# A simplified approach for evaluating seismic-induced actions on non-structural components in buildings

**E. Martinelli & C. Faella**
*Dipartimento di Ingegneria Civile, Università di Salerno, Fisciano, SA (Italy)*

**SUMMARY:**
The present paper deals with the dynamic response of non-structural components of civil and industrial buildings under seismic excitations. Recent seismic events pointed out that a huge lack of knowledge still affects both analysis procedures and design or assessment methods currently adopted for the rather wide class of "objects" generally referred as "non-structural components" (e.g., partitions, masonry infill, suspended ceilings, finishing and so on). Since the most common code provisions and guidelines addressing the issue of non-structural components provide rather diverse relationships for evaluating the maximum earthquake-induced actions on the non-structural components, a wide parametric analysis based on a 2DOF system is presented. It simulates the coupled response of both main structure and non-structural component. The key parameters which actually control the dynamic response of non-structural components emerge from this study and are considered in the preliminary proposal of a simplified formula to evaluate the maximum earthquake-induced inertial actions.

*Keywords: Earthquake, Seismic response, Non-structural components, Dynamic analysis*

## 1. INTRODUCTION

In the last decades, the research efforts carried out to formulate sound design criteria for structures in seismic areas led to the current generation of seismic codes (i.e., EN 1998-1, 2004). They provide designers with a consistent performance-based approach for protecting structures against earthquake-induced actions (FEMA 356, 2000). However, recent earthquake events, such as the one which struck L'Aquila in 2009, emphasised a series of critical issues which are not completely covered by the current provisions (Verderame et al., 2009). One of such critical issues is related to the prediction of the seismic response of "non-structural components" (EERI 1984; EFRC 2005; De Sortis et al, 2009). The first critical aspect in handling such issues deals with properly defining the very wide class of components mentioned above (FEMA 356, 2000). Several definitions are currently available in both codes of standards and scientific studies. However, as a matter of principle, any "object" which is supposed not to play a role in defining the schemes considered in common structural analyses (under both gravity and seismic actions) can be considered as a "non-structural" or "secondary" component. This is probably the broadest definition of non-structural components and is adopted within the present study. Under this standpoint, partitions, masonry infill, suspended ceilings, finishing, as well as specific equipment can be generally regarded as "non-structural" components. The various seismic codes and guidelines currently in force in earthquake-prone countries (e.g., EN 1998-1, 2004; SIA 261 2003; IBC 2006; NBCC 2005; NZS 4203 1992) provide designers with simple (and generally simplistic) rules and relationships for determining the maximum inertial action induced by the expected seismic shaking on non-structural components. They are based on few parameters dealing with:

- the intensity of the expected seismic event;
- the elastic properties of both the main structure and the non-structural component;
- the position in height of the non-structural components within the main structure.

Some of the most recent codes also consider a reduction parameter related to the inelastic response of

the secondary component. On the contrary, the nonlinear behaviour of the main structure is either disregarded or not explicitly considered in the above mentioned code provisions, even though it clearly affects the excitation of the non-structural components by “filtering” the seismic signal (Villaverde and Chauduri 2008).
This paper is basically aimed at formulating a comprehensive (though simplified) method for determining the actions induced on “non-structural” component during seismic events.
A wide parametric analysis aimed at quantifying the inertial actions induced on non-structural components is presented in Section 2. It is based on a two-degree-of-freedom (2DOF) system which is the simplest way to analyse the nonlinear response of a secondary member connected to a primary structure whose cyclic response is often investigated through a single-degree-of-freedom (SDOF) system. The key results of the parametric analysis are summarised in section 3 and compared in section 4 with the predictions of the above mentioned code relationships.

## 2. PARAMETRIC DYNAMIC ANALYSIS

The simplified formulae currently available in codes and guidelines lead to rather diverse predictions of the maximum earthquake-induced actions on non-structural components. Moreover, they generally neglect important parameters, such as those related to the elastic and post-elastic response of the main structure. In fact, only the period ratio $T_a/T_1$ is generally considered. On the contrary, the same relationships generally involve neither the elastic period $T_1$ nor a parameter related with the force reduction factor (or design ratio) of the main structure. As far as the latter is of concern, it is reasonable to figure out that the lower the elastic strength of the main structure, the lower its accelerations and, consequently, the inertial actions induced in the non-structural components.
The three following subsections introduce the key information about the numerical model adopted for this parametric investigation, the seismic signals employed in the nonlinear time-history analyses and the range of variation of the key parameters considered in the present study.

### 2.1. A simplified numerical model

The two-degree-of-freedom (2DOF) system considered in this numerical investigation is the simplest possible representation of the dynamic interaction between the main structure, connected to the ground and directly shaken by the earthquake motion, and the non-structural component which is connected to the main structure under consideration. The system is schematically represented in Figure 1.

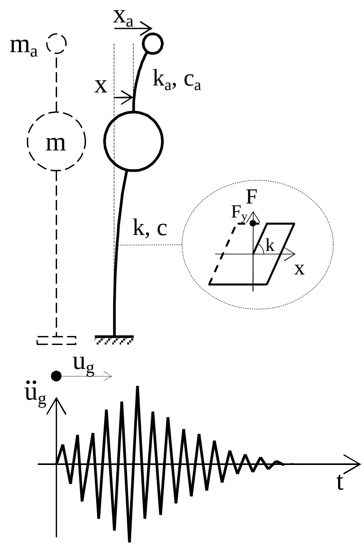


**Figure 1**. The 2DOF system considered in the nonlinear time-history analyses

The main structure is represented by its mass *m* which is connected to the ground by an elastic-perfectly-plastic element whose elastic stiffness *k* and yielding force $F_y$ are also represented in Figure

1. The relative displacement of the main system with respect to the ground is denoted by $x$. Viscous damping is also considered through the coefficient $c$ which relates the viscous force with the relative velocity $\dot{x}$.
The non-structural component is represented by its mass $m_a$ which is connected to the main structure. The relative displacement of the former (still with respect to the ground) is denoted with $x_a$ and a simple elastic behaviour is considered for the member which connects the non-structural component to the main structure. The stiffness $k_a$ and the damping coefficient $c_a$ completely describe the dynamic properties of such a member.
As a matter of principle, nonlinear behaviour could be generally considered for the non-structural component, too. Nevertheless, since this study is mainly devoted at evaluating the maximum inertial actions induced on that component (and does not cover the aspects related to displacements) an elastic behaviour is considered for the secondary component as assumed in other similar studies already available in the literature (Oropeza et al 2010). On the contrary, for the sake of generality, the coupled behaviour of the system represented in Figure 1 is considered in the analyses, even though similar studies (Lin and Mahin 1985; Oropeza et al 2010) are often carried out by considering two single-degree-of-freedom (SDOF) systems in series. In fact, if the mass ratio is kept small (i.e., $m_a/m \to 0$), the dynamic response of the main structure is not substantially influenced by the mass $m_a$ and can be simulated by a SDOF system whose response can be, subsequently, considered as the base motion for the secondary system, represented in turn by another SDOF system. However, this approximation is not considered herein and the following coupled equilibrium equations are actually solved:

$$\begin{cases} m\ddot{x} + c\dot{x} - c_a\left(\dot{x}_a - \dot{x}\right) - k_a\left(x_a - x\right) + \\ +F_r\left(x;k,F_y\right) = -m\ddot{u}_g \\ \\ m_a\ddot{x}_a + c_a\left(\dot{x}_a - \dot{x}\right) + k_a\left(x_a - x\right) = -m_a\ddot{u}_g \end{cases} \tag{2.1}$$

where $\ddot{u}_g$ represents the seismic action in terms of ground acceleration. The reaction $F_r(x;k,F_y)$ is the only nonlinear part in equations in (2.1) and involves both the main structure relative displacement x and its elastic and inelastic properties (namely, $k$ and $F_y$) represented in Figure 1. The equations (2.1) are solved numerically by means of a piecewise approach which is needed for the "non-smooth" nature of the seismic input. Moreover, a numerical algorithm inspired to the well-known Beta-Newmark family (Clough and Penzien 1993) has been implemented for handling nonlinearities in the dynamic response of the system.

### 2.2. Natural seismic signals considered in this study

A set of 264 natural records was collected to be employed in the nonlinear time-history analyses which have been carried out in the present research. The database of those records has been built by considering the same seismic events and possibly the same records (which was the case for the large majority of signal actually collected within the set) considered by Miranda (2000). Thus, a very wide parametric analysis can be carried out. Moreover, the dispersion of results deriving by the aleatoric nature of the seismic input can be described through statistical measures.

### 2.3. The structural parameters of relevance

Figure 1 clearly points out the main parameters governing the dynamic response of the system under consideration. Besides the mass ratio $m_a/m$, the key parameters needed to describe the response of SDOF oscillators can be considered for both the main structure and the non-structural component. Thus, the elastic period $T$ and the damping ratio $\xi$ (Clough and Penzien 1993) can be defined for both parts of the 2DOF system:
- main structure:

$$T_1 = 2\pi\sqrt{\frac{m}{k}} \tag{2.2}$$

$$\xi = \frac{c}{2\sqrt{km}} \tag{2.3}$$

- non-structural component:

$$T_a = 2\pi\sqrt{\frac{m_a}{k_a}} \tag{2.4}$$

$$\xi_a = \frac{c_a}{2\sqrt{k_a m_a}} \; . \tag{2.5}$$

The properties defined in (2.2)-(2.5) completely control the response of the 2DOF system in the linear-elastic range. Thus, for a given seismic signal the maximum inertial forces $F_{el}$ and $F_{a,el}$ induced on the main structure and the non-structural component, respectively, can be determined through a linear time-history analysis. Then, the elastic threshold $F_y$ which corresponds in principle to a given value of the force reduction factor R, can be easily defined as a further parameter of interest for the present parametric analysis:

$$F_y = \frac{F_{el}}{R} \; . \tag{2.6}$$

As a matter of principle, the yielding force of the non-structural components could be defined in a completely similar way. However, in this study the response of the non-structural component is kept in the linear range. Finally, the range of variation of the parameters defined above is reported below:

- mass ratio $m_a/m \in \{0.01;0.001\}$;
- main structure period $T_1 \in [0.2 \text{ s}; 2.0 \text{ s}]$;
- secondary period $T_a \in [0.05 \text{ s}; 5.0 \text{ s}]$;
- force-reduction factor $R \in [1; 6]$.

The other parameters are kept constant. In particular, both damping ratios $\xi$ and $\xi_a$ will be assumed equal to 0.05.

## 3. RESULTS

Since five values of $T_1$ and nine for $T_a$ have been considered within the ranges reported at the end of section 2.3, a total number of 142560 nonlinear time-history analyses have been carried out on 2DOF systems like the one represented in Figure 1 and considering the 264 seismic signals mentioned in section 2.2, two mass ratios and six values of the force-reduction factor $R$. General trends of the dynamic response of the non-structural component are presented in the following, along with a comparison against the code provisions of EN 1998-1 (2005). Then, the results in terms of two relevant response parameters, already defined in the scientific literature (Lin and Mahin 1985; Oropeza et al 2010) are quantified and discussed.

### 3.1. Preliminary observations

General trends can be captured by analysing the results obtained in numerical analyses introduced in section 2. Since the comparison between the code provisions is the first aim of this discussion, Figure

2 and Figure 3 reports the ratio of the maximum absolute acceleration $F_a/m_a$ and the corresponding peak ground acceleration ($PGA=Sa_g=\alpha Sg$) against the period ratio $T_a/T_1$ for various values of the reduction factor $R$. It is worth to precise that each point represented in terms of $F_a/m_aSa_g$ is the average of the same ratio obtained for the 264 seismic signals considered in the present parametric study. In particular, Figure 2 refers to the case of a short period structure ($T_1$=0,2 s) and shows that the ratios $F_a/m_aSa_g$ are significantly affected by the force reduction factors. The simplified code provisions basically miss this effect; the EN 1998-1 (2005) formula is generally in good agreement only in the case of R≈3÷4, which is the range of values of the q-factor generally adopted for a large majority of new structures.

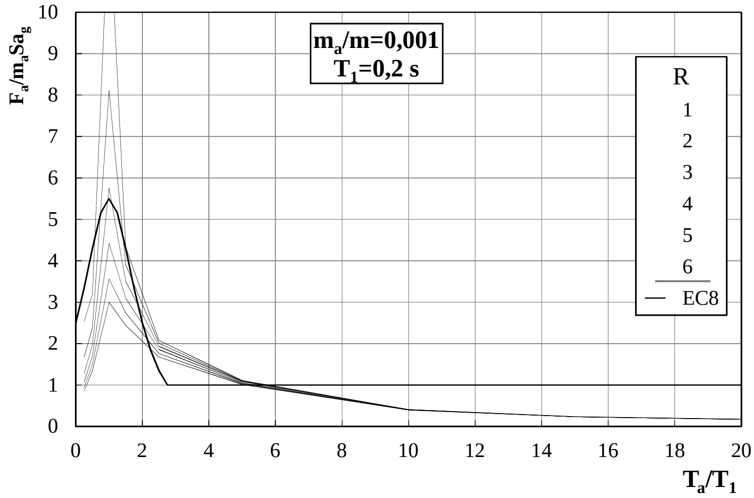


**Figure 2**. Maximum absolute acceleration on the structural components ($T_1$=0,2 s)

Similar comments can be reported for Figure 3 which deals with the case of a medium-to-long-period main structure. The maximum values of the ratio $F_a/m_aSa_g$, obtained around the unit period ratio are lower than the corresponding ones represented in Figure 2. This is a result of the reduction in the acceleration induced by the main structure whose period is $T_1$=1,0 s. However, the force reduction factor still affects significantly the dynamic response of the non-structural component and in this case the predictions based on EN 1998-1 (2005) are generally very conservative.

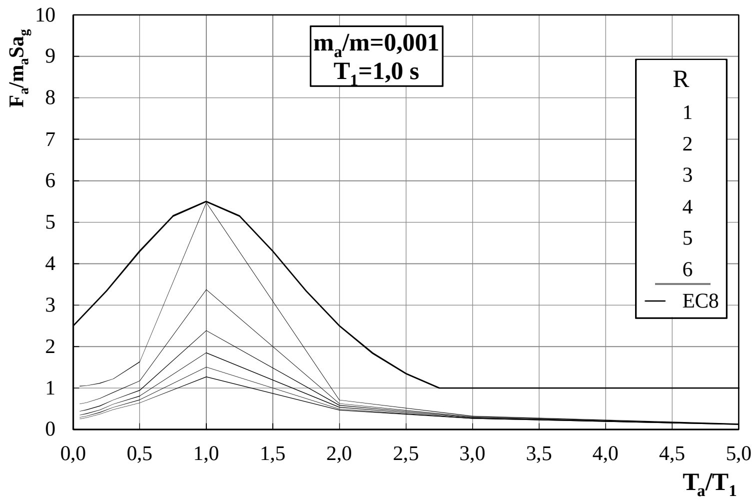


**Figure 3**. Maximum absolute acceleration on the structural components ($T_1$=1,0 s)

## 3.2. Definition of relevant response parameters

The numerical results reported in section 3.1 and particularly the comparison with the simplified formula adopted in EN 1998-1 (2005) points out the limited predictive capacity of the considered formulation. A wider number of parameters needs to be considered for enhancing that capacity. Moreover, the definition of more consistent response parameters can also be useful for better understanding the key features of the dynamic response of non-structural components. Two of such parameters are already defined in the scientific literature:

- the Amplification Factor AF, which is the ratio of the maximum total acceleration in the non-structural member evaluated for an inelastic main structure and the corresponding one derived by considering an elastic behaviour of the latter:

$$AF = \frac{F_a\left(R;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)}{F_a\left(R=1;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)} \; ; \tag{3.1}$$

- the Resonance Factor RF, which is the ratio of the maximum total acceleration of the non-structural component over the maximum value of the total acceleration in the main structure:

$$RF = \frac{F_a\left(R;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)/m_a}{F_r\left(R;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)/m} \; . \tag{3.2}$$

### 3.3. The Resonance Factor

The results of the parametric analysis carried out in this study can be easily presented in terms of both parameters defined in 3.2. For instance, the amplification factor AF can be plotted against the period of the non-structural component for various values of the factor R and a given period $T_1$. Figure 4 reports this diagram which actually comply with the non-monotonic shape of the various curves already described by Lin and Mahin (1985). It confirms once again the key role played by the factor R (especially in the case of low period components) which is completely neglected by the current code formulations.

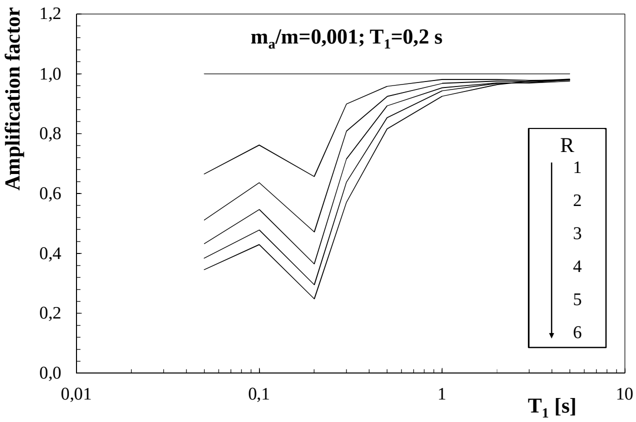


Figure 4. Amplification factor against the $T_a$ ($T_1$=0,3 s)

However, the research for a more compact representation of the huge amount of numerical results obtained in the parametric analysis can be accomplished by considering the Resonance Factor. Since the denominator of RF in (3.2) is clearly represents to the inelastic spectral pseudo-acceleration of the main structure for the period $T_1$ and the damping ratio $\xi$, the possible analytical description of RF in terms of the other relevant parameters would straightforwardly lead to the quantification of $F_a$. The following figures report the values obtained for RF through the nonlinear time-history analyses. Each point has to be intended as the average of 264 values derived by considering the set of seismic signals outlined in section 2.2.

Figure 5 reports the mean values of RF for the case of a $T_1$=0,2 s main structure. As a result of both the short period of the main structure and the range of variation of the secondary system periods (see section 2.3) the $T_a/T_1$ ratio spans over a rather wide range. Thus, the curves (one for each value of the R factor) clearly highlight the following key features of RF:

- all curves stem out from the unit at $T_a/T_1$=0, as a clear consequence of the definition of RF;

- an almost linear branch connects the unit with the maximum value of RF (denoted as $RF_{max}$, in the following) which depends on a resonance condition between the two components and is almost unaffected by R (at least for R>2);
- a decreasing branch follows the resonance point and describes the behaviour of RF which clearly vanishes as $T_a/T_1 \rightarrow \infty$.

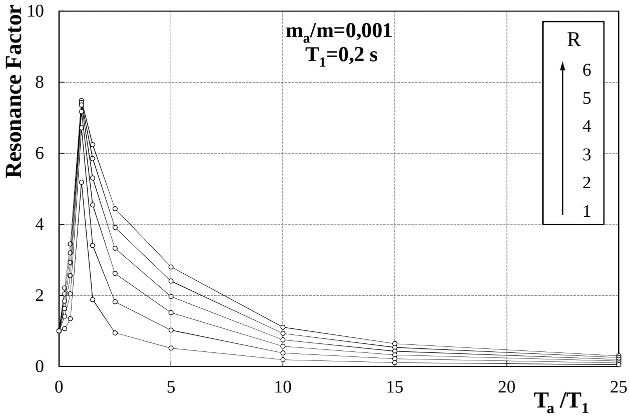


Figure 5. Mean value of RF against the period ratio $T_a/T_1$ ($T_1$=0,2 s)

A rather similar behaviour can be read in Figure 6 which refers to the case of $T_1$=0,3 s and the key points listed above can be easily recognised also in this case. Moreover, similar shapes are represented in Figure 7, Figure 8 and Figure 9, for longer periods.

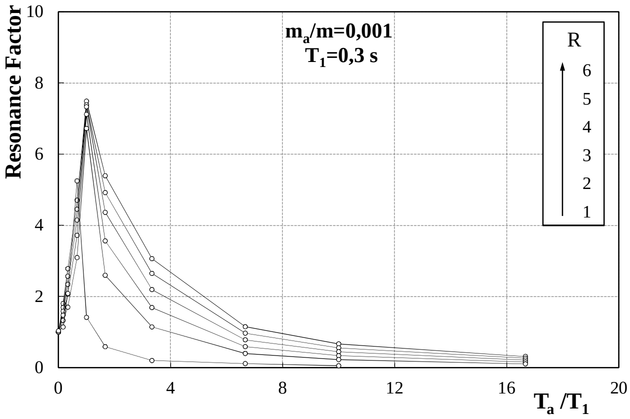


**Figure 6**. Mean value of RF against the period ratio $T_a/T_1$ ($T_1$=0,3 s)

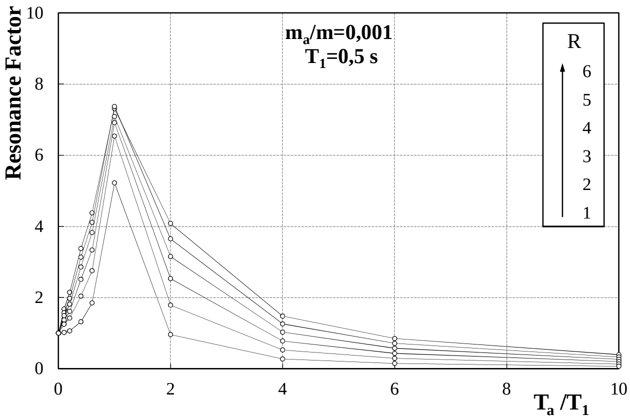


**Figure 7**. Mean value of RF against the period ratio $T_a/T_1$ ($T_1$=0,5 s)

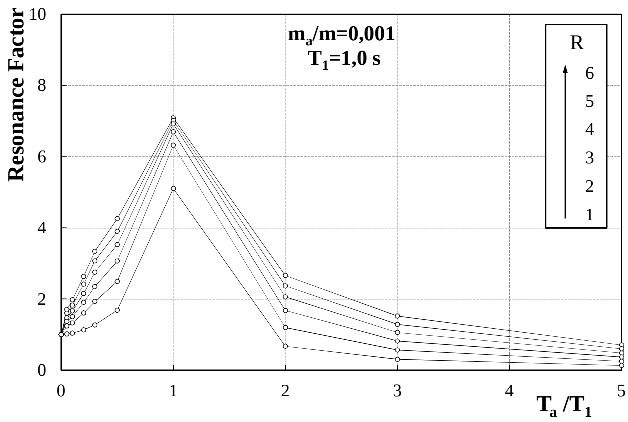


**Figure 8**. Mean value of RF against the period ratio $T_a/T_1$ ($T_1$=1,0 s)

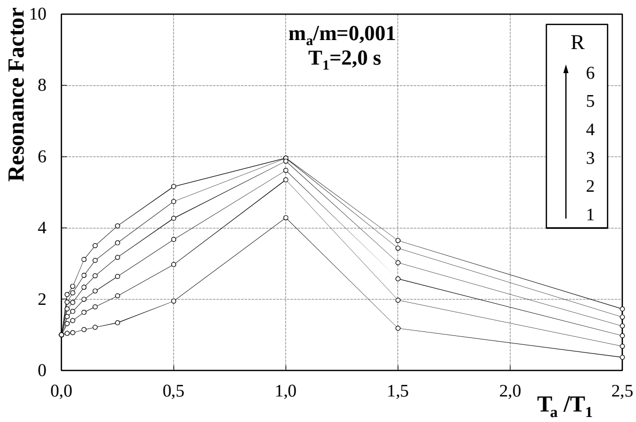


Figure 9. Mean value of RF against the period ratio $T_a/T_1$ ($T_1$=2,0 s)

Similar results have been found for the higher mass ratio $m_a/m$=0,01; thus, they are omitted herein for the sake of brevity. Since only the mean values of the key numerical results have been reported in this paper, a final comment addresses the key properties observed for the distribution of RF due to the variability of the seismic input. In particular, the distribution of RF obtained for a given structure in the analyses under the 264 seismic signals considered in this study is represented in Figure 10. Although no further details are present herein about this aspect, it is apparent that the variability in the seismic response of the non-structural component induced by the aleatoric nature of the seismic signals can be described by a lognormal statistical distribution.

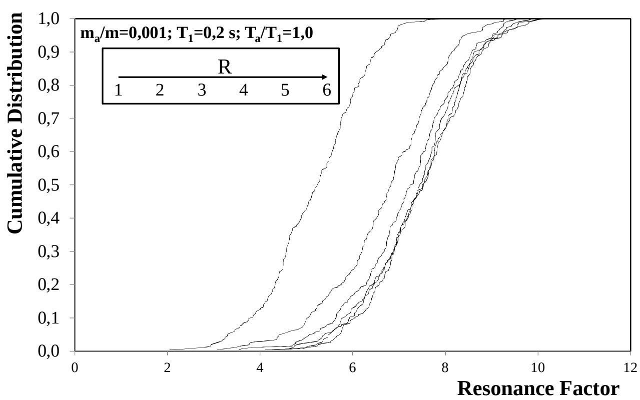


**Figure 10**. Typical distribution of RF for the considered seismic signals

As a matter of principle, such a distribution can be described by two independent parameters, i.e. the mean value and the standard variation $\sigma_{RF}$. Since the former has been already described, only some information about the latter are needed for a possible complete description of the variability of the structural response due to the seismic signals. Thus, Figure 11 shows the values of the standard variation against the period ratio $T_a/T_1$ for all the numerical results for $m_a/m$=0.001.

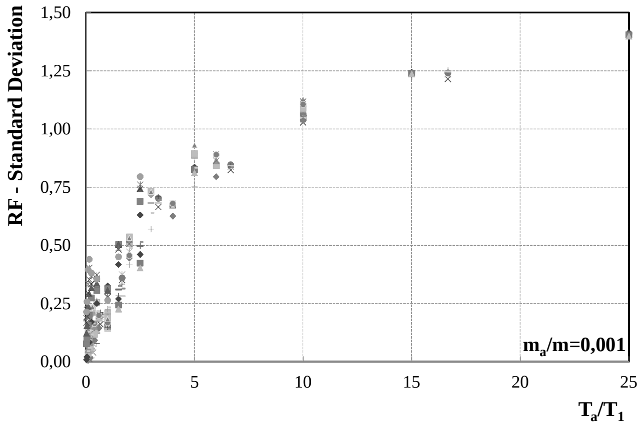


**Figure 11**. Standard Deviation of RF against the period ration $T_a/T_1$

It points out a key property of the dispersion parameters which is basically influenced by only the period ratio, whereas it is slightly influenced by the other relevant parameters (i.e., $T_1$ and $R$).

## 4. PRELIMINARY PROPOSAL FOR A SIMPLIFIED FORMULATION

Based on the results observed in section 3.3, a possible analytical formulation can be proposed for making explicit the relationship of the mean value $RF_m$ of the resonance factor with the period ratio $T_a/T_1$. In particular, the following double branch analytical expression can be adopted for describing the mean value of RF:

$$RF_m = \begin{cases} 1+\left(RF_{\max}-1\right)\cdot\dfrac{T_a}{T_1} & for \quad \dfrac{T_a}{T_1}\leq 1 \\ \dfrac{A\cdot e^{\left(-B\cdot\frac{T_a}{T_1}\right)}}{\left(\dfrac{T_a}{T_1}\right)^C} & for \quad \dfrac{T_a}{T_1}>1 \end{cases}, \tag{4.1}$$

where $RF_{max}$, $A$, $B$ and $C$ depend on both the force reduction factor R and the natural period $T_1$ of the main structure. Of course, $RF_{max} = A\cdot e^{-B}$ for the sake of continuity of the function (4.1) for $T_a/T_1$=1. As a matter of principle, their expressions can be calibrated on the numerical results obtained in the parametric analysis described in sections 2 and 3. The definition of the expressions of such coefficients depending on the above mentioned couples of parameters is still in progress and will be presented in one of the very next stages of this research. Moreover, a similar procedure can be carried out for calibrating an analytical relationship aimed at describing the variability of the response which derives from the aleatoric nature of the signals. Based on the results in Figure 11 it would be much simpler than the relationship (4.1), as $\sigma_{RF}$ basically depends on the period ratio only.

## 5. CONCLUDING REMARKS

This paper addresses the issue of determining the maximum actions induced in non-structural components of buildings under earthquake excitation. A wide parametric analysis has been presented and it results can be summarised as follows:

- the available code provisions lack in predicting the seismic response of non-structural components;

- the response of the main structure plays a key role (although neglected in the mentioned provisions) in influencing such a response;
- the definition of the "response factor" RF is a key step in quantifying the maximum seismic-induced actions;
- the relationship between RF and the other parameters clearly emerged by the parametric analysis: the main period $T_1$, the ratio $T_a/T_1$ and the reduction factor R are key quantities which influence the average value of RF determined in the nonlinear time-history analyses carried out on a wide set of recorded seismic signals;
- the standard deviation of RF is basically affected by the period ratio $T_a/T_1$ only.

Finally, the explicit evaluation of the relationships between $RF_m$ and the mentioned parameters is the next step in the future development of this study. Moreover, validating such relationships on the results of analyses carried out on multi-degree-of-freedom systems is the final goal of this research.

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