunch system.

According to the state of the art, it is concluded that the studies on seismic retrofitting strategies can be divided into two main groups. The first group is focused on obtaining the structural parameters and the hysteresis behaviour of the materials by means of laboratory tests. The second group is based on the analysis of the effects of these measures on the buildings' seismic performance. Nevertheless, there is a lack of studies that bear in mind the evaluation of the efficiency, the construction costs or the architectural suitability of these strategies. Furthermore, these studies do not compare them to define which solution is more profitable or optimal.

Chapter 5

Results

In this chapter, the main publications derived from the research work are presented. Each contribution has been added considering the design of the publication.

6.1. An index-based method for evaluating seismic retrofitting techniques. Application to a reinforced concrete primary school in Huelva

Maria Victoria Requena-Garcia-Cruz
Antonio Morales Esteban
Percy Durand Neyra
João MC Estêvão

PlosOne (2019)

6.2. Influence of the constructive features of RC existing buildings in their ductility and seismic performance

Maria Victoria Requena-Garcia-Cruz
Antonio Morales Esteban
Percy Durand Neyra
Beatriz Zapico-Blanco

Bulletin of Earthquake Engineering (2021)

6.3. Optimal ductility enhancement of RC framed buildings considering different non-invasive retrofitting techniques

Maria Victoria Requena-Garcia-Cruz
Antonio Morales Esteban
Percy Durand Neyra

Engineering Structures (2021)

6.4. Soil-structure interaction in the seismic vulnerability analysis of RC buildings. Application to a case study building located in southwestern Spain

Maria Victoria Requena-Garcia-Cruz
Antonio Morales Esteban
Percy Durand Neyra
Emilio Romero-Sánchez

8th ECCOMAS Thematic Conference on Computational Methods in
Structural Dynamics and Earthquake Engineering (COMDYN 2021) (2021)

6.5. Effects of soil-structure interaction in seismic vulnerability analyses of RC buildings. Methodology and application to a case study in Lisbon

Maria Victoria Requena-Garcia-Cruz
Rita Bento
Antonio Morales Esteban
Percy Durand Neyra

Journal of Building Engineering (Under review)

6.6. Final discussion of the results

In this section, the results obtained during the research work are presented and described. They have all contributed to a better understanding of the seismic performance of RC buildings; in particular, the primary schools of the province of Huelva, and to the reduction of their seismic vulnerability.

In the light of the results, it is evident that, **the buildings do not comply with the seismic safety requirements**. The damage in the case study buildings has been identified in the limit states of significant damage and even near collapse. Therefore, the results show that **these buildings need to be further analysed and retrofitted to reduce their expected seismic damage**.

Several case study buildings with irregularities in height have been selected to be analysed. It has been identified that the **columns located at the soft storey mechanism will firstly collapse** due to failure in both directions. This is produced by the heterogeneous distribution of forces due to the irregularities in plan and in height, which leads to the generation of additional torsional effects. The short columns located at the base of the structures will also firstly collapse. This collapsing effect in these latter columns is increased even when retrofitting the building. This is due to the increasing of the stiffness of the rest of the floors but not considering the short-columns' irregularity. In terms of damage, it has been obtained that the models behave worse due to the failure of columns located in these irregularities.

According to the results obtained in all of the publications, the RC buildings behave better in the direction with a higher number of vertical structural elements (columns) if there are not irregularities. Also, the higher the number of infills in a certain direction, the higher the capacity the building has in this direction if infills are regularly distributed. Nevertheless, it has been seen that the capacity of the models has been lower if the infills present a higher number of openings or if they are irregularly distributed due to the generation of soft-storey mechanisms or short-columns (Requena-Garcia-Cruz et al., 2020b). The RC buildings' irregularities have been further analysed in both research works published in (Requena-Garcia-Cruz et al., 2020a). Moreover, it has been obtained that the ageing effects worsen the performance of RC buildings constructed prior to seismic codes (Couto et al., 2020)

Overall, the results from the nonlinear static analyses have revealed that differences can be found in the capacity curves of the models including the different seismic retrofitting techniques with respect to the as-built models. Therefore, it can be seen that to some extent, **the retrofitting solutions assessed can improve the seismic performance of RC buildings**. However, **this improvement can be more or less significant depending on the position, the amount and the properties of the retrofitting elements**. This is also related to the values of the fundamental periods, which have been reduced when adding the retrofitting elements and materials by up to 30%.

In addition, the results have revealed that **adding the retrofitting element in the most vulnerable direction** of the building has had the **highest efficiency**. In fact, it has been proved that solutions that only added elements in this direction have had higher values of efficiency rather than those which included fewer elements in both directions.

An index-method has been proposed that takes into account the **efficiency, the construction costs and the architectural impact of the retrofitting techniques** (Requena-García-Cruz et al., 2019). It has been obtained that a maximum 40% of improvement resulted from comparing the effects of adding the elements in only one and in both storeys.

Regarding the efficiency, **the most efficient solution** have been the addition of **steel bracings** in both X and V positions. However, the latter resulted in lower values of seismic performance, therefore, efficiency. These solutions have been followed by the addition of **single diagonal braces** in a considerable percentage of columns. In the case of the construction costs, the cheapest techniques have been the implementation of steel jackets and steel braces. Nonetheless, the addition of X-bracings has had an acceptable cost. The solutions with a higher architectural impact have been the addition of X-bracings and walls. Concerning the rehabilitation index proposed, the solution with the best index has been the addition of steel diagonal braces in a small percentage of columns due to its minimum economical cost and architectural impact. Despite being the most profitable solution, it has not been the most efficient, this being the addition of X-bracings.

The influence of the constructive features of existing RC buildings in their ductility and seismic performance has been analysed (Requena-Garcia-Cruz et al., 2020b). To do so, and due to the lack of guidance in seismic codes on the **analysis of the ductility of existing buildings**, a new method has been proposed. The sensitivity analysis performed on the variability of the material properties suggests that the behaviour of the models studied barely depends on them. A maximum variation of 3% of the seismic capacity of models has been observed for variations of up to +/− 10% in the material properties.

Regarding the constructive features, it has been observed that the **deep-beam models have outperformed the rest of the models**. They have also presented the highest values of ductility. Deep-beam models have reached up to 60% of ductility improvement compared to the existing building. However, some of these solutions have been the most expensive due to the increase of the dimensions of beams and reinforcement ratios to comply with the code provisions. Still, the cost increase has been moderate (16% and 24%, respectively), especially considering the enhancements achieved.

Models with wide beams (like the existing buildings) and increased reinforcement ratios have merely shown a slight enhancement of the resistant capacity. These enhancements have ranged from 5% to 10% in the case of the μ-factor and 8% to 18% for the q-factor. The construction cost ratios have been below 7%.

Modifying the transversal reinforcement by adding four legged stirrups has caused a considerable enhancement of the μ-factor and the q-factor by up to 23% and 21%, respectively. This is due to the reduction of the distance between the consecutive longitudinal rebar engaged by stirrups. This solution has presented almost no increase in costs compared to the existing building.

Based on these results, the deep-beam model considering the same dimensions as the as-built model has been selected as the best alternative to the existing building. This is due to the combination of the great improvement of the μ-factor and q-factor, the simplicity and feasibility of the solution and its relatively low increase in costs. The damage level expected for the existing building has been significant while the model with deep-beams has caused a reduction of the damage level of up to 28% compared to the existing building. In this latter model, wide beams have been changed to deep beams, so this reduction can be further improved by also increasing the reinforcement ratio.

T**he enhancement of the ductile response behaviour of RC framed buildings considering different non-invasive retrofitting techniques** has been assessed (Requena-Garcia-Cruz et al., 2021a). According to the results, some columns will collapse in the X direction (fewer columns) before the seismic demand requirement. These solutions are those when only 25% of the structural elements have been retrofitted. In the Y direction (high number of columns), the improvement is outstanding, obtaining target displacements near to the DL limit state.

Regarding the specific results, FRP–wrapping has been one of the solutions with better benefit ratios, performing better than its most similar solution, i.e., adding steel-jackets. These improvements have been by up to 46%. In the case of steel jackets, the improvement ratio has not been higher than 26%, resulting in the worst benefit percentage. Despite this ratio of the FRP-wrapping, when considering the costs, this retrofitting solution has resulted to be the most expensive. Therefore, **FRP-wrapping of elements performs well if, due to their high costs, only up to 50% of them are retrofitted**.

The addition of steel plates (SP) and beams (SB) under the RC beams has resulted in the lowest reduction of the damage (in some cases just 5%). **Adding single braces (VB)** in columns has led to higher percentages of ductility, obtaining higher damage reduction (up to 98%) and benefit improvement (up to 37%) percentages. However, these solutions are expensive since a considerable amount of working hours and material are needed to properly connect the retrofitting element with the RC structure Nevertheless, the **non-invasive technique has obtained the highest benefit improvement** as shown in both of the publications.

As previously demonstrated, **the addition of X-bracings in the most efficient position has resulted in the highest benefit improvement**. The ductility has been enhanced by up to 53% and the damage reduced by up to 300%. Moreover, this solution has been the cheapest, leading to the highest benefit-cost ratio.

The **effects of the soil-structure interaction (SSI) in this type of buildings have been assessed by modelling the soil as a continuum** (Requena-Garcia-Cruz et al., 2021b). It has been obtained that the settlement of the structure is higher when the height increases but this does not increase linearly. It can be observed that **the higher the structures, the greater the soil effects**. In the case of the low-rise model, the SSI just decreases the initial stiffness of the systems. However, when including the SSI effects, it does not comply with the seismic safety requirements. Mid-rise buildings are more affected by the SSI than low-rise buildings due to the considerable modification of the initial stiffness. The maximum capacity has been reduced by around 10%. High-rise models are the most affected by the SSI, the maximum capacity being reduced by up to 30%. It has been obtained that the fragility curves for the models with SSI are worse than the F-model's curves. Therefore, **the probability of reaching higher damage increases in models that bear the soil influence in mind**. This probability also increases with the height. This results in high-rise models being the most affected. Moreover, the fragility curves of high-rise buildings are worse than the rest due to the statistical parameters' values.

The SSI effects in the seismic vulnerability analysis of a pre-code RC mid/high-rise building have been analysed. Different SSI modelling approaches have been assessed. The results have shown that **the modal behaviour and the deformed shape of the building is the same with and without considering the SSI**. Nonetheless, it has been demonstrated that **increasing the soil flexibility leads to higher periods** (ranging from 7% to 42%) **and higher seismic damage**. The probability of exceedance the Significant Damage Limit State can be up to 20% if SSI effects are considered. For this case study, **the maximum capacity of the models can be reduced** by up to 15% if the SSI effects are considered. It was also demonstrated that the existing RC case study building is affected by the *p-Δ* effects, since the maximum capacity strength of the models can be reduced by up to 42%.

Conclusions

According to the results obtained, the main conclusions of the thesis have been presented in this section. Additionally, the future research work is described.

C. 1. Final remarks

This thesis addresses one important challenge established by current European and national policies: the mitigation of geological and geotechnical risks associated with natural disasters that affects the security of citizens.

To do so, the thesis pursues the following main objectives: i) to **assess the seismic vulnerability** of RC buildings focusing on the primary school buildings located in the southwestern Iberian Peninsula; and, ii) to develop **specific seismic retrofitting** methods for the schools to improve their seismic behaviour and to reduce their expected seismic damage.

This work has focused on the study of RC primary school buildings in southwestern Spain due to their vulnerability: i) a major part of them was constructed with RC structures prior to restrictive seismic codes (i.e., aseismic design, low-quality structural materials, reinforcement ratios, among others); ii) the considerable seismic hazard of the area, characterised by far away earthquakes of a long-return period and large-very large magnitude; iii) the low adult/child ratio and the post-traumatic stress and depressive disorders that children can suffer from after surviving an earthquake.

The **innovative contributions** of this thesis are:

- The analysis of the **considerable differences that can be found in the seismic codes of Spain and Portugal**, particularly in the definition of the response spectra. It has been concluded that the seismic demand for locations at the border can differ by up to 60%. This is due to the seismic hazard approaches followed in each code (i.e., average event distribution in the Spanish code and maximum values distribution in the Portuguese code). Moreover, the impact factor that amplifies the ground acceleration value differs. Despite the fact that the EC8 was proposed as a homogenisation tool, the seismic action is obtained from the National Annexes, whose values considerably differ from each other. Therefore, although buildings in the perimeter are close and share a similar geology, different values of ground acceleration are obtained when considering the different codes.

- The assessment of the characterisation and the seismic vulnerability of the primary schools' buildings located in Huelva, which has not been performed to date. According to the results, **the buildings** selected in the analyses do not comply with the seismic safety requirements. Therefore, they **are seismically vulnerable**.

- **The retrofitting solutions assessed can improve the seismic performance of RC buildings**. However, this improvement can be more or less significant depending on the position, the amount and the properties of the retrofitting elements. It has been found that adding retrofitting elements in the worst behaving direction is a very efficient action. Therefore, specific analyses should be carried out to determine the worst behaving direction of the building to find out the most optimal retrofitting configuration.

- **A new index-based method for assessing different seismic retrofitting techniques** has been presented and applied to a representative RC school in Huelva. This method can evaluate the retrofitting solutions to select the most suitable according to the **efficiency, the construction cost and the architectural impact**. It can be reproduced to assess and compare any building's typology and any retrofitting technique.

- A **specific analysis of the seismic codes has been performed in terms of ductility considerations**. It has been concluded that the NCSE02 and the EC8 share similar considerations concerning the ductile capacity of new-designed buildings. However, each code establishes different procedures and factors to determine this capacity, i.e., the μ-factor in the NCSE02 and the q-factor in the EC8, respectively.

- **A methodology to assess the ductility of existing Spanish buildings** due to the lack of guidance in the NCSE02 and the EC8 revealed by this research work. Although EC8-3 points out the importance of analysing their seismic behaviour, no ductility considerations are described to assess existing buildings.
- The influence of several constructive features of existing RC buildings in their ductility and seismic performance has been assessed. It has been obtained that **the beams dimensions are the main parameter affecting the ductility,** followed by the increase of the transversal ratio.
- Some solutions present higher ductility improvement than others. However, it has been proved that **enhancing the ductility leads to higher damage reduction, resulting in configurations that are more beneficial**. In fact, ductility affects the shear resistant capacity and, therefore, the seismic performance and the expected damage of RC buildings. Hence, the ductility assessment of these buildings must be performed thoroughly in order to propose appropriate seismic retrofitting solutions.
- **Irregularities in plan and in height due to infills and structural elements distribution can worsen the seismic performance of buildings**, owing to the generation of additional torsional effects.
- The enhancement of the ductile response behaviour of RC framed buildings considering different **non-invasive retrofitting techniques** has been assessed. In order to analyse the suitability and efficiency of each solution, a benefit/cost ratio has been calculated taking into account the ductility improvement and the damage reduction with regards to the retrofitting costs.
- **Soil-structure interaction (SSI) effects must be considered in the seismic analyses of buildings**, especially for mid- and high-rise buildings. In the light of the fragility assessment results, the probability of reaching higher seismic damage increases when considering the SSI can be concluded. Moreover, this probability increases as the height increases.
- The behaviour of the models is not modified by the **SSI**, however, it **worsens the performance, leading to higher seismic damage**.

According to the results obtained during this research work, **specific conclusions** have been obtained:

- The buildings behave better in the direction with a higher number of vertical structural elements (columns). Also, the higher the number of infills in a certain direction, the greater the capacity the building has in this direction if infills are regularly distributed. Nevertheless, it has been obtained that the capacity of the models is lower if the infills present a higher number of openings or if they are irregularly distributed due to the generation of soft-storey mechanisms or short-columns.
- The nonlinear static analyses have revealed that just adding **retrofitting elements in the most vulnerable direction** of the building can lead to higher values of efficiency than including fewer elements but in both directions.
- The **number and position of the retrofitting elements** have been determinant in obtaining higher efficiency ratios.
- Adding the retrofitting elements in every column or bay of the building has been proved not to be needed. **Selecting the most effective positions** for the retrofitting element implementation should be carefully carried out to obtain a profitable improvement.

- The expected seismic damage of the case study buildings will be severe damage according to the seismic safety assessment. **The retrofitting solutions have been able to reduce** it up to **damage** limitation to life operancy damage.
- The **best performance**, regarding the ductility, has been obtained with the **models designed with deep beam**s. It has also been demonstrated that these are as well the best models when considering the costs. Conversely, models with wide beams, and where only the reinforcement ratios have been varied, have merely shown a slight enhancement of the resistant capacity. The addition of four legged stirrups has brought about a considerable enhancement of these factors. This is due to the reduction of the distance between consecutive longitudinal rebars engaged by stirrups.
- The expected damage has been severe for the existing building and moderate for the deep beam model, respectively. Therefore, it can be concluded that, for a minimum increase in cost, buildings using deep beams achieve an important enhancement in their seismic behaviour.
- The variability of the structural materials values has been analysed by means of a sensitive analysis. The results in terms of ductility assessment have not considerably differed from those considering the real material values.
- The **most profitable solutions have been the addition of steel bracings (X and V).** Adding single steel braces has also been proved to be an acceptable technique to be implemented in the retrofitting process of buildings.
- Adding FRP-wrapping in the structural elements has performed well if no more than 50% of them are retrofitted due to its high construction costs. Steel jackets present the lowest construction cost and benefit improvement.
- The steel plates and the beams under the RC beams have produced a negligible reduction of the seismic damage. No significant differences have been found when adding both retrofitting elements in 25%, 50% and all RC beams, concluding that the beams do not considerably affect the seismic performance of buildings.
- **No significant differences have been found when retrofitting just 1/3 or the entire length of the structural elements**. This is due to the fact that the beam-column joints play a key role in the resistant capacity of RC buildings. In fact, solutions that aimed to improve the stiffness of the joints have led to higher improvement percentages.
- **Adding single braces in columns has been the non-invasive technique that has obtained the highest benefit improvement**, i.e., the highest ductility improvement and damage reduction. The addition of X-bracings, as expected, has resulted in the highest benefit improvement.
- The soil does not significantly influence the behaviour of low-rise buildings. However, in the case of mid- and high-rise buildings, the maximum capacity can be reduced by up to 10% and 30%, respectively. Moreover, according to the local damage assessment, **structural elements might collapse due to considering the soil, even for low-rise buildings**.
- **Modelling the footings** is one of the most important aspects to obtain reliable results in the Beam on Nonlinear Winkler method (BNWM). These affect the initial stiffness and the maximum strength of the capacity curves. In this method, the dynamic characteristics cannot be directly compared due to its inability to consider the masses of the footing and the soil. Modelling footings with shells has obtained more similar results to the solid configurations curves.

- **Horizontal springs** are the most significant in the buildings' seismic performance. They tend to capture the soil horizontal passive pressure and the slippage of the foundation on the soil, which is important in horizontal analyses.
- Coarse meshes and linear soil models lead to 3D rigid soil behaviours resulting in unreliable results. The **3D continuum modelling of soil** can better capture the soil behaviour since they perform rigorous modelling.
- The **parameters affecting the performance** of the BNWM models are the Mohr-Coulomb strength parameters (ϕ, c) and, to a lower extent, the soil weight (γ), the depth and the area of the footings. In the case of the solid models, these are the shear (G) and bulk (B) moduli, which are related to the shear waves velocity (V_s) and γ.

C. 2. Future research work

The research work developed in this thesis has established a scientific base on how to analyse and improve the seismic vulnerability of buildings, focusing on the RC structures. This work has provided the researchers with the tools and procedures to continue studying earthquake engineering and the analysis of structures. This can be carried out during a postdoctoral phase, establishing a new research topic at the University of Seville. This topic has emerged from the combination of transversal topics of the research group TEP-107 in which this thesis is framed.

As shown in this thesis, **irregularities in plan and in height** due to infills and structural elements distribution can worsen the seismic performance of buildings, owing to the generation of additional torsional effects. Therefore, further research and case study testing are surely needed to thoroughly determine their effects.

The seismic retrofitting can improve the seismic performance of buildings and therefore, decrease their seismic vulnerability. Hence, **thoroughly assessing the seismic retrofitting strategies** is needed to properly determine their effects. Furthermore, **the development of retrofitting techniques and effective design optimisation space restriction** techniques that bear in mind the complete behaviour of the building should be performed. This can be done through **sensitivity analyses** by varying the percentage of the retrofitting material, the position or the configuration

The method proposed to assess the retrofitting techniques could be improved by including a **multi-criteria evaluation**. This can allow weighting the importance of each criterion by defining **decision matrices**. This work has already been started to be developed.

A research topic that is directly related to the work developed up to date is the implementation of the **SSI effects**. These effects are usually omitted in the seismic vulnerability analyses of buildings. However, as briefly shown in this thesis as a first attempt, they have been proved to affect the performance of the buildings under study. Therefore, it would be necessary to include the SSI effects **in the future seismic vulnerability analyses** in order not to overestimate the capacity of the buildings.

The first attempt carried out in this thesis has also revealed the **lack of studies** and guidance, even in codes, **on the quantification of the SSI effects**. However, the European seismic codes establish that they should be included in the analyses of certain structures: with considerable second order (p-Δ) effects or mid/high-rise buildings. Therefore, most of the RC buildings in Spain could be affected by SSI.

The SSI effects can be taken into account by modifying the flexibility at the base of the buildings. There are **several approaches to model this soil flexibility.** These can be implemented and analysed in future works. Furthermore, research on the **uncertainty of the soil properties or the presence of different soft layers**, which may worsen the seismic capacity of the buildings, could be carried out. In addition, **ground-improvement techniques** effects can be analysed and **compared to structural-improvement techniques**. They can even be combined to define **hybrid configurations** which can **minimise the architectural impact**. Moreover, it is possible to also compare the performance of the buildings designed with **deep and superficial foundations**.

As previously mentioned, a new publication on the influence of the soil effects on the performance of a building in Lisbon considering two modelling approaches of the soil flexibility has already been submitted to an indexed journal.

In this work, the analyses carried out have been static. **Dynamic analyses** are commonly used in this research field to obtain the performance of buildings. Nevertheless, they are more time consuming (modelling and calculations) than the static ones. However, they provide more realistic results, especially in the case of mid/high-rise buildings or those which have irregular configurations. Dynamic analyses can be implemented to define the **specific fragility functions of the buildings** by means of sensitivity analyses. In fact, in this research the statistical parameters have been considered from other works for the fragility assessment. Yet, further research should be assessed to properly determine these values according to the models' characteristics and uncertainties or even the type of soil. These functions may be useful to compare the seismic performance of different buildings' typologies or configurations. Moreover, these functions can be compared with the results obtained from the static analyses. The fragility functions can even be useful to compare the behaviour of the building considering the retrofitting techniques or the SSI effects.

The dynamic analyses and fragility functions are used in the **loss assessment of buildings**. This type of analyses can be useful to communicate the damage and losses of buildings due to seismic events to authorities and emergency corps. The loss assessment is useful to determine the losses derived from the retrofitted and un-retrofitted buildings or due to the inclusion of the SSI effects.

The lack of a **modelling guide** has been identified to include the SSI effects while performing **dynamic analyses**. There are several aspects that need to be further analysed such as the absorbing boundaries or the definition of the dynamic properties of the soil.

This thesis has focused on school buildings, particularly on RC structures. However, it could be extended to other structural systems or **other building typologies,** such as those that are residential. In fact, these buildings are usually **higher** than schools, which make them **more seismically vulnerable** and more affected by the SSI effects: the higher the building, the greater the effects.

The work developed can also be used in the analysis of the **seismic risk of buildings on an urban scale,** combining macroseismic and mechanical approaches.

Conclusiones

Según los resultados obtenidos, las conclusiones principales de esta tesis se presentan en esta sección. Además, se muestran las futuras líneas de investigación.

C.1. Conclusiones finales

Esta tesis pretende dar respuesta a una problemática planteada por las actuales políticas europeas y nacionales: la reducción de los riesgos geológicos y geotécnicos asociados a los desastres naturales que afectan a la seguridad de la población.

Para ello, este trabajo se centra en los siguientes objetivos principales: i) **analizar la vulnerabilidad símica** de los edificios de hormigón armado, particularmente en los colegios de educación primaria del suroeste de la Península Ibérica; y, ii) desarrollar **métodos específicos para la rehabilitación sísmica** de los colegios, para mejorar su comportamiento sísmico y, por tanto, reducir el daño sísmico esperado.

Esta tesis se ha centrado como caso de estudio en los colegios de educación primara de hormigón armado debido a su vulnerabilidad: i) la mayor parte de éstos edificios fueron construidos con estructuras de hormigón armado previamente a la entrada en vigor de normativas sísmicas restrictivas (presentan diseño asísmico, materiales de baja calidad estructural, bajos ratios de armadura de acero, entre otros aspectos); ii) la considerable peligrosidad sísmica de la zona, caracterizada por terremotos lejanos de largos periodos de retorno y alta o muy alta magnitud; iii) la baja proporción de adultos/niños y el estrés post traumático y los trastornos depresivos que los niños pueden sufrir tras sobrevivir a un terremoto.

Las principales **contribuciones innovadoras** de esta tesis son:

- El análisis de **las considerables diferencias que pueden encontrarse entre las normativas sísmicas de España y Portugal**, particularmente en la definición del espectro de respuesta. Se ha obtenido que la demanda sísmica para las localizaciones en la frontera España-Portugal puede diferir hasta un 60%. Esto se debe a los diferentes métodos empleados en cada código para determinar la peligrosidad sísmica: el español considera una distribución de eventos de valores medios mientras que en el portugués se consideran los valores máximos. Asimismo, el factor que amplifica los valores de aceleración del suelo difiere entre los códigos. Pese a que el EC8 se propuso como una herramienta para la homogenización de normativas sísmicas, la acción sísmica se obtiene de los Anexo Nacionales, cuyos valores varían significativamente. Por tanto, aunque los edificios situados en la frontera España-Portugal estén próximos y presenten similares perfiles geotécnicos, los valores de aceleración del suelo son distintos según cada código.
- La evaluación de la caracterización y la vulnerabilidad sísmica de los colegios de educación primaria localizados en Huelva, no realizada hasta la fecha. Según los resultados obtenidos, **los edificios** seleccionados para los análisis no cumplen con los requerimientos de seguridad sísmica. Por tanto, son **sísmicamente vulnerables**.
- **Las soluciones de refuerzo evaluadas pueden mejorar el comportamiento sísmico de los edificios de hormigón armado.** Sin embargo, esta mejora puede ser más o menos significativa dependiendo de la posición, la cantidad y las propiedades de elementos de refuerzo. Se ha concluido que la implementación de elementos de refuerzo en la dirección de comportamiento más desfavorable es muy eficiente. Por tanto, se deberían llevar a cabo análisis específicos para determinar la dirección en la que se da el peor comportamiento del edificio, para establecer la configuración óptima.
- **Un nuevo método basado en índices para la evaluación de las diferentes técnicas de refuerzo sísmico** se ha presentado y se ha aplicado a un edificio de hormigón armado representativo ubicado en Huelva. Este método puede evaluar las soluciones de mejoras para determinar la más óptima según **la eficiencia, los costes de**

construcción y el impacto arquitectónico. Éste se puede reproducir para evaluar y comparar cualquier tipología de edificio, así como cualquier medida de mejora.

- **Un análisis específico de los criterios de ductilidad establecidos en las normativas sísmicas.** Se ha concluido que la NCSE02 y el EC8 comparten consideraciones similares en lo relativo a la determinación de la capacidad dúctil de los edificios de nuevo diseño. Sin embargo, cada norma establece diferentes procedimientos y factores numéricos para determinar esta capacidad, como son el factor de ductilidad *“μ”* de la NCSE02 y el factor de comportamiento *“q”* del EC8, respectivamente.
- **Una metodología para analizar la ductilidad de los edificios existentes ubicados en España** se ha presentado debido a la falta de información de la NCSE02 y el EC8. Pese a que el EC8-3 destaca la importancia de analizar el comportamiento sísmico de los edificios, no se refiere a cómo realizar el análisis de la ductilidad de edificios existentes.
- La influencia de varias características constructivas de los edificios de hormigón armado existentes en su comportamiento dúctil y sísmico se ha evaluado. Se ha obtenido que **las dimensiones de las vigas son el principal parámetro que afecta a su ductilidad**, seguido del incremento de la ratio de armadura transversal.
- Algunas soluciones presentan mayores porcentajes de mejora de la ductilidad que otras. Sin embargo, se ha probado que la **mejora de la ductilidad conlleva a una mayor reducción del daño, resultando en configuraciones más beneficiosas.** De hecho, la ductilidad afecta a la capacidad del edificio frente a esfuerzos cortantes, y, por tanto, al comportamiento sísmico y el daño esperado de los edificios de hormigón armado. Por tanto, el análisis de la ductilidad de los edificios debe ser llevada a cabo minuciosamente de cara a proponer soluciones de mejora sísmica adecuadas.
- **Las irregularidades en planta y altura debido a los cerramientos y los elementos estructurales pueden empeorar el comportamiento sísmico de los edificios,** ya que dan lugar a la generación de efectos adicionales de torsión.
- La mejora de la respuesta dúctil de los edificios de hormigón armado se ha evaluado mediante diferentes **técnicas de refuerzo no invasivas.** Con objeto de analizar la aplicabilidad y eficiencia de cada solución, se evalúa el ratio beneficio/coste, teniendo en cuenta la mejora dúctil y la reducción de los daños con respecto al coste económico.
- **Los efectos de la interacción suelo-estructura (ISE) debe ser considerados en los análisis sísmicos de edificios,** especialmente para aquéllos de altura media y alta. Según los análisis de fragilidad, se puede concluir que la probabilidad de mayores daños sísmicos aumenta cuando se consideran los efectos del suelo. Asimismo, la probabilidad de daño aumenta con la altura del edificio.
- El comportamiento de los modelos no se modifica por la ISE. Sin embargo, la ISE empeora el rendimiento de las estructuras, aumentando el daño sísmico esperado.

Asimismo, como resultado del trabajo de investigación, se han obtenido las siguientes **conclusiones específicas**:

- Los edificios se comportan mejor en la dirección con mayor número de elementos estructurales verticales (pilares). Cuanto mayor sea el número de cerramientos en una determinada dirección, mayor capacidad tendrá el edificio en dicha dirección, siempre y cuando los cerramientos se distribuyan regularmente. No obstante, se ha obtenido que la capacidad de los modelos ha sido menor si los cerramientos presentan un mayor número de huecos o si están distribuidos de forma irregular, debido a la generación de mecanismos de planta débil o pilares cortos.

- Los análisis estáticos no lineales han revelado que al agregar únicamente **elementos de refuerzo en la dirección más vulnerable** del edificio puede conducir a valores más altos de eficiencia que incluir menos elementos, pero en ambas direcciones.
- **El número y la posición de los elementos de refuerzo** han sido determinantes para obtener mayores ratios de eficiencia.
- La inclusión de los elementos de refuerzo en cada pilar o vano del edificio se ha demostrado que no es necesaria. **La selección de las posiciones más efectivas** para la implementación del elemento de refuerzo debe llevarse a cabo rigurosamente para obtener una mejora más rentable.
- El daño sísmico esperado de los edificios caso de estudio es significativo según los análisis de seguridad sísmica. Sin embargo, **las soluciones de refuerzo han supuesto la reducción del daño hasta ser mínimo**.
- El **mejor comportamiento**, en cuanto a ductilidad, se ha obtenido con los **modelos diseñados con vigas de canto.** También se ha demostrado que éstos también son los mejores modelos a la hora de considerar los costes. Por el contrario, los modelos con vigas planas, y en los que solo se han variado los ratios de armadura, solo han mostrado una ligera mejora de la capacidad resistente. La adición de estribos de doble cercado ha mejorado considerablemente estos factores. Esto se debe a la reducción de la distancia entre las barras de refuerzo longitudinales consecutivas y enganchadas por los estribos.
- El daño esperado ha sido severo para el edificio existente (vigas planas) y moderado para el modelo de vigas de canto, respectivamente. Por tanto, se puede concluir que, por un mínimo incremento de coste, las edificaciones que utilizan vigas de canto consiguen una importante mejora en su comportamiento sísmico.
- La variabilidad de los valores de los materiales estructurales se ha analizado mediante análisis de sensibilidad. Los resultados de la ductilidad no han variado considerablemente de los que se consideran valores reales.
- Las **soluciones más rentables se han conseguido con la incorporación de cruces de acero** (X y V). También se ha demostrado que agregar diagonales de acero individuales en los nudos viga-pilar es una técnica aceptable para ser implementada en el proceso de rehabilitación sísmica de edificios.
- La implementación de FRP en los elementos verticales estructurales ha funcionado bien si no se refuerzan más del 50% debido a sus altos costes de construcción. Las camisas de acero presentan el coste de construcción y las mejoras más bajos.
- Las placas y las vigas de acero bajo de las vigas de hormigón armado han producido una reducción insignificante del daño sísmico. No se han encontrado diferencias significativas al agregar elementos de refuerzo en 25%, 50% de los pilares o en todos los elementos estructurales. Por tanto, se concluye que las vigas no afectan considerablemente el comportamiento sísmico de las edificaciones.
- **No se han encontrado diferencias significativas al reforzar solo 1/3 o la longitud total de los elementos estructurales.** Esto se debe a que las nudos viga-pilar juegan un papel clave en la capacidad resistente de los edificios de hormigón armado. De hecho, las soluciones que tenían como objetivo mejorar la rigidez de estos encuentros han dado lugar a mayores porcentajes de mejora.

- La **adición de diagonales de acero en los pilares ha sido la técnica no invasiva que ha obtenido el mayor beneficio de mejora**, es decir, la mayor mejora de ductilidad y mayor reducción de daños. La adición de cruces de acero, como se esperaba, ha dado como resultado la mayor mejora en los beneficios.
- El suelo no influye significativamente en el comportamiento de los edificios de poca altura. Sin embargo, en el caso de edificios de mediana y gran altura, la capacidad máxima se puede reducir hasta en un 10% y un 30%, respectivamente. Además, de acuerdo con la evaluación de daños local, los **elementos estructurales podrían colapsar debido a la consideración del suelo, incluso para edificios de poca altura**.
- El **modelado de la cimentación** es uno de los aspectos más importantes para obtener resultados fiables al emplear el método de Winkler. La cimentación afecta a la rigidez inicial del sistema y a la máxima capacidad de los modelos. En este método, las características dinámicas no se pueden comprobar directamente ya que no se consideran las masas de la cimentación ni las del suelo. Los modelos con cimentaciones modeladas con láminas han obtenido resultados similares a los modelos con suelo sólido.
- Los muelles horizontales son los más importantes para determinar el comportamiento sísmico de los edificios. Estos capturan el empuje horizontal del terreno y el desplazamiento entre la cimentación y el suelo. Estos aspectos son importantes en los análisis horizontales.
- Mallados gruesos o el modelado lineal del suelo dan lugar a comportamientos rígidos del suelo que conllevan a resultados irreales. El modelado continuo del suelo en 3D puede capturar mejor el comportamiento del suelo dado que precisa de modelados rigurosos.
- Los parámetros que más afectan al comportamiento de los modelos con el método de Winkler son los parámetros resistentes de Mohr-Coulomb (ϕ, c). En menor medida, el peso específico del terreno (γ), y la profundidad y área de la cimentación. En el caso de los modelos continuos del suelo, los parámetros que más afectan son los módulos de cortante (G) y volumétrico (B), que están relacionados al fin y al cabo con la velocidad de ondas de corte (V_s) y el peso específico del suelo.

C.2. Futuras líneas de investigación

El trabajo de investigación desarrollado en esta tesis ha establecido la base científica sobre cómo analizar y mejorar la vulnerabilidad sísmica de los edificios, particularizando en las estructuras hormigón armado. Este trabajo ha proporcionado a los investigadores las herramientas y procedimientos necesarios para continuar sus estudios sobre ingeniería sísmica y el análisis de estructuras. Este trabajo puede ser continuado durante una futura fase postdoctoral y estableciendo una nueva línea de investigación en la Universidad de Sevilla. Esta línea ha surgido de la combinación de temas transversales del grupo de investigación TEP-107 en el que se enmarca esta tesis.

Como se muestra en esta tesis, las **irregularidades en planta y en altura**, debidas a la distribución de los cerramientos y a la configuración de los elementos estructurales, pueden empeorar el comportamiento sísmico de las edificaciones, ya que dan lugar a la generación de efectos torsionales adicionales. Por lo tanto, es necesario investigar más y considerar más casos de estudio diferentes para determinar sus efectos.

La rehabilitación sísmica permite mejorar el comportamiento de las estructuras y por tanto disminuir su vulnerabilidad sísmica. Por tanto, se hace imprescindible **estudiar más exhaustivamente las estrategias de refuerzo sísmico** para así determinar mejor sus efectos. Además, es necesario el desarrollo de técnicas de refuerzo que consideren la **restricción del espacio para optimizar el diseño**, siempre y cuando tengan en cuenta el comportamiento completo del edificio. Estos trabajos se pueden realizar **mediante análisis de sensibilidad** variando el porcentaje del material de refuerzo, la posición o la configuración.

El método propuesto para evaluar las técnicas de refuerzo se podría mejorar mediante la inclusión de una **evaluación de criterios múltiples**. Esto puede permitir ponderar la importancia de cada criterio mediante la definición de **matrices de decisión**. Este trabajo ya ha comenzado a desarrollarse en la actualidad por parte de la doctoranda.

Un tema de investigación que está directamente relacionado con el trabajo desarrollado hasta la fecha es la implementación de los **efectos de la interacción suelo-estructura**. Estos efectos generalmente se omiten en los análisis de vulnerabilidad sísmica de edificios. Sin embargo, y de acuerdo a lo concluido en esta tesis superficialmente, afectan al comportamiento sísmico de los edificios caso de estudio. Por tanto, sería necesario incluir los efectos de la interacción suelo-estructura **en futuros análisis de vulnerabilidad sísmica**, de manera que no se sobreestime la capacidad de las edificaciones.

Tras el primer acercamiento desarrollado en este trabajo sobre la interacción suelo-estructura, se ha identificado una **falta de estudios** y orientaciones, incluso en los códigos sísmicos, sobre la **cuantificación de este tipo de efectos**. Sin embargo, los códigos sísmicos europeos establecen que deben incluirse en los análisis de determinadas estructuras: con efectos considerables de segundo orden (p-Δ) o edificaciones de media a gran altura. Por tanto, la mayoría de los edificios de hormigón armado (y otros sistemas estructurales) en España podrían verse afectados por los efectos del suelo.

Los efectos del suelo se pueden tener en cuenta modificando la flexibilidad en la base de los edificios. Existen **varios métodos para modelar esta flexibilidad del suelo** que se pueden implementar y analizar en trabajos futuros. Además, se podrían realizar investigaciones sobre la **incertidumbre de las propiedades del suelo o la presencia de diferentes estratos blandos**, que pueden empeorar la capacidad sísmica de las edificaciones. Los efectos de las **técnicas de mejora del suelo** se pueden analizar y comparar con las **técnicas de refuerzo estructural**. Incluso, se pueden combinar para definir **configuraciones híbridas**, que pueden **minimizar el impacto arquitectónico**. También es posible comparar el comportamiento de los edificios diseñados con **cimentaciones profundas y superficiales**.

Como se mencionó anteriormente, ya se ha enviado una nueva publicación a una revista indexada sobre la influencia de los efectos del suelo en el comportamiento de un edificio de hormigón armado de Lisboa considerando dos enfoques de modelado de la flexibilidad del suelo.

En este trabajo, los análisis realizados han sido estáticos. Los **análisis dinámicos** se utilizan comúnmente en este campo de investigación para obtener el comportamiento de los edificios. Sin embargo, consumen más tiempo de computación y modelado que los estáticos. Pese a ello, proporcionan resultados más realistas, especialmente en el caso de edificios de altura media-alta o con volumetrías irregulares. En futuros trabajos de investigación, se pueden implementar análisis dinámicos para definir **funciones de fragilidad específicas de los edificios** mediante análisis de sensibilidad. En esta investigación, se han considerado los parámetros estadísticos de otros trabajos para la evaluación de la fragilidad. Sin embargo, se hace necesaria la investigación sobre la determinación adecuada de estos valores según las características e incertidumbres de los modelos o incluso el tipo de suelo. Estas funciones pueden resultar útiles para comparar el comportamiento sísmico de diferentes tipologías o configuraciones de edificios. Además, estas funciones se pueden comparar con los resultados obtenidos de los análisis estáticos. Incluso, las funciones de fragilidad pueden ser útiles para comparar el comportamiento del edificio considerando las técnicas de refuerzo o los efectos de la interacción suelo-estructura.

Los análisis dinámicos y las funciones de fragilidad se utilizan en la **evaluación de pérdidas de edificios**. Este tipo de análisis puede ser útil para comunicar a las autoridades y cuerpos de emergencias los daños y las pérdidas sufridos de los edificios debido a futuros eventos sísmicos. La evaluación de pérdidas es útil para determinar las pérdidas derivadas de los edificios antes y después de los trabajos de investigación o debido a la inclusión de los efectos de la interacción suelo-estructura.

Se ha determinado una **falta de información en cuanto al modelado** de los efectos de la interacción suelo-estructura al realizar **análisis dinámicos**. De hecho, hay varios aspectos y parámetros que necesitan ser analizados y modelados exhaustivamente como los límites absorbentes o la definición de las propiedades dinámicas del suelo.

Esta tesis se ha centrado en los colegios de educación primaria, y particularmente, en las estructuras de hormigón armado. No obstante, podría extenderse a otros edificios de diferentes sistemas estructurales o a **tipologías edificatorias diferentes** como la residencial. De hecho, estos edificios suelen ser más altos que las escuelas, por tanto, pueden ser **más vulnerables sísmicamente. L**os efectos de la interacción suelo-estructura podrían llegar a ser mayores puesto que cuanto más alto es el edificio, mayores son los efectos.

El trabajo desarrollado también puede ser utilizado en el **análisis del riesgo sísmico de edificaciones a escala urbana** combinando enfoques macrosísmicos y mecánicos.

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