Assessment of the variability of the buildings response due to the variability of ground motion from a database of earthquakes recorded within buildings

M. Perrault & P. Guéguen
Institut des Sciences de la Terre, Université de Grenoble 1, IFSTTAR, CNRS, France

SUMMARY:
The seismic vulnerability of the existing buildings is a difficult concept to study. Main difficulties are provided by the lack of knowledge on the structure and by the use of models of deformation and damage. The definition of fragility curves, which give the probability that a building being damaged for a given strong motion, is a solution that allows taking into account the uncertainties. This article aims at analyzing the uncertainty sources and assessing them from the study of ground motions recorded within buildings. The strategy followed by the authors is to use Californian buildings database (CSMIP, USGS) in order to assess one component of the total variability: the variability of the building response due to the variability of ground motion. Finally we provide regression parameters that link the building response to a ground motion parameter.

Keywords: seismic vulnerability, uncertainty in the building response, US buildings database

1. INTRODUCTION

Seismic vulnerability of existing buildings can be assessed using damage probability functions, i.e. fragility curves, which provide the probability of a structure to suffer a level of damage for a given seismic demand. These functions involve a standard deviation term, which is modeled by the combination of three uncertainties (Michel *et al.*, 2012): the uncertainty in the damage state threshold, the variability in the properties of the building model and the uncertainty in response due to the variability of ground motion. These uncertainties can be aleatory or epistemic, depending on the level of knowledge. In Hazus methodology, the first two uncertainties are considered equal to 0.4 and 0.3, respectively, in the case of the study of the structural damage within buildings. However the last component due to the effect of the ground motion variability is not provided.
This study aims at evaluating the variability in the buildings' response due to the variability of ground motion. From a database of earthquakes recorded within US buildings, we study the variability of the response of buildings and the correlation with the ground motion parameters. Depending on the parameter that describes the strong motion, this variability can reach low values. First we present the database of strong motions recorded within buildings used in the following of the study. Then we focus on the variability in the response of buildings depending on different seismic parameters.

2. DATABASE OF STRONG GROUND MOTIONS RECORDED WITHIN BUILDINGS

In order to study the response of buildings under seismic strong motions, earthquake recordings in 236 buildings have been collected. These data are available on the website of the California Strong Motion Instrumentation Program (CSMIP). This database contains recordings of 100 earthquakes – the first seismic event being the San Fernando earthquake that occurred on February 9, 1971 – and contains 837 time histories recorded in buildings, i.e. 837 pairs {building, earthquake}.
Buildings of the database are mostly composed by concrete (76) or steel (114) structures (Fig. 2.1). Only 12 masonry buildings and 8 wooden buildings were identified. Structures with seismic isolated

dampers (19) were classified in a separate category. Buildings are also classified following three categories, depending on the number of floors: 70 low-rise (L) buildings (1-3 stories), 61 moderate-rise (M) buildings (4-7 stories) and 103 high-rise (H) buildings (at least 8 stories).
For the whole database, peak ground accelerations (Fig. 2.1) range from 0.015 to 8.491 m/s^2, and peak ground velocities and displacements range from 0.0780 to 113.636 m/s and from 0.006 to 27.874 m, respectively.

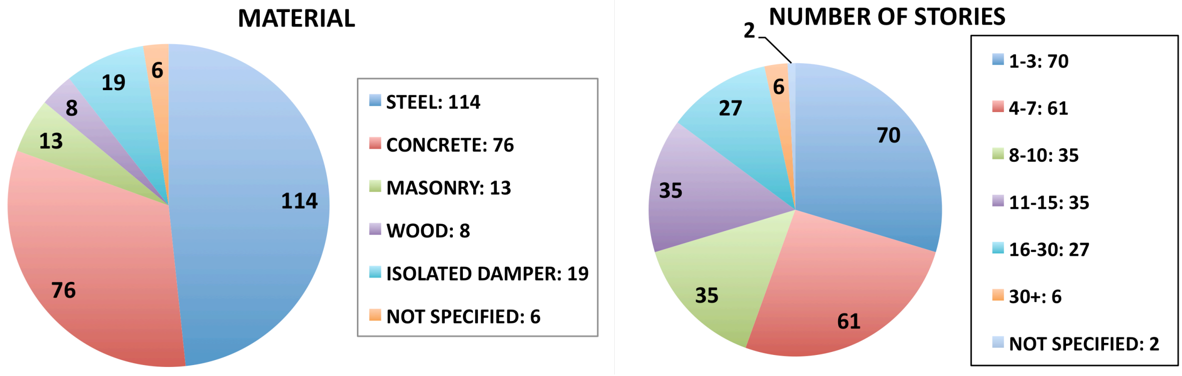

Figure 2.1. Description of the buildings of the database, classified by predominant design material (left) and by number of floors (right).

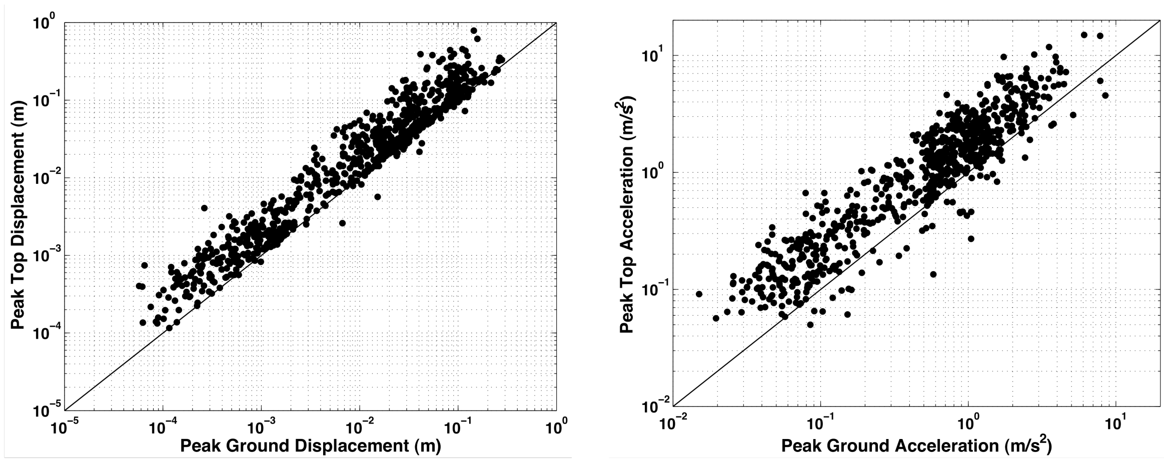

Figure 2.2. Distributions of the displacements (left) and the accelerations (right) recorded at the bottom and the top of the buildings of the database.

3. VARIABILITY IN BUILDINGS' RESPONSE DUE TO THE GROUND MOTION VARIABILITY

In order to fit the seismic vulnerability criteria generally used for giving the damage level, the response of the structures is provided by the computation of the maximum Normalized Relative Roof Displacement (NRRD), which is defined by the difference between the roof displacement and the ground floor displacement, divided by the height of the building. Furthermore, as it corresponds to the mean value of all the inter-story drifts in the structure, it can provide information on the structural damage state of the buildings under strong motions.
From the records of the database, we analyse the relations between the NRRD and the parameters of noxiousness, i.e. the parameters which describes the ground motions as the Peak Ground Acceleration, Velocity and Displacement (PGA, PGV and PGD), the Cumulative Absolute Velocity (CAV; EPRI, 1991), the Arias (1970) and Housner (1952) Intensities (Ia and Ih, respectively) and the Spectral Acceleration, Velocity and Displacement (Sa, Sv and Sd).
Bommer *et al.* (2004) considered the averaged and the maximum spectral displacement computed

between T_0 and FT_0, the F factor reflecting an increase of the period of the building when it becomes damaged. Todorovska and Trifunac (2007) and Michel and Guéguen (2010) tracked the resonance frequency of buildings under strong motions by applying a time-frequency processing on the records. They measured variations of the frequency, relating to the building integrity during an earthquake. Dunand *et al.* (2004) also provided analysis of the variation of the resonance frequency between before and after the Boumerdes (Algeria) earthquake for characterizing the damage. We performed herein the same process by applying a S-transform (Stockwell *et al.*, 1996) on each record at the top of the buildings, in order to point at the initial frequency (f_0) and the minimum frequency (f_{min}) of a structure during earthquakes. We also consider the frequency pointed at the Fourier Transform (f_{FT}) directly computed using the time-histories and corresponding to the maximal amplitude. Then we compute the spectral displacements, velocities and accelerations at these frequencies, and also the averaged and maximum spectral parameters obtained between the initial frequency and the minimum frequency of the building.

On Fig 3.1 are plotted the maximum NRRD versus the PGA, the CAV and the Ia, considering all the buildings of the database. It provides uncertainties, which are the uncertainties of the response (NRRD) due to the variability of ground motion, represented by these three parameters. For these parameters of noxiousness, it results uncertainties exceeding 0.4. In general, for all the buildings, whatever the parameter of noxiousness we choose for representing ground motions, the variability is at least equal to 0.4 (see the first column of the Tab. 3.1).
However, the variability of the response due to the ground motion variability can be modeled as a combination of epistemic uncertainties – due to a lack of knowledge in the response of structures – and aleatory uncertainties – due to the randomness of the seismic ground motions. By definition the aleatory component cannot be reduced, whereas the epistemic component is depending on the knowledge of the dynamic response of buildings. By classifying buildings by materials – steel and concrete – and number of stories – 1-3, 4-7 and more than 8 – i.e. by improving the building description, we can reduce the epistemic uncertainty, and therefore reduce the values of variabilities (Tab 3.1).
The averaged spectral displacement computed between the frequencies f_0 and f_{min} provide the lowest uncertainties, of about 0.15 to 0.20 for almost all classes of buildings (Tab 3.1 and Fig 3.2). In order to assess NRRD from this parameter, we provide linear regression coefficients for the following equation:

$$\log_{10}(NRRD) = \alpha + \beta \log_{10}\left[\overline{Sd}\left(\left[f_{\min}, f_0\right], 5\%\right)\right] \quad (3.1)$$

where *NRRD* and $\overline{Sd}\left(\left[f_{\min}, f_0\right], 5\%\right)$ correspond, to the normalized relative roof displacement and the average of the spectral displacement computed between the minimum frequency f_{min} and the initial frequency f_0 of the building during strong motions, respectively. Eqn 3.1 and NRRD data plotted versus $\overline{Sd}\left(\left[f_{\min}, f_0\right], 5\%\right)$ are shown in Fig 3.2. We obtain very good correlation between the logarithms of these parameters, with coefficients of correlation exceeding 0.80 for almost all classes (Tab 3.2).

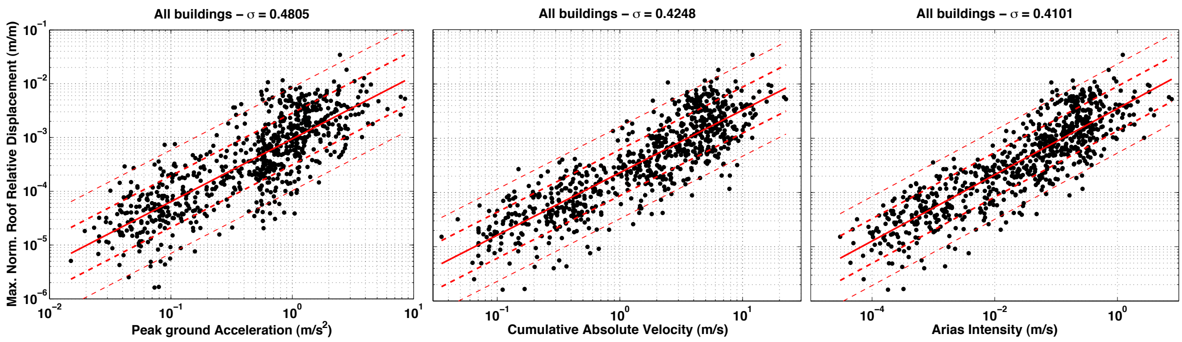

Figure 3.1. Variability in the buildings' response due to the variability to the ground motion, considering all the buildings of the database, for three parameters of noxiousness: PGA, CAV and Ia. The variability values are provided in the headers.

Table 3.1. Values of the variability between the Normalized Relative Roof Displacement and the parameters of noxiousness, depending on the typologies of buildings previously defined. The number of data of each class is indicated in the head of the table.

	All Nb: 772	**Steel** Nb: 312	**Conc.** Nb: 317	**Steel L** Nb: 86	**Steel M** Nb: 81	**Steel H** Nb: 145	**Conc. L** Nb: 71	**Conc. M** Nb: 116	**Conc. H** Nb: 130
PGA	0.4805	0.5189	0.4067	0.3528	0.4286	0.6302	0.4501	0.4070	0.3951
PGV	0.3953	0.3514	0.3491	0.2987	0.3045	0.3366	0.4304	0.3873	0.2684
PGD	0.4096	0.3465	0.4025	0.3627	0.3487	0.2687	0.4526	0.4146	0.3430
CAV	0.4248	0.3861	0.3553	0.3362	0.3752	0.3425	0.3717	0.3950	0.2712
Ia	0.4101	0.3848	0.3384	0.2968	0.3283	0.4075	0.3937	0.3631	0.2820
Ih	0.4121	0.3740	0.3283	0.2967	0.2779	0.3693	0.3998	0.3760	0.2422
Sd(f_{FT}, 5%)	0.4004	0.3281	0.3377	0.1772	0.1522	0.3581	0.5472	0.1977	0.1563
Sd($f_{0,ST}$, 5%)	0.3989	0.3326	0.3385	0.1857	0.1568	0.3608	0.5527	0.2545	0.1565
Sd($f_{min,ST}$, 5%)	0.3925	0.3144	0.3350	0.1740	0.1515	0.3309	0.5259	0.2366	0.1682
Max Sd([f_{min}-f_0],5%)	0.3927	0.3114	0.3347	0.1756	0.1525	0.3243	0.5264	0.2422	0.1632
Mean Sd([f_{min}-f_0],5%)	0.3944	0.3211	0.3325	0.1578	0.1528	0.3410	0.5428	0.2019	0.1526
Sv(f_{FT}, 5%)	0.3853	0.2810	0.3156	0.1876	0.1753	0.3206	0.4986	0.2957	0.2282
Sv($f_{0,ST}$, 5%)	0.3785	0.2963	0.3037	0.2033	0.2033	0.3473	0.5057	0.2975	0.2094
Sv($f_{min,ST}$, 5%)	0.3864	0.2853	0.3213	0.1877	0.1981	0.3259	0.4825	0.2913	0.2467
Max Sv([f_{min}-f_0],5%)	0.3774	0.2737	0.3114	0.1961	0.1942	0.3049	0.4906	0.2864	0.2277
Mean Sv([f_{min}-f_0],5%)	0.3782	0.2801	0.3070	0.1781	0.1766	0.3269	0.4957	0.2872	0.2168
Sa(f_{FT}, 5%)	0.6109	0.5743	0.5396	0.3292	0.4254	0.4946	0.4980	0.5506	0.4780
Sa($f_{0,ST}$, 5%)	0.5851	0.5408	0.5194	0.3225	0.4156	0.4652	0.4810	0.5238	0.4479
Sa($f_{min,ST}$, 5%)	0.6184	0.5718	0.5613	0.3427	0.4587	0.4807	0.4966	0.5571	0.5104
Max Sa([f_{min}-f_0],5%)	0.5878	0.5414	0.5261	0.3352	0.4230	0.4572	0.4736	0.5241	0.4664
Mean Sa([f_{min}-f_0],5%)	0.6006	0.5533	0.5384	0.3266	0.4343	0.4677	0.4844	0.5461	0.4726

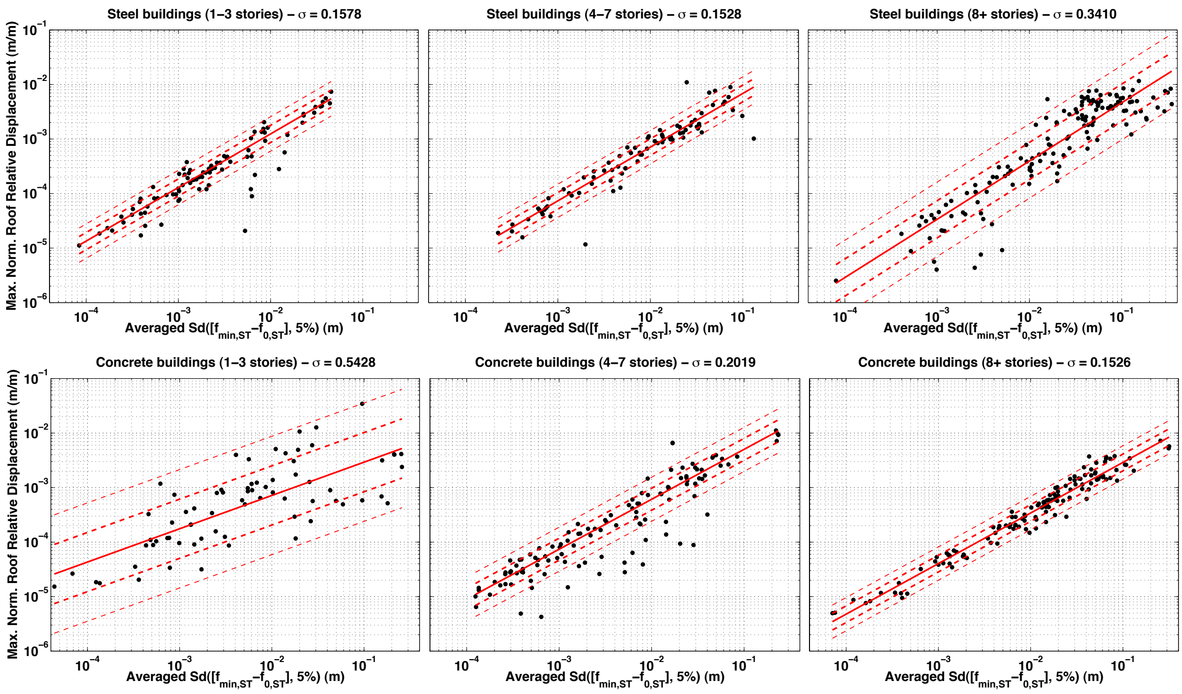

Figure 3.2. Eqn 3.1 and NRRD data plotted versus $\overline{Sd}\left(\left[f_{\min}, f_0\right], 5\%\right)$, for 6 classes of building.

Table 3.2. Coefficients **α** and **β** of the linear regression (Eqn. 3.1) between $\log_{10}$(NRRD) and $\log_{10}$(Sd), for the different classes of buildings: all buildings and steel, concrete, low height steel, moderate height steel, high height steel, low height concrete, moderate height concrete and high height concrete buildings)

	All	Steel	Conc.	Steel L	Steel M	Steel H	Conc. L	Conc. M	Conc. H
α	-1.598	-1.408	-1.706	-0.942	-1.180	-1.265	-1.922	-1.383	-1.611
β	0.845	0.892	0.827	0.982	0.985	1.069	0.611	0.916	0.927
R^2	0.734	0.804	0.763	0.833	0.892	0.839	0.547	0.817	0.959

In the Hazus methodology (FEMA, 2012), the variability of the response due to the variability of ground motion is assessed at 0.45 to 0.50 for the non-structural damage assessment and is not specified for the structural damage study. In this study this variability can reach 0.15 to 0.20 for almost all classes of buildings, providing that the ground motion is described by the average of the spectral displacement computed between the minimum frequency f_{min} and the initial frequency f_0.

4. CONCLUSION

In seismic vulnerability assessment methodologies such as Hazus, the building response variability due to the ground motion variability is introduced but not provided. Using a database of earthquakes recorded within Californian buildings, we aimed at assessing this variability.

Depending on the parameter that describes the seismic ground motion, low uncertainties between ground motion parameters and the response of buildings can be observed, considering the normalized relative roof displacement as parameter describing the building response. Furthermore, improving the building typologies allows decreasing the variability of the building responses. The parameter which provides lowest variabilities – about 0.15 to 0.20 following the building classes – is the mean spectral displacement computed between the initial frequency and the minimum frequency of the structure under seismic motions, this parameter taking into account both the elastic and non linear behaviors of structures under strong motions.

Finally, we provide regression coefficients between this ground motion parameter and the normalized relative roof displacement, which were given for different building classes and which lead to coefficients of correlation exceeding 0.80 for almost all classes.

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