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CONSIDERATION OF INTERSTORY DRIFT PROFILE IN SELECTION AND SCALING OF GROUND MOTION RECORDS

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Abstract

In the case of seismic assessment or design of special structures such as bridges and high-rise buildings, it is crucial to employ Nonlinear Dynamic Analysis (NDA) due to important role played by higher modes of vibration.

However, the issue of selection of input ground-motions for NDA and of adjusting them to ensure the quality and reliability of the results is still a matter requiring further investigation and widespread consensus. In particular, regardless of their type (natural, artificial or synthetic), the selection and adjusting of ground motions should be carried out with care; there are a large number of methods present in the literature, however none of them simultaneously take into account properties such as strength, ductility and dynamic characteristics of the structure.

The aim of this research is thus to introduce a new records selection criterion that takes into consideration the aforementioned properties of the structure, and then to test its adequacy. This method introduces an additional step to a recent, but well-known selection algorithm with the help of static nonlinear static analysis. Its adequacy is tested on a reinforced concrete structure and the results of NDA with and without this new step are compared.

Keywords: Ground motion selection and scaling; higher mode effects; modal pushover analyses

1. Introduction

Nonlinear dynamic analyses (NDA) are considered as the most accurate method to assess existing structures and design the new ones. As computer technology advances and more powerful computers become available, NDA is becoming more and more commonly used. However, as these analyses require inputs which stimulate the effect of ground shaking on the structure, the uncertainties in the properties of these inputs remain and have been the focus of many past and ongoing research. Although these inputs can be artificially simulated by the help of some methods available in the literature, selecting and modifying natural earthquake records is still the most commonly-used method.

As engineering structures are designed to or assessed for rare events and because such events are not abundantly recorded and available for use, the need for appropriate selection and modification methodologies to be used for less rare events is obvious. Although there are some procedures which alter the frequency content of the records, the more commonly-used methods do not modify them but alter the intensity by introducing a scale factor. The earliest approaches to calculate these scale factors were dependent purely on the properties of the record such as peak ground acceleration, Arias intensity, effective peak velocity, amongst other intensity measures. Such methods, however, may introduce non-negligible scatter in NDA results [1,2], whilst the consideration of a structural response parameter in the scale factor calculation leads instead to improved results.

The first structural response parameter to be considered in the selection and scaling of records was the elastic fundamental period and corresponding spectral acceleration, which may indeed be appropriate for single-mode dominant structures, but found to be insufficient for structures with important response contributions from higher modes [3,4]. Given the elongation of the fundamental period due to inelastic response and also taking into consideration the contribution from the higher modes, seismic codes such as e.g. ASCE/SEI 7-05 [5] require the average spectrum of the selected and scaled ground motions to be higher than design spectrum over the period range $0.2T_1$ to $1.5T_1$. Although this is the most commonly-used method in practice and proved to be relatively efficient, it does not take into consideration other structural properties such as the strength or the distribution of the stiffness over height, which, as discussed subsequently, may constitute an improvement.

Whilst nonlinear static analyses (NSA) are often not preferred over NDA, they still have practical utility thanks to their simplicity and low computational demand. The concept of using NSA to have quick insight about a specific structure and use such info for a better selection and scaling of input for NDA has been proposed in some recent studies [6,7,8].

The purpose of the current work is to include the distribution of stiffness and plasticity over height in the selection and scaling procedure of NDA. A selection/scaling procedure proposed by Baker and Lee [9] is adopted which selects the ground motions on an individual basis and scales them to match a conditional mean spectrum (CMS) or a code-based design spectrum. This procedure includes a step to further optimize the selection at which the average of the selected motions is compared to the target spectrum (as stated already, CSM or design spectrum) and if the error does not satisfy a predefined tolerance, the records in the set are replaced one-by-one and the improvement in the error is observed.

As the novelty of this study is inclusion of the distribution of the properties of a structure over its height, the target spectrum is chosen to be the code-based design spectrum to simplify the study. The NSA is selected to be Modal Pushover Analyses (MPA) [10], as this method requires the ground motion spectrum input at a stage after running analyses unlike other methods available in the literature which require spectrum input from the very beginning [11,12].

2. Drift-based scaling procedure: The procedure

The proposed methodology for selecting and scaling records is summarised in the flowchart included in Fig.1 below, with each step being described in more detail in the text that then follows.

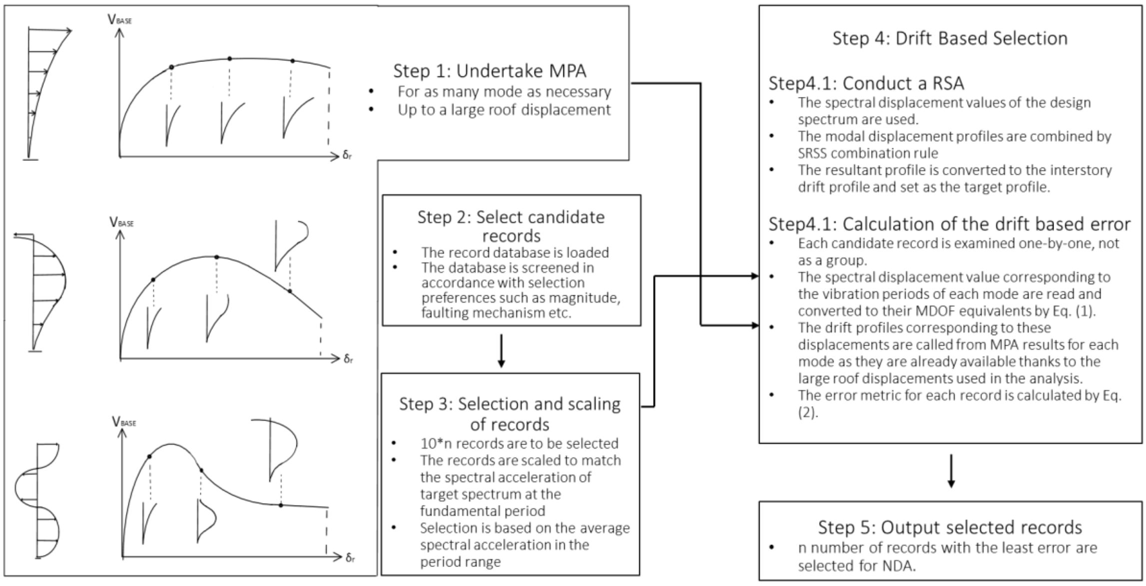

Fig. 2 – Flowchart of proposed drift-based scaling procedure

Step 1: Undertake Modal Pushover Analysis

In this step, a modal pushover analysis is conducted as described in the corresponding study [10]. The number of modes seemed to be adequately representing the structure has to be used. It is important to note that this MPA does not have a demand parameter yet, therefore the modal pushovers have to be done until large displacement demands. The inter-story drift profiles (IDP) corresponding to each step in each mode should be recorded.

Step 2: Select candidate records

A preferably large ground motion database should be used. In this step, the candidate motions are typically selected to match seismological and other parameters such as e.g. magnitude, site-to-source distance, faulting mechanism, $V_{S,30}$ of the site, etc. (see for instance SeismoSelect [13]).

Step 3: Selection and scaling records to match the target spectrum

In standard applications, in this step a relatively limited number of ground motion records is selected based on the average spectral acceleration in the period range. However, in this work, a large number of records needs instead to be selected as further selection criteria will be introduced later on. To avoid increasing the computational cost significantly, 10*n records seemed to be appropriate where n is the desired number of records to be selected at the end. It is also noted that a *greedy algorithm* [9] is used for a further optimization at this point, if the candidate motions do not satisfy the predefined tolerance as described earlier.

Step 4: Drift based selection

Step 4.1: Conduct a Response Spectrum Analysis (RSA)

An elastic RSA is done in this step to define the IDP demand. As already mentioned, an adequate number of modes has to be considered in the analysis and corresponding elastic spectral displacements from the design spectrum should be used.

Step 4.2: Calculation of the drift-based error

In this step, the spectral displacement values of the candidate motions ($S_{D,SDOF}$) for each mode are read and converted to their multi-degree-of-freedom equivalents ($S_{D,MDOF}$) by applying Eq. (1).

$$S_{D,MDOF} = \Gamma * S_{D,SDOF} \quad (1)$$

where ***Γ*** is the modal participation factor.

As the modal pushovers done for each mode are done up to a large top-story displacement in *Step 1* and interstory drift profiles during these analyses are recorded step-by-step, the profiles corresponding to the drift demands calculated by Eq. (1) are called for each mode. These profiles for each mode are combined through a Square-Root-of-Sum-of-Squares (SRSS) approach, and thus an interstory drift profile for each of the candidate records are obtained.

The error metric of each record is calculated by the following formula:

$$Err(j) = \sum_{i=1}^{m} \frac{|\Delta_{i,j} - \Delta_{i,target}|}{\Delta_{i,target}} \quad (2)$$

where ***j*** is the numerator of each record and ***i*** is the story numerator.

Step 5: Results output

The n number of records yielding the least error are selected and adopted in the NDA.

3. Verification study

A 20-story reinforced concrete structure designed according to Eurocode-8 provisions [14] in High Ductility Class (DCH) is tested in this study. The design properties and outcome are summarized in Fig.2, Fig.3 and Fig.4.

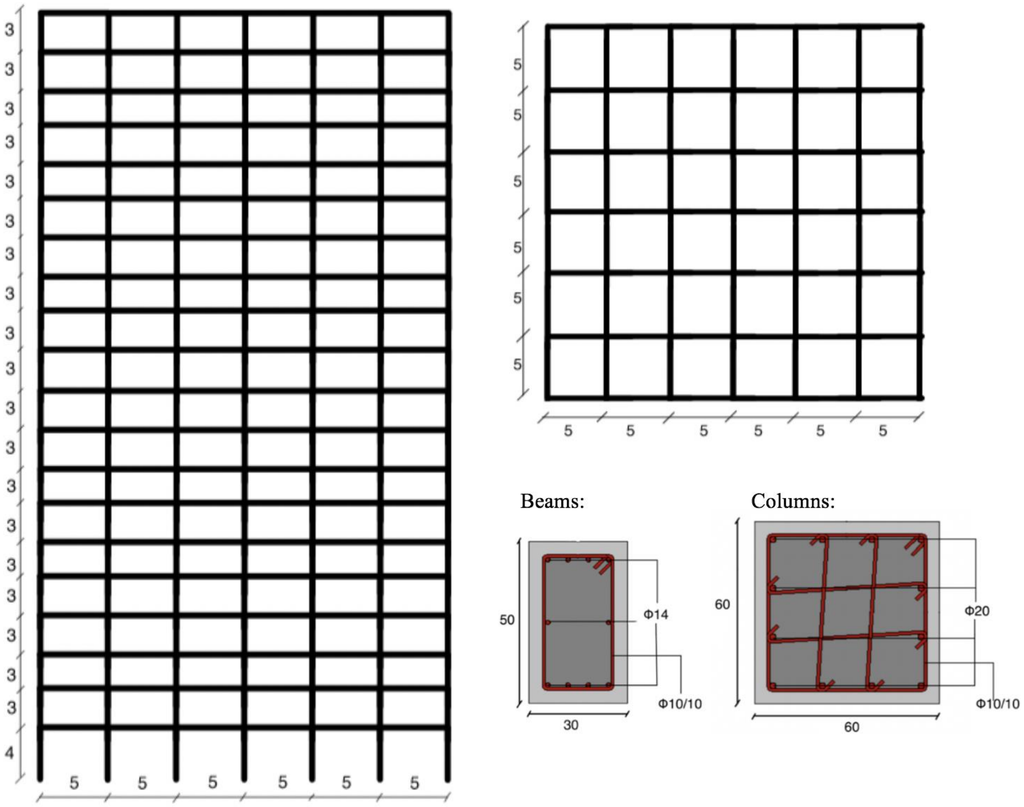

Fig. 2 – The structural layout and section reinforcement details

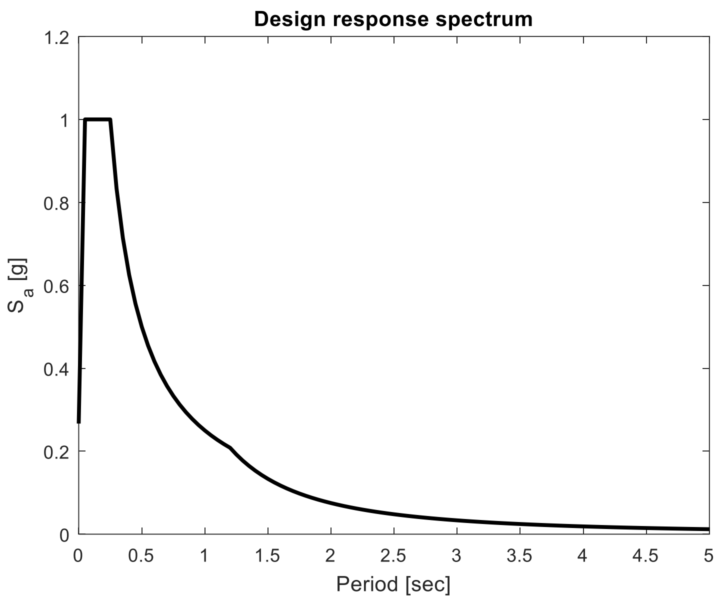

Fig. 3 – The code-based design response spectrum

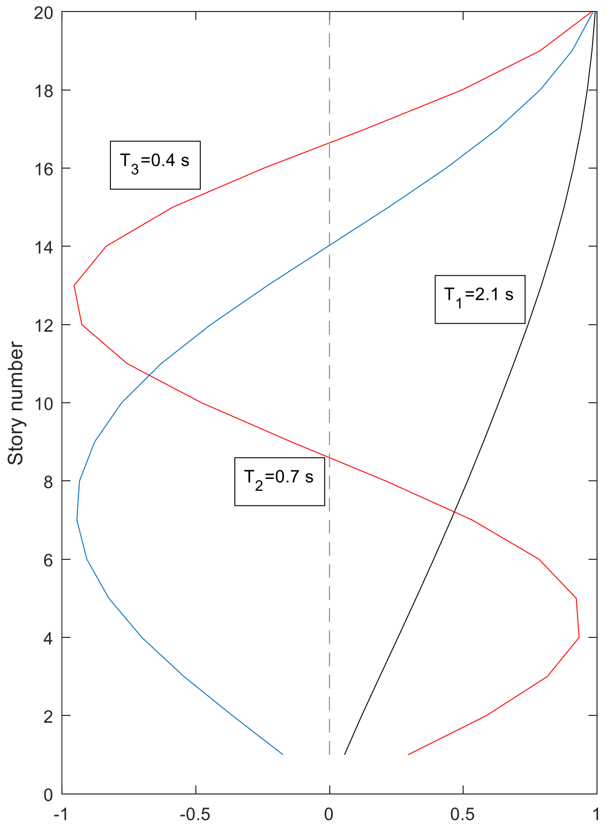

Fig. 4 – The eigenvector and eigenvalues

As the first step of the analysis, an MPA is applied to the structure by the help of analysis software SeismoStruct [15]. Three modes are used; therefore, three pushover analyses are done until a very large roof displacement (2.5 meters) and the drift profile at each step in all of the three analyses are recorded.

The NGA-West2 ground motion database [16] is used for the study. The motions to be selected are to be recorded on sites with $V_{S,30}$ from 240 to 480 m/s^2, distance to the source from 10 to 30 km and magnitude values from 6.5 to 7.5 M. Screening the database for the defined preferences has yielded more than three hundred candidate motions.

These ground motions are scaled to the spectral ordinate of the fundamental period and the errors they produce compared to the design spectrum over the periods from 0.4 to 4.2 seconds are computed and 10*10 records with the least error are selected. As described in [9], if the error of the average spectrum of these candidate motions does not satisfy a predefined tolerance, the records are replaced one-by-one with the non-selected records and the improvements are observed if there are any. Please note that, this step is repeated as a side calculation to select ten records instead of one hundred. These ten records are the direct resultant set of the original algorithm as there is nothing added yet to the work up to this point. Therefore, this set of ten records is saved for the sake of comparison and will be referred as *Set 1* afterwards.

The target IDP is calculated by employing an RSA. The elastic spectral displacement values are used.

To test the adequacy of the candidate records, MPA results are calculated for each record. As the result of pushover corresponding to the spectral ordinates of each motion for all three modes are already made available in *Step 1*, this step includes only reading the spectral ordinates of the records for three modes, converting them to their MDOF equivalents and loading the corresponding MPA drift profiles and combining them by SRSS. As these are simple and quick calculations carried out only one hundred times, it does not introduce significant additional computational effort to the algorithm.

The fifth and last step of the algorithm is the calculation of the errors of each record by using Eq. (2) and selecting ten of them with least errors. This set of ten records will be referred as *Set 2* hereafter.

3.1 Obtained Results

Using Set 1 and Set 2, nonlinear dynamic time-history analyses are conducted on the specimen structure, with the selected engineering demand parameters (EDP), i.e. interstorey drift (Fig. 5) and storey shear profiles (Fig. 6) being obtained.

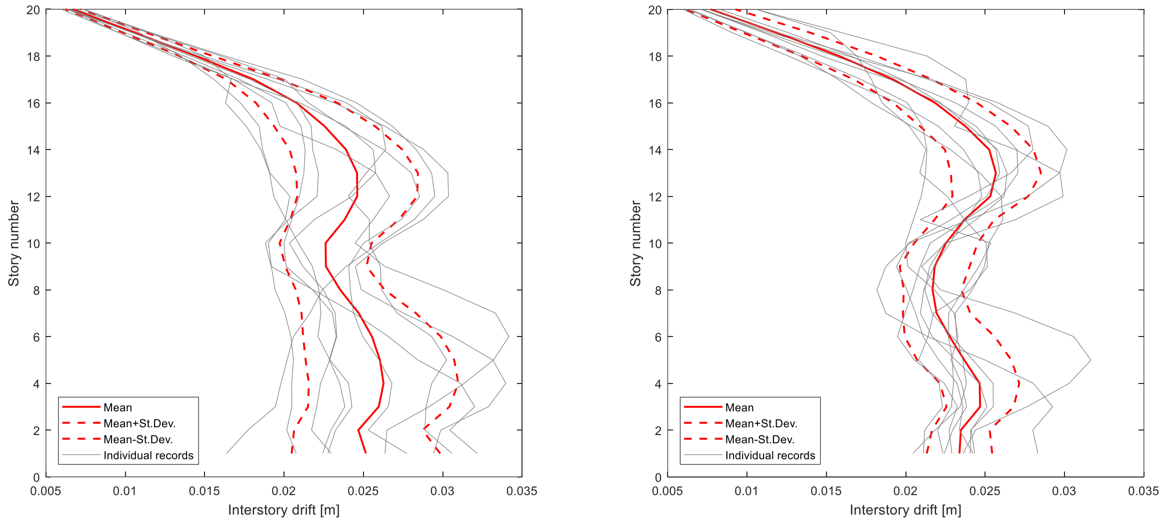

Fig. 5 – The interstorey drift profiles of *Set1* (left) and *Set2* (right)

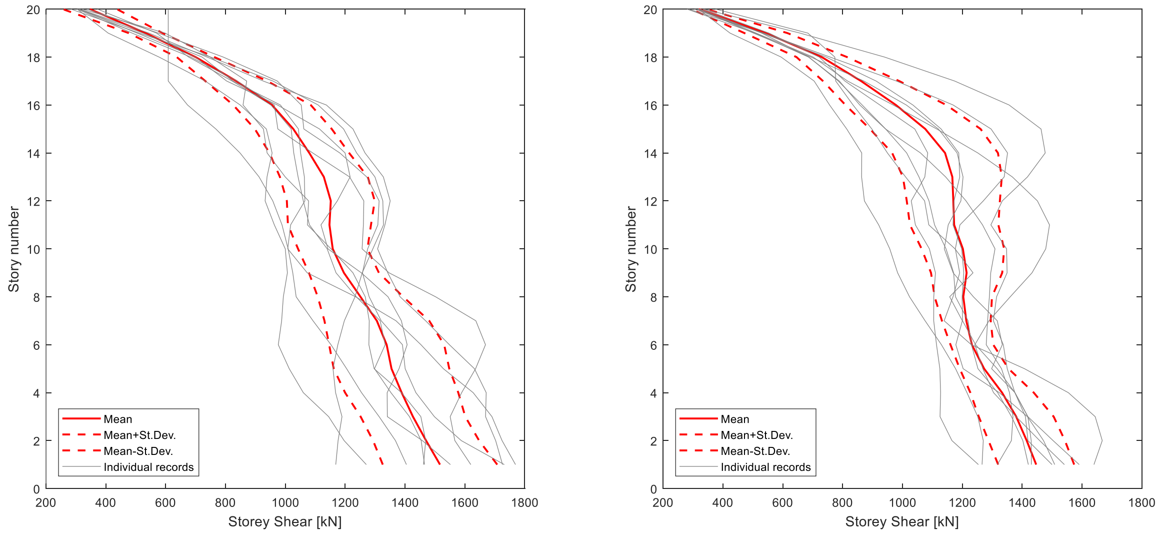

Fig. 6 – The story shear profiles of *Set1* (left) and *Set2* (right)

3.2 Results comparison

Even if the improvements in the results from *Set 1* to *Set 2* can already be gathered through visual inspections of the plots above, they are herein assessed also in relation to efficiency and sufficiency [see e.g. 17]. The efficiency of an IM can be tested through the consistency of the results produced by using it; in other words, a regression analysis done for this IM over the EDP (Fig. 7) should yield as little error variance as possible. In that purpose, a regression analysis for the EDP story drift is done to test the efficiency of the IMs. While the analysis for *set1* results yield an estimate of the error variance 0.0197, this parameter for *Set2* is 0.0074. Therefore, it can be said the analyses done by using *Set2* has introduced less scatterness of the results and the IM of the method described in this work is more efficient that the IM of the modified algorithm.

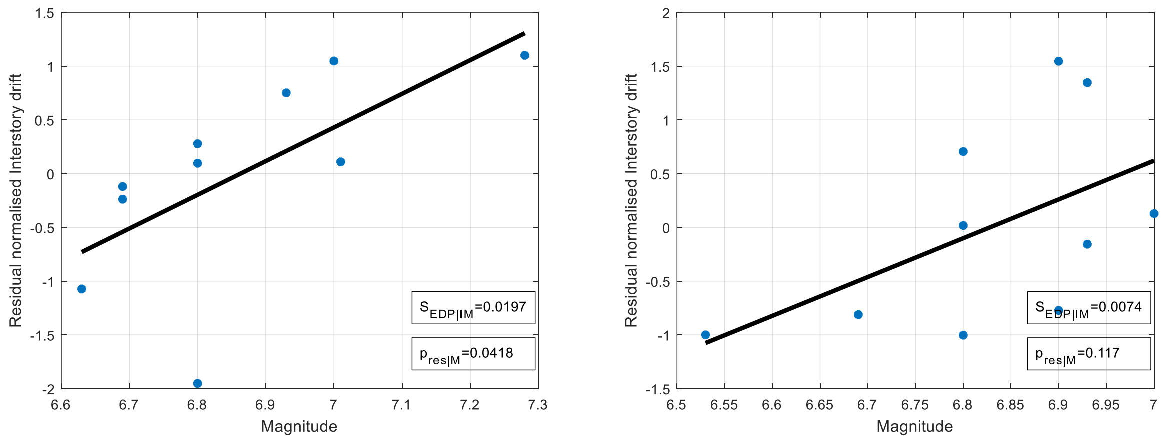

Fig. 7 – The regression analyses of *Set 1* (Left) and *Set2* (Right) results

Secondly, the sufficiency of the IMs is examined by the *p-value* that their regression analysis of the residuals over ground motion parameters (magnitude, in this case) yield. While this parameter for *Set1* is 0.0418, it is 0.117 for *Set2*. This indicates that the first IM has a significant statistical relation with magnitude, while the second IM has an insignificant, or at least less significant, one. This is also visible through the regression lines on the plots in Fig. 7 as the slope of the regression line is higher for the first IM, which again indicates a higher statistical connection between IM and the magnitude. Therefore, it can be said that the IM of the method described here is a more sufficient one compared to its counterpart.

Although it is difficult to judge if a method is more successful over another by using such a small sample size (ten records each in this case), it may nonetheless be stated that the results obtained here seem to indicate that the method described in the work leads to improvements in terms of intensity measure efficiency and sufficiency.

4. Conclusions

The output of nonlinear dynamic analyses is highly dependent on their input, i.e. ground motion records, the current work aimed at improving the selection and scaling procedure of such records by introducing a new selection criterion based on interstory drift.

The proposed methodology was tested, in preliminary fashion using a limited records sample, on a reinforced concrete 20-story building designed for high ductility according to Eurocode 8 provisions, and the results obtained do seem to indicate that ground motion sets selected with the proposed methodology may constitute a more efficient and sufficient intensity measure.

It is however important to note that this method needs to be further tested, considering e.g. reinforced concrete frames with different geometric layouts or subjected to different hazard levels, steel structures, bridges, etc.

Further, bidirectional and torsional effects should also be scrutinised. In addition, more thorough comparisons with the relatively vast range of alternative record selection and scaling proposals available in the literature need also to be carried out. Finally, a larger sample of records will also need to be employed in order to more robustly compare the proposed approach with other methods.

5. References

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