ASSESSING THREE REAL RC BUILDINGS USING DIFFERENT ACCELEROMGRAM SELECTION APPROACHES

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ABSTRACT

Within the realms of seismic vulnerability assessment of existing structures, current seismic codes, such as EC8 and the Italian code (NTC), allow the use of nonlinear dynamic analysis. The application of this analysis method requires the seismic action to be represented by a suite of ground motion records, whose selection should be compatible with a reference spectrum. Since the selection and scaling of accelerograms is still an “evolving” topic both for researchers and practitioners, the main goal of this work is to investigate the impact that different selection strategies may or may not have in the seismic assessment of existing structures. For this purpose, three real RC buildings were considered, and nonlinear dynamic analyses were performed in order to evaluate the structural performance at the element level (by carrying out the capacity checks in terms of element chord rotation, as well as shear resistance). Furthermore, a “seismic risk index”, defined as the ratio (in terms of PGA) between the capacity and the demand at the ultimate limit state (i.e. SLV referring to the Italian code), was computed for each performed analysis. A comparison was made of the results obtained with the different accelerogram selection approaches and between each case-study.

Keywords: Nonlinear dynamic analysis; Accelerogram selection; Seismic assessment; RC buildings

1. INTRODUCTION

Nonlinear dynamic analyses (i.e. NDA analyses) are acknowledged as the most accurate tool for understanding the behaviour of buildings when subjected to seismic excitations. As such, the most recent editions of current building codes worldwide require the use of nonlinear dynamic analyses not only in the seismic design of new buildings situated in high seismicity regions but, mainly, in the seismic assessment of existing structures.

One of the key issues in using nonlinear dynamic analyses for seismic assessment is related to the selection and the scaling, when needed, of accelerograms that are compatible with a reference design spectrum associated to a specific site and then consistent with the specific seismic hazard of the site itself. Typically, an accelerogram is deemed to be compatible with a given design spectrum if its 5%-damped response spectrum is “close” to the design spectrum within a specified period range of interest. Each record to be selected is required to be consistent with a predetermined scenario, typically consisting in magnitude, source-to-site distance and site classification. Nowadays, a good number of software tools are available to select and scale accelerograms, depending on the parameters fixed in such a pre-set scenario.

Another critical issue is related to the appropriate number of accelerograms to be used to perform dynamic analyses in order to obtain a reliable nonlinear response of the building. The term "appropriate" refers to the discrepancy between the true response and the one predicted from the selected suite of records (i.e. accuracy) and to the intraset variability of responses given a specific scenario (i.e. efficiency). Therefore, the procedure to select and scale accelerograms should lead to the definition of

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a suite of ground motions that induces almost the same inelastic response on a building, in other words the mean response that would be found if the structure were subjected to a very large suite of seismic inputs consistent with the design scenario.

Most of the research endeavours currently available are related to the selection of ground motion records, and a great number of different simplified techniques to select and scale accelerograms have been consequently developed during the last decades (eg. Haselton et al., 2017). However, only few comparative studies have been carried out to compare the effects of such different approaches in the code-based evaluation of the nonlinear response of buildings. Likewise, only relatively limited guidance is given to engineers (in particular, practitioners) on which methods may be the more appropriate for their specific purposes.

Hence, our purpose is to investigate how different accelerogram selection approaches may influence the code-base assessment of the seismic response of existing reinforced concrete buildings, with the hope that this may then serve as complementary guidance, especially for practitioners, on how to select accelerograms to perform nonlinear dynamic analyses.

2. OVERVIEW OF THE THREE EXISTING RC BUILDINGS

Italy is characterized by a high seismic hazard and, likewise, by a very vulnerable building heritage. For these reasons, seismic assessment of existing buildings is one of the most relevant activities for both researchers and practitioners.

The majority of buildings in Italy was built before the 1970s, when new editions of design/assessment featuring explicit seismic requirements (Legge n.64/1974) firstly appeared. However, even earlier structures built after the 1970s are mostly inadequate according to the most recent codes, since only in 2003, with the introduction of a new seismic design/assessment prescriptions (OPCM 3274, 2003), was the full national territory classified as seismic and more stringent design/assessment requirements introduced not only for new constructions but also for existing buildings. These became compulsory with in 2008, with the introduction of the current Italian building code (NTC 2008). Therefore, and in short, the Italian building stock can by and large be deemed as seismically vulnerable.

For the purpose of this work, three existing RC structures, built in different years, were selected from three Italian regions. Each building’s site is characterized by a different seismic hazard and consequently chosen to represent a range from low to high seismicity. Therefore, three-dimensional multi-storey buildings were modelled with the fibre-based analysis software SeismoStruct (Seismosoft, 2016), a Finite Element package capable of predicting the large displacement behaviour of space frames under static or dynamic loading, taking into account both geometric nonlinearities and material inelasticity. The same software was used to perform nonlinear dynamic analyses for each building using the suites of accelerograms that were selected respectively for the low, medium, and high seismicity. Finally, it was possible not only to investigate the response of a single building at an average level of seismicity but also to compare the responses of the three buildings at the same level of seismicity.

2.1 Geometries of the case-studies

2.1.1 Case-study 1

A commercial/residential building, built in 2008 in a municipality of Lombardia (Italy), was selected as the first case-study. According to the Italian seismic hazard map, the site is characterised by a reference peak ground acceleration in the range between 0.075g and 0.1g. Therefore, it was chosen to represent a low-seismicity site.

The structure, approximately 14 m high, counts four above-ground floors with variable plans and interstorey heights, and is composed of seven-bay frames in the X direction, two and four-bay frames in the Y direction, respectively at the ground floor and at the higher floors. Two lift shafts are symmetrically located in the structure. The building was initially modelled by Galdi (2016). The 3D Finite Element model of case-study 1 is shown in Figure 1.
2.1.2 Case-study 2

The second case-study was constructed in the 1970s in the Emilia-Romagna region (Italy) and represents a public building. The site in which it is located is characterised by a reference peak ground acceleration in the range between 0.125g and 0.15g. Therefore, it was selected to represent a medium-seismicity site. The structure, approximately 18 m high, is a five-storey frame with four above-ground levels and an underground floor and it shows neither fully regular plans nor constant interstorey heights. A lift shaft is eccentrically located in plan. The building was initially modelled by Lanza (2016). Figure 2 shows two perspective views of the FE model of case-study 2.

2.1.3 Case-study 3

The third residential building, built in the 1980s, is located in Molise (Italy). The site is characterized by a reference peak ground acceleration in the range between 0.2g and 0.225g. For these reasons, it was selected to represent a high-seismicity site. The building, approximately 14 m high, counts four floors. The structure is symmetric in plan along only one direction and the interstorey heights vary over the floors. The structure is composed of three-bay frames in the X direction and of four-bay frames in the Y direction. A stairwell is eccentrically located in plan. The building was initially modelled by Di Lascio (2016). In Figure 3 is represented the Finite Element model of case-study 3.
3. INPUT GROUND MOTION SELECTION

Very extensive research on this topic has been carried out in the recent years, leading to a significant number of publications, which however cannot be reviewed herein, due to obvious issues of space limitation. Generally speaking, accelerograms that can be used for nonlinear dynamic analysis are of three types: (a) artificial records; (b) simulated accelerograms; and (c) real records.

Inputs of type (a) can be obtained generating a power spectral density function starting from a code-specified response spectrum and then deriving signals compatible to that. The evident advantage of using artificial signals is related to the opportunity to obtain time-series that are fully compatible with the elastic design spectrum. However, the basic problem is that such a kind of accelerograms is usually characterised by several cycles of strong motion, which are not very representative of the real phasing of seismic waves because of their unreasonable high energy content.

Type (b) signals are obtained from seismological source models, so they take into account propagation, path and site effects. These methods range from stochastic simulations of point or finite sources to dynamic models of fault rupture, hence they may be difficult and time-consuming to be carried out, and are thus hardly justified for assessment of standard non-critical structures.

Signals of type (c) are ground motions recorded during real seismic events occurred in the past. Their availability on a great number of online databases of strong motion recordings makes them one of the most popular candidates for the seismic assessment of structures, both for code-based purposes and for probabilistic risk analyses. However, real signals are characterized by non-negligible record-to-record variability in records representing a specific magnitude-distance scenario (the typical pair of selecting parameters), which renders their uncritical use unadvisable. Moreover, in the case of code-based seismic assessment, another critical issue is related to the fact that non-smooth spectra of real recordings may need to be manipulated to match a smooth code-specified spectrum, either by frequency-domain or by time-domain modification methods such as wavelet transform.

3.1 Selecting and scaling accelerograms

According to the Italian building code (§7.3.5 of NTC 2008), at least seven pairs/triplets of accelerograms have to be used to perform nonlinear dynamic analyses and the mean of the most unfavourable effects has to be considered to assess the building’s seismic response. In this work, only horizontal components were considered, since it was felt that the vertical component would not have an impact on the study being carried out.

In this study, six different record selection/scaling/generation approaches, as implemented in six software tools, were used to select the accelerograms. Therefore, six sets of seven pairs of accelerograms were selected, including scaled real and artificial accelerograms. All suites of recordings were checked to be compatible with the design spectrum corresponding to each site. At the end, three groups of six sets of accelerograms were defined, corresponding respectively to low, medium and high seismicity; the target spectra for the three level of seismicity considered are represented in Figure 4.
As previously stated, real and artificial accelerograms were selected by means of six different software tools, for which reason a brief description is herein provided for each one of them.

- **Rexel** (Iervolino et al. 2015) allows the selection of groups of real accelerograms compatible to code-specified response spectra (NTC 2008 and Eurocode 8). Such selection counts four steps: (1) the definition of the target spectrum that the set of accelerograms has to match on average; (2) a preliminary records search, setting ranges of magnitude and source-to-site distance; (3) the assignment of another matching parameter, i.e. a period range; (4) the final selection of the appropriate combination of accelerograms: a set of seven accelerograms for each horizontal direction.

- **Seism-Home** (Rota et al. 2012) is a web-based application that allows the selection of sets of real accelerograms on average compatible to code-specified response spectra (NTC 2008 and Eurocode 8). The webGIS platform returns, for each Italian municipality, seven real accelerograms, considering a 475-years return period and a flat rock site. Scaling factors are applied then to such records to satisfy the spectrum-compatibility.

- **Select&Match** (Barri 2015) allows selection and scaling of real accelerograms that are individually and on average compatible with Eurocode 8-specified spectra. Once a target spectrum is defined, a preliminary search is undertaken into the database depending on a predetermined magnitude range and on the site characteristics. Then, a standard deviation from the target spectrum and a period range are needed to complete the selection. Importance factors are assigned to each parameter, in this work the maximum importance factor was assigned to the PGA and the minimum one to the other selection parameters, to finally select the group of accelerograms. The accelerograms can also be scaled, defining a number of iterations and a period range, in which one wants to narrow the compatibility with the target spectrum.

- **Select&Scale** (Ay and Akkar 2014) allows, once magnitude and source-to-site distance ranges are set, for a preliminary selection of real accelerograms to be undertaken. Then, the sets of accelerograms are scaled to match on average the target spectrum. The final selection is made by means of the following criteria: maximum number of records, maximum number of records corresponding to the same seismic event, a period range and a range of scaling factors. The selected accelerograms in the two directions are very different one from another, with different frequency contents and shorter durations than the others.

- **SeismoArtif** (Seismosoft 2016) is able to generate groups of artificial accelerograms that are individually compatible to the code-specified response spectra. The software randomly provides artificial signals, depending on the definition of an envelope type (e.g. a trapezoidal shape), to reproduce the typical path of a seismic motion. Then, the Fourier transform is computed to apply the appropriate correction to the records to make them comparable with the target spectrum. The suite of accelerograms is finally obtained performing the inverse Fourier transform. All these accelerograms have almost the same shape, defined by the envelope type.

- **SeismoMatch** (Seismosoft 2016) can be used to modify any accelerogram introduced by the user to match the target spectrum using the wavelet algorithm developed by Hancock et al. (2006). After defining the reference spectrum, the user sets a period range and a maximum tolerance to match on
average the target spectrum.
For the sake of simplicity, for each level of seismicity (low, medium and high), the response spectra corresponding to only real and artificial accelerograms selected with respectively Rexel and SeismoArtif are reported in the figures below (Figure 5, Figure 6 and Figure 7).

Figure 5. Low-seismicity site: response spectra corresponding to the suites of (a) real accelerograms selected by means of Rexel and (b) artificial accelerograms selected by means of SeismoArtif

Figure 6. Medium-seismicity site: response spectra corresponding to the suites of (a) real accelerograms selected by means of Rexel and (b) artificial accelerograms selected by means of SeismoArtif

Figure 7. High-seismicity site: response spectra corresponding to the suites of (a) real accelerograms selected by means of Rexel and (b) artificial accelerograms selected by means of SeismoArtif
4. DISCUSSION ON THE LOCAL RESULTS

Nonlinear dynamic analyses were performed for each building and shear force and chord-rotation acceptance criteria checks, according to the requirements of the Italian building code, were used as comparing parameters. Namely, two different comparisons were conducted: (a) among the responses of a single case-study at an “averaged level of seismicity” (as shown in Figure 8, Figure 9 and Figure 10), and (b) among the responses of the three buildings at the same “averaged level of seismicity” (Figure 11).

Both comparisons were made starting from the number of elements that, in each building, reached the shear force or the chord-rotation acceptance criteria if subjected to low, medium and high seismicity. In the following histograms, the arithmetic mean values among the results given for the three levels of seismicity are shown in order to represent an “averaged level of seismicity”. However, to highlight any possible trend and to allow the comparison among the results obtained performing nonlinear dynamic analysis with accelerograms selected with different approaches, a normalisation of such values was made. Hence, for each case-study and for each acceptance criterion, the ordinates represent a Comparison Index, defined as follows:

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CI = \frac{\text{average number of elements that reached the acceptance criterion}}{\text{maximum number of elements that reached the acceptance criterion}}
\]

The first comparison was conducted, for each case-study, considering the mean value among the number of elements that reached the acceptance criteria and normalising such values. Figure 8, 9 and 10 show the results for each building.

Figure 8. Case-study 1: CI referring to the (a) shear force and the (b) chord-rotation acceptance criteria

Figure 9. Case-study 2: CI referring to the (a) shear force and the (b) chord-rotation acceptance criteria
First of all, as expected, the number of elements that reached both the shear force and the chord-rotation acceptance criteria grows for increasing levels of seismicity, hence the mean between the three levels of seismicity effectively represents an average seismicity that can be used as reference seismicity to conduct the comparisons. Moreover, the number of elements reaching the chord-rotation acceptance criterion considerably increases with the high-seismicity inputs, making the chord-rotation check more significant with respect to the shear force one.

Concerning the shear force verification checks, generally speaking, the number of non-verified elements seems not to be significantly influenced by the accelerogram selection approach used, given that the results appear all very close to the mean value among the six suites. The only exception is Seism-Home that, for each case-study, returns the lowest CI values and the farthest from the mean value. On the other hand, more visible differences are highlighted by the results of the chord-rotation checks. Seism-Home, similarly to the shear force checks, and SeismoArtif are the accelerogram selection tools that seem to provide the lowest number of non-verified elements, whilst Rexel and Select&Scale, in each of the three case-studies, always yield the higher number of non-verified elements. Intuitively, we would have expected the number of non-verified elements obtained by using artificial accelerograms (SeismoArtif) to result higher than the number attained using the other tools, given the unreasonable number of cycles that characterises artificial signals and, consequently, their somewhat unrealistic energy input. However, at the element level, CI obtained selecting input ground motions by means of SeismoArtif are mostly around the mean value and often even lower.

As stated above, in order to understand if there are differences in the results trend between the three case-study buildings, their results are directly compared in Figure 11.
have the lowest CI values, since it should have been built according to OPCM-3274. Further developments of this study will aim at a distinction of the non-verified elements in terms of beams and columns, in order to check if the OPCM-3274 prescriptions (inc. capacity design principles) were effectively considered or not in the design of this building.

5. COMPARISON IN TERMS OF SEISMIC RISK INDEX

Within the realms of seismic vulnerability assessment of existing structures in Italy, another important parameter to be investigated is the so-called seismic risk index. This parameter, already defined in several seismic regulations, was recalled by the recent Italian seismic risk classification guidelines (D.M. 58/2017), that suggest its computation as the capacity to demand ratio in terms of PGA at the SLV (life-safety) limit state.

Given that nonlinear dynamic analyses were performed in this study, the aforementioned capacity was computed considering the Peak Ground Acceleration of the elastic spectrum, defined starting from the accelerogram time-history from the beginning to the instant in which the first element reached its shear capacity.

The following plots (Figure 12) show the results, in terms of mean values of the seismic risk index, obtained for each case-study, averaging the risk indices obtained for the three level of seismicity from low to high.

These results paint a slightly different picture with respect to what was observed and discussed in Section 4, above. Indeed, and considering that a low value of RI implies a higher level of seismic assessment conservatism, it is noticed that SeismoArtif appears to now be one of the most conservative of all approaches, together with SeismoMatch, which constitutes the sort of intuitive result that was not transpiring from the results in Section 4.
6. CONCLUSIONS

The recent increase in computing power and the now large availability of ground motions recordings is leading to a steady increase in the use of nonlinear dynamic analyses by the practicing engineering community.

The purpose of this work was thus to investigate how different accelerogram selection strategies may influence the outcomes of code-based seismic assessment of existing reinforced concrete buildings. Hence, six different procedures, as implemented in six software tools, were employed to select and, if needed, scale accelerograms, including both real and artificial accelerograms.

Three real reinforced concrete buildings, built in different years, were considered, and nonlinear dynamic analyses were performed in order to carry out the capacity checks in terms of element chord rotation and shear resistance, following the Italian seismic design/assessment building code. Each case-study was selected to represent a site characterised by a specific seismic hazard and a level of seismicity in a range from low to high.

Since nonlinear dynamic analyses were performed for each building, for each level of seismicity, it was possible not only to investigate the response of a single case-study at an averaged level of seismicity, but also to compare the responses of the three buildings at the same level of seismicity. Real accelerograms appeared to confirm themselves as attractive and efficient inputs to perform nonlinear dynamic analyses, leading to a number of elements reaching the code performance thresholds that are around the mean value for all employed accelerogram selection methods. The use of artificial records, on the other hand, was confirmed, albeit only through the seismic risk index results, as a conservative approach.

Finally, it is noted that wavelet spectrum matching was applied only on the accelerograms previously selected by means of Rexel. Future developments of this work may foresee spectrum of also other groups of accelerograms, with a view to be able to more solidly judge this approach.

6. ACKNOWLEDGMENTS

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