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On Predicting the Seismic Response of Acceleration-Sensitive Non-Structural Components in Buildings

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Abstract: This paper is intended at highlighting the main mechanical parameters controlling the behavior of the so-called "acceleration-sensitive" Non-Structural Components (NSCs). In the first part a short review of the current state of knowledge and the critical issues related to the prediction of the seismic response of NSCs is reported. Then, the paper presents the results of a numerical parametric analysis intended to capture the key features of the dynamic response of a two-degree-of-freedom (2DOF) system which is supposed to be representative of both the main structure and the "non-structural" component (NSC). Particularly, it allows to simulate the coupled behaviour of both main structure and NSC and evaluating their response. The main parameters controlling the dynamic response of NSCs emerge from this study, which could pave the way towards formulating more mechanically consistent relationships for evaluating the maximum accelerations induced by seismic shakings on NSCs.

Keywords: seismic analysis; non-structural components; nonlinear analysis; 2DOF; maximum acceleration

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1. Introduction

Significant research efforts have been produced in the last decades in order to formulate sound criteria for the design of structures in seismic areas resulting in the current generation of seismic codes and guidelines [1,2]. Such codes provide designers with consistent performance-based approaches for designing and assessing structures against earthquake-induced actions. However, a series of critical issues, which are not completely assessed by the current code provisions, emerge by analyzing damages suffered from existing structures in recent earthquake events [3]. Specifically, the most evident critical issues are related to the not accurate prediction of the seismic response of "non-structural components" (NSCs) [4-6] as it emerges in the aftermaths of the event occurred in Emilia Region, Italy [7], where several precast buildings mainly suffered damage related to inadequate design of connections between structural members and NSCs [8,9]. Therefore, predicting the seismic response of NSCs is perceived as one of the most important challenges in the seismic engineering community [10,11].

Several definitions for the very wide class of objects often referred to as NSCs are available in the scientific literature and recent seismic codes [2]. As a general definition any "object" which does not contribute to support both gravity and seismic actions in the model considered in structural analysis is considered a "non-structural" or "secondary" element. As matter of fact, partitions, masonry infill, suspended ceilings, finishing, as well as specific equipment are the most common NSCs in buildings.

Moreover, recent scientific researches and technical codes introduced further definitions and classifications of NSCs: a review of these definitions is available in the literature [12]. Generally, they are based on different aspects, such as the component's purpose or function, its connection to the

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main structure and the sensitivity to particular aspects of the dynamic response (acceleration, displacement, and so on).

Over the classification of NSCs, the main objective of various seismic codes in force in earthquake-prone countries (e.g., [1,13-16]) is to evaluate the maximum acceleration, and thus the maximum inertial force, on NSC induced by the expected seismic shaking. However, rules and relationships provided with this purpose are generally simple (and often simplistic) and disregard fundamental parameters which could significantly affect the dynamic response of NSCs.

As matter of principle, rules and relationships currently provided involve few parameters dealing with the intensity of the expected earthquake, the elastic properties of both the main structure and the NSC and the position in height of the NSCs within the main structure. A thorough discussion about the limitation of code formulations has been recently proposed [12]; specifically, it emerges that the analyzed code-provisions either disregard or not explicitly consider the nonlinear behavior of the main structure which may clearly affect the excitation of the NSCs by "filtering" the seismic signal [17].

Therefore, this paper presents a wide parametric analysis based on a two-degree-of-freedom (2DOF) system used for simulating the dynamic response of a general structure equipped with a NSC. The study is aimed at quantifying the inertial forces induced on NSCs. The key results of the parametric analysis are summarized in section 3 which demonstrate what are the relevant parameters which affect the prediction of the maximum seismic actions induced on NSCs and their variations.

2. Parametric Investigation

The interaction which affect the dynamic response of the main structure and the NSC connected to the main structure itself is investigated considering a two-degree-of-freedom (2DOF) system. It is considered as a simple possible representation of the main structure directly shaken by the earthquake ground motion and the NSC. The system considered in this study is schematically represented in Figure 1.

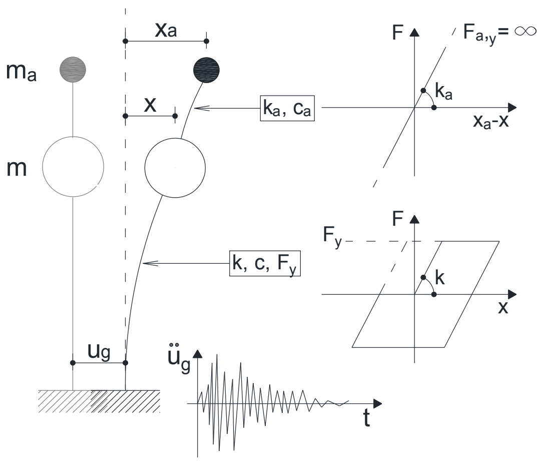

Figure 1. The 2DOF system considered in the Nonlinear Time-History Analyses.

An elastic-perfectly-plastic behaviour is supposed for the main structure which is denoted in Figure 1 by the mass m. It is characterised by elastic stiffness k, viscous damping c and yielding force F_y (Figure 1). The parameters x and $\dot{x}$ denote the relative displacement and velocity of the main structure with respect to the ground, respectively. The NSC is represented by its mass m_a and it is connected to the main structure by an elastic element with stiffness k_a. The relative displacement of the NSC with respect to the ground is denoted with x_a. The viscous damping coefficient c_a, which relates the viscous force with the relative velocity $\dot{x}_a$ of the NSC with respect to the ground, completes the description of the 2DOF system under investigation.

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However, nonlinear behavior is not considered for the NSC in this study, since it is mainly devoted at evaluating the maximum forces induced on secondary components without covering aspects related to displacements.

The system represented in Figure 1 allows to consider the coupled behaviour of the main structure and NSC and can result more appropriate than systems generally adopted in similar studies which are often based on the dynamic analysis of two uncoupled single-degree-of-freedom (SDOF) systems in series [18,19]. As matter of fact, the latter systems are based on the simulation of a SDOF system representing the main structure whose response is, subsequently, considered as the ground motion for the secondary SDOF system which simulates the NSC. Such a study can result in accurate prediction if the NSC-to-structure mass ratio is quite small (i.e., $m_a/m \rightarrow 0$) and thus the mass m_a does not influence the dynamic response of the main structure. For sake of generality, the present study does not consider this approximation and a system of coupled equilibrium equations is actually solved by means of a piecewise approach based on the Beta-Newmark numerical algorithm [20]. Such an algorithm is used in order to handle nonlinearities in the dynamic response of the following system:

$$\begin{cases} m\ddot{x} + c\dot{x} - c_a\left(\dot{x}_a - \dot{x}\right) - k_a\left(x_a - x\right) + F_r\left(x; k, F_y\right) = -m\ddot{u}_g \\ m_a\ddot{x}_a + c_a\left(\dot{x}_a - \dot{x}\right) + k_a\left(x_a - x\right) = -m_a\ddot{u}_g \end{cases} \tag{1}$$

In eq. (1) the reaction $F_r(x,k,F_y)$ is the unique nonlinear part which includes both the relative displacement x of the main structure and its stiffness k and yielding force F_y (Figure 1).

A set collecting 264 natural records has been employed as ground motion in the nonlinear time-history analyses of the 2DOF system described above carrying out a very wide parametric analysis. Such a set is based on the seismic events and records considered in an important study investigating the nonlinear response of SDOF systems [21].

The main parameters that govern the dynamic response of the 2SDOF system representing the main structure and NSC (Figure 1) can be easily derived from eq. (1). As matter of fact, the mass ratio m_a/m, as well as other parameters usually considered for describing the response of SDOF oscillators can be identified as key parameters which control the response of both the main structure and the NSC.

$$\text{- Main structure:} \quad T_1 = 2\pi\sqrt{\frac{m}{k}}\ ; \quad \xi = \frac{c}{2\sqrt{km}}\ ; \tag{2}$$

$$\text{- Non-structural component:} \quad T_a = 2\pi\sqrt{\frac{m_a}{k_a}}\ ; \quad \xi_a = \frac{c_a}{2\sqrt{k_a m_a}}\ . \tag{3}$$

The elastic period T and the damping ratio ξ [20] defined in eqs. (2) and (3) for the main structure and the NSC, respectively, completely control the response of the 2DOF system in the linear-elastic range. Thus, a linear time-history analysis performed for a given seismic record the allows to evaluate both the maximum inertial force on the main structure F_{el} and the one induced on NSC $F_{a,el}$. Then, the elastic threshold F_y denoting the yielding of the main structure (Figure 1) can be easily defined as a further parameter of interest for the present parametric analysis as it corresponds in principle to a given value of the force reduction factor R:

$$F_y = \frac{F_{el}}{R}\ . \tag{4}$$

However, the yielding force of the NSCs could be defined in a completely similar way, but it is omitted in this study as the response of the NSC is kept in the linear range. Finally, the parameters defined above have been changed within the range of variation defined below:

- mass ratio $m_a/m \in \{0.01; 0.001\}$;
- main structure period $T_1 \in [0.2\ \text{s}; 2.0\ \text{s}]$;

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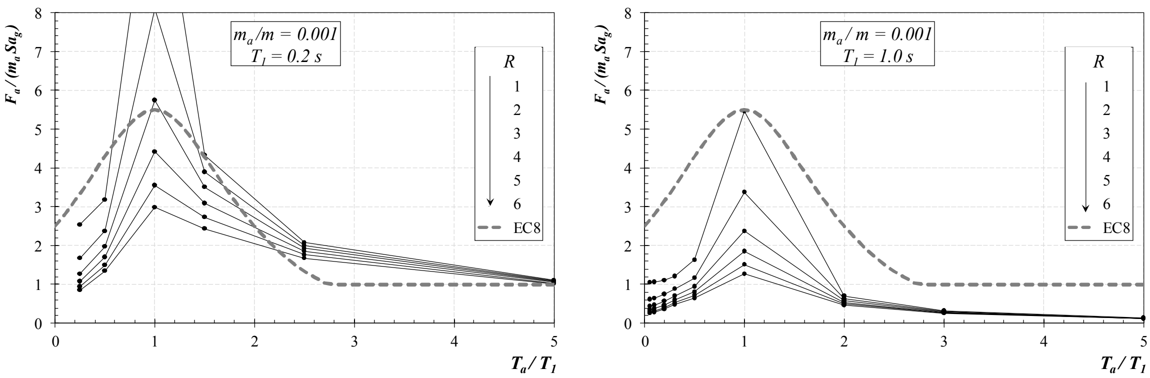
- secondary period $T_a \in [0.1\ \text{s}; 5.0\ \text{s}]$;
- force-reduction factor $R \in [1; 6]$.

Otherwise, both damping ratios ξ and ξ_a referred to the main structure and NSC have been assumed constant and equal to 0.05. As one can see, the considered mass ratios refer to a class of NSCs (such as systems, ceilings, etc.) whose mass is significantly lower (and fairly negligible) with respect to the structural one. The values of period T_1 are intended to cover the whole range of low-medium rise buildings, either made of steel or concrete, meanwhile, the values assumed for T_a are intended to cover a wide spectrum of NSCs and their connections to the main structures, ranging from very stiff (and rigidly connected) components to fairly soft (or flexibly connected) ones. Finally, the values of R range from non-dissipative structures (R=1) up to highly dissipative ones (R=6, simulating high ductility steel frames).

3. Results of the Parametric Analysis

The parametric analysis has been performed considering the 264 seismic signals mentioned in section 2 [21] and the range of variation of the relevant parameters listed in the previous section. As a result, 142560 nonlinear time-history analyses have been carried out on 2DOF systems considering five values of T_1 (ranging between 0.2 s and 2.0 s) and nine for T_a (between 0.1 s e 5.0 s). Two mass ratios (0.01 and 0.001) and six values of the force-reduction factor R (from 1 to 6) have been also considered.

Figure 2 depicts the behaviour of the ratio between the maximum absolute acceleration F_a/m_a of NSC and the corresponding peak ground acceleration ($PGA=S\cdot a_g=\alpha\cdot S_g$) against the period ratio T_a/T_1. The reduction factor R ranges from 1 to 6 and each point is the average of the results obtained from the 264 seismic signals considered in the parametric study. Furthermore, the response of the code provision reported in EC8 [1] is also depicted resulting in a unique trend as such code formulation does not depends from the inelastic behaviour of the main structure which is simulated by R in this study. Specifically, Figure 2,a refers to the case of main structures characterised by short period of vibration (T=0.2 s) and demonstrates that the force reduction factor R significantly affect the maximum ratios $F_a/m_a{\cdot}S{\cdot}a_g$ corresponding to the resonance condition (T_a=T_1), while the effect of R results less important for long periods of NSC (T_a/T_1>2). Moreover, the simplified code provision reported in EC8 [1] miss this effect resulting in good agreement with numerical experiments 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 RC structures.



(a) (b)

Figure 2. Maximum absolute acceleration on the structural components (T_1=0.2 s and T_1=1.0 s).

A similar response is observed in Figure 2,b in which the case of a medium-to-long-period of the main structure is represented. Furthermore, the maximum values of the ratio $F_a/m_a{\cdot}S{\cdot}a_g$, obtained for medium-to-long period structures (Figure 2,b) are lower than the corresponding ones evaluated for short-period structures represented in Figure 2,a. This effect is due to the reduction in the acceleration induced on the main structure for long periods. However, the force reduction factor still affects

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significantly the dynamic response of the NSC for ratios of periods $T_a/T_1 < 2$, while the prediction based on EC8 [1] results too conservative especially for high values of R.

Moreover, the results obtained for the mass ratio m_a/m=0.01 overlap the ones obtained for m_a/m=0.001, pointing out that, in this range of values, the mass ratio has a negligible influence on the resulting response. Therefore, the results for m_a/m=0.01 are omitted hereinafter for sake of brevity.

As a final remark, easily supported by elementary mechanical intuition, Figure 2 shows that the two parameters T_1 and R play a fundamental role in determining the maximum absolute acceleration S_a of NSCs and should be considered as key parameters in order to improve the relationships currently available for evaluating the dynamic response of non-structural components [1] which generally does not take into account the effect of the force reduction factor R.

3.1. Definition of relevant response parameters

The results reported Figure 2 and, specifically, the comparison with the simplified formula adopted in EC8 [1] point out the significant lack of predictive capability affecting the aforementioned seismic code. As matter of fact, a wider number of parameters should be considered with the aim of enhancing the accuracy of formulations currently available. Moreover, more consistent response parameters can also be defined for describing the dynamic response of NSCs. For this purpose, [18,19] defined the following two parameters:

- the *Amplification Factor*: $$AF = \frac{F_a\left(R;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)}{F_a\left(R=1;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)}; \qquad (5)$$

- the *Resonance Factor*: $$RF = \frac{F_a\left(R;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)/m_a}{F_r\left(R;T_1,T_a/T_1,m_a/m;\xi,\xi_a\right)/m}. \qquad (6)$$

The AF 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, while the RF is the ratio between the maximum total acceleration of the NSC and the maximum value of the total acceleration in the main structure.

In the following two subsections, the variation of the aforementioned parameters is deeply analyzed against the properties which fully describe the dynamic response of the system.

3.1.1. The Amplification Factor

The amplification factor AF is analysed and plotted against the period of the NSC for values of the factor R ranging from 1 to 6 and a given period T_1. Specifically, Figure 3 reports this diagram for the case of m_a/m=0.001 for two values of T_1 (namely, 0.2 and 1.0 s) and confirms the non-monotonic shape of the curves already described in the literature [19]. Moreover, it highlights once again the key role played by the factor R (especially in the case of NSCs with low period of vibration) which is completely neglected by the current code formulations.

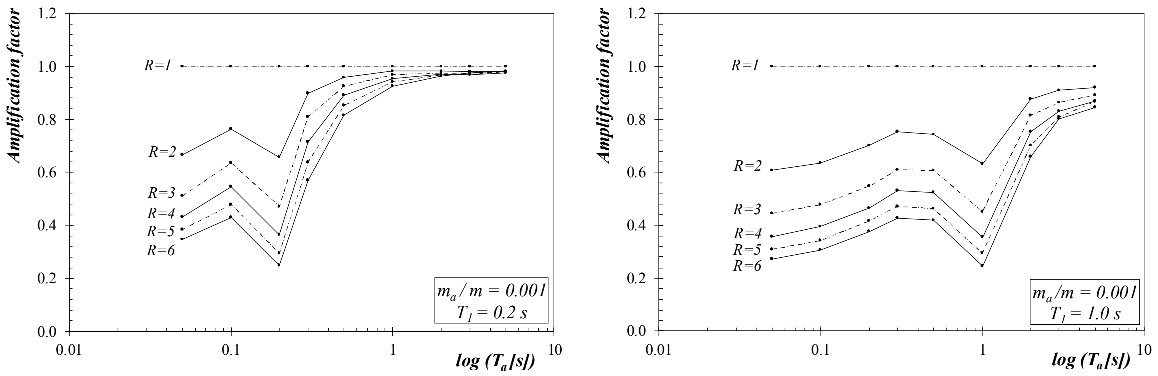

Figure 3. Amplification factor vs. the T_a (T_1=0.2 s; T_1=1.0 s).

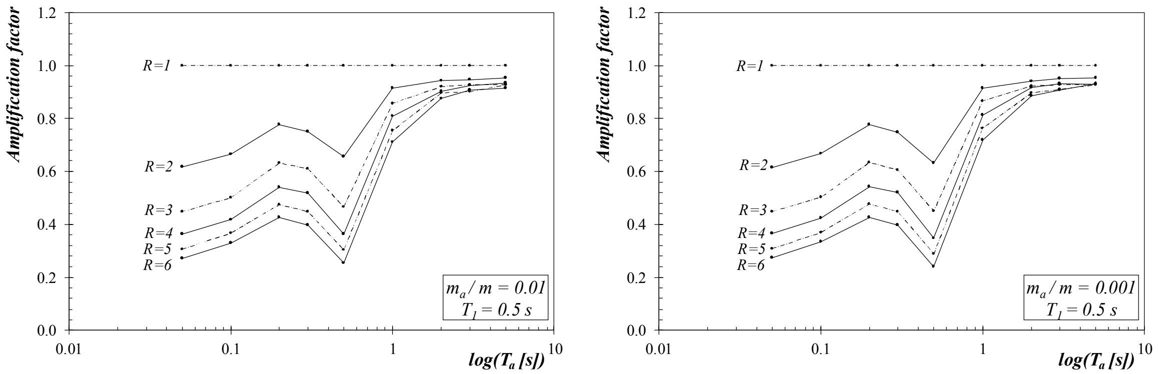

Figure 4. Amplification factor vs. the T_a (m_a/m=0.01; m_a/m=0.001).

Moreover, Figure 4 consists of two diagrams reporting AF for the same fundamental period T_1=0.5 s and two different mass ratio m_a/m. It confirms that mass ratio is almost irrelevant for the resulting response, at least if it is kept lower than 0.01.

3.1.2. The Resonance Factor

The Resonance Factor allows to obtain a more compact and representative representation of the huge amount of numerical results obtained in the parametric analysis herein performed. As shown in eq. (6), the denominator of RF is clearly related to the elastic spectral pseudo-acceleration of the main structure for the period T_1 and the damping ratio , thus the possible analytical description of RF in terms of the other relevant parameters would straightforwardly lead to the quantification of F_a which is the numerator in eq. (6).

The following figures report the trend obtained for RF by the NLTH analyses. It is worthy to note that each point represents the average of 264 values derived by considering the set of seismic signals considered.

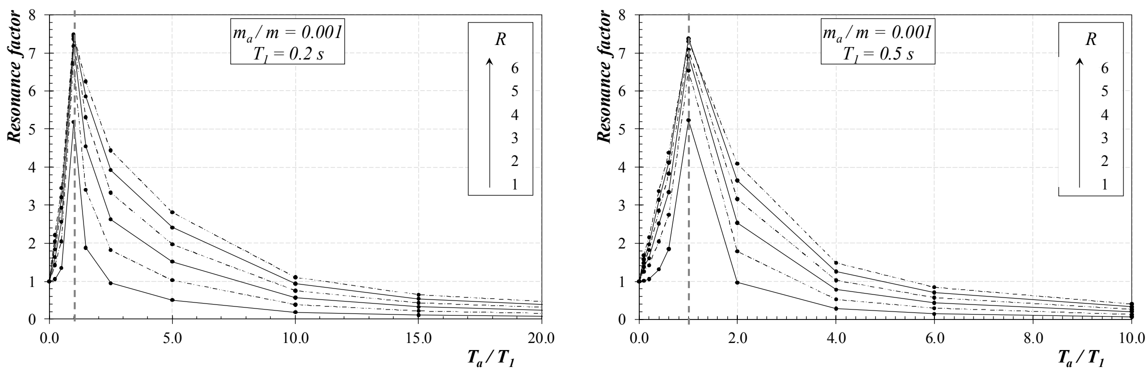

Figure 5. Mean value of RF vs. period ratio T_a/T_1 for m_a/m=0.001 (T_1=0.2 s and T_1=0.5 s).

Figure 5 reports the (mean) values of RF for the cases of $T_1 \in$ {0.2 s; 0.5 s} and mass ratio equal to 0.001. As a result of the short period of the main structure and the range of variation of the secondary system periods (see section 2) the T_a/T_1 ratio spans in a rather wide range. Therefore, 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 depend 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 $T_a/T_1 \rightarrow$.

Similar shapes are represented in Figure 6 for longer periods and in Figures 7 and 8 which report the same results for the higher mass ratio m_a/m=0.01.

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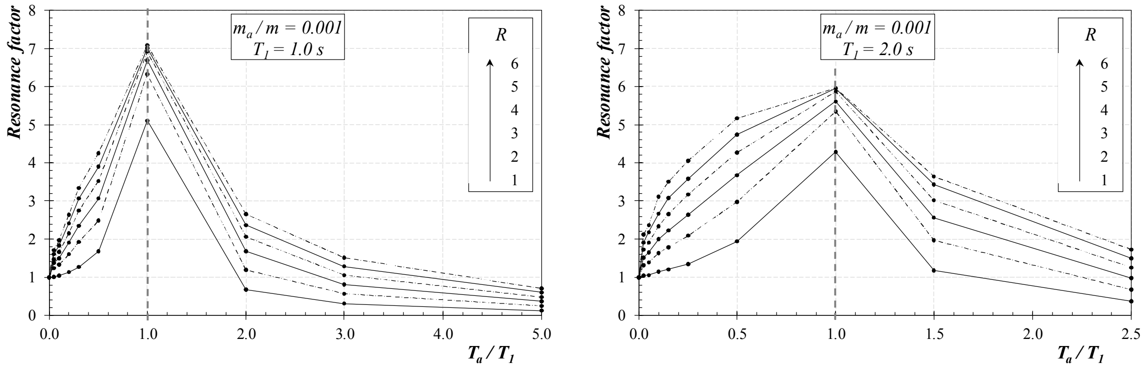

Figure 6. Mean value of RF vs. period ratio T_a/T_1 for m_a/m=0.001 (T_1=1.0 s and T_1=2.0 s).

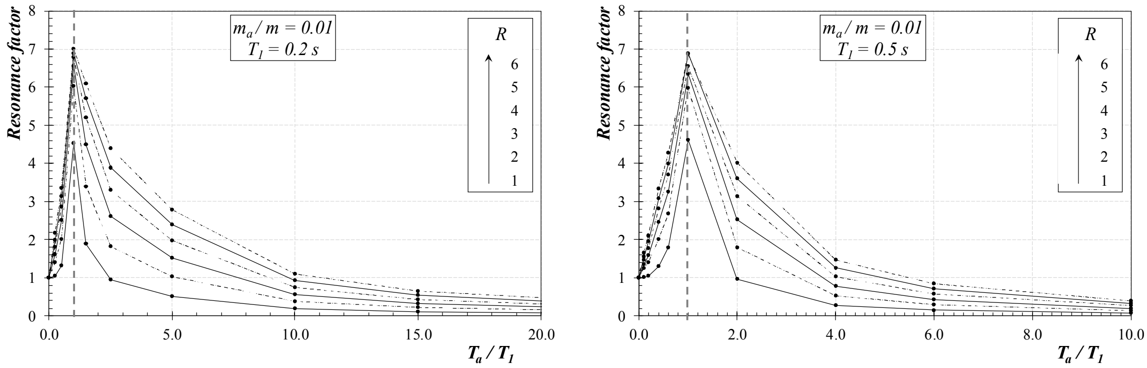

Figure 7. Mean value of RF vs. period ratio T_a/T_1 for m_a/m=0.01 (T_1=1.0 s and T_1=2.0 s).

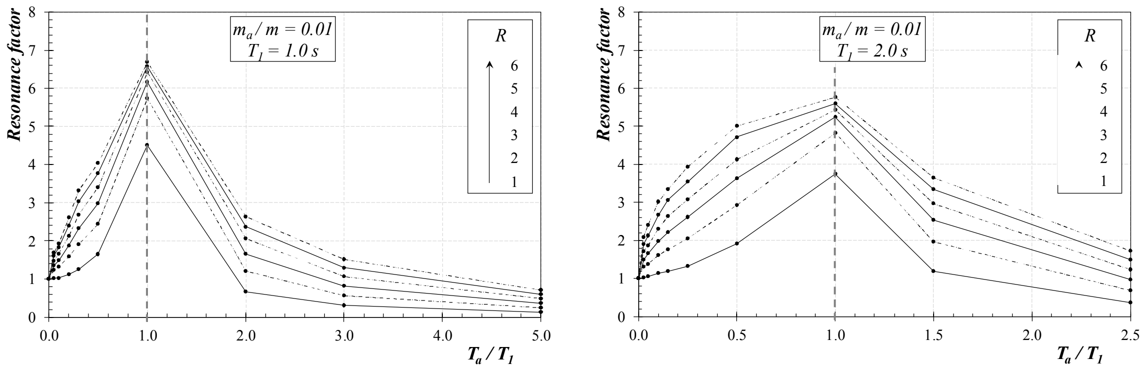

Figure 8. Mean value of RF vs. period ratio T_a/T_1 for m_a/m=0.01 (T_1=1.0 s and T_1=2.0 s).

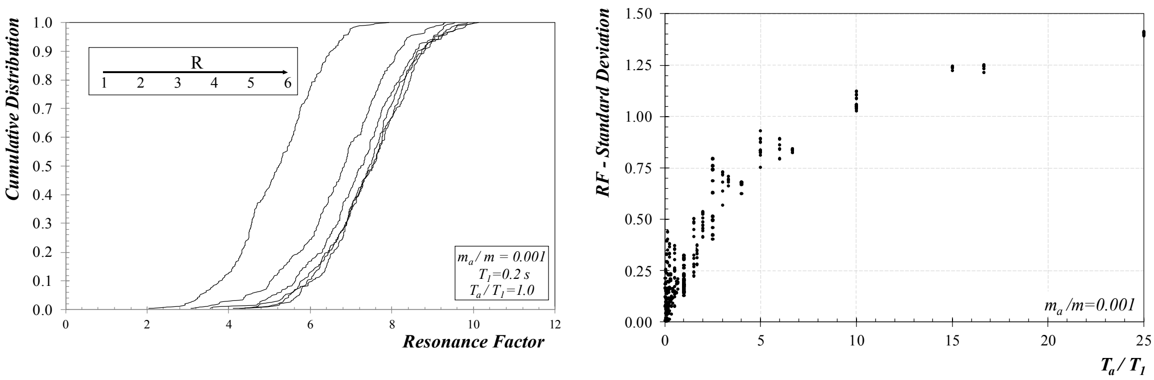

Figure 9. Typical distribution of RF for the considered seismic signals and its Standard Deviation against the period ratio T_a/T_1.

Finally, since only the mean values of the key numerical results have been reported in the previous figures, further aspects dealing with the record-to-record variability of the RF need to be addressed. Therefore Figure 9 reports both cumulative distribution and standard deviation of the RF obtained for the structural systems analysed in this study. As for the former, the curves plotted in Figure 9 shows that the R only influences the median value of RF. As for the latter, the standard deviation is mainly controlled by the period ratio Ta/T1.

4. Concluding remarks

This paper addressed the issue of determining the maximum actions induced in NSCs of structures under earthquake excitation. The results of the wide parametric analysis reported in this paper can be summarized as follows:

- the available code provisions lack in predicting the seismic response of NSCs often neglecting relevant parameters which control the dynamic response of such components;
- the nonlinear behavior of the main structure, although neglected in the current code provisions, significantly affect such a response;
- the definition of the "resonance 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; specifically, 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.

Although further and more accurate calibrations might be proposed in the future, in the Author's opinion, relating the non-structural response to the structural one is the key conceptual contribution of this study.

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