Effects of the Seismic Input Variability on the Seismic Risk Assessment of RC Bridges

P. Ceresa
Istituto Universitario di Studi Superiori (IUSS), Pavia, Italy

E. Fiorini & B. Borzi
European Centre for Training and Research in Earthquake Engineering, Pavia, Italy

SUMMARY:
Aim of this study is the evaluation of input ground motion on the computation of fragility curves for RC bridges. Accounting for the different characteristics of the real and artificial accelerograms, this research aims to study the effects of the input variability on the computation of the fragility curves and on the seismic risk assessment of existing RC bridges. A probabilistic mechanics-based method is applied for the computation of the fragility curves performing nonlinear time-history analyses. Some cases-of-study are considered: three bridges located on four sites with increasing level of seismicity. Considering the mean value of the demand-to-capacity ratio and its standard deviation, the effects of the input variability on the computed responses are numerically estimated. The large variability related to real records has a reduced impact on the variability of the bridge response. However, the latter does not significantly affect the computed fragility curves.

Keywords: natural accelerograms, artificial accelerograms, fragility curves of RC bridges

1. INTRODUCTION

Following the prescriptions of the Italian seismic code (D.M. 14.01.2008, herein called NTC08), there is the possibility for the engineers to employ real or artificial ground motions in the assessment of the nonlinear response of existing reinforced concrete (RC) structures. There are several databanks for downloading real accelerograms. However, accurate and reliable tools are required in order to ensure their spectral compatibility with a given elastic response spectrum (Bommer and Acevedo, 2004). On the other hand, the use of artificial accelerograms in the evaluation of the nonlinear response of the structures has become an interesting approach for practitioners when appropriate recorded motions are not available and when several time-history nonlinear analyses have to be performed.

If the vulnerability assessment of existing RC bridges is concerned, it is important to know the degree of damage of the structures due to earthquakes. To estimate damage level, fragility curves are found to be valuable tools since they give the probability of reaching or exceeding a certain level of damage for a given ground motion intensity. As stated by Choi et al. (2004), analytical fragility curves are developed through seismic response data from the analysis of bridges. The fragility analysis generally includes three major parts: (a) the simulation of ground motions, (b) the simulation of bridges to account for uncertainty in bridge properties, and (c) the generation of fragility curves from the seismic response data of the bridges which can be obtained from nonlinear time history analysis, nonlinear static analysis or elastic spectral analysis.

In order to evaluate the seismic risk of the Italian RC multi-span simply supported and multi-span continuous bridges, a probabilistic mechanics-based method has been applied for the computation of their fragility curves performing nonlinear time-history analyses. The application of the methodology and the obtained results are presented by Ceresa et al. (2012, in these Proceedings). The time-history analyses are performed with suites of spectrum-compatible artificial accelerograms generated by means of an automatic procedure, as it will be explained in the following sections. Object of this research is the evaluation of the effects of the different types of input ground motion on the computation of fragility curves. Taking into account the different characteristics of the real and artificial accelerograms, this research aims to study the effects of the input variability on the computation of the fragility curve and on the seismic risk assessment of existing RC bridges.

2. APPLIED METHODOLOGY FOR COMPUTING FRAGILITY CURVES

The study has been carried out within the project "Seismic risk of the national road transport network", commissioned by the Italian Civil Protection Department. An ad-hoc database has been developed in order to collect the bridge information in terms of position, geometry and structural data. A complete set of data is available for about four hundreds bridges allowing the creation of an accurate digital model for each one of these bridges. By means of an automatic procedure, BRIdge auTomatic Nltha-based Earthquake fragilitY (BRI.T.N.E.Y.), n-suites of m-simulations are carried out for each bridge. The number n of suites corresponds to the 9 return periods, T_r, characterising the ground shaking (30, 50, 72, 101, 140, 201, 475, 975 and 2475 years). Each suite consists of m couples of artificial horizontal records, generated for being statistically independent in x and y directions and compatible with the elastic spectra associated to each bridge according to the NTC08 prescriptions. The seismic response data of the bridges are obtained performing nonlinear time-history analyses. The bridges are analysed as fully restrained at the base. Each time-history analysis requires two orthogonal components of horizontal motion to be used. Two limit states are considered – damage and collapse limits states (DLS and CLS, respectively) considering ductile and brittle mechanisms of the piers as well as the span unseating. The ductile mechanisms are checked considering the chord-rotation of the pier bottom segment. The brittle mechanisms are verified with respect to the column shear strength. The span unseating is evaluated computing the relative displacement between the superstructure and the pier. The conditional probability of exceeding a specific limit state for a ground motion intensity level is derived from Monte Carlo analyses. The selected measure of the ground motion intensity is the peak ground acceleration at bedrock, a_g. An overall seismic demand-to-capacity ratio Y of the bridge is computed, being a measure of the global state of a structure according to the cut-set formulation, whereby a structural system is described as sub-systems in series of its components. Y is the ratio between demand and capacity for the component that leads the system closer to considered LS, at the attainment of which Y equals unity. For each one of the 9 T_r, the peak values of Y are computed for each simulation, leading to m values of Y (Y_i). The Y_i values computed for each T_r are then fitted with a lognormal distribution. The probability of reaching or exceeding a limit state is then analytically computed from the probability distribution of the Y_i, conditioned by the considered T_r (i.e., a_g) of the ground motion.

After a validation study of the accuracy of the obtained results as a function of the number of m simulations per each n-th suite and taking into account the computational resources required for performing the analyses and manipulating their results, the number m of simulations was assumed equal to 10. This means that the computation of each fragility curve requires 90 simulations to be performed. Furthermore, the majority of the bridges for which it is possible to compute the fragility curves is characterised by the presence of rubber bearings. As explained in Ceresa et al. (2012), two different assumptions have been introduced for modelling these devices: with friction devices and with fixed devices. Therefore, the 336 RC bridges of the database with rubber bearings have to be analysed twice.

In the first steps of this research, there were some doubts in relation to the use of artificial accelerograms rather than natural accelerograms. It is well known that real records are the best representation of seismic loading for structural assessment and design. However, it was decided to generate artificial signals considering the large amount of simulations to be performed. The generated artificial records have an equal duration per each simulation. It has to be pointed out that the record duration is a parameter, as the number of n-suites and m-simulations, which can be changed before performing the calculation of each fragility curve.

2.1. Main characteristics of the generated artificial records

As previously introduced, the application BRI.T.N.E.Y. generates, for each n-th suite, artificial accelerograms independent in the two orthogonal directions and whose response spectra match the target spectrum at the site of interest (corresponding to the location of the bridge). The application provides m accelerograms for the x-direction and m accelerograms for the y-direction and each time-series has to be compatible with the target elastic spectrum. The latter is computed according to the NTC08 prescriptions, using the parameters (a_g, F_0, and T^*_c) of the NTC grid, derived from the probabilistic seismic hazard study carried out by INGV (http://esse1-gis.mi.ingv.it/), having 5 km spacing and covering the whole Italian territory, and computing the weighted average of the four points of the grid related to the site of interest. The approach employed for generating artificial spectrum-compatible accelerograms is close to the one implemented in programs such as SIMQKE (Gasparini and Vanmarcke, 1979), using the following steps:

i) Generation of a power spectral density function from the smoothed response spectrum, according to the work of Muscolino (2002);
ii) Improvement of the match between the computed and the target response spectrum with some iterations (Cerami and Ricciardi, 1989);
iii) Baseline correction, imposing the following conditions:
   a. $a(t = 0) = 0$, $v(t = 0) = 0$, $d(t = 0) = 0$;
   b. $a(t = T) = 0$, $v(t = T) = 0$, $d(t = T) <> 0$;
   c. addition of an adequate tail of zero intensity allowing the decay of the structure transient response with time.

For each suite, the set of generated records has to satisfy the conditions recommended by the NCT08: the average elastic spectrum has not to underestimate the 5% damping elastic code spectrum with a 10% tolerance in the larger range of period between [0.15s, 2s] and [0.15s, $2T_1$], where T_1 is the fundamental period of vibration of the bridge.

The generated accelerograms are compatible with the target spectrum in a range of periods between 0.01 and 4 seconds. They are then filtered up to 50 Hz with a Butterworth band-pass filter of order four. In the seismic risk evaluation of the Italian RC bridges presented in Ceresa et al. (2012), the total duration of each signal is set equal to 15 seconds with a pseudo-stationary part whose length is equal to 10 seconds (according to NTC08 prescriptions). The total duration of each signal is less than the duration of 25 seconds recommended by the NTC08. However, there are several reasons that can justify the choice of a signal duration of 15 seconds as a good compromise between the accuracy of the results and the required computational resources for obtaining them, such as: i) the large amount of simulations to be carried out per bridge, ii) the number of bridges to be analysed. Furthermore, the fragility curves are computed from the peak values of the demand over the capacity. It has been assumed that the peak values of the demand are related to the pseudo-stationary part of the signal whose length satisfies the NTC08 prescriptions.

3. EVALUTATION OF THE EFFECTS OF THE INPUT GROUND MOTION VARIABILITY

The input ground motions to be compared in this study refer to artificial accelerograms and natural scaled records. The approach described in Section 2.1 provides artificial records whose response spectra match the target response spectrum. It is well known (i.e., Pousse et al., 2006) that the matching procedure may generate too many cycles of strong motion. Therefore, the artificial records usually have high energy content. On the other hand, if real records are concerned, to find a suite matching the target response spectrum may be hard or practically unfeasible if appropriate tools are not available (Beyer and Bommer, 2007; Iervolino et al., 2009). In addition, despite the increasing number of strong-motion networks installed, the availability of natural records is sometimes limited because of the absence of nearby recording stations or because the site is in a low to moderate seismicity region (Pousse et al., 2006). Real earthquake records could have very long durations and this has to be taken into account when an analytical fragility curve has to be computed applying a methodology as the one described in Section 2.

There are tools for computer aided code-based record selection, such as REXEL (Iervolino et al., 2009) which allow the user to build design spectra and to search for groups of real records (7, 14, 21). However, even if there are advanced tools like REXEL, the final aim is to produce, for each return period T_r, an optimal suite of accelerograms for which there is a good match with the elastic spectral ordinates related to the site of interest, and for which there is low variability amongst the spectral ordinates of the scaled records; an additional objective is to obtain the suite with the least amount of scaling possible (Bommer and Acevedo, 2004). Furthermore, the records have to be selected for a given range of magnitude and distance in relation to the disaggregation of hazard derived by INGV (http://esse1-gis.mi.ingv.it).

For the evaluation of the effects of the input ground motion variability on the computation of the fragility curves, some comparisons have to be carried out. Applying the probabilistic methodology described in Section 2, the seismic demand of some cases-of-study has been considered. In particular, three RC bridges have been selected as representative of the multi-span simply supported bridges belonging to the available database. Then, four sites have been chosen in order to increase the level of seismicity accounted for in the generation of the input ground motion, or in the selection of the real records, and in the computation of the fragility curves.

3.1. Selected cases-of-study

The selected RC bridges are schematically represented in Figure 3.1. They are named B1, B2 and B3.

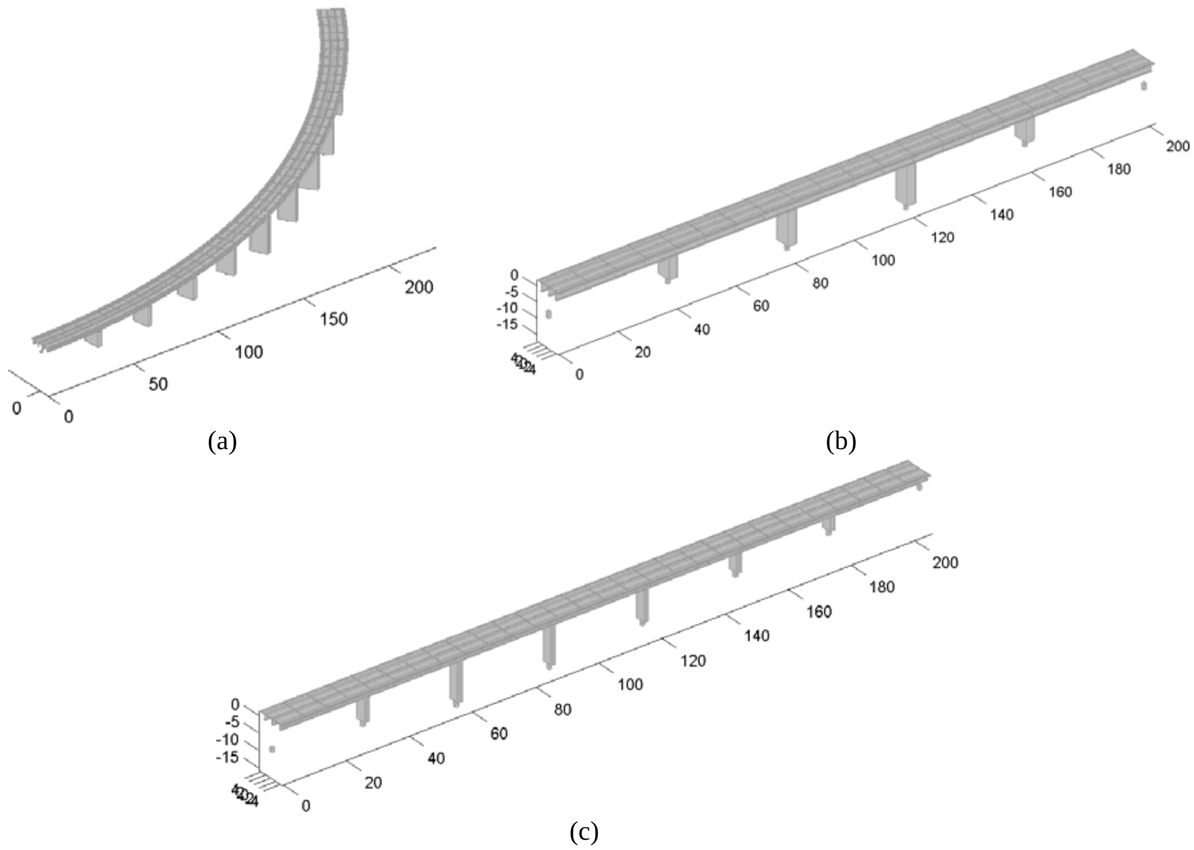


Figure 3.1. Three RC multi-span simply supported bridges selected as cases of study. a) Bridge B1, b) B2 and c) B3. Their main characteristics are summarised in Table 3.1

They have been selected because their characteristics are common to several other bridges of the available database. The bridge B1 is a curved bridge whose piers have hollow rectangular cross-sections; B2 and B3 are straight bridges whose piers have hollow rectangular and rectangular cross-sections, respectively. Their period of construction is between 1960 and 1970. Their main characteristics are summarised in Table 3.1. In addition to these data, it has to be noted that these bridges have rubber bearings. Therefore, as explained in Section 2, they have to be modelled with friction devices and with fixed devices, respectively. In this validation study, only the results obtained from the analysis with friction devices are discussed. According to this modelling assumption, the fundamental periods of vibration of the three bridges are: T_1 = 0.745 seconds for B1, 0.527 s for B2, and 0.933 s for B3 (referred to the elastic branch of the nonlinear devices). According to NTC08 classification, the site class of the three bridges is B.

Table 3.1. Main characteristics of the three selected multi-span simply supported RC bridges

Bridge	Total length (m)	Max span length (m)	Min span length (m)	Max span weight (kN)	Min span weight (kN)	Max pier height (m)	Min pier height (m)
B1	354.85	33.01	28.98	6568.99	5767.02	19.74	6.88
B2	201.50	40.30	40.30	6081.70	6081.70	10.60	5.00
B3	205.00	29.50	28.75	3267.50	3184.43	10.01	2.12

Table 3.2. Geographical coordinates, parameters derived from the probabilistic seismic hazard study and disaggregation data for the four selected sites derived by INGV (http://esse1-gis.mi.ingv.it)

	Longitude	Latitude	T_r	a_g (m/s^2)	Fo	Tc*	M	R (km)	ε
			50	0.30	2.47	0.21	5.29	85.13	1.10
site 1	12.83	45.49	**475**	**0.64**	2.55	0.38	**5.80**	**76.70**	1.70
			975	0.79	2.63	0.43	5.95	75.17	1.87
			50	0.50	2.47	0.33	5.63	56.81	0.94
site 2	14.96991	41.97552	**475**	**1.17**	2.59	0.40	**5.82**	**38.23**	1.44
			975	1.49	2.60	0.42	5.89	33.63	1.56
			50	0.62	2.36	0.30	5.52	30.64	0.31
site 3	15.92	37.93	**475**	**1.83**	2.42	0.37	**5.81**	**18.58**	0.83
			975	2.45	2.44	0.40	5.90	16.81	1.00
			50	0.80	2.40	0.28	5.31	22.58	0.30
site 4	15.38686	37.91841	**475**	**2.41**	2.43	0.35	**5.82**	**14.21**	0.73
			975	3.29	2.45	0.37	6.03	13.41	0.89

Table 3.2 summarises the four sites selected with the aim of considering sites with an increasing level of seismicity. The data of the table refer to the coordinates of the sites, the parameters of the probabilistic seismic hazard study and the disaggregation data derived by INGV (http://esse1-gis.mi.ingv.it), where M is the moment magnitude, R the source-to-site distance and ε is the number of (logarithmic) standard deviations by which the (logarithmic) ground motion deviates from the median value predicted by an attenuation equation for a given M = m and R = r pair.

The criterion for increasing the level of seismicity accounted for is the following: given a return period of 475 years, the selected sites have to be characterised by increasing a_g values, keeping M approximately constant. For T_r equal to 475 years, the four selected sites (Table 3.2) have increasing a_g values (equal to 0.64, 1.17, 1.83, 2.41 m/s^2, respectively) with decreasing source-to-site distances R (equal to 76.70, 38.23, 18.58 and 14.21 km, respectively), and keeping M varying in the range of 5.80-5.82.

In order to perform the validation study, each one of the bridges B1, B2 and B3 is located on each one of the four sites. The fragility of each bridge has to be computed using as input ground motion artificial records or natural scaled accelerograms. The former are generated by mean of the automatic procedure implemented in BRI.T.N.E.Y (and described in paragraph 2.1). The natural scaled accelerograms have been selected using the code REXEL, according to the criteria (good match, low variability, small mean scaling factor, and, whenever feasible, duration not too long) previously discussed. Taking into account the high number of nonlinear time-history analyses to be carried out and the non-negligible effort required for the selection of an optimal suite of natural scaled accelerograms, it was decided to perform the comparisons considering three return periods of reference – 50, 475 and 975 years. The REXEL option of searching for 7 pairs of accelerograms has been selected, allowing the search of 14 records, that is 7 in the x-direction and 7 in the y-direction, which, on average, are compatible with the target spectrum of the site of interest. The European Strong Motion database (ESD) has been chosen taking into account the large number of signals to be selected which have to satisfy the characteristics specified in Table 3.2. The criteria used during the selection of the accelerograms are the followings:

i) To find records for the site class B (which is the site class of the bridges B1, B2 and B3);
ii) To derive the average elastic spectrum of the 14 records matching the target spectrum with the lower and upper tolerances of 10% (lower limit) and 30% (upper limit), respectively. These tolerances are the maximum deviations, in percentage terms, that the average spectrum of the suite of accelerograms can have with respect to the target in the specified range of periods. Taking into account the NTC08 prescriptions and the fundamental periods of vibration of the three bridges (T_1), the considered range of periods is [0.15s, 2s].
iii) To have a good fit of the average displacement spectrum with the target spectrum.
iv) To select the records of the database for a given range of magnitude and distance compatible with the (M, R) pairs of the disaggregation of hazard listed in Table 3.2.

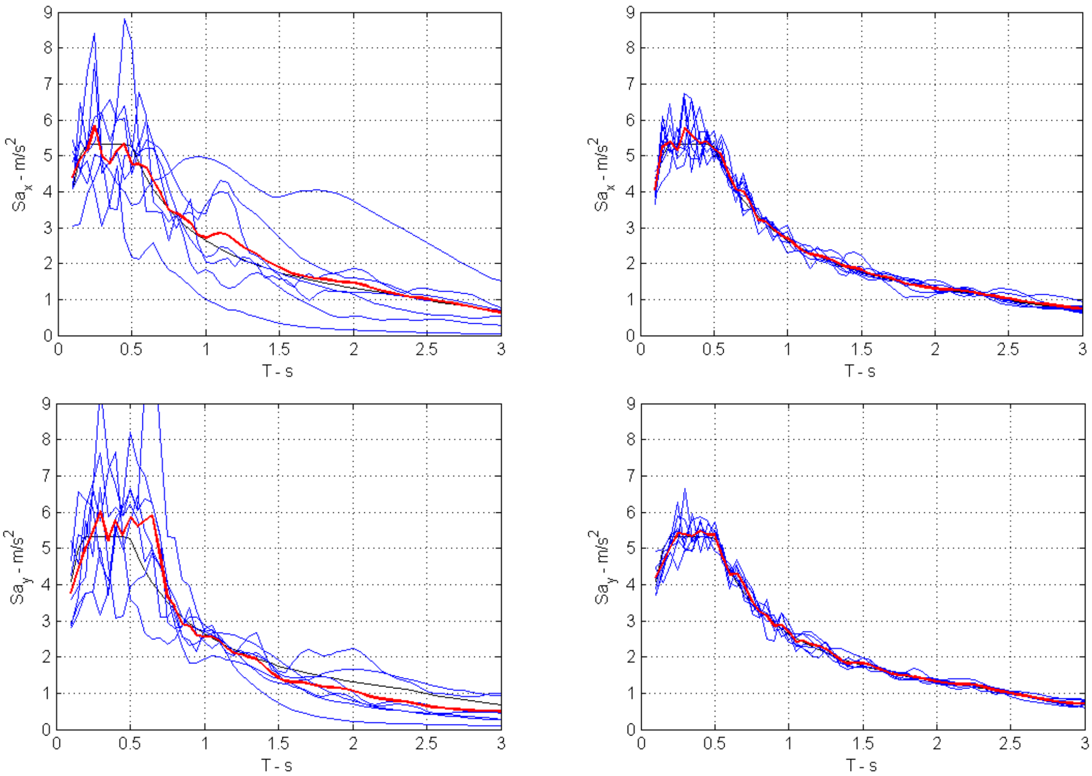


Figure 3.2. Site 3 and T_r = 475 years: acceleration spectra for the x-direction (on the top) and y-direction (on the bottom): spectrum-compatible suites simulating the input ground motion with natural scaled accelerograms (on the left) and artificial records (on the right).

Even if these four criteria are satisfied, one of the difficulties in the selection of the final optimal suite of accelerograms was related to the large variability amongst the spectral ordinates of the scaled records, mainly in a range of periods (between 0.5s and 1.0s) close to the fundamental periods of vibration of the three bridges. In order to reduce this variability, the amount of scaling of the suite of

14 records has been increased up to a maximum factor of 5 in the case of some return periods. For a given return period, the mean duration of the selected 14 natural scaled records varies between 30 to 55 seconds. On the opposite, the duration of the 14 artificial records, generated for a given T_r by means of the automatic procedure previously described, is always equal to 15 seconds.

Figure 3.2 shows the target code spectra (x- and y-direction, respectively) for the site 3 and T_r equal to 475 years, and the mean spectra obtained with the selected suite of natural scaled signals (on the left) and the artificial records (on the right). The large variability of the spectral values related to natural scaled signals can be seen in both x- and y-directions.

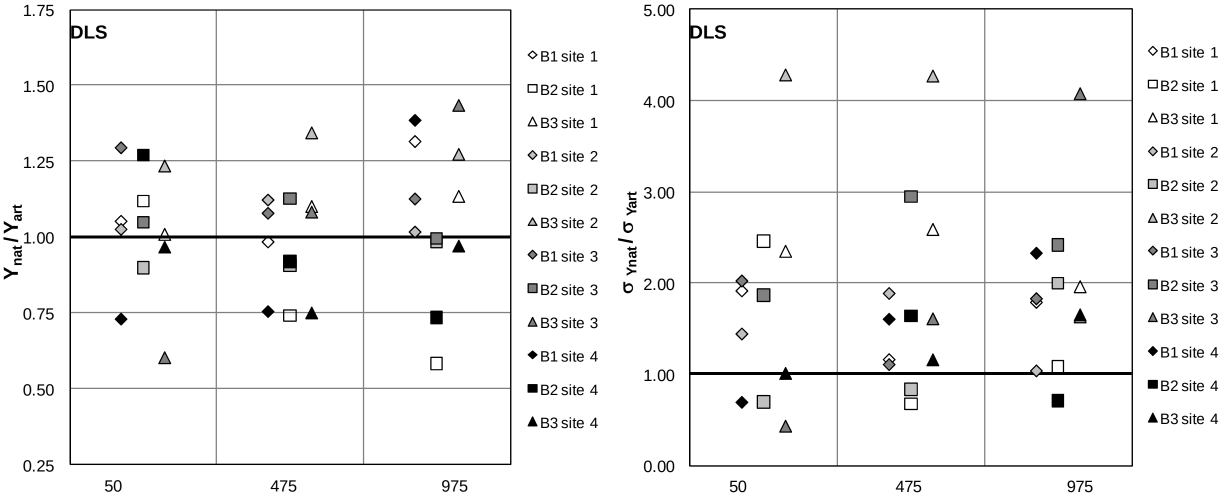
For the three bridges B1, B2, and B3 the computation of the fragility curves is performed twice for each one of the four sites of interest (Table 3.2). The first analysis is carried out using as input ground motion the natural scaled accelerograms derived for the three return periods per site. Then, the analysis is performed considering the artificial ground motions generated for the 3 T_r per site.

3.2. Comparison of the obtained results

The effects of the type of input ground motion used and its variability on the seismic fragility of the bridges B1, B2 and B3 are firstly evaluated comparing the mean value of the demand-to-capacity ratio Y and its standard deviation (defined in Section 2). For the sake of clarity, the mean value of Y derived from the simulations with natural scaled records is called Y_{nat}; if artificial records are concerned, the mean value is named Y_{art}. The same notation is followed for identifying the standard deviations of Y_{nat} and Y_{art} as σ_{Ynat} and σ_{Yart}, respectively.

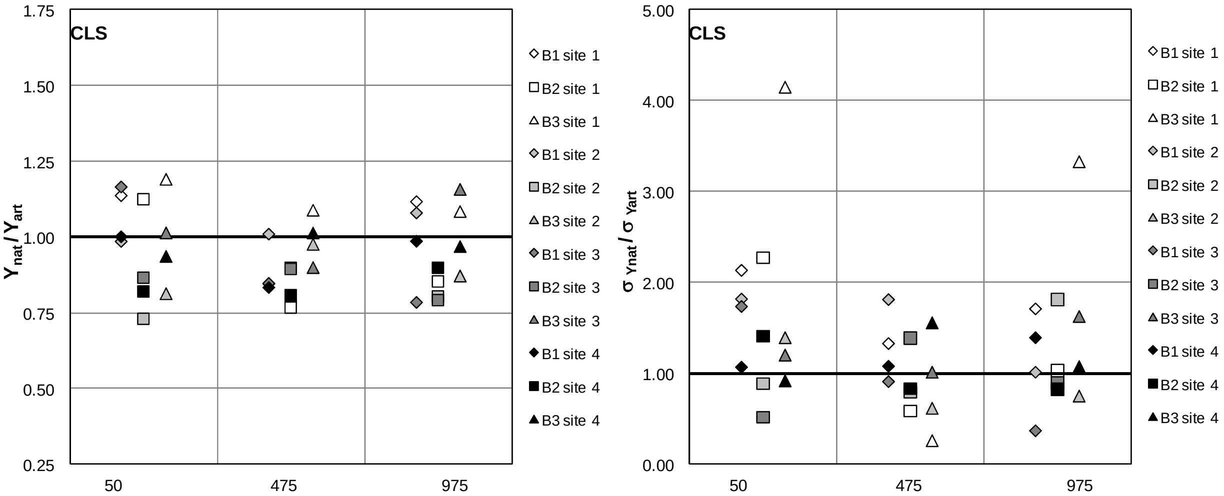
Figure 3.3 shows the results obtained for the damage limit state (DLS) for the three bridges located in the four sites with increasing level of seismicity. The ratio between Y_{nat} and Y_{art} is plotted in Figure 3.3(a), whereas the ratio in terms of standard deviations ($\sigma_{Ynat}/\sigma_{Yart}$) is in Figure 3.3(b). The data plotted in these figures give several interesting information. First of all, the mean values of the Y_{nat}-to-Y_{art} ratios are almost constant for the three bridges on the four sites and they are close to one, mainly if the return periods of 50 and 475 years are concerned. Considering, for example, the 475 year return period, the bridge B1 has the following values of the ratios Y_{nat} over Y_{art}: 0.98 on site 1, 1.12 on site 2, 1.08 on site 3 and 0.75 on site 4; the mean value of these four ratios is 0.98. Considering T_r equal to 50 years, the bridge B2 is characterised by these Y_{nat}-to-Y_{art} ratios: 1.12, 0.90, 1.05, 1.27 moving from site 1 to site 4, with a mean value of 0.98. Taking into account the standard deviations of Y, Figure 3.3(b) shows that the σ_{Ynat}-to-σ_{Yart} ratios have values generally greater than one, meaning that standard deviation of Y_{nat} is greater than the one related to Y_{art}. The mean value of all the ratios σ_{Ynat} over σ_{Yart} is about 2 (the latter has been computed taking into account the responses of the three bridges on the four sites for each one of the three considered return periods; the mean value of the three ratios computed for the 3 T_r is then derived). This means that the large variability of the spectral ordinates related to the choice of the natural scaled accelerograms (depicted, for example, in Figure 3.2) has an extremely reduced impact (the mean value is about equal to 2) on the variability of the bridge response. This trend can be observed for each one of the bridges, for each of the considered return periods T_r and for each one of the four considered seismicity levels. The observed trend seems to be independent from the considered level of seismicity. Finally, it could be noted that the bridge B3 is always characterised by σ_{Ynat}-to-σ_{Yart} ratios that are greater than those computed for B1 and B2. This probably could be justified taking into account that its fundamental period of vibration is 0.933 s and that the larger variability amongst the spectral ordinates of the natural scaled records have been observed in the range of this period.

If the collapse limit state (CLS) is concerned, Figure 3.4 shows the trend of the Y_{nat}-to-Y_{art} ratios (on the left) and σ_{Ynat}-to-σ_{Yart} ratios (on the right) for the three bridges located on the four sites of interest. The mean value of the Y_{nat}-to-Y_{art} ratios remains close to 1 for the three bridges, for the 3 T_r and the 4 seismicity levels (Figure 3.4a). The effects of the input variability due to the natural scaled records can be shown in Figure 3.4(b) and the mean value of all the ratios σ_{Ynat} over σ_{Yart} is about 1.5. Even for this limit state, the effects of the input variability are negligible if the mean Y values are concerned. These effects increase on the variability of the Y, even if the induced variability is limited if compared with the one associated to the natural scaled signals.



(a) (b)

Figure 3.3. Ratios between (a) Y_{nat} over Y_{art} and (b) σ_{Ynat} over σ_{Yart} for the three RC bridges (Figure 3.1) on the four sites with increasing seismicity (Table 3.2) – Damage Limit State



(a) (b)

Figure 3.4. Ratios between (a) Y_{nat} over Y_{art} and (b) σ_{Ynat} over σ_{Yart} for the three RC bridges (Figure 3.1) on the four sites with increasing seismicity (Table 3.2) – Collapse Limit State

The probability of reaching or exceeding a limit state is then analytically computed from the probability distribution of the Y values (Y_{nat_i} and Y_{art_i}, according to the notation introduced in Section 2) conditioned by the considered T_r (i.e., a_g) of the ground motion. The effects of the input ground motion and its variability are evaluated with an additional comparison considering the median value of the cumulative distribution functions related to the Y_{nat_i} and Y_{art_i} distributions. The difference between the median obtained from the simulations with natural scaled accelerograms and the median obtained with the generated records are plotted in Figure 3.5 for the three bridges of four sites of interest, considering the DLS. As it could be expected, the variability of the input ground motion has not significant effects on the median values.

Figure 3.6 shows the comparison of the fragility curves computed for the bridge B1 on the site 3 for damage and collapse limit states. As it can be noted, the probabilities of exceedance of the limit states are slightly larger when artificial records are used as input ground motion. As previously discussed, this could be justified knowing that the artificial records usually have high energy content. However, the evaluated variability of the response does not significantly affect the computed fragility curves.

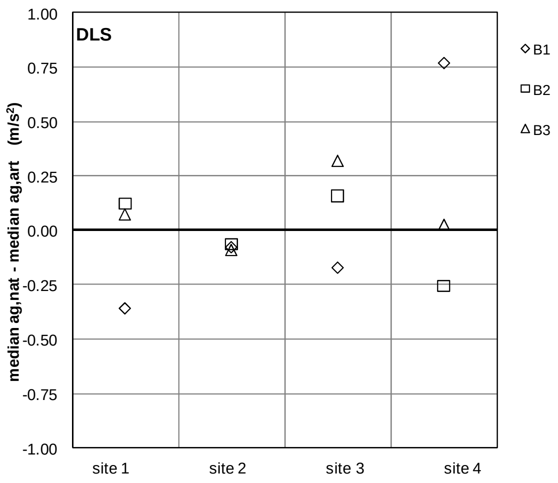


Figure 3.5. Differences of the median values of the cumulative distribution functions related to Y_{nat} and Y_{art} distributions. The DLS condition of the three bridges on the four sites is taken into account

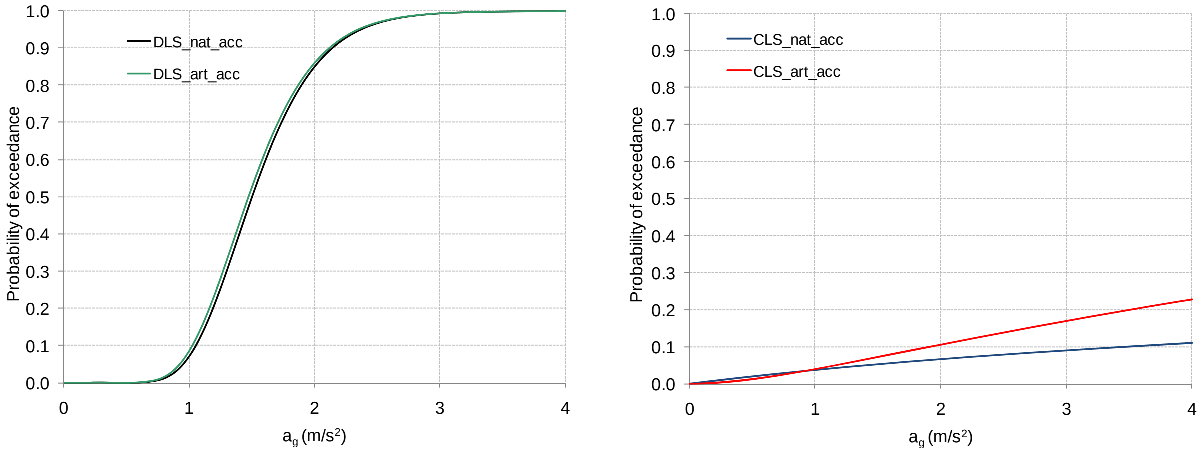


Figure 3.6. Bridge B1 on site 3 - Comparison of the fragility curves for the DLS and the CLS computed with different types of the input ground motion: natural scaled accelerograms and artificial accelerograms

4. CONCLUSIONS

The effects of the input variability on the computation of the fragility curves and on the seismic risk assessment of existing RC bridges have been evaluated, taking into account the different characteristics of the natural scaled and artificial accelerograms. A probabilistic mechanics-based method has been applied for the computation of the fragility curves performing nonlinear time-history analyses. Three bridges have been selected as representative of the RC multi-span simply supported bridges of the available database. The response of these bridges has been computed considering four sites with increasing levels of seismicity. The mean value of the demand-to-capacity ratio Y derived from the simulations with natural scaled records is compared with the mean value of demand-to-capacity ratio Y computed with artificial signals. Then, the standard deviations of the mean value of Y are compared. For the considered cases-of-study the effects of the input variability related to natural scaled records are negligible if the mean values of Y are concerned. Considering the standard deviation of Y, a slightly larger variability is numerically estimated when real records are considered. However, the evaluated variability of the response is extremely reduced if compared to the variability of the natural scaled signals. For the considered cases-of-study, it has been calculated that the variability of the response does not significantly affect the computed fragility curves.

Future developments of the applied probabilistic mechanics-based method for the seismic risk assessment of RC bridges are still required. One of the developments should be related to the use of more realistic time series, as natural accelerograms or, for instance, the records produced from seismological source models, accounting for path and site effects. Taking into account the large amount of analyses to be performed and the great number of RC bridges for which the seismic risk has to be evaluated, the use of natural records is not a viable option. Also the use of strictly seismological models that require many parameters to characterize the source rupture process, path and site effects cannot be easily applied to a national scale project such as the one presented here. A good compromise between the accuracy of the computed seismic response and the computational efforts required for the seismic risk assessment could be the generation of synthetic ground motions for a given set of earthquake and site characteristics. An interesting possibility is the application of the method developed by Rezaeian and Der Kiureghian (2010). More study is required on this subject and it will be the object of future work and applications.

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