COMPARISON OF NATURAL AND ARTIFICIAL TIME HISTORIES FOR NON-LINEAR SEISMIC ANALYSES OF STRUCTURES

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Abstract

Due to increased potentialities of computers, it is nowadays possible to perform dynamic non-linear computation of structures to evaluate their ultimate behavior under seismic loads using refined finite element models. Nevertheless, one key parameter for such complex computations is the input load (i.e. input time histories), which may lead to important discrepancies in the results and therefore difficulties to deal with for engineering purpose (variability, number of time histories to use …). In this situation, the opportunity to use artificial time histories or not and the way to account for scattering must be carefully assessed.

The objective of this study is to give some elements concerning (i) the potential effectiveness of artificial time histories to reproduce structural damages led by real earthquakes and (ii) the number of accelerograms to be used for non-linear computations and the way to account for scattering of results.

1 Context and objectives of the study

The French Basic Safety Rule concerning seismic design of civil structures (RFS V.2.g, [5]) is currently under revision. In that situation, the potential use of dynamic transient non-linear computation for specific cases is under assessment.

Independently on methods of solutions, which have to be used within their domain of qualification, the question of the input loads (i.e. time histories) is to be assessed in detail in terms of (i) representativeness, (ii) number of accelerograms to be used and (iii) resulting scattering of results.

In that context, the objective of this study is to give some elements concerning the influence of time histories on results of dynamic transient non-linear seismic computation. The specific points more specifically analyzed are :

Representativeness of times histories : This point is presented is chapter 2, based on the comparison of natural and artificial time histories in terms of induced damage on
reinforced concrete structures.

Scattering of results: This point is presented is chapter 3, based on considerations concerning the number of accelerograms to be used and the way to account for scattering.

2 Part one - Comparison of natural and artificial time histories in terms of induced damages on reinforced concrete structures

The objective of this part is to give some elements concerning the effectiveness of artificial time histories to reproduce damage of structures. The following paragraphs present the tools and the input data used, describe the calculations that were performed and give the main results and conclusions.

2.1 Description of tools and input data

2.1.1 Strong Motion Data Based description

The Strong Motion Data Base (SMDB) used in this study was established by several European scientific organisms [1]. This SMDB is made of 965 seismic records (horizontal and vertical ones) recorded in Europe and USA. Each record is characterized by local magnitude $M$ of the corresponding earthquake, focal distance $R$ from the source and soil characteristics of the station. This SMDB covers approximately earthquakes from magnitude 4.5 to 7.3 and focal distance 7 km to 100 km.

This SMDB was used to establish regression laws to determine the Ground Response Spectrum (GRS) of an earthquake based on its magnitude $M$, its focal distance $R$ and soil characteristics of the site (i.e. rock : $Vs > 800$ m/s or medium : $300$ m/s < $Vs < 800$ m/s). These regression laws are used in application of the French Basic Safety Rule, which defines the method to be used for the evaluation of seismic hazard for nuclear facilities (RFS 2001-01, [5]).

The Safe Shutdown Earthquake (SEE) GRS can be calculated based on the following regression law.

$$\log_{10} PSA (F) = \alpha(F) M + \beta(F) R - \log_{10} R + \gamma_{SOIL}(F) (+/- \sigma)$$

where :

- $PSA (F)$ is the pseudo-acceleration of the ground response spectrum, for the corresponding frequency $F$,
- $\alpha(F)$, $\beta(F)$ and $\gamma_{SOIL}(F)$ are the regression coefficients determined using the SMDB, depending on the frequency $F$ and calculated for each damping ratio of interest,
- $\sigma$ is the standard deviation.

2.1.2 Regression laws for Ground Motion Parameters

In order to extend the previous regression law to other ground motion parameters, EDF and CEA (Commissariat à l’Energie Atomique - France) have carried out a study [2] to calculate regression laws for classical Ground Motion Parameters (GMP). The same type of law than the one used for the ground response spectrum was selected and the SMDB was also used to remain fully consistent with the RFS 2001-01 GRS methodology.
Nevertheless, a preliminary study showed that the regression law could be simplified and expressed in the following form:

\[ \log_{10} GMP = \alpha M + \gamma \log_{10} R + \delta \ (\pm \sigma) \]

The selected GMP are the following:
- A (maximal acceleration or peak ground acceleration),
- V (maximal velocity or peak ground velocity),
- D (maximal displacement or peak ground displacement),
- A/V ratio,
- CAV (Cumulative Absolute Velocity) equal to \( \int |\gamma(t)| dt \) where \( \gamma(t) \) is the time history,
- Ia (Arias Intensity) equal to \( \frac{\pi}{2g} \int \gamma^2(t) dt \),
- T (duration defined as duration from 5% to 95% Ia),

In table 1 are given calculated \( \alpha \), \( \gamma \), \( \delta \) and \( \sigma \) coefficients for each GMP.

<table>
<thead>
<tr>
<th>GMP</th>
<th>( \alpha )</th>
<th>( \gamma )</th>
<th>( \delta )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (m/s²)</td>
<td>0.295</td>
<td>-0.985</td>
<td>1.575</td>
<td>0.309</td>
</tr>
<tr>
<td>V (m/s)</td>
<td>0.432</td>
<td>-0.945</td>
<td>-2.468</td>
<td>0.340</td>
</tr>
<tr>
<td>D (cm)</td>
<td>0.570</td>
<td>-0.585</td>
<td>-2.236</td>
<td>0.470</td>
</tr>
<tr>
<td>A/V (s⁻¹)</td>
<td>-0.137</td>
<td>-0.041</td>
<td>2.043</td>
<td>0.197</td>
</tr>
<tr>
<td>CAV (m/s)</td>
<td>0.324</td>
<td>-0.308</td>
<td>-1.058</td>
<td>0.230</td>
</tr>
<tr>
<td>Ia (m/s)</td>
<td>0.495</td>
<td>-0.912</td>
<td>-2.517</td>
<td>0.424</td>
</tr>
<tr>
<td>T (s)</td>
<td>0.164</td>
<td>0.324</td>
<td>-0.483</td>
<td>0.204</td>
</tr>
</tbody>
</table>

### 2.1.3 Simplified reinforced concrete structure

In our case, simplified reinforced concrete structures are modeled as a single degree of freedom (SDOF) oscillator governed by bilinear Takeda's constitutive law that takes into account stiffness degradation. Post-elastic behavior can be modeled to reproduce typical behavior of a (shear) wall type RCS or a frame type RCS, as shown in figure 1.

![Figure 1 - Single DoF with bilinear Takeda's constitutive law](image)

Wall type RCS          Frame type RCS
2.2 **Natural and artificial time histories selection**

For this study, one case has been selected, representative of a typical SSE for a French nuclear Pressurized Water Reactor. The SSE characteristics are the following.

- **Magnitude** $M = 5.5$
- **Focal distance** $R = 9$ km
- **Rock soil** ($V_s > 800$ m/s)

The corresponding ground response spectrum (GRS) is determined based on RFS2001-01 regression law. The GRS is shown on figure 2 (maximum ground acceleration is 0.2g).

![Figure 2 - Ground Response Spectrum (M = 5.5 - R = 9 km)](image)

According to regression laws described in chapter 2.1.2, the corresponding GMP are given in table 2.

**Table 2 - Ground Motion Parameters (M = 5.5 - R = 9 km)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude</td>
<td>$M = 5.5$</td>
</tr>
<tr>
<td>Focal distance</td>
<td>$R = 9$ km</td>
</tr>
<tr>
<td>Rock soil</td>
<td>($V_s &gt; 800$ m/s)</td>
</tr>
</tbody>
</table>
In the next paragraphs, this selected earthquake will be called SSE.

2.2.1 Natural time histories selection

Based on the previous characteristics of the SSE, 26 natural time histories have been selected among the SMDB. The main criteria used to select these time histories are the following:

- $M_{SSE} - 0.5 < \text{Magnitude of the selected earthquake} < M_{SSE} + 0.5$
- $R_{SSE} - 10 \text{ km} < \text{Focal Distance of the selected earthquake} < R_{SSE} + 10 \text{ km}$
- Average ground response spectrum of the 26 accelerograms $\geq GRS_{SSE}$

Two examples of selected accelerograms are shown in figure 3.

2.2.2 Artificial time histories generation
Based on the previous characteristics of the SSE, 30 artificial time histories have been generated using POWERSPEC [3] computer program. The main criteria used to generate these time histories are the following:

Average ground response spectrum of the 30 accelerograms $\geq \text{GRS}_{\text{SSE}}$

$\text{GMP}_{\text{SSE}} - \sigma < \text{GMP}_{\text{artificial accelerogram}} < \text{GMP}_{\text{SSE}} + \sigma$

Two examples of generated accelerograms are shown in figure 3.

Figure 4 - Example of generated artificial time histories

2.2.3 Comparison of natural and artificial time histories in terms of Ground Motion Parameters

The natural and artificial accelerograms are compared in this paragraph on the basis of GRS and GMP. The corresponding values obtained from the regression law are also given to illustrate the scattering around average values.

Figure 5 gives the comparison in terms of GRS.

Figure 5 - Comparison of Ground Response Spectra - Natural and artificial time histories
One can observe that, in terms of average GRS, there is a very good agreement between natural and artificial time histories. In addition, scattering around the average value is higher for natural accelerograms than for artificial ones.

Table 3 gives the comparison in terms of GMP.

**Table 3 - Comparison of Ground Motion Parameters - Natural and artificial time histories**
Ground Motion Parameters
(regression laws)

<table>
<thead>
<tr>
<th></th>
<th>Average value</th>
<th>Average val. - Std deviation</th>
<th>Average val. + Std deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (s)</td>
<td>5.3</td>
<td>3.3</td>
<td>8.6</td>
</tr>
<tr>
<td>V (m/s)</td>
<td>0.101</td>
<td>0.05</td>
<td>0.22</td>
</tr>
<tr>
<td>D (cm)</td>
<td>2.2</td>
<td>0.7</td>
<td>6.5</td>
</tr>
<tr>
<td>A/V (s-1)</td>
<td>18</td>
<td>11</td>
<td>28</td>
</tr>
<tr>
<td>CAV (m/s)</td>
<td>2.7</td>
<td>1.6</td>
<td>4.6</td>
</tr>
<tr>
<td>Ia (m/s)</td>
<td>0.22</td>
<td>0.08</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Natural</td>
<td>Artifical</td>
<td></td>
</tr>
<tr>
<td>accelerograms</td>
<td>(average)</td>
<td>(average)</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.087</td>
<td>0.080</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.19</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In terms of GMP, one can see a very good agreement between natural and artificial accelerograms considering average values. Figures 6, 7 and 8 show the scattering around the average values for T, V and D.

Figure 6 - Comparison of significant duration T - Natural and artificial time histories

Figure 7 - Comparison of maximum velocity V - Natural and artificial time histories

Figure 8 - Comparison of maximum Displacement D - Natural and artificial time histories
2.2.4 Analysis

In general, one can see a very good agreement between natural and artificial accelerograms in terms of average values for GRS as well as for GMP. In another hand, natural accelerograms lead to a higher scattering around the average value than artificial ones.

One explanation of this last result is that, for this study, we wanted to obtain a high number of accelerograms (to get proper trends) so that a relatively large variability around the SSE characteristics was intentionally left to select enough natural accelerograms. In addition, artificial accelerograms are known to be less scattered around the average (especially the GRS which is usually the main input data for the generation of such time histories).

2.3 Non-linear seismic response of simplified reinforced concrete structures

The simplified RCS model described in paragraph 2.1.3 are used to evaluate potential damage induced by natural and artificial accelerograms. For this study, the parameters used for the simplified RCS are the following:

- Frequency: 5 Hz (typical frequency of a nuclear RC building)
- Damping: 5% of critical
- Elastic threshold: Defined based on a ground response spectrum identical to the SSE in shape but scaled to a ZPA less than the SSE one (in order to get plastic deformation). Two different design levels (in terms of ZPA) were defined:
  - 0.05 g (i.e. 1/4 of the SSE)
  - 0.1 g (i.e. 1/2 of the SSE)
- Plastic stiffness: 0.2 x elastic stiffness

The difference between the wall type structure and the frame type structure comes essentially from the dissipative effects (loading and unloading behavior), cf. figure 1.

The results are expressed in terms of ductility. Ductility is defined here as the ratio between the maximum non-linear displacement over the elastic threshold displacement. This parameter is admitted to be a representative indicator of damage on RCS.

Table 4 gives the comparison between natural and artificial accelerograms in terms of average ductility obtained with the different sets of time histories.

| Table 4 - Ductility calculated on simplified RCS - Natural and artificial time histories |
Once again, a very good agreement between natural and artificial accelerograms in terms of average values is observed. Figures 9 and 10 give the detailed results respectively for the wall type structure and for the frame type structure. These results illustrate the scattering around the average values of calculated ductility.

**Figure 9 - Comparison of ductility - Wall type RCS - Natural and artificial time histories - Scattering**
Figure 10 - Comparison of ductility - Frame type RCS - Natural and artificial time histories - Scattering
2.4 **Analysis of results**

As a general observation, one can see that natural and artificial accelerograms lead to really good consistency of results in terms of average values. This is the case for GRS, GMP and induced damage (ductility) to RCS. In that context, we remind that artificial accelerograms have been generated in order to get realistic GMP that is, according to us, one key factor of the good agreement between natural and artificial accelerograms.

In another hand, natural accelerograms seem to induce a higher scattering around average values than artificial ones. One explanation of this result is that, for this study, we wanted to obtain a high number of accelerograms (to get proper trends) so that a relatively large variability around the SSE characteristics was intentionally left to select enough natural accelerograms. In addition, artificial accelerograms are known to be less scattered around the average (especially the GRS which is usually the main input data for the generation of such time histories).

Anyway, scattering around average values of calculated ductility is significant and remains within the same order of magnitude, for both natural and artificial accelerograms. However, as far as we know, there is no consensual engineering practice to deal with such scattering for design purpose (the number of accelerogram to be used is still an open question). The next paragraph deals with this aspect and proposes a method to account for scattering.

3 **Part two - Considerations on the number of accelerograms to be used and a the way to account for scattering**

This part gives some elements on the effect of the number of accelerograms used on the results of non-linear computations and proposes a method to account for scattering for design studies. For this purpose, two types of non-linearities are analysed. The first one, an impact non-linearity is described in paragraph 3.1. The second one, a plastic non-linearity is base on the simplified RCS used and described in paragraph 2.3.

3.1 **First type of non-linearity : Impact**

The considered structure is a PWR core. A PWR core, constituted of fuel assemblies, is designed against seismic event to prevent excessive impact loads between fuel assemblies. This justification is performed by means of time-history analyses with dynamic models of an assembly row in the core accounting for impacts between fuel assemblies (see [4] for
The present study was performed using a high number of artificial accelerograms (500 time histories) all generated with the same input parameters. The objective is to show how a result of a non-linear computation may depend on the set of accelerograms used for the calculation.

Figure 11 shows the results in the following form:

- **Base case - Population = 500 calculations**: This case gives the average value of the impact force of the population.
- **Additional cases**: Selection of different sets of 50 (different) accelerograms (7 sets) taken among the population, and for each set, presentation of:
  - The evolution of the average value of the impact force with the number of accelerogram used to calculate it (from 3 to 50),
  - The comparison of the evolution of the average value of the impact force between sets.

The first comment is that different sets of accelerograms may lead to significant differences in terms of average values. One can also observe that for low number of accelerograms (typically less than 10), the scattering on the average value of the non-linear parameter (i.e. impact force) may be very important depending on the different sets of accelerograms used for the calculations.

In another hand, the scattering remains significant for high number of accelerograms and the convergence to the average of the population is very low, even for numbers of accelerograms higher than 30.

Although scattering of results is known for such non-linear analyses, the previous results quantify the impact of using of a reduced number of accelerograms for non-linear computation and also illustrates that different sets of accelerograms may lead to different results. As the number of accelerograms has to remain reasonable for design studies, an appropriate method to account for scattering should be applied for engineering purpose.
The next paragraph proposes such a method.

3.2 A way to account for scattering: Student-Fisher estimator

This paragraph proposes a method to account for scattering based on statistical considerations. The objective is to determine a conservative value of a design parameter $D$ based on results obtained from non-linear computations with a set of $N$ accelerograms.

The results obtained from the $N$ computations can be expressed in terms of average value $D_{AV}$ and standard deviation $S_D$, these two parameters being characteristic of the sample (i.e. set of $N$ calculations). To reach the objective expressed previously, a statistical estimator can be used to predict the average value of the population, with an appropriate confidence level.

The statistical estimator used here is the Student-Fisher estimator. The main characteristics of this estimator are described in the next paragraph.

3.2.1 Description of Student-Fisher estimator

Student-Fisher law $S_N$ ($N$ being its degree of freedom) is commonly used in statistics. Its main characteristic is to tend to a Normal law when $N$ tends to infinite. This law is particularly appropriate to predict the average value of a population $D$ based on the average value of the sample $D_{AV}$ and its standard deviation $S_D$, for a desired confidence level and depending on the size of the sample $N$, considering the following expression.

$$D_{95\%} = D_{AV} + \frac{t_{0.05;N-1}}{\sqrt{N}} S_D$$

Where $t_{0.05;N-1}$ is the Student-Fisher parameter taken for $N-1$ degrees of freedom and for the appropriate probability (0.05 unilateral for 95% confidence level in our case). See next table to get characteristic values of Student-Fisher parameter.

<table>
<thead>
<tr>
<th>Student parameter</th>
<th>Confidence level : 95% (unilateral)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>$t(0.05;N-1)$</td>
</tr>
<tr>
<td>9</td>
<td>2.13</td>
</tr>
<tr>
<td>10</td>
<td>1.83</td>
</tr>
<tr>
<td>15</td>
<td>1.76</td>
</tr>
<tr>
<td>20</td>
<td>1.73</td>
</tr>
<tr>
<td>30</td>
<td>1.70</td>
</tr>
<tr>
<td>50</td>
<td>1.68</td>
</tr>
</tbody>
</table>

The Student-Fisher gives an appropriate estimator of the average value of the population when the following conditions are respected:

- The statistical distribution of the population follows a Normal law,
- The standard deviation of the population is unknown,
- The size of the sample is small (typically less than 50).

3.2.2 Application to impact non-linearity

In this part, Student-Fisher estimator is used to predict the average value of the population from the previous results shown in figure 11. The estimation of the average value of the population with a confidence level of 95% is then evaluated and compared to the calculated one (500 calculations). Figure 12 shows the comparison of the estimated average value of
the population using Student- Fisher estimator for the different sets of accelerograms and its evolution with the number of accelerograms used to calculate it within a set.

**Figure 12 - Use of Student estimator - Evolution with the number of accelerograms**

**Impact non-linearity**

One can see that the use of Student-Fisher estimator (95% confidence level) leads to a conservative prediction of the average value of the population, even with a low number of accelerograms. One can also observe that, the higher the number of accelerogram is, the more accurate the estimation is.

For low number of results (less that 10 in that situation), estimation may be very conservative in some case (+50% approximately), it may also be a little under conservative in some cases (one case in fig. 12, for 3 and 4 calculations). For a high number of results, this estimator tends to a precise estimation of the average value of the population.

In the next paragraph, the Student-Fisher estimator is applied on the simplified RCS used in paragraph 2.3.

**3.2.3 Application to simplified RCS - Plastic non-linearity**

The results presented in paragraph 2.3 are used once again but with Student-Fisher estimator to show the effect of the estimator on another type of non-linearity. Figure 13 shows the results (calculated ductility) obtained for frame type structure and for wall type structure, respectively with natural accelerograms and artificial accelerograms.

**Figure 13 - Use of Student estimator - RCS plastic non-linearity**
3.3 Analysis of results

In most of cases, the use of Student-Fisher estimator (95% confidence level) leads to a conservative prediction of the average value of the population, even with a low number of accelerograms. This result is confirmed with two different types of non-linearity (impact and plastic non-linearities).

In addition, the results show that the higher the number of accelerogram is, the more accurate the estimation is. In that situation, a relative freedom is left to the designer for engineering purpose (more calculations can be performed to get an optimized estimation of the design parameter or a lower number of calculations is possible but with a more conservative estimation of the design parameter).

4 Conclusions and perspectives

The objective of this study was to give some elements concerning (i) the potential effectiveness of artificial time histories to reproduce structural damages led by real earthquakes and (ii) the number of accelerograms to be used for non-linear computations and the way to account for scattering of results.

The results show that artificial accelerograms may lead to equivalent damages on structures than natural ones, if they are generated based on Ground Response Spectrum and other Ground Motion Parameters (such as ground velocity, ground displacement, significant duration, CAV, Arias Intensity …). In that context, this paper gives some regression laws (previous study) to evaluate Ground Motion Parameters based on characteristics of the earthquake under consideration (i.e. magnitude and focal distance).

In addition, a method to account for scattering of the results is proposed, based on Student-Fisher statistical estimator and allows to estimate the design parameter with an appropriate confidence level. This method leaves a relative freedom to the designer for engineering purpose (more calculations can be performed to get an optimized estimation of the design parameter or a lower number of calculations is possible but with a more conservative estimation of the design parameter).

This study will be extended in the future with other earthquake characteristics (high magnitude - far field earthquakes ; low magnitude - near field earthquake especially) and with other types on non-linearities (uplift especially).
5 References

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