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FLOOR RESPONSE SPECTRA FOR NONLINEAR SDOF NONSTRUCTURAL COMPONENTS

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ABSTRACT

Acceleration-sensitive nonstructural components (NSCs), commonly referred to as equipment or secondary systems, recently attracted significant attention, mainly in terms of seismic analysis, assessment and design. There is a constant improvement of the state-of-knowledge on floor response (acceleration) spectra (FRS), which represent the basic input for NSCs sensitive to accelerations. Among others, it has been found that nonlinear behaviour of a NSC strongly reduces the values of FRS in resonance and post-resonance regions, leading to reduced seismic demands. Based on the results of a parametric study performed on (non)linear single-degree-of-freedom (SDOF) NSCs attached to (non)linear SDOF structures, and on a method for the direct determination of FRS previously developed by the authors, new formulas for the estimation of FRS accounting for the NSC nonlinearity were proposed. The accuracy of the formulas was examined in a case study example.

INTRODUCTION

Seismic considerations of NSCs started in nuclear industry in 1960s since it was recognized that their safety and survivability are of crucial importance. Seismic demands for acceleration-sensitive NSCs are usually expressed through FRS. They are generally applicable in the analysis, assessment and design of NSCs. An early method for direct determination of FRS was developed and proposed by Biggs (1971). The list of the further developments of various direct FRS methods can be found in several review papers, e.g., Villaverde (1997) and Wang et al. (2021).

In the past, the influence of structural nonlinearity on acceleration-sensitive NSCs has been widely investigated, and its beneficial effects, reflecting through the reduction of FRS values, were recognized. In opposite, when it comes to the influence of NSC nonlinearity on FRS, only a limited number of studies has been performed so far.

Villaverde (2006) proposed a method for the estimation of the response of NSCs in buildings, considering the nonlinear behaviour of both the structure and the NSC. Chaudhuri and Villaverde (2008) performed a parametric study in which both linear and nonlinear SDOF components attached to rigid and flexible spatial steel moment-resisting frames were considered. Tamura et al. (2016) observed that the nonlinear behaviour of SDOF NSCs significantly reduces the required yield strength, and proposed simple equations for the estimation of NSC strength reduction factors. Vukobratović and Fajfar (2017) briefly studied the influence of nonlinear NSC behaviour on FRS, and proposed a code-oriented version of the direct FRS method, in which the NSC nonlinearity is implicitly taken into account through an increased NSC damping. Based on floor motions recorded in instrumented buildings in California, Kazantzi et al. (2020) conducted the statistical analysis of NSC strength reduction factors, and proposed approximate equations for their estimation. Anajafi et al. (2020) demonstrated that NSC nonlinearity can significantly reduce the peak FRS values in the resonance region. In a recent paper (Vukobratović and Fajfar 2023), the authors presented an extended version of their method which takes into account both the NSC and structural nonlinearity in a consistent manner.

The purpose of this paper is to inform the nuclear engineering community about the benefits of taking the NSC nonlinearity into account when determining floor acceleration spectra. There are several potential sources of NSC and anchorage ductility (ductility in the NSC, the attachment of the NSC to the anchor, the anchor itself, or a combination of any of these items) which may contribute to the reduction of seismic action on the NSC. The paper represents a condensed version of the authors' paper (Vukobratović and Fajfar 2023) and contains some new results of numerical studies.

PARAMETRIC STUDY

Within the parametric study, uncoupled analysis of structures and NSCs was performed. Seismic input consisted of 30 ground motion records, whose mean acceleration spectrum closely matched Eurocode 8 (EC8, CEN 2004) Type 1 spectrum for soil type B (the characteristic period of ground motion T_C = 0.5 s) for 5% damping, considering the peak ground acceleration (*PGA*) of 0.35 g (Figure 1).

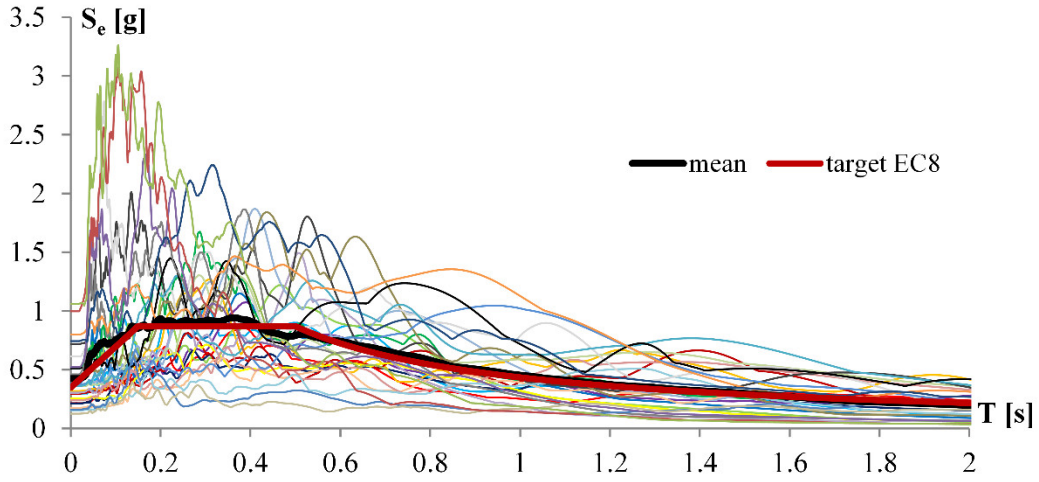

Figure 1. The acceleration spectra of individual records, their mean, and Eurocode 8 target spectrum (Type 1, soil type B, *PGA* = 0.35 g), all for 5% damping.

Two structural natural periods (T_p) were taken into account, i.e., 0.3 s and 1.0 s, representing rigid and flexible structures, respectively. Nonlinear structural behaviour was taken into account through ideal elastic-plastic (EP) and stiffness degrading (Q) models, whereas nonlinear NSC behaviour was assumed to be EP in all cases. For nonlinear structures and NSCs, constant target ductility factors μ_p equal to 2 and μ_s equal to 1.25-4, respectively, were assumed throughout the whole range of periods. Mass-proportional damping amounted to 5% for the structures, and 1-10% for NSCs. The latter covered a wide range of NSCs. Natural period and damping of NSCs were denoted as T_s and ξ_s, respectively, whereas FRS values were denoted as A_s.

The mean values of elastic (blue) and inelastic (red) FRS obtained for the considered input, linear elastic, EP and Q structures with T_p = 0.3 s, and linear elastic and nonlinear NSCs with μ_s = 2 and ξ_s equal to 3% and 7%, are shown in Figure 2. The A_s values at zero period (T_s = 0 s), which represent peak floor accelerations (*PFA*s), depend only on the structural response, i.e., the properties of NSCs are irrelevant. Furthermore, the nature of nonlinear structural behaviour controls spectral shapes: for the EP model peaks are located at $T_s \approx T_p$, while for the Q model peaks shift towards longer periods due to stiffness degradation. Finally, structural nonlinearity influences the FRS values in the pre- and resonance regions. It can be seen that the influences of the above mentioned structure-related factors on elastic and inelastic FRS are similar.

When it comes to the NSC damping and nonlinearity, their influences on FRS are basically essential in the resonance and post-resonance regions. In the resonance region, the NSC nonlinearity effect is much more pronounced than the one produced by the structural nonlinearity. It should also be noted that the NSC nonlinearity obviously has much larger influence than the NSC damping. Therefore, the main difference between elastic and inelastic FRS is that in the resonance region the influence of the NSC nonlinearity, which strongly reduces peak values, suppresses the influence of the NSC damping. Also, the influence of the NSC damping tends to diminish in the post-resonance region, as presented in Figure 3. Both findings represent a basis for the improvement of knowledge on inelastic FRS, and were considered within the development of new formulas for the direct FRS determination.

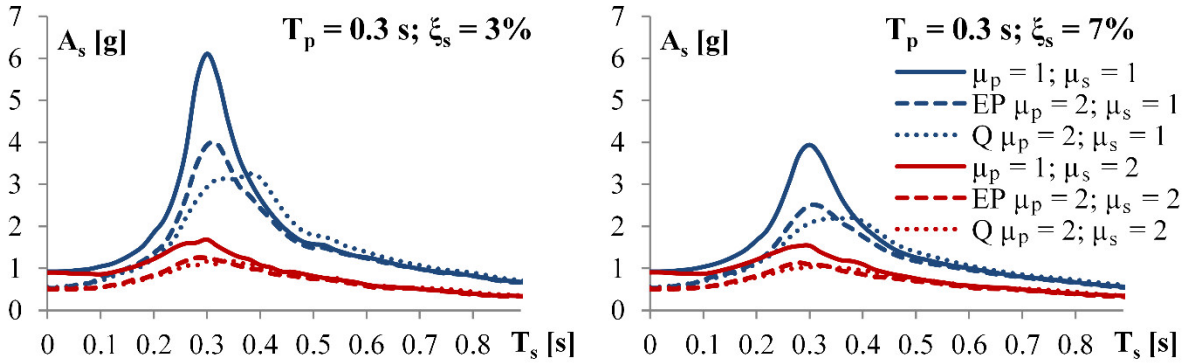

Figure 2. Mean elastic and inelastic FRS for the linear, EP and Q structures with $T_p = 0.3$ s.

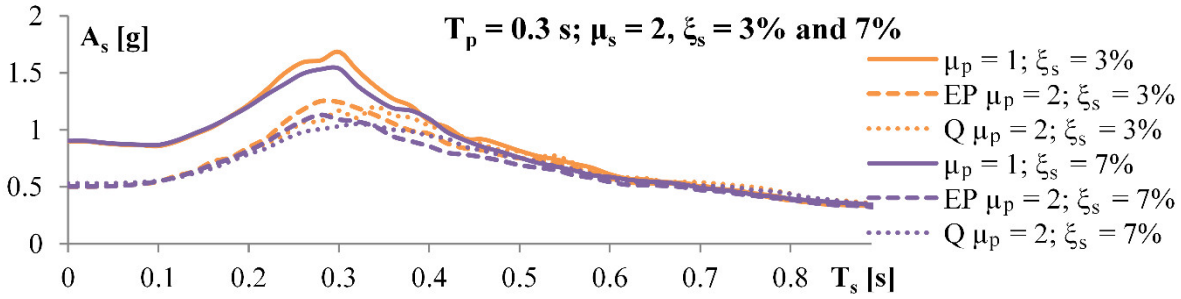

Figure 3. Comparison of inelastic FRS shown in Figure 2.

The ratios of elastic and inelastic FRS, which represent the NSC strength reduction factor R_s, are shown Figure 4 for linear elastic, EP and Q structures with $T_p = 0.3$ s, and nonlinear NSCs with $\mu_s = 2$ and $\xi_s = 3\%$. It can be seen that the R_s factor strongly depends on the period. Furthermore, similarly as the strength reduction factor for the primary structure, denoted as R_p herein, R_s increases in the pre-resonance region, and it is approximately constant in the post-resonance region, where its value roughly corresponds to the assumed value of NSC ductility demand μ_s (the well-known equal displacement rule approximately applies). However, in contrast to the R_p, the R_s factor has a sharp peak in the resonance region. Although not shown here, it was observed that the values of R_s follow the same trend for both rigid and flexible structures, and for both the EP and Q hysteretic models throughout the whole range of periods. Finally, it was noticed that the R_s factor is sensitive to the NSC damping.

For practical applications, it is convenient to apply a simple form of R_s. The suggestion proposed herein, consistent with the common form of the structural strength reduction factor R_p (Vidic et al. 1994), is to use a bilinear R_s in the off-resonance regions (red line in Figure 4). In the short period range ($T_s < T_p$), R_s linearly increases from 1 at $T_s/T_p = 0$ to μ_s at $T_s/T_p = 1$. For the NSC periods larger than the natural period

of the structure T_p, $R_s = \mu_s$. In the resonance region, R_s is increased, which depends on the NSC ductility and damping. In the method presented in this paper, the influence of the NSC ductility on R_s is taken into account both in the off-resonance regions and in the resonance (indirectly, via amplification factors that are discussed below), while the influence of the NSC damping on R_s is neglected in the off-resonance regions.

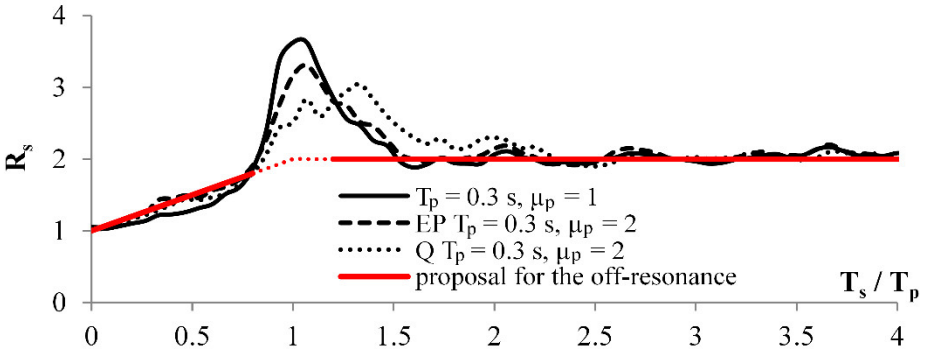

Figure 4. NSC strength reduction factor R_s for linear elastic and nonlinear structures with $T_p = 0.3$ s and NSC with $\mu_s = 2$ and $\xi_s = 3\%$ in the off-resonance region.

As will be discussed in more detail in the next section, in the direct method previously developed by the authors (Vukobratović and Fajfar 2015, 2016, 2017), amplification factors (*AMP*s) are used in the formula for the resonance regions. An *AMP* is defined as the ratio of the peak spectral floor acceleration $A_{s,max}$ (the floor spectral acceleration in resonance) to the peak floor acceleration *PFA* ($AMP = A_{s,max}/PFA$). Selected results of the parametric study, in terms of *AMP*s, are shown in Figure 5. It can be seen that the NSC nonlinearity has stronger influence on *AMP*s than the NSC damping. Additionally, the *AMP* values also depend on the properties of the primary structure, i.e., they are larger for a rigid structure ($T_p = 0.3$ s) than for a flexible one ($T_p = 1.0$ s), and are larger for the EP hysteretic behaviour compared to the Q. In Figure 5, the dashed blue lines were obtained by using the newly proposed equation for the determination of *AMP*, provided in the next section.

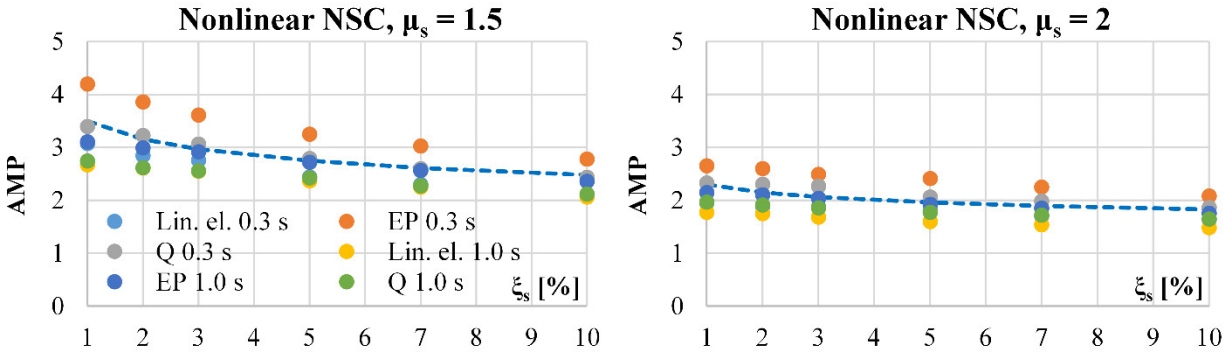

Figure 5. *AMP* as a function of the NSC damping obtained for two different target NSC ductilities and different structures with $\mu_p = 1$ (linear elastic) and $\mu_p = 2$ (EP and Q); comparison with the new formula for *AMP* provided in the next section.

OVERVIEW OF THE DIRECT FRS METHOD

As mentioned in the Introduction, the first direct FRS method was proposed by Biggs (1971). Two limit cases of the NSC response were identified. Very rigid NSCs have accelerations equal to the ones of the

structure at the attachment points, whereas very flexible NSCs respond as they were supported directly on the ground. Between these two extreme cases, the NSC response is amplified as the ratio T_s/T_p approaches unity, representing the resonance.

An important step forward, in terms of the theoretical definition of the NSC response, was made more than two decades later by Yasui et al. (1993), who derived an equation for the determination of FRS by using the basic structural dynamics, taking into account the structural and NSC properties. The equation represents a theoretical justification of Biggs's assumptions. However, both approaches are limited to linear elastic structures and NSCs.

In order to take into account the beneficial effects of structural nonlinearity on FRS, Vukobratović and Fajfar (2015, 2016, 2017) extended the Yasui's approach in off-resonance regions, and defined an independent formula for the resonance region. In the simplified, code-oriented version of the method (Vukobratović and Fajfar 2017), an empirical formula for *AMP*s was used, according to the proposal of Sullivan et al. (2013). Furthermore, the influence of the NSC nonlinear behaviour was also taken into account, implicitly, through an increased (equivalent) NSC damping. In Vukobratović and Fajfar (2023), an explicit consideration of the NSC nonlinearity was incorporated in the method: (1) in the off-resonance region (Equation 1), the NSC nonlinearity is considered in a similar way as the nonlinearity of the primary structure, i.e., by using the NSC strength reduction factor R_s corresponding to the considered structural mode (Equation 6), and (2) in the resonance region, the empirical formula for the amplification factor *AMP* (third line of Equation 4) was extended in order to take into account the NSC nonlinearity. A summary of the direct method is provided below.

Floor acceleration spectra are determined separately for each considered structural mode, and are combined in order to obtain the resulting FRS. For mode 'i' and floor 'j', the FRS value is determined as:

$$A_{s,ij} = \frac{\Gamma_i \phi_{ij}}{\left|\left(T_s / T_{p,i}\right)^2 - 1\right|} \sqrt{\left(S_{ep,i} / R_p\right)^2 + \left\{\left(T_s / T_{p,i}\right)^2 \left(S_{es} / R_s\right)\right\}^2} \tag{1}$$

$$\left|A_{s,ij}\right| \le AMP_i \times \left|PFA_{ij}\right| \tag{2}$$

$$PFA_{ij} = \Gamma_i \phi_{ij} S_{ep,i} / R_p \tag{3}$$

$$AMP_i = \begin{cases} 2.5\sqrt{10/\left(5+\xi_s\right)}, & T_{p,i}/T_C = 0 \\ \text{linear between } AMP_i\left(T_{p,i}/T_C = 0\right) \text{ and } AMP_i\left(T_{p,i}/T_C = 0.2\right), & 0 \le T_{p,i}/T_C \le 0.2 \\ c/\xi_s^k \ge 1, & T_{p,i}/T_C \ge 0.2 \end{cases} \tag{4}$$

$$R_p = \begin{cases} T_p\left(\mu_p - 1\right)/T_C + 1, & T_p < T_C \\ \mu_p, & T_p \ge T_C \end{cases} \tag{5}$$

$$R_s = \begin{cases} T_s\left(\mu_s - 1\right)/T_{p,i} + 1, & T_s < T_{p,i} \\ \mu_s, & T_s \ge T_{p,i} \end{cases} \tag{6}$$

The indices 'p' and 's' correspond to the primary structure and NSC, respectively. $S_{ep,i} = S_e(T_{p,i}, \xi_{p,i})$ represents the value in the elastic ground motion acceleration spectrum for the ith mode of the structure, whereas $S_{es} = S_e(T_s, \xi_s)$ applies to the NSC. The natural periods of the ith structural mode and of the NSC are denoted as $T_{p,i}$ and T_s, respectively, while $\xi_{p,i}$ and ξ_s represent the structural (for the ith mode) and NSC damping, respectively, and are expressed as the percentage of the critical damping. T_C is the characteristic period of the ground motion (equal to T_C in EC8). Γ_i is the modal participation factor for the ith mode, and ϕ_{ij} represents the ith mode shape value at the jth floor. AMP_i is the amplification factor (for the ith mode, it applies to all floors 'j'). The proposal of values for coefficients c and k, used in the third line of Equation 4, is based on the results of the parametric study, and is provided in Table 1.

Thus, the consideration of the NSC nonlinearity represents a new feature of the direct method shown herein. In the off-resonance regions, it is taken into account explicitly, through the NSC strength reduction factor R_s (determined for each considered structural mode 'i'), whereas in the resonance R_s is implicitly included in the *AMP*. Empirical coefficients c and k in the third line of Equation 4 depend on the NSC ductility (see Table 1). In the special case of a linear elastic NSC ($\mu_s = 1$), the third line of Equation 4 reads $10/\sqrt{\xi_s}$, which is the equation proposed by Sullivan et al. (2013), used in (Vukobratović and Fajfar 2017), as mentioned above.

Table 1: Coefficients c and k for different NSC ductility values and corresponding *AMP*s.

μ_s	c	k	$AMP = c / \xi_s^k$					
1	10	0.5	10	7.1	5.8	4.5	3.8	3.2
1.25	5	0.25	5.0	4.2	3.8	3.3	3.1	2.8
1.5	3.5	0.15	3.5	3.2	3.0	2.7	2.6	2.5
2	2.3	0.1	2.3	2.1	2.1	2.0	1.9	1.8
3	1.6	0.07	1.6	1.5	1.5	1.4	1.4	1.4
4	1.3	0.03	1.3	1.3	1.3	1.2	1.2	1.2
		ξ_s	1%	2%	3%	5%	7%	10%

The nonlinear behaviour of the structure is taken into account by the ductility and period dependent strength reduction factor R_p. The term $S_{ep,i}/R_p$ represents the value in the inelastic acceleration spectrum for the structure. It can be replaced by the ratio of the yield force and the mass of the equivalent SDOF primary system. In the method, it is assumed that the nonlinear behaviour is related only to the fundamental mode, whereas all higher modes are treated as linear elastic. Therefore, R_p should be determined only for the fundamental mode, whereas for all higher modes ($i > 1$), $R_p = 1$. The fundamental mode shape ϕ_1 is, in the case of a nonlinear structure, approximated with the deformation shape determined by pushover analysis (e.g., the N2 method by Fajfar 2000). It is assumed that the nonlinear structural behaviour does not influence the *AMP*, which is reduced for small values of the ratio T_p/T_C (see Equation 4). More elaborate empirical formulas for *AMP*, which also take into account the effects of hysteretic behaviour, ductility, and the ratio T_p/T_C, were proposed by Vukobratović and Fajfar (2015, 2016).

FRS calculated for individual modes should be combined in order to determine the resulting FRS. In the case of the proposed direct method, the standard SRSS (Square Root of Sum of Squares) or CQC (Complete Quadratic Combination) modal combination rules are used for both linear elastic and nonlinear structures, with the exception of the post-resonance region of the fundamental mode, where the algebraic sum (ALGSUM) is used, in which the relevant signs of individual modes are taken into account.

Finally, along the bottom third (1/3) of the building height, the lower limit of the resulting FRS is represented by the ground motion acceleration spectrum corresponding to the NSC damping and ductility. Note that in the case of nonlinear NSCs, the inelastic ground motion spectrum, representing the lower limit, should be determined as for the structure (e.g., by using the Vidic et al. 1994 formula for R_p, Equation 5), but by considering the NSC damping and ductility. In addition, due to uncertainties in the estimation of structural and NSC periods, a broadening of FRS peaks in the resonance region is required by some seismic codes, e.g., ASCE 4-16 (2017). A broadening is implicitly included in the presented direct method.

CASE STUDY EXAMPLE

In order to examine the accuracy of new formulas for the direct FRS determination, a three-storey reinforced concrete frame structure known as the "SPEAR building" was considered, by using the variant "EC8 H", re-designed according to Eurocode 8 by Rozman and Fajfar (2009).

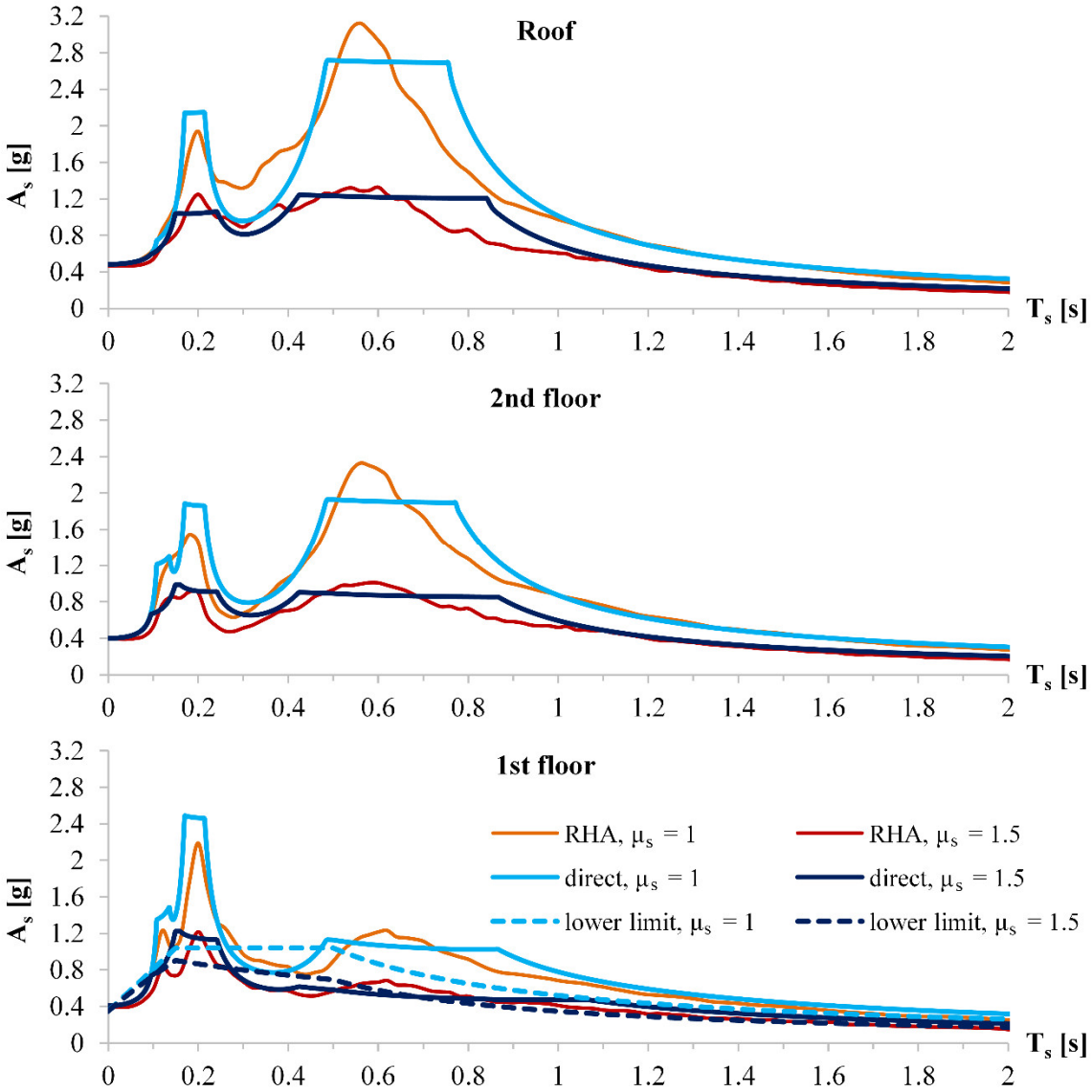

Figure 6. FRS for linear elastic and nonlinear NSCs with ξ_s = 2% in the SPEAR building.

The most important properties of the mathematical model and the analysis were described by Vukobratović and Fajfar (2017). In short, the first three natural periods of the building in the considered direction amount to 0.56 s, 0.19 s, and 0.12 s, and its global ductility demand for the applied ground motions (the same set which was used in the parametric study described above) amounts to 2.4, meaning that R_p = 2.4.

For linear elastic (μ_s =1) and nonlinear (μ_s =1.5) NSCs with ξ_s = 2%, FRS were determined at all levels, by using the response-history analysis (RHA) and the direct method. The obtained results are shown in Figure 6, and a fair agreement of the results obtained by the RHA and the proposed direct approach can be observed. At the first building floor the lower limit, equal to the ground motion acceleration spectrum corresponding to the NSC damping and ductility, applies in the very short period range, as well as in the range from about 0.3 s to about 0.5 s and to about 0.6 s for linear elastic and nonlinear NSCs, respectively.

The influences of the NSC ductility and damping on FRS values were further examined by applying the direct method to nonlinear NSCs with μ_s equal to 1.5 and 2, and ξ_s equal to 2% and 5%. FRS at the roof level of the SPEAR building, shown in Figure 7, clearly confirm that the influence of the NSC ductility is by far larger than the influence of its damping.

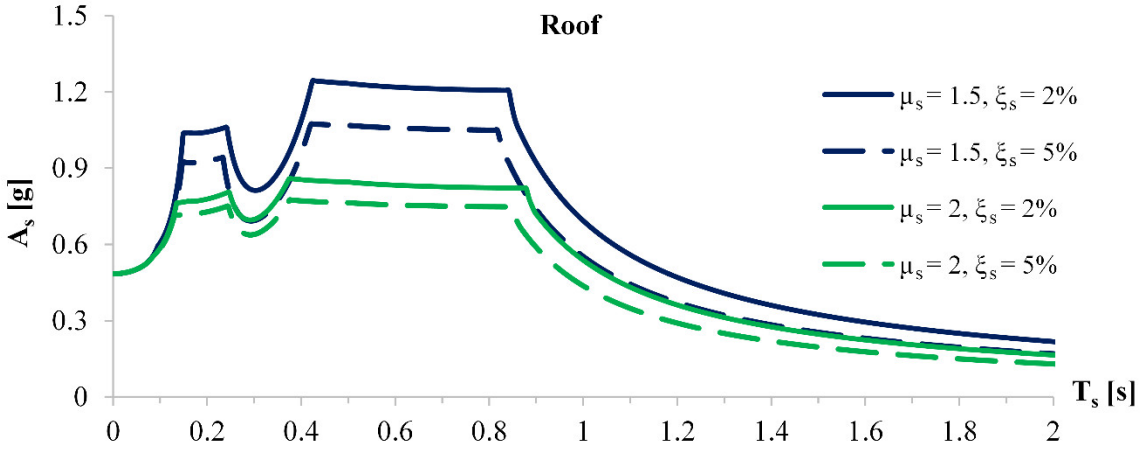

Figure 7. Direct FRS obtained at the roof level of the SPEAR building by considering NSCs with different ductility and damping values.

CONCLUSION

Acceleration-sensitive NSCs currently represent a hot research topic, and there is a constant improvement of the state-of-knowledge on FRS, which represent their basic seismic input. Nonlinear structural and NSC behaviour significantly affect FRS values, i.e., they reduce them in the pre- and post-resonance regions, respectively, while in the resonance region both reduce peak spectral accelerations. However, the influence of NSC nonlinearity is much larger than the influence of the structural one, which is a phenomenon that has been observed in a limited number of previous studies. Furthermore, it was shown that the influence of the NSC ductility on the FRS values is by far larger than the influence of its damping.

Major reduction of FRS in the resonance and post-resonance regions has been confirmed with the results of an extensive parametric study presented herein, which served as a basis for the development of new formulas used to update the direct FRS method previously developed by the authors. In a case study example, it was shown that the method, in which the NSC nonlinearity is explicitly taken into account, provides results which are in a fairly good agreement with the ones obtained by using the RHA.

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