Smart Scaling of Accelerograms Applied to the Study of Steel Buildings

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SUMMARY:
An important method of nonlinear dynamic analysis of structures is employing ground acceleration time-histories and step by step integration of the equation of motion. Building codes establish different requirements for accelerograms used for this purpose. To meet such requirements it is usual to multiply all values of the series by the same number. As a result the response spectrum can become non-compatible with the design spectrum. This study presents a technique to get a record that is very close to the design spectrum along all frequencies. This technique involves the following steps: (1) spectral analysis of the original accelerogram, (2) filtering by bands of the original accelerogram, (3) scaling of each band of filtering, and (4) adding up the filtered and scaled accelerograms. This technique has been applied to buildings representing main steel frames subclasses. The results are very similar to those obtained with the method of nonlinear static analysis.

Keywords: Steel buildings, non-linear dynamic analysis, spectrum scale factor.

1. INTRODUCTION

In seismic engineering problems is common to need ground acceleration time-histories meeting certain requirements. Even though there are many techniques for generation of artificial accelerograms, all of them could be grouped into two broad categories responding two different approaches: 1) adequate representation of the characteristics of the earthquakes expected in a specific place and 2) compatibility with a specific spectrum of design. These two accelerograms classes enable us to simulate respectively seismic scenarios and accelerograms compatible with design earthquake. Seismic methods allow finding synthetic accelerograms modelling seismic source, the way of propagation and site conditions. We can also find accelerograms compatible with any spectral form using standard numerical methods. However, it is advisable to use real accelerograms, if it is possible, since these are those who best represent the reality of the source, the way of propagation and the registration place. But while every day there are more and better database of acceleration records, produced by earthquakes of different focal mechanisms, size and distances, obviously the density of their space distribution is not homogeneous. For that reason, in many locations even now it is difficult to find out real records with adequate size and frequency content. When not right size real accelerograms are available, this problem is usually drastically resolved by scaling the available accelerograms. This technique involves multiplying each value of the acceleration by a unique factor in order to reach the required spectral acceleration for a given period. Often, the amount used to scaling the accelerogram is the effective peak acceleration, which is directly related with the intensity or magnitude of the earthquake. To multiply all the accelerogram by a fixed amount generally overestimates the response spectrum in certain frequency bands. In this way the accelerogram can become incompatible with the design spectrum of the building which its seismic behaviour is being evaluated. In this paper we present the case of the Colombian code NSR-98 (AIS 1998) requirements for accelerograms used in time-history analyses and an original method which allows conciliating real accelerograms with design spectra. The method is illustrated through that smart scaling of the typical accelerograms for the city of Manizales to make them compatible with the requirements of the NSR-

98 standard.

2. NSR-98 COLOMBIAN CODE REQUIREMENTS

In dynamic analysis methods the structures are subjected to earthquake shaking represented by ground motion time histories, i.e. acceleration time series. The A.2.7 section of the Colombian code NSR-98 (AIS 1998) describes the conditioning that must be complied by the acceleration time-histories or by the family of accelerograms used in dynamic analysis procedures. According to that code, when the time-dependent response of the structure is obtained through direct numerical integration of its equation of motion, the accelerograms used must comply with the following requirements:

a) A minimum of three different accelerograms should be used; all of them representing the expected ground movements, but fulfilling the great range of frequencies and amplifications as possible,
b) No value of the 5% damping elastic spectrum, calculated from all accelerograms, should be less than 80% of the corresponding value of the 5% damping design elastic response spectrum.

Nothing is said about superior limits of the spectral response, which can result in incoherency or inconsistency among the design spectrum and the scaled spectra, which can easily overcome the design conditions and, as a result, produce over-dimensioned buildings. In order to improve this situation, the new code NSR-10 (AIS 2010) modifies this last requirement as follows: Within a range between 0.8T and 1.2T, where T = expected inelastic period of vibration for the fundamental mode, no value of the 5% damping elastic spectrum, calculated from all accelerograms, should be less than 80% of the corresponding value of the 5% damping design elastic response spectrum, and the average of the spectral ordinates within a range between 0.2T and 1.5T should be no less than the corresponding value of the 5% damping design elastic response spectrum. The above suggests that it is sufficient that the spectral ordinates of the used accelerograms are not less than 80% of the design spectrum within a narrow frequency band around the building natural frequency. But, as the inelastic fundamental vibration period depends on turn of the action, since it decreases as the structure penetrates into plastic field, comply with this condition may require iterative procedures of esteem for the own period and scaling factor. Other seismic design codes can impose other similar conditions. The Eurocode 8: Design of the Structures for Earthquake Resistance (CEN 2004), establishes a range between 0.2T1 and 2.0T1, being T1 the fundamental period of the structure in the direction of application of the accelerogram. In any case these types of criteria seem to oblige different scales according with the building and also the signal in use. Here we describe a new method that could let the usage of real accelerograms to generate compatible ones with any spectra of design but conserving its principal spectral characteristics.

3. THE METHOD

Consider a design spectrum D(ω), an accelerogram in time domain a(t) and frequency domain A(ω) with a response spectrum R(ω). This method involves defining a new accelerogram γ (t) as shown in Eqn. 3.1.

$$\gamma(t) = \sum_{j=1}^{k} C_j F_j(t) \tag{3.1}$$

Where C_j are coefficients or scaling factors and $F_j(t)$ are functions defined through Eqn. 3.2:

$$\mathrm{F_j(t)} = \Psi_{(\mathrm{f_{j-1}, f_j, norden})}\left[\mathrm{a(t)}\right] \tag{3.2}$$

Where $F_j(t)$ is a filtered accelerogram a(t) that results from applying the operator Ψ to the signal a(t). For j=1, $f_0 = f_{j-1}$ is the nule frequency and this is a low-pass filter. For j=k, f_k corresponds to the infinite frequency, for that reason, the filter is a high-pass one. For medium values of j the filter is band-pass, *norden* is the number of filter order. These frequencies and the coefficients C_j are both selected so that it can be complied with scaling conditions required. So, if $\Gamma(\omega)$ is the response spectra of $\gamma(t)$ then it must be fulfil certain conditions represented by function $h(\omega)$ in Eqn. 3.3.

$$h(\omega) = \phi(D(\omega), \Gamma(\omega)) \tag{3.3}$$

A sample could be:

$$0.8\mathrm{D}(\omega) \leq \Gamma(\omega) \leq 1.2\mathrm{D}(\omega) \therefore \omega_1 \leq \omega \leq \omega_2 \tag{3.4}$$

Where ω_1 and ω_2 are two characteristics frequencies.

Design spectra $D(\omega)$ are softened and they can be represented by simple frequency functions, but the functions $a(t)$, $A(\omega)$, $R(\omega)$ and $\Gamma(\omega)$, are not usually known in analytical way, but digitally, i.e., a finite data list. For this reason the selection of frequency bands and amplification factors is not a trivial-one. In some case would be possible to design algorithms to automate this process of selection, but in this example of applying, it has been done by inspection and comparison between the design response spectrum $D(\omega)$ and $R(\omega)$ and $\Gamma(\omega)$.

4. THE COLOMBIAN CASE IN MANIZALES

The analysis is focused on 6 steel structure buildings hypothetically belonging to the National University of Colombia and they are located in a soil type 3.

4.1. Design spectrum

Fig. 4.1 shows the elastic response spectrum (5% damped) taken from NSR-98 code where Aa is the peak ground acceleration; I is an importance factor; S is a soil factor; Sa is the spectral acceleration measured in units of 'g' (gravity) and T is the period in seconds. Peak ground acceleration for Manizales, with a return period of 500 years, is 0.25 g. The importance factor is adopted as I=1.1 and the soil factor S=1.5 so that the spectral acceleration corresponding to the constant acceleration zone in Fig. 4.1 is 0.6875g and the periods T_C and T_L respectively are 0.72s and 3.6 s.

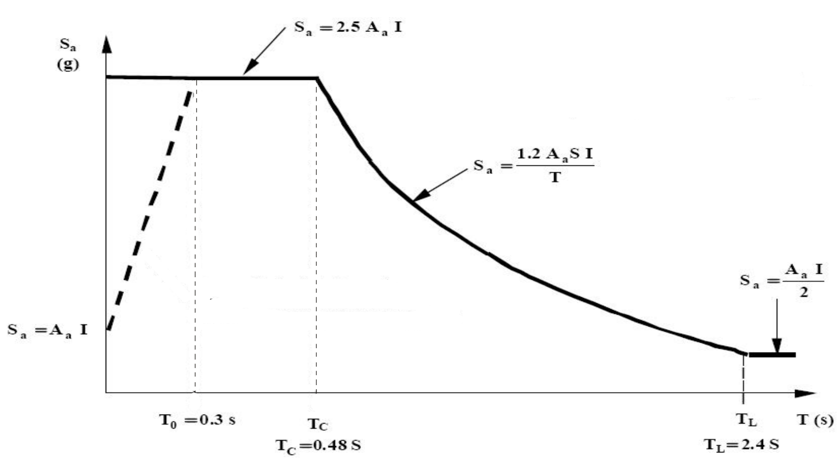

Figure 4.1. Elastic response spectrum 5% damped

Studied buildings are steel moment resistance frames (RM) and steel braced frames (AR) and respectively low-rise (B), mid-rise (M) and high-rise (H). In this way all three types RM are called RMB, RMM and RMH and its proper periods are 0.64, 0.97 and 1.55s, while the buildings AR are named ARB, ARM, and ARH and its proper periods are: 0.25, 0.62 and 1.30s. Fig. 4.2 shows the spectrum for the location of the studied buildings. Fig. 4.3 shows the same spectrum in Sa-Sd format or ADRS (Acceleration Displacement Response Spectra). Both figures contain the corresponding spectra to 80% and 120% of the design spectrum and proper elastic periods of the 6 studied buildings are included.

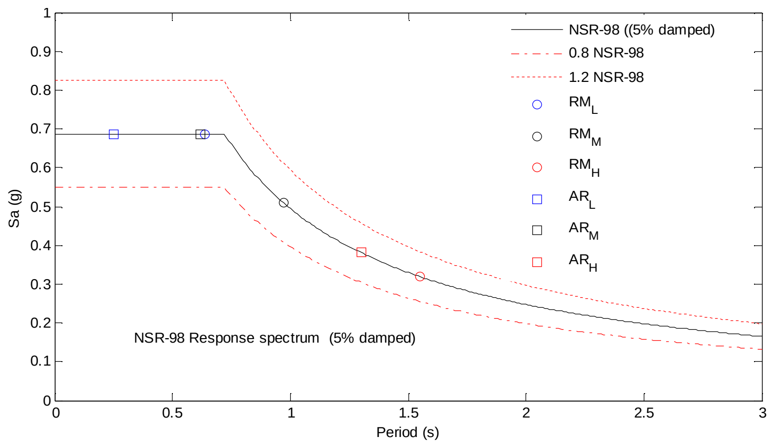

Figure 4.2. Design spectrum for the location site of the studied buildings in Manizales. It has been taken Aa=0.25g, I=1.1, corresponding to educational buildings, and S=1.5 corresponding to a soil type 3.

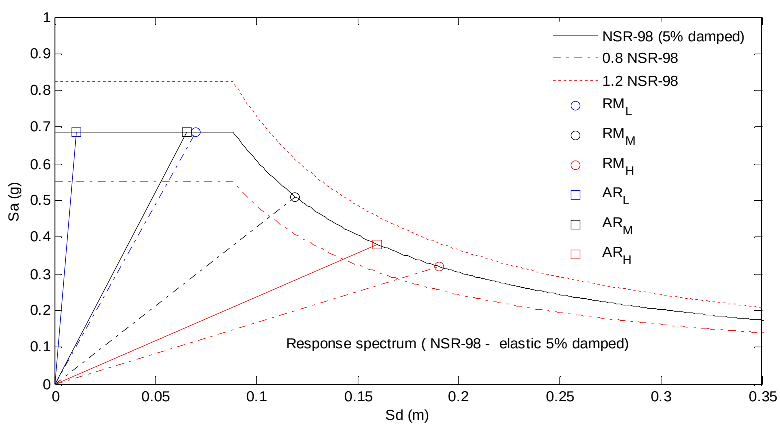

Figure 4.3. Design spectrum for the location of the studied buildings in Manizales in ADRS format.

4.2. Design accelerograms

Micro-zoning seismic study for Manizales recommended the use of the following four accelerograms: Benioff-Calima, Benioff-Synthetic, Romeral-Deconvolution and Romeral-Synthetic. Fig. 4.4 shows those accelerograms and their amplitude Fourier spectra. To illustrate this method in detail it has been selected the accelerogram Romeral-Deconvolution. The smart scaling of this accelerogram involved the use of six frequencies and 7 amplification factors. The Table 4.1 shows parameters defined in Eqns. 3.1 and 3.2. Parameters in Table 4.1 have been used to define seven filters of nule phasing. This ensures that no temporal shift will occur. Filters were used such as Butterworth of third order: one low-pass filter at 10 Hz; five band-pass filters with pass frequencies defined by numbers 1-2, 2-3, 3-4, 4-5 and 5-6 on Table 4.1 and one 0.47 Hz high-pass filter type. Fig. 4.5 shows these seven signals resulting from filtering process, both for period and time domains. In the period domain, spectra of filtered signals are compared with the original accelerogram spectrum. Fig. 4.6 displays the response spectra of both original accelerogram and seven accelerograms from Fig. 4.5. Fig. 4.7 shows response spectra of both original and band-scaled accelerograms. In Fig. 4.6 and 4.7 are shown also the design spectrum and the periods of six buildings analyzed. Fig. 4.8 displays original and scaled accelerograms in time, period and frequency domains.

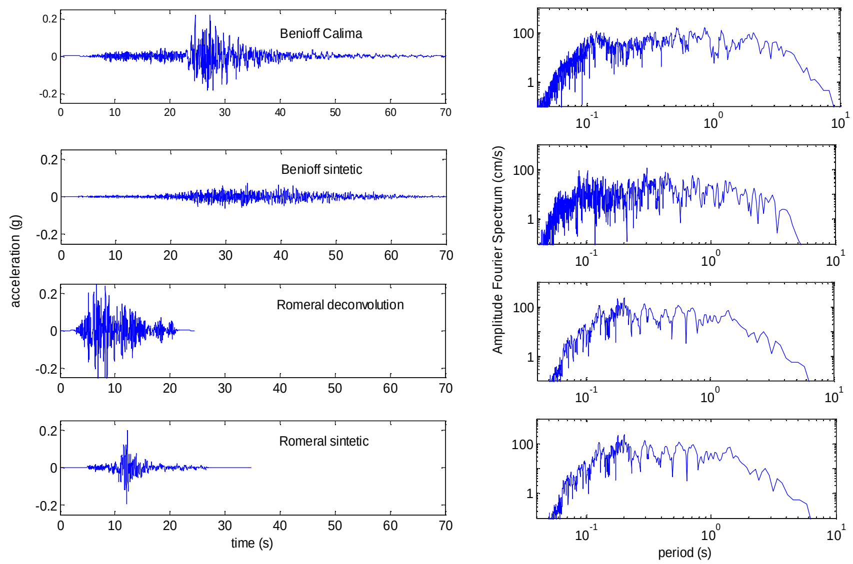

Figure 4.4. Recommended accelerograms by the micro-zoning seismic study for Manizales for be used in dynamical analyses. For easy comparison all the graphics have the same scale.

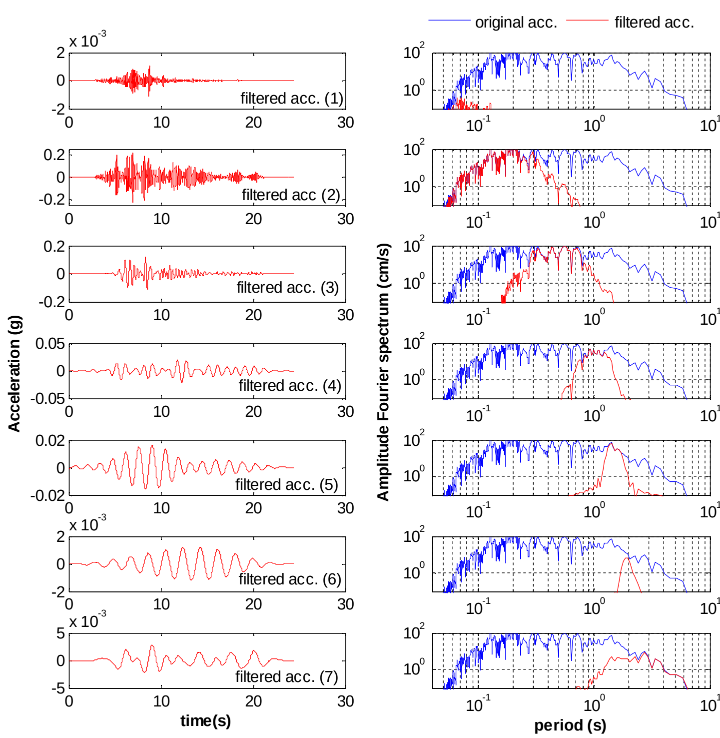

Figure 4.5. Accelerograms resulting from applying filters, based on limit frequencies of Table 4.1, to Romeral-deconvolution accelerogram included in Fig. 4.4. To the left seven signals in time domain are displayed; to the right seven response spectra in period domain, aside the amplitude Fourier spectrum for original accelerogram

are displayed.

Table 4.1. Frequencies, periods and amplification factors used for making compatibles that design spectrum and the 5% damping elastic response spectrum of the accelerogram Romeral-Deconvolution.

Number(j)	0	1	2	3	4	5	6	7
Period (s)	0.0	0.05	0.30	0.80	1.30	1.80	2.15	$+\infty$
Frequency (Hz)	$+\infty$	10.0	3.33	1.25	0.77	0.56	0.47	0.0
Amplification	---	100	0.65	1.4	5.0	-0.81	15.0	25.0

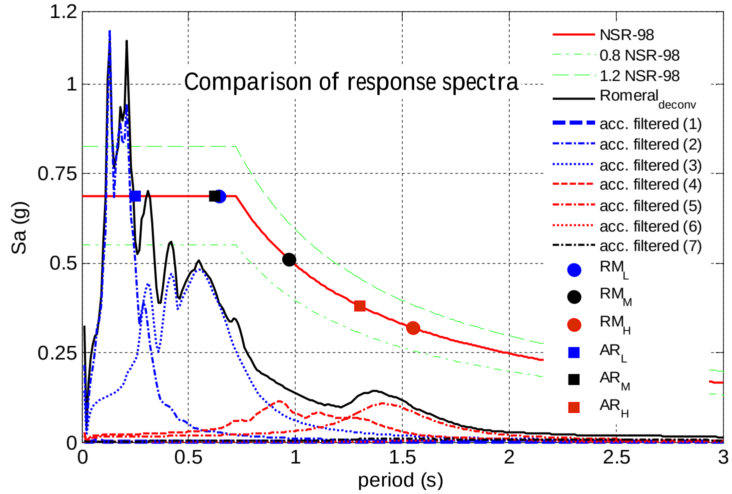

Figure 4.6. Response spectra of both original accelerogram and seven accelerograms from Fig. 4.5.

From Fig. 4.6 the accelerograms 2, 3, 4 and 5 have greater relative importance, but those of 1, 6 and 7 have been essential to obtain adequate scaling in low and high frequencies. Figure 4.7 shows that response spectra of design and band-scaled accelerogram are mutually compatible along all the domain frequency and, particularly, around the 6 building proper periods. Fig. 4.8 displays that original and scaled accelerograms in both time and frequency domains are also mutually compatible.

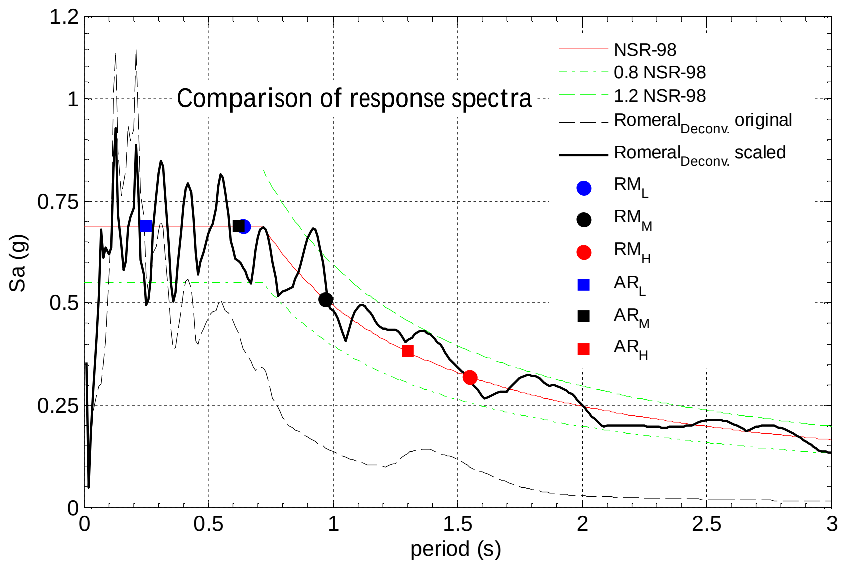

Figure 4.7. Original accelerogram and band-scaled accelerogram response spectra. For both cases 80% and 120% limits of design spectra were drawn.

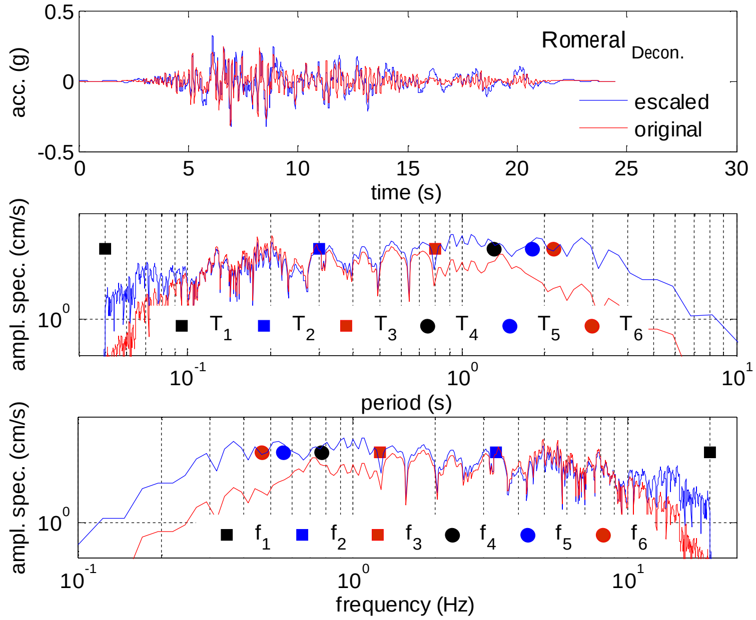

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Figure 4.8. Original and scaled accelerograms. Up: Time domain. Down: Fourier amplitude spectra for period and frequency domains. Also periods and frequencies of Table 4.1 are displayed.

5. DISCUSSION AND RESULTS

The described method has been applied to the other three accelerograms suggested for dynamics analyses for Manizales city. Figs. 5.1, 5.2 and 5.3 are analogues to Fig. 4.7. All of them show the comparison between the original accelerograms and the band-scaled accelerograms.

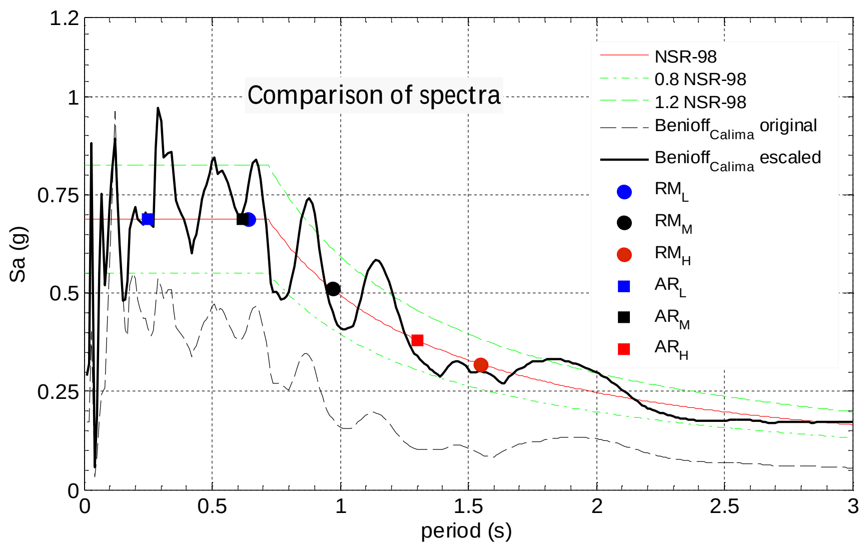

Figure 5.1. Original Calima-Benioff accelerogram and band-scaled accelerogram response spectra. For both cases 80% and 120% limits of design spectra were drawn.

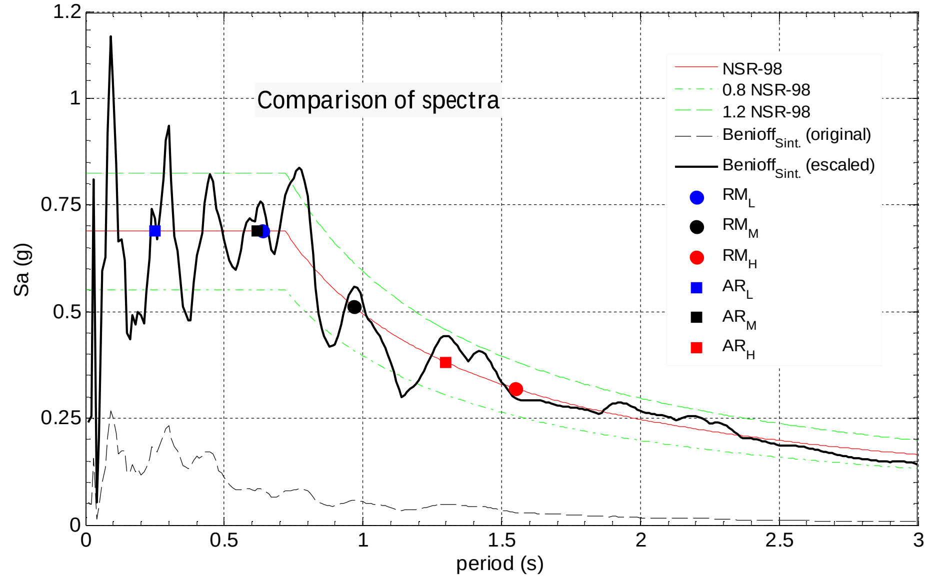

Figure 5.2. Original Synthetic-Benioff accelerogram and band-scaled accelerogram response spectra. For both cases 80% and 120% limits of design spectra were drawn.

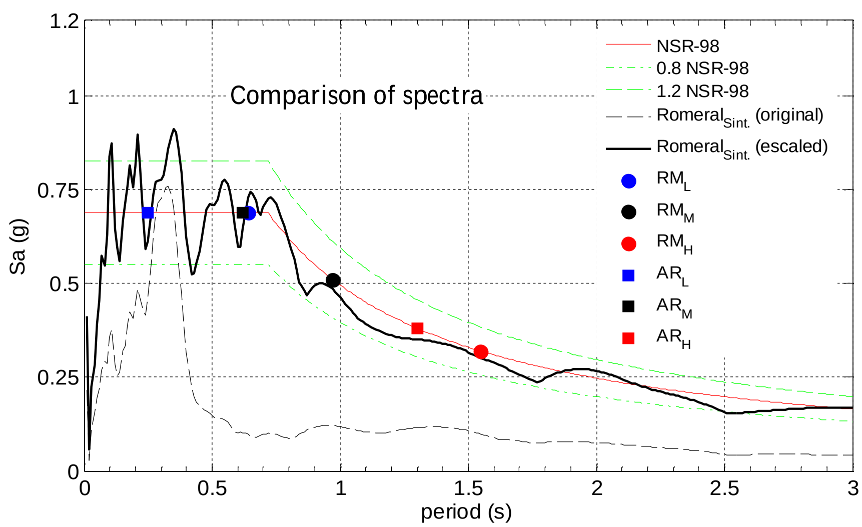

Figure 5.3. Original Synthetic-Romeral accelerogram and band-scaled accelerogram response spectra. For both cases 80% and 120% limits of design spectra were drawn.

Fig. 5.4 shows original and band-scaled accelerograms in both time and period domains. For the four analyzed cases it has been possible to obtain accelerograms which are similar to those original and compatible with the design spectrum. We refer to these accelerograms as hybrids accelerograms because they are not real records nor synthetic records. They are compatible with real accelerograms since the duration and frequencies are taken rigorously from the original accelerograms. They are compatible with the design spectrum since frequency bands and amplification factors are cleverly chosen for getting the same spectral response along all period domain. Therefore, for any real record and design spectrum, the technique described allow finding a lineal combination of accelerograms whose response spectrum is compatible with the design spectrum. Fig. 5.5 summarizes these results and shows alongside the design spectrum, the response spectra of the four analyzed accelerograms.

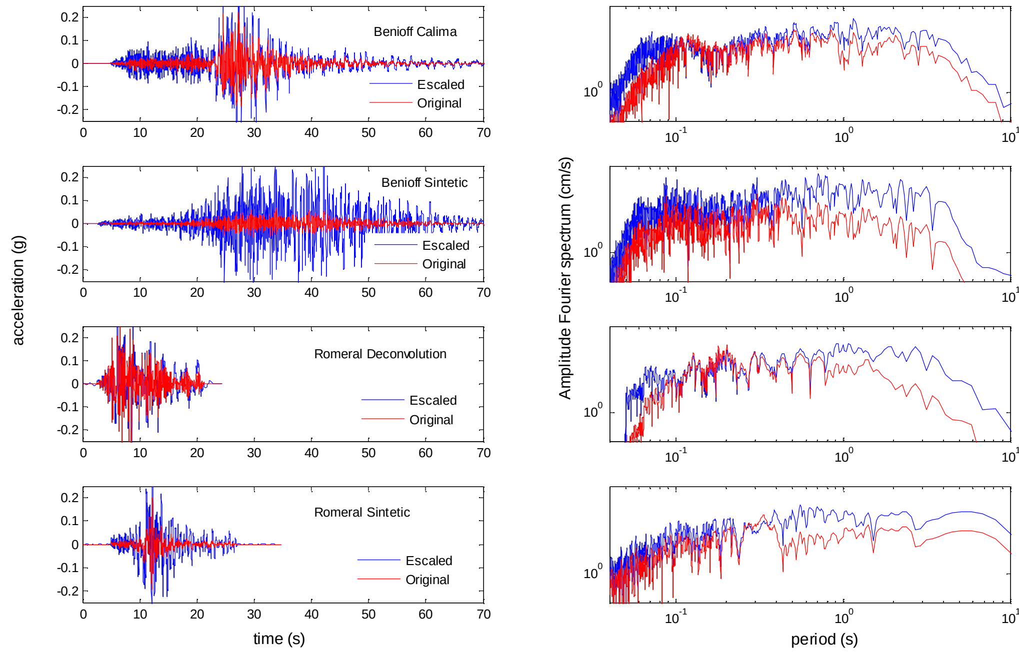

Figure 5.4. Accelerograms scaling equal to original.

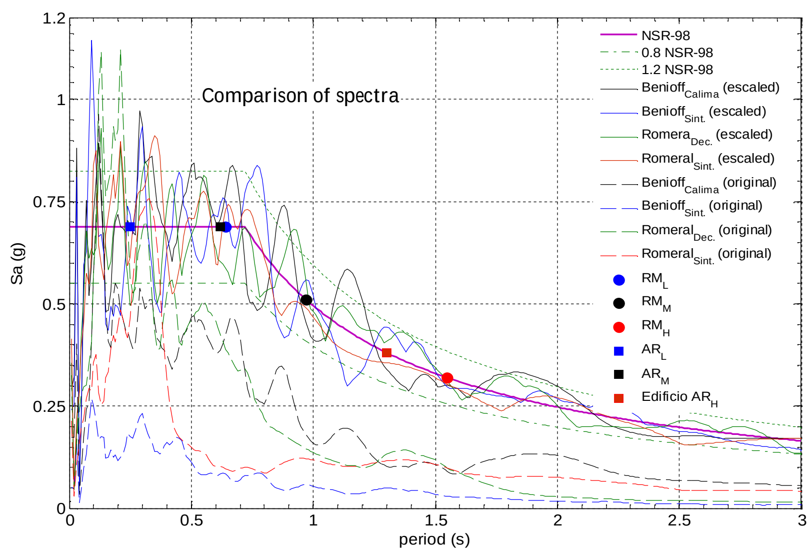

Figure 5.5. Considered steel building properly periodically included also, with hybrid and original accelerograms compared all together.

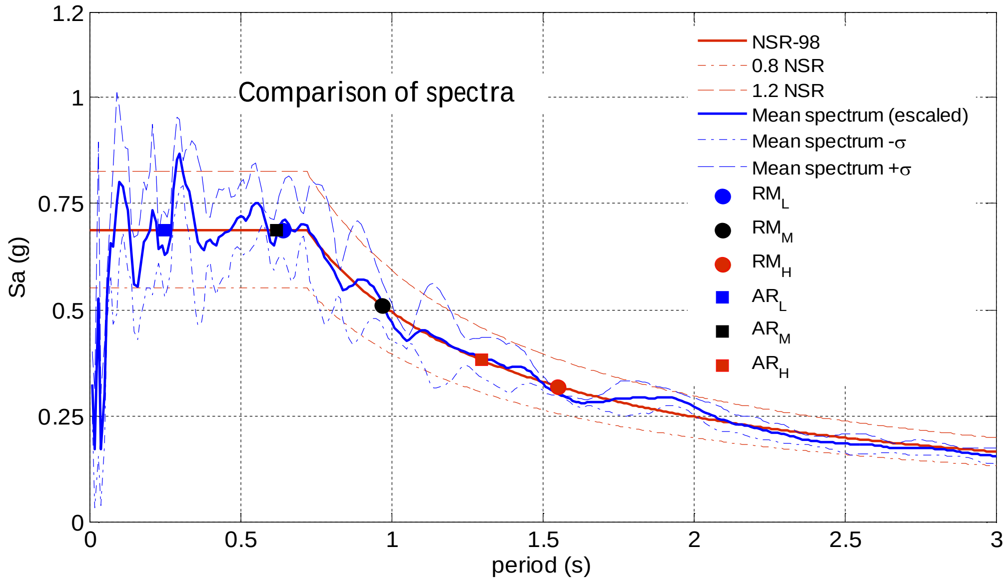

Figure 5.6.

Finally, Fig. 5.6 shows the average response spectrum for the four accelerograms along with the intervals defined by its typical deviation. The average response spectrum and the design spectrum coincide very well. Defined intervals for typical deviation fall in the range of 80% and 120% of design spectrum. Therefore, it can be stated that the accelerations induced by the band-scaled accelerograms will not underestimate nor overestimate those of design.

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