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ABSTRACT. *Earthquake shaking represents complex loading to the structure. It cannot be accurately characterized by a single parameter, e.g. peak ground acceleration. The goal of this work is to compare the role of various strong-motion parameters on the induced damage in the structure through numerical calculations. To this end, a robust structural model that can perform several dynamic calculations, with an acceptable cost, is required. The developed methodology is based on the use of structural elements with nonlinear behaviour of damage mechanics and plasticity type. The damage level of a typical reinforced concrete structure is evaluated by the use of nonlinear numerical calculations. The effect of numerous ground-motion parameters on the computed damage is analyzed and discussed. A set of weakly-correlated parameters are chosen that characterize different aspects of the shaking. Natural accelerograms were chosen based on a consideration of the magnitude-distance ranges of design earthquakes. It is expected that an increase from one to two or three ground-motion parameters would lead to a significant reduction in the scatter in the fragility curve, which when more than one parameter is used will be a surface.*

RÉSUMÉ. *Le mouvement sismique applique un chargement complexe aux structures. Un seul paramètre, e.g. « PGA », ne peut pas caractériser correctement ce chargement. L'objectif de ce travail est d'évaluer le rôle de plusieurs paramètres caractérisant un séisme sur le niveau de dégradation des structures. Pour y parvenir, il est essentiel de disposer de modèles fiables et robustes nous permettant de réaliser plusieurs calculs de structures avec un coût limité. La méthodologie développée s'appuie sur l'emploi d'éléments de structure capables de tirer profit des lois de comportement non-linéaires de type mécanique de l'endommagement et plasticité. Les simulations sont réalisées à l'aide d'accélérogrammes naturels ayant des caractéristiques variées et imposées suivant les trois directions de l'espace. Ces études permettent d'estimer les niveaux d'endommagement des structures en béton armé pour différentes intensités de l'action sismique. Lors des simulations E.F. réalisées sur un modèle d'un bâtiment R+7 les effets de plusieurs paramètres du mouvement sismique sur l'endommagement ont été analysés. Grâce à deux ou trois paramètres caractérisant l'action sismique, nous espérons diminuer significativement la dispersion des résultats des études de vulnérabilité sismique du bâti.*

KEYWORDS: *Seismic vulnerability, Dynamic analysis, Strong-motion parameters, Induced damage.*

MOTS-CLÉS : *Vulnérabilité sismique, Analyse dynamique, Paramètres du mouvement fort, Endommagement.*

1. Introduction

An accurate earthquake risk evaluation requires a correct estimation of the seismic hazard and a good evaluation of the seismic vulnerability of structures. The main objective of the present article is to investigate the influence of strong-motion characteristics on the dynamic response of buildings through numerical calculation of the induced damage.

Earthquake shaking represents complex loading to the structure. It cannot be accurately characterized by a single parameter, e.g. peak ground acceleration (PGA), and the use of the seismic acceleration time-history together with the structural damage models seems to be unavoidable for critical infrastructures. Nevertheless, in applications for ordinary buildings simple methods are usually preferred due to computational constraints. Therefore, earthquake hazard is often currently characterized by a single parameter, e.g. PGA or elastic response spectral displacement for 5% damping (SD) at a single period, which is perhaps modified by a factor to account for earthquake duration, such as in the HAZUS methodology.

However, this standard method neglects the uncertainty in the estimated damage caused by the use of a single ground-motion parameter. For example, the same structure could be damaged more by long-duration shaking than by shaking of only a few seconds even if the amplitude of the shaking characterized, for example, by PGA is the same.

The damage level of a typical reinforced concrete structure is evaluated by the use of nonlinear numerical calculations. The peak roof drift is used to define the damage level of the studied structure

The goal of this work is to compare the role of various strong-motion parameters on the induced damage in the structure. Such a study can help find a small number of ground-motion parameters that lead to, when used together to characterize the shaking, the smallest scatter in the estimated damage. It is expected that an increase from one to two or three ground-motion parameters would lead to a significant reduction in the scatter in the fragility curve, which when more than one parameter is used will become a surface.

2. Models and analysis

This section discusses the structural and material models used and the analysis conducted.

2.1. Structural model

For the purpose of this work, a hypothetical reinforced concrete building was chosen. This is an eight-story regular frame reinforced concrete structure as shown in Fig. 1. The building is mainly constituted of parallel shear walls along Y direction, and columns.

To create its finite element mesh, three different types of elements were used: shells to represent slabs and walls, beams for columns, and discrete rotational elements for beam / slab connections. Slabs were considered elastic linear, as were the columns. Shear walls were also considered linear elastic. The only non-linearity that could take place is at both ends of each column through the formation of plastic hinges. These were modelled using discrete elements with their characteristics adjusted regarding reinforcement detailing of columns.

These elements may be used to provide rigid links, linear elastic stiffness, and non-linear connections between any of the six degrees of freedom, between two nodes. In our case, only the flexural bending rotations were allowed to behave nonlinearly. The other degrees of freedom were adjusted as rigid links. Details on the material model for this element are provided in the next paragraph.

The building is anchored at its base, without considering any flexibility from the soil. Body weight and other masses are also included in the modelling, which are then shaken by the horizontal acceleration time-history.

Finally, Rayleigh damping is included in the calculation algorithm to assure a certain level of energy dissipation necessary to guarantee the stability in results due to high frequencies. The damping fixed at 5% for the first two eigen frequencies. The earthquakes are then applied to the structure as an acceleration field using several accelerograms. Calculations were then carried out using *Code_Aster*® and an implicit algorithm based on the Newton-Raphson's formulation.

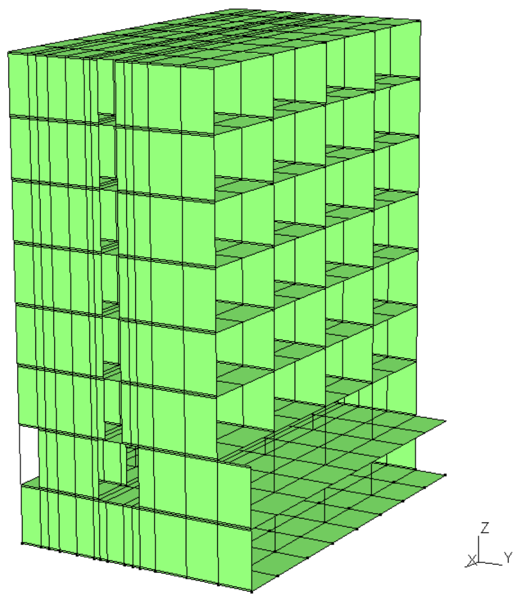

Figure 1. Finite element mesh of the studied building.

2.2. Nonlinear material model

At each end of every column of the mesh, a discrete element allows the creation of plastic hinges. The material model is capable to dissipate energy, exhibit ductility and limit the moment capacity. The formulation of the model is the one indicated bellow:

Yield function $f = |F - X| - F_e$

If f <0 the behaviour remains elastic, otherwise the evolution follows the following conditions:

$$f = 0 \text{ and } \dot{f} = 0 \text{, with } \dot{U}^{an} = \dot{\lambda}\frac{\partial f}{\partial F}, \; -\dot{\alpha} = \dot{\lambda}\frac{\partial f}{\partial X}, \; \dot{F} = K_e\left|\dot{U} - \dot{U}^{an}\right| \qquad [1]$$

$$X = \frac{k_x.\alpha}{\left(1+\left(\frac{k_x.\alpha}{F_u}\right)^u\right)^{1/n}}$$

K_e	Elastic stiffness
F_e	Stress yield
K_c	Kinematic stiffness
F_u	Kinematic yield
n	Exponent

The behaviour of the model for a cyclic loading is shown in Fig. 2.

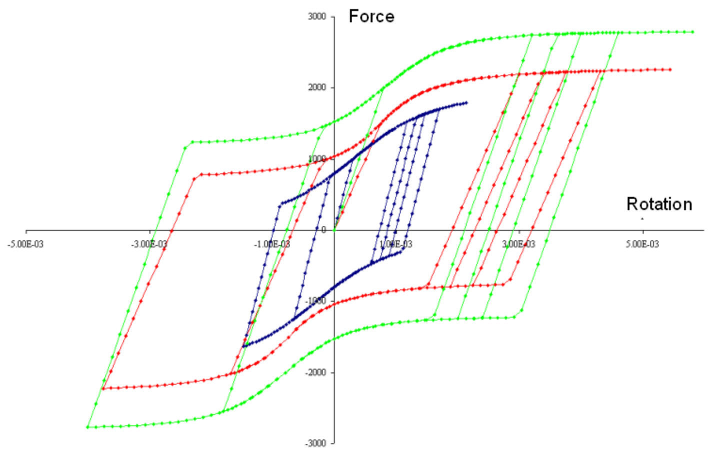

Figure 2. Nonlinear behaviour of discrete models used to represent the formation of plastic hinges.

3. Selection of input time-histories

In the past couple of decades, many new sources of earthquake strong-motion records have been developed: on the Internet, e.g. ISESD (http://www.isesd.cv.ic.ac.uk), COSMOS (http://db.cosmos-eq.org/scripts/default.plx) or the PEER NGA database (http://peer.berkeley.edu/nga/index.html), or on CD ROMs (e.g. Ambraseys et al., 2004). These are the source of many thousands of potential input accelerograms to structural analysis. However, structural testing is a time-consuming and expensive exercise therefore the number of input time-histories used should be kept to a minimum but at the same time the selected records should allow the behaviour of the structures to be investigated and also the sensitivity of this behaviour to variations in ground motions to be understood. This section summarises a method developed for the efficient selection of time-histories - more details are given in Douglas (2006).

In order that an efficient set of input accelerograms is selected some ideas from the theory of Design of Experiments (DOE) (e.g. http://www.itl.nist.gov/div898/handbook/pri/section1/pri1.htm) are employed. Well design experiments maximize the amount of information that can be obtained for a given amount of experimental effort. Since one purpose of structural testing should be to decide which characteristics of strong ground motions are important for the modelled structures, the experimental design required has a screening objective. The primary purpose of these experiments is to select or screen out the few important main effects from the many less important ones. These designs are also termed main effects designs.

In the terminology of black box process models of DOE, the structural model is the process and the estimated damage parameters from these models are the outputs (responses). The controlled inputs (factors) are split into the parameters defining the structural model (strength of concrete etc.) and the input ground motions. At this stage, there are no uncontrolled inputs (co-factors) since everything can be set by the experimenter. (In reality, the parameters required for the structural model are not known exactly.) Since there is an infinite variety of possible earthquake ground motions it is useful to characterise them using a number of scalar strong-motion parameters that approximately measure different properties of the motions (amplitude, frequency content, duration, energy etc.). Hence the set of strong-motion parameters becomes the controlled inputs to the process (and the main effects in the model). The benefit of this approach is that it is then easier to understand the results of the structural modelling with respect to properties of the input accelerograms. However, since these strong-motion parameters do not perfectly characterise the ground motions (no small set of scalars can hope to fully characterise the true complexity of ground motions) the use of strong-motion parameters introduces uncontrolled factors (co-factors) due to the complexity of the motions not measured by the strong-motion parameters chosen.

3.1. Selection based on seismic hazard of a region

The first stage of the proposed method is to apply a magnitude-distance filter to exclude records from magnitudes and distances that are not possible for the considered region by considering the seismogenic sources in the region in terms of their location and maximum magnitude or by making use of disaggregation results. Also records from small earthquakes and great distances should be excluded since these will not lead to significant damage unless the structures are particularly weak. For this study, use was made of published seismic hazard studies for the French Antilles to make this magnitude-distance selection.

After this first step there are still be too many strong-motion records to use all as input to the structural models because of the long run times of numerical models. Therefore an additional selection procedure must be employed to further reduce the total number of selected accelerograms. This additional step is based on selecting records with different characteristics measured by the values of various strong-motion parameters, as discussed above.

3.2. Selection based on strong-motion parameters

The selection procedure proposed here is to use a two-level factorial technique where for each strong-motion parameter selected records are chosen to fall within two intervals: either high or low value bins. This experimental design then allows the effect of each strong-motion parameter on the damage sustained to the structure to be investigated but also the interaction effects due to the combined effects of two parameters, for example amplitude and duration.

In order that the number of different records required is small and that there are sufficient records for each combination of parameters only three strong-motion parameters were selected. Therefore, sets of $2^3=8$ accelerograms were selected from the available data for the magnitude-distance ranges of interest. So that an efficient set of strong-motion parameters (i.e. the smallest set that allows the effect of different aspects of the motions on the structure's behaviour to be investigated) is used it is preferable if a set of poorly correlated (ideally orthogonal) parameters is chosen so that the same characteristics of the motions (e.g. amplitude or duration) are not measured twice by two different parameters. For this study the three parameters: SD at 0.1s (roughly characterising short-period amplitudes), SD at 1.0s (roughly characterising long-period amplitudes) and the relative significant duration (the interval between 5 and 95% of the total Arias intensity) were used.

4. Dynamic time-history analysis

This section discusses the dynamic analysis conducted using the acceleration time-histories selected.

4.1. Simulation process

Since the building is located in the French Antilles, we chose to use strong-motion records corresponding to the seismotectonics of that region. Five series, each containing eight ground-motion records, were used, so that each set could represent the various combinations of the three tested parameters (SD at 0.1 s, SD at 1.0 s and relative significant duration). The response of the modelled building was then evaluated for each of the forty ground-motions inputs, the analysis being conducted with *Code_Aster*®. We measured peak drift and peak inter-story drift, as these damage indicators are the easiest to measure.

4.2. Results

In order to evaluate the significance of the three parameters, the calculated peak roof drift values were segregated into six categories, depending on the value – high or low – of the three parameters. For each parameter, we compared the mean value of the peak roof drift which resulted from the ground-motion inputs with high values of the parameter and those with low values.

Figures 3 displays the results obtained using the Design of Experiments approach for each of the three parameters. The damage indicator (here, the peak roof drift) is shown on the ordinate. The slope of the line gives an idea of the significance of the parameter: the steeper it is the more important the parameter.

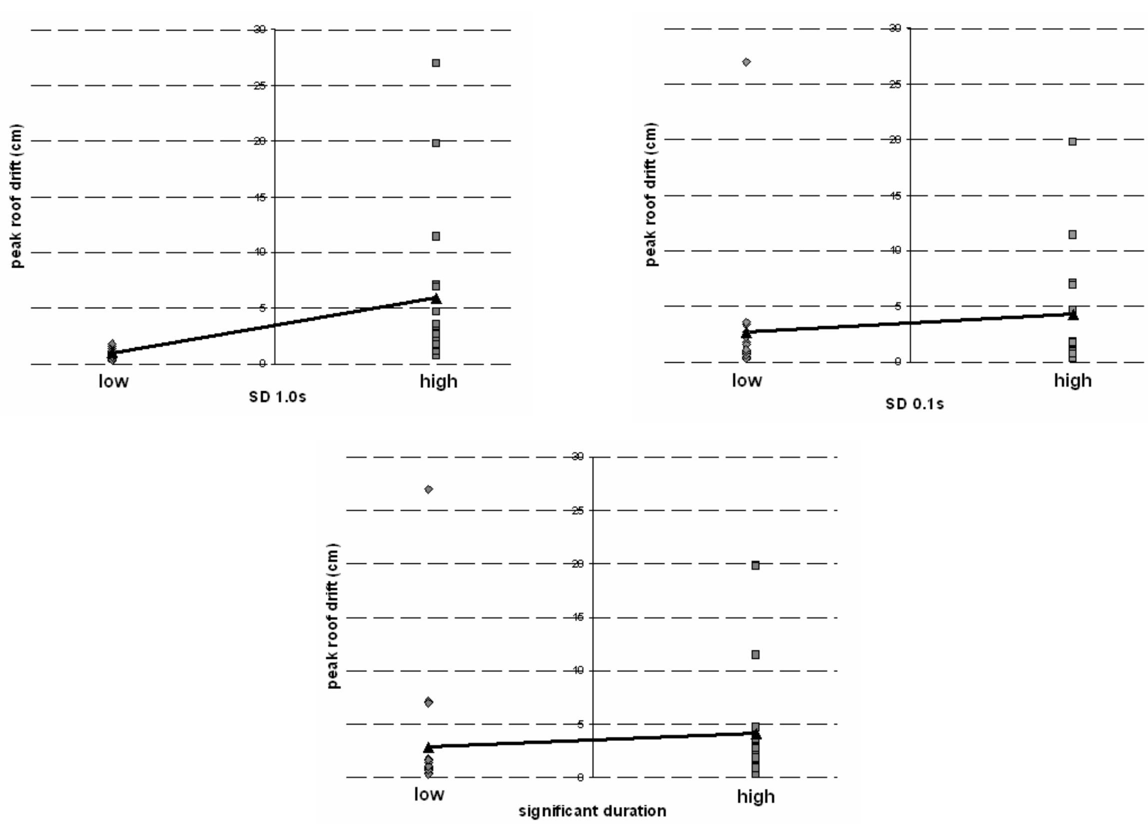

Figure 3. Plots showing the effects of the three studied parameters on the building response (peak roof drift). The slope of the black line gives an idea of the influence of each parameter.

It is noticed that SD at 1.0s has a big influence on the results, whereas spectral displacement at 0.1s and relative significant duration are much less important. This can be explained by the fact that the first mode of the building is activated around 0.7 Hz (1.4s): therefore high displacement values around this frequency can induce significant damage.

These results are corroborated by the same dynamic time-history analysis, performed on a 2D model of the building with the finite-element program SeismoStruct (SeismoSoft, 2005). The peak drift values are not exactly the same (due to the differences between 2D and 3D models), yet both studies lead to the same conclusion regarding the influence of the three parameters.

Finally, to confirm the validity of the results shown by Figure 3, it was decided to plot the forty calculated peak roof drifts versus several parameters defining ground-motion inputs, i.e. the three already considered plus number of cycles, PGA and Arias intensity. To estimate the number of cycles, the rainflow cycle counting method was used, as recommended by Hancock and Bommer (2005). The results are displayed on Figure 4, along with regression lines for each parameter.

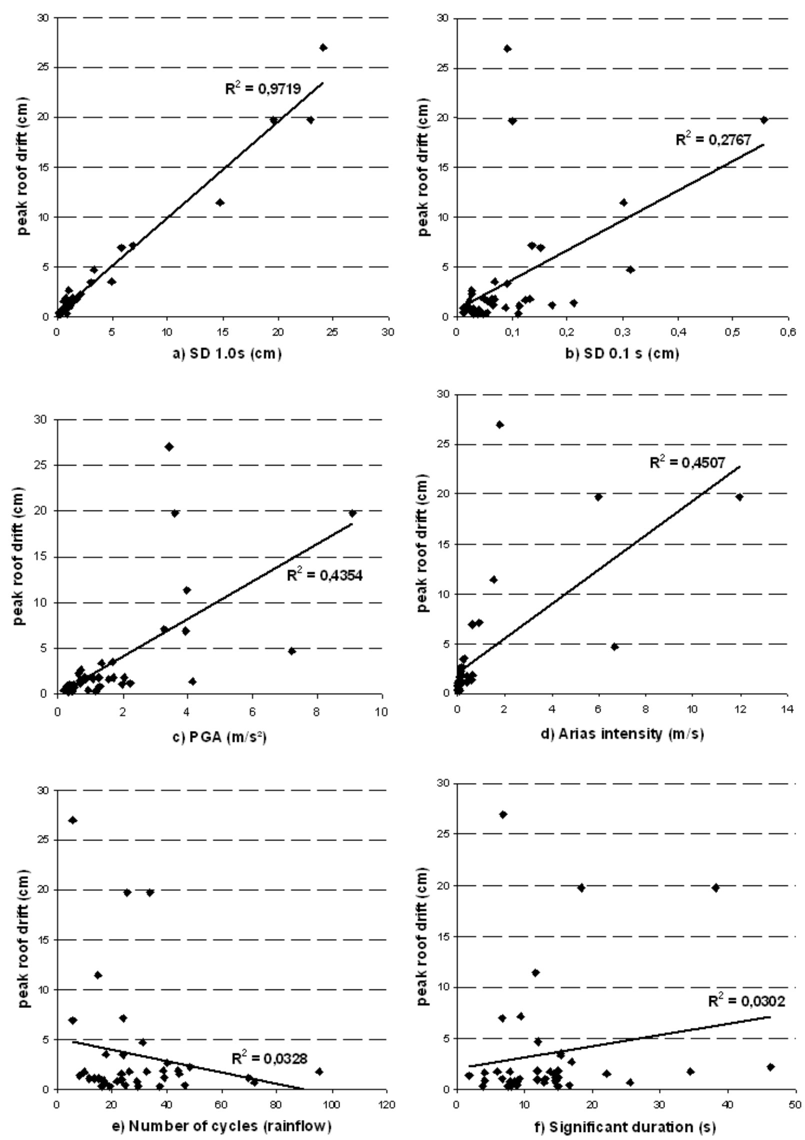

Figure 4. Plots of the peak roof drift versus several strong-motion parameters. The black line represents the curve from linear regression.

A strong correlation between SD at 1.0s and the peak roof drift is again evident (Figure 4a). On the contrary, for SD at 0.1s and relative significant duration, the points show a wide dispersion. Some parameters, like PGA or Arias intensity, have great influence on the peak roof drift, while others, like duration or the number of cycles, do not seem very significant. This conclusion is shared by Hancock and Bommer (2007), who state that damage analysis based only on peak drift does not usually reveal a close correlation with duration or number of cycles: a more detailed damage analysis, based on energy measures, using a damage model taking into account the fatigue effects should be performed in order to properly evaluate the role of these parameters.

5. Conclusion and perspectives

The current methods used to evaluate the seismic vulnerability of structures (e.g. through fragility curves) often represent the ground motion by a single parameter (e.g. PGA). However, a single parameter cannot fully represent the effect of an earthquake on the seismic response of the structure. It is expected that an increase from one to two or three ground-motion parameters would lead to a significant reduction in the scatter in the fragility curve, which when more than one parameter is used will be a surface.

To this end, a nonlinear structural model to calculate the induced damage in a reinforced concrete structure is developed. Three non-correlated parameters are chosen to represent the characteristics of the strong motion. Five series, each containing eight ground-motion records, were used, so that each set could represent the various combinations of the three tested parameters. A strong correlation between SD at 1.0s and the peak roof drift (as the damage measure) is observed whereas spectral displacement at 0.1s and relative significant duration are much less important. Some parameters, like PGA or Arias intensity, have great influence on the peak roof drift, while others, like duration or the number of cycles, are not useful for predicting damage.

A more detailed damage analysis should be performed in order to properly evaluate the role of these parameters. In this view, the effect of each parameter on several damage indicator (e.g. energy based indicators, combination measures, etc) will be investigated. Based on the obtained results, fragility surfaces that relate the strong-motion intensity (represented by several parameters) to the possible damage of the structure will be developed.

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