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Επιρροή της απόσβεσης στις σεισμικές απαιτήσεις μη δομικών στοιχείων και περιεχομένων κτιρίων

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ΠΕΡΙΛΗΨΗ

Ο σχεδιασμός των μη δομικών στοιχείων στους περισσότερους αντισεισμικούς κανονισμούς βασίζεται στην εκτίμηση των σεισμικών απαιτήσεων (απόλυτης) επιτάχυνσης στους ορόφους, θεωρώντας συνηθέστερα 5% κρίσιμη απόσβεση για τα στοιχεία αυτά. Ωστόσο, η πραγματική κρίσιμη απόσβεση των μη δομικών στοιχείων είναι γνωστό ότι αποτελεί μία αβέβαιη παράμετρο, που μπορεί να αποκλίνει σημαντικά από την παραπάνω τιμή, ενώ η επιρροή της παραμένει ένα πεδίο το οποίο δεν έχει διερευνηθεί ακόμα επαρκώς.

Για τη μελέτη επιρροής της απόσβεσης των μη δομικών στοιχείων στις επιβαλλόμενες σε αυτά σεισμικές απαιτήσεις επιλέχθηκαν 113 καταγραφές σεισμικών επιταχύνσεων ορόφου σε κτίρια των Η.Π.Α. Η μελέτη κατέληξε στα εξής: (α) η χρήση διορθωτικού συντελεστή απόσβεσης βασισμένου σε εδαφικές επιταχύνσεις δεν ενδείκνυται για τη διόρθωση φασματικών επιταχύνσεων μη δομικών στοιχείων και (β) η επιρροή της απόσβεσης μη δομικών στοιχείων στις επιβαλλόμενες σε αυτά φασματικές επιταχύνσεις ορόφων εξαρτάται σε μεγάλο βαθμό από τη σχέση της ιδιοπεριόδου τους με εκείνη του κτιρίου. Βάσει των παραπάνω και μίας λεπτομερούς στατιστικής ανάλυσης, προτείνονται συναρτήσεις για τον υπολογισμό της μέσης τιμής και της διασποράς του διορθωτικού συντελεστή απόσβεσης για μη δομικά στοιχεία.

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The damping effect on the seismic demands of nonstructural components and building contents

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ABSTRACT

In most seismic code provisions, the design of nonstructural elements is based on the evaluation of the (absolute) acceleration demands at the floor levels, usually assuming a critical damping of 5% for those elements. However, the actual critical damping for the nonstructural components is well known to be an unknown parameter, that could well deviate from the abovementioned value, whereas its influence remains by large an unexplored field.

To study the effect of damping on the seismic demands of nonstructural elements 113 actual seismic records obtained from instrumented buildings in the USA were selected. The study concluded that: (a) the use of damping modification factors evaluated based on ground level excitations are not suitable for correcting the nonstructural component spectral accelerations demands and (b) the component damping effect on the imposed to the nonstructural elements floor spectral demands is highly dependent on the proximity of their natural period to that of the building. On account of the above and a detailed statistical analysis two equations are proposed for estimating the mean and coefficient of variation of the component damping modification factors.

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1 INTRODUCTION

Nonstructural components typically represent between 70 and 85% of the initial construction cost of commercial building [1]. Furthermore, in most buildings the ground motion intensity level that triggers nonstructural damage is usually much smaller than the one required to initiate structural damage. Therefore, nonstructural components are often one of the main contributors to economic losses from earthquakes [2].

A large percentage on nonstructural components are primarily acceleration-sensitive ones [3]. If the weight of the component is small relative to the weight of the floor system (e.g., less than 0.1%), then it is possible to neglect the dynamic interaction effects between the primary and secondary systems [4-5] and use floor spectra ordinates to estimate seismic demands on the secondary systems, what is sometime referred to as “cascade analysis” [6].

The design of nonstructural components in most seismic design codes is based on the evaluation of the acceleration demands imposed on them, often provided as floor acceleration spectra that form the basis for computing the maximum inertia forces. A floor spectrum is computed considering a Single Degree Of Freedom (SDOF) oscillator that is subjected to floor (absolute) acceleration histories. Floor acceleration histories, and consequently floor spectra, can be evaluated either (semi) empirically, i.e., via floor recordings obtained from instrumented buildings, or purely analytically, on the basis of structural response time-history analyses of the supporting structure. So far, pertinent literature has focused on the latter approach.

Floor spectra are typically computed for a component damping ratio ξ_p equal to 5% (ξ_p=5%). Past analytical studies (e.g. [7-12]) have demonstrated that the effect of the secondary system damping is a crucial factor that could strongly affect the floor acceleration demands. However, the majority of these analytical studies carry within them uncertainties related to the primary structure modelling and analysis choices, potentially limiting the validity of the resulting expressions. For instance, most of them are limited to the realm of simplified models for the supporting structure, that could be either represented by means of SDOF systems or linear 2D regular MDOF models. A further significant source of bias is also associated with the Rayleigh damping assumption for the primary structural system, that requires highly uncertain assumptions to be made for the damping ratio of usually the 3rd or the 4th structural mode of vibration.

Further to the above, our knowledge on the actual component damping ratio and its effect on systems subjected to floor motions is, for the time being, incomplete. In fact, the uncertainty associated with the component damping level is deemed to be either equal to or greater than the uncertainty associated with the building damping level, which has already been acknowledged by several past studies to be a highly uncertain property (e.g., [13]).

The influential effect of structural damping on the seismic demands of buildings has long been recognized and taken into account by means of the damping modification factor (DMF), $C_{\xi\%}$. By idealizing the primary structure as an SDOF, the DMF is the ratio of the peak response (displacement, velocity or acceleration) of a linear SDOF having damping ratio ξ and period equal to that of the building, over the peak response of a linear SDOF having the same period of vibration but a damping ratio equal to 5% [14]. Evidently from the above definition, $C_{\xi\%}$ is no more than a scaling factor that is used to modify the elastic 5% spectrum to a response spectrum representing a higher or a lower damping level.

This same concept could be employed to transform floor acceleration spectra from the typical 5% damping to the damping of the non-structural or secondary component. Expressions for the secondary system DMF are typically based on regressing analytical results from timehistory analyses and have appeared, for example, in the work of Sullivan *et al*. [10], Calvi and Sullivan [15] and Vukobratovic and Fajfar [16-17]. However, they are subject to the limitations outlined before for the analytical studies (e.g. structural modeling simplifications, structural damping assumptions etc.).

Hence, in order to overcome these issues, in the proposed study we have decided to employ a semi-empirical approach for DMF estimation, using actual floor recordings from instrumented buildings of California as the basis for explicitly exploring the period dependency and the potential effect of higher modes on the DMF. The proposed study will also employ the binormalization concept of the floor spectra that is deemed to provide a better characterization of the peak component acceleration demands for narrow-band spectra. Likewise, binormalized response spectra provide enhanced lateral force demand estimates for very soft soil deposits [18] or in the cases of soil-structure interaction (e.g., [19]).

2 FLOOR RECORDS ENSEMBLE

We considered a total of 113 floor acceleration recordings obtained from 47 instrumented buildings located in California, with heights ranging from 2 to 52 stories. The floor recordings were selected from a large database [20] on account that their 5% damped floor response spectral accelerations are larger than 0.9g at any predominant modal periods of the considered instrumented buildings. The resulting floor acceleration data was recorded during eight major earthquake events, mostly at the roof level (where accelerometers are typically located), but also at intermediate floors, when available. The selected floor recordings are further discretized into two groups, with Group 1 containing 86 floor recordings having their maximum 5% spectral acceleration ordinate at the fundamental translational period of the instrumented building and Group 2 containing 27 floor recordings that have their maximum 5% spectral acceleration ordinate at the second or third vibration period of the building in the translational direction of interest. A more elaborate description of the floor motions and instrumented buildings considered in this study may be found in [21].

3 DMFS FOR NONSTRUCTURAL ELEMENTS

Similar to the soft soil deposits that filter and modify the ground motions frequency content, buildings also filter and modify the frequency content of motions. In both cases, this process results in the filtered motions producing narrow-band spectra, i.e. spectra with large amplifications for structures with periods close the predominant period of the ground motion in the case of soft soils or for components with periods close to a modal period of the supporting structure in the case of components attached to upper building floors.

Miranda [18] proposed to undertake a normalization of the periods in the abscissas by the predominant period of the ground prior to average the narrow-band spectra from different soft soil sites having different predominant periods. Herein, the same normalization process is adopted for the floor narrow-band spectra, with the abscissas of the periods normalized by the building's resonant period. The scope of this process is to maintain the information related to the period of the supporting structure since the level of amplification in the acceleration ordinates depends on how close the nonstructural component period (T_p) is to being tuned to the modal period of the building (T_m). Kazantzi *et al.* [22] demonstrated that averaging not-normalized narrow-band floor spectra, results in a systematic underestimation of the narrow-band floor spectra peaks and, with reference to the present study, of the estimated period-dependent DMFs.

The DMF for nonstructural elements $C_{\xi\%}$ may be defined as:

$$C_{\xi\%}\left(\frac{T_p}{T_m}\right) = \frac{PCA_{\xi\%}}{PCA_{5\%}} \quad (1)$$

where, $PCA_{\xi\%}$ is the Peak Component (spectral) Acceleration ordinate for a given component period and damping level $\xi_p=\xi\%$ and $PCA_{5\%}$ is the Peak Component (spectral) Acceleration ordinate at the same component period and a damping level of ξ_p=5%.

4 STATISTICAL RESULTS AND ANALYTICAL EXPRESSION

For each building-floor recording pair, a total of 591 $C_{\xi\%}$ factors have been evaluated for five component damping ratio levels (ξ_p =1%, 2%, 3%, 5%, and 7%). That yields for the 113 building-floor recording pairs that were considered in this study, a total of 333,915 $C_{\xi\%}$ factors evaluated at equally spaced normalized period ($T_r=T_p/T_m$) intervals between 0 to 3. Both the mean and the coefficient of variation (CoV) of $C_{\xi\%}$ have been computed. Results are presented separately for the two considered groups of records (i.e. Group 1 and 2).

Figures 1a and 1b present the mean $C_{\xi\%}$ corresponding to component damping ratios of 1%, 2%, 3%, 5%, and 7%, as these were obtained considering (a) the 86 first-mode-tuned recordings of Group 1, and (b) the 27 higher-mode-tuned recordings of Group 2, respectively. Apparently, the mean $C_{\xi\%}$ follows the same trends at all the examined component damping ratio levels, showing considerable period dependence. Overall, there is significant amplification/deamplification with damping lower/higher than 5% around T_r =1, where the component matches the predominant building period (i.e., the fundamental mode for Group 1 or higher ones for Group 2), as well as around T_r=0.3 in Group 1 and T_r=0.5-0.6 in Group 2, which generally correspond to even higher modes.

In fact, the effect of the period of the nonstructural contents being tuned to the predominant building period (T_r = 1) is more dominant for lower component damping ratios, in which case the mean DMF becomes as high as 2.1 for ξ_p = 1%. To fully acknowledge the consequences of the aforementioned observation one may consider the damping correction factor η proposed by Eurocode 8 [23], which was derived via broadband ground motions, to account for different building damping ratios:

$$\eta = \sqrt{\frac{10}{(5+\xi)}} \geq 0.55 \tag{2}$$

For $\xi_p = 1\%$ the aforementioned equation suggests that the 5% ground spectral acceleration ordinates may be amplified by a factor of 1.29 to account for the lower actual damping. If we apply this value, which is intended to convert the 5% ground spectral acceleration of broadband motions, to adjust the PCAs resulting from narrow-band motions for $\xi_p = 1\%$ we will end up underestimating the component acceleration/displacement demands by ~60% for the particular case of $T_r = 1$. By contrast, for a $\xi_p = 7\%$ and $T_r = 1$ Equation (2) suggests a damping correction factor of about 0.91 when only about 0.81 is needed. This scenario would result to an overdesign of any relevant anchoring system by ~10%. Although over-design is usually not a problem, at least in terms of occupants' safety, under-design could have various adverse consequences in the seismic resilience of the building contents and the building itself.

Figures 1c and 1d illustrate the coefficient of variation (CoV) of $C_{\xi\%}$ for the considered levels of damping for both groups of floor motion recordings. Obviously, there is zero variability at the baseline damping of 5%, as $C_{\xi\%}$ becomes 1.0 by definition. The variability increases with both higher and lower damping values, albeit more slowly when increasing rather than decreasing damping.

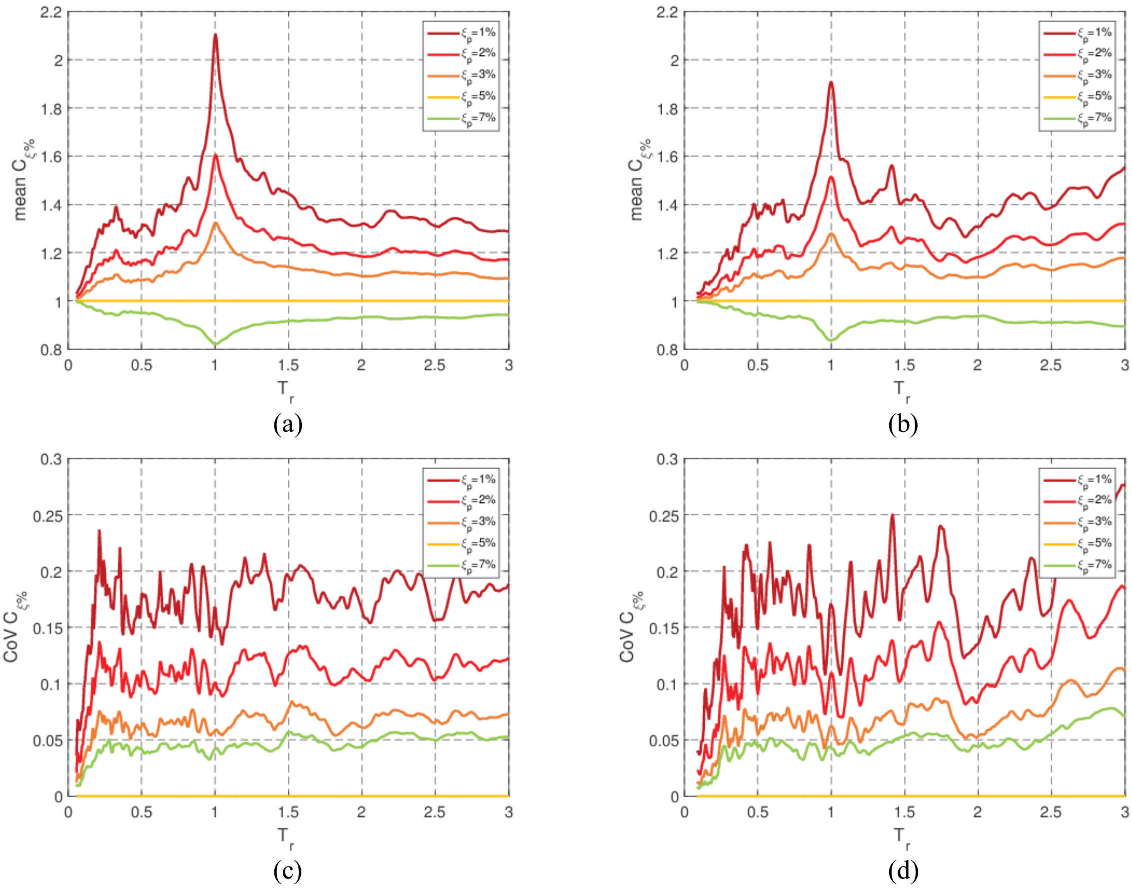

Figure 1: Mean of $C_{\xi\%}$ for (a) Group 1 and (b) Group 2 and CoV of $C_{\xi\%}$ for (c) Group 1 and (d) Group 2 floor recordings at five component damping ratios, ξ_p.

5 PROPOSED DMF PROBABILISTIC MODEL

The Lilliefors [24] test confidence intervals for a confidence level of 5%, showed that the lognormal probability distribution provides a reasonable representation of the empirical distribution for the DMFs. Thus, fitting the mean (or median) and dispersion (or CoV) is adequate for defining a two-parameter probabilistic model.

A simplified equation is proposed for estimating the mean $C_{\xi\%}$ values for use in practical nonstructural component design applications with damping ratios ranging from ξ_p=1% to ξ_p=7%. This was obtained by undertaking a nonlinear least square regression analysis and is a function of the component damping ratio ξ_p and the period ratio T_r:

$$
\begin{gathered}
m_{C\xi\%} = 1 + a \cdot (0.05 - \xi_p) \cdot \{A + B + C + D\} \\
A = exp\left[-\frac{(\ln(T_r))^2}{b} - c \cdot \sqrt{\xi_p}\right] \\
B = d \cdot T_r^e \cdot exp\left[-f \cdot (\ln(T_r))^2 - g \cdot \sqrt{\xi_p}\right] \\
C = \frac{exp[-h \cdot (\ln(T_r))^2]}{i} \\
D = \frac{1}{T_r} \cdot exp\left[-\frac{(ln(T_r) - j)^2}{k}\right]
\end{gathered} \tag{3}
$$

Table 1 summarizes the eleven constants, a-k, for the two Groups of floor motions that were considered. Figures 2a and 2b compare the mean $C_{\xi\%}$ computed using Equation (3) against the mean $C_{\xi\%}$ evaluated using the data from the recorded floor motions. Evidently, the proposed equation fits well the recorded data for all considered component damping ratios, ξ_p, across the entire range of T_r ratios from 0 to 3s. The coefficient of determination, R^2, was evaluated to be 0.99 and 0.98 for Group 1 (see Figure 2a) and Group 2 (see Figure 2b), respectively. The overall fitting error can be considered to be negligible for all practical purposes.

Table 1: Coefficients evaluated for the $C_{\xi\%}$ regression of Equation (3).

Coefficient	**Group 1**	**Group 2**
a	18.21	22.11
b	5.31	2.60
c	7.41	9.33
d	1.85	0.72
e	5.55	-1.09
f	187.36	136.80
g	10.96	5.04
h	8.32	1.69
i	3.96	8.96
j	3.38	1.25
k	2.85	0.11

For the small values of dispersion attained, the latter is practically identical to the CoV displayed in Figures 1c and 1d [25]. Given the noise present in the data, and the overall lack of significant variation, a simpler model is adopted:

$$\sigma_{\ln C\xi\%} = \begin{cases} \sigma_o \cdot \dfrac{T_r}{0.2}, & \text{if } T_r \in [0,0.2] \\ \sigma_o, & \text{otherwise} \end{cases} \qquad \sigma_o = \begin{cases} a \cdot (0.05 - \xi_p), & \text{if } \xi_p \in [1\%, 5\%] \\ b \cdot (\xi_p - 0.05), & \text{if } \xi_p \in (5\%, 7\%] \end{cases} \tag{4}$$

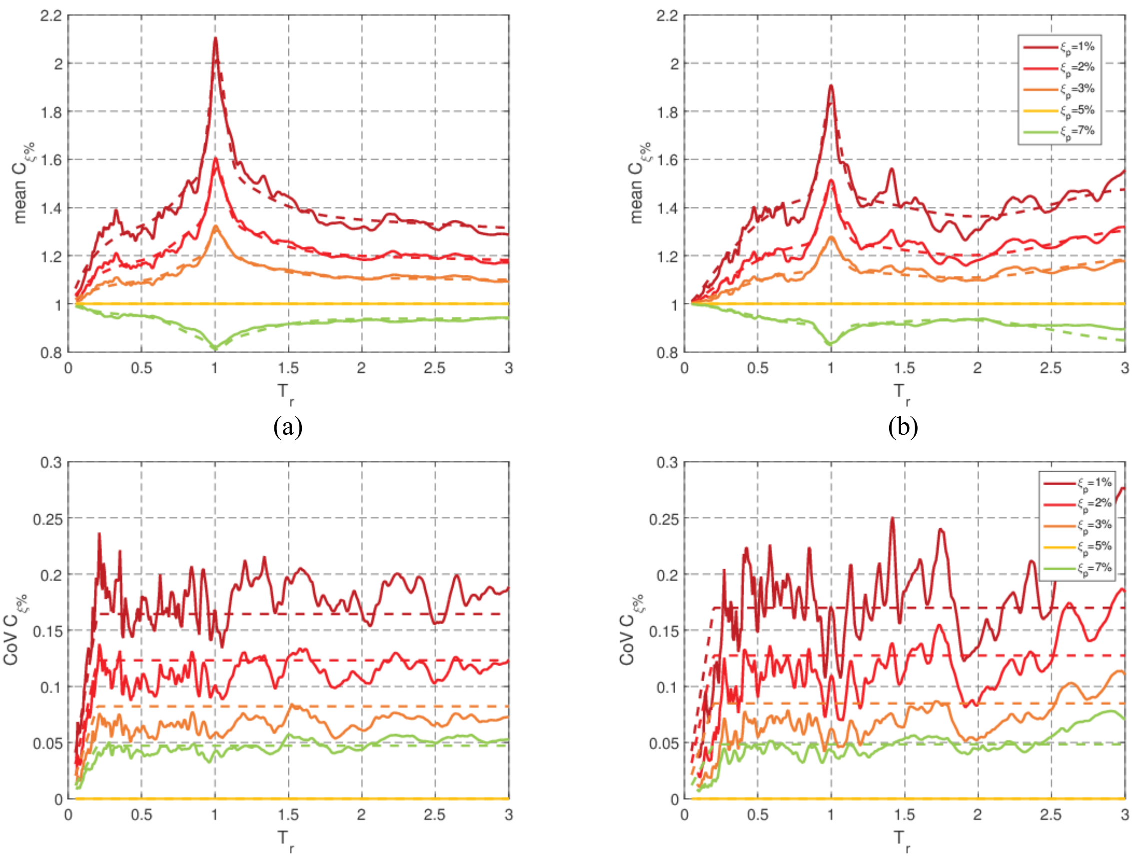

Figure 2: Mean of $C_{\xi\%}$ using Equation (3) for (a) Group 1 and (b) Group 2 and CoV of $C_{\xi\%}$ using Equation (4) for (c) Group 1 and (d) Group 2 floor recordings. Solid lines show the computed values, while dashed lines show the fit.

The two coefficients, a-b, appear in Table 2, while the fitted results are shown in Figures 2c and 2d. Typically, a lognormal model is estimated based on the logarithmic mean and standard deviation. While, the latter is directly available from Equation (4), we chose instead to provide a model for the mean, $m_{C\xi\%}$, rather than the logarithmic mean, $m_{lnC\xi\%}$, via Equation (3), as the mean is often considered more compatible with deterministic applications (e.g., in a design code). Still, it is an easy operation to determine $m_{lnC\xi\%}$ from Equations (3) and (4) for the lognormal distribution [25]:

$$m_{\ln C\xi\%} = \ln m_{C\xi\%} - 0.5\sigma_{\ln C\xi\%} \quad (5)$$

Table 2: Coefficients evaluated for the $\sigma_{lnC\xi\%}$ regression of Equation (4).

Coefficient	**Group 1**	**Group 2**
a	4.11	4.25
b	2.36	2.43

6 CONCLUSIONS

Our primary scope was to explore the effect of the component damping on the seismic acceleration demands imposed on them using actual recordings of floor motions rather than analytically derived ones. On account of 113 recorded motions from US instrumented buildings and eight major seismic events, we confirmed that the effect of the component damping on the floor spectral demands is strongly period dependent and it depends on how far or close the period of the component is to the modes of the supporting structure. Specifically, the component damping effect becomes more severe when the component period is tuned to any modal period of the supporting structure and the amplification of the acceleration demands within this region is more severe for lower component damping ratios. On account of the above findings, a comprehensive probabilistic model is proposed for estimating the distribution of component DMFs based on (a) the component damping and (b) the ratio of the component period over the predominant building period.

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