IMPROVED ESTIMATION OF FLOOR SPECTRA IN RC WALL BUILDINGS

P. M. Calvi\textsuperscript{1} and T. J. Sullivan\textsuperscript{2}

ABSTRACT

Adequate seismic design of non-structural elements can only be guaranteed if floor seismic demands can be appropriately quantified. To this extent, most international codes currently suggest an equivalent static method where the seismic force acting on a component is computed as a function of the component mass and the peak acceleration that the component experiences throughout the seismic event. However, recent studies have shown that current code approaches are, in most cases, unreliable as they do not adequately address important aspects related to the properties of the elements to be designed as well as characteristics of the supporting structure. This work examines floor accelerations and acceleration response spectra for a 20-storey case study structure consisting of a RC wall system, subjected to a set of ground motions scaled to various levels of intensity. Firstly, the shortcomings of international code approaches are highlighted, showing that floor spectra and peak floor accelerations are generally poorly predicted even for linear supporting systems. Secondly, a discussion of the factors that affect the peak floor accelerations as well as the shape and intensity of acceleration demands on secondary structural and non-structural elements is presented. A new method that addresses aspects such as damping of the secondary system as well as effects of non-linearity and higher modes relative to the primary structure is then reviewed. Finally, the performance of the proposed procedure to estimate acceleration floor spectra is investigated by comparing predicted spectra with those obtained from time-history analyses of the case study building. The results of the research indicate that the newly proposed methodology is very promising, providing considerably improved prediction of floor spectra compared to existing code methods and should therefore be developed further as part of future research.

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Adequate seismic design of non-structural elements can only be guaranteed if floor seismic demands can be appropriately quantified. To this extent, most international codes currently suggest an equivalent static method where the seismic force acting on a component is computed as a function of the component mass and the peak acceleration that the component experiences throughout the seismic event. However, recent studies have shown that current code approaches are, in most cases, unreliable as they do not adequately address important aspects related to the properties of the elements to be designed as well as characteristics of the supporting structure.

This work examines floor accelerations and acceleration response spectra for a 20-storey case study structure consisting of a RC wall system, subjected to a set of ground motions scaled to various levels of intensity. Firstly, the shortcomings of international code approaches are highlighted, showing that floor spectra and peak floor accelerations are generally poorly predicted even for linear supporting systems. Secondly, a discussion of the factors that affect the peak floor accelerations as well as the shape and intensity of acceleration demands on secondary structural and non-structural elements is presented. A new method that addresses aspects such as damping of the secondary system as well as effects of non-linearity and higher modes relative to the primary structure is then reviewed. Finally, the performance of the proposed procedure to estimate acceleration floor spectra is investigated by comparing predicted spectra with those obtained from time-history analyses of the case study building. The results of the research indicate that the newly proposed methodology is very promising, providing considerably improved prediction of floor spectra compared to existing code methods and should therefore be developed further as part of future research.

Introduction

Recent earthquakes as well as earthquakes from the past have highlighted that even well designed structures cannot meet desired performances if the non-structural elements are poorly designed or detailed. In addition to often being the cause of large financial losses [1] [2], the collapse of components can become a safety hazard and hamper the safe movement of occupants as they evacuate or rescuers as they enter the building [3] and [4], as well as severely limit the functionality of critical facilities such as hospitals ([5] and [6]).

Various attempts to improve our understanding of the seismic response of non-structural elements connected at various levels of supporting buildings have been made over the past few decades. It is now common belief that non-structural elements can generally be grouped into two categories, namely drift-sensitive and acceleration-sensitive components. The implication is that secondary elements can be effectively designed if the seismic demand in terms of either drift or acceleration can be quantified, depending on the type of element that needs to be designed. With the continuing development of displacement-based design ([7], [8], [9], [10], [11], [12], [13], [14]), one could argue that tools for the control of drift demands are well developed but the same

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cannot be said for the prediction of acceleration demands. The most diffused approach to obtain
the acceleration demand on non-structural elements consists in the use of acceleration floor
response spectra. In this regard, many different approaches are now available in the literature
(see [15], [16] and [17] amongst others). The limitation of most of the existing approaches is that
they are either simple but not reliable [18] or reliable but require relatively advanced analysis
capabilities [16]. This reflects the fact that it is quite challenging to formulate simplified
approaches that are capable of addressing the complicated aspects that influence the shape and
intensity of floor spectra.
Some progress towards the realization of accurate simple methods has been made recently [19],
with the proposal of a procedure for the estimation of floor spectra atop single-degree of freedom
(SDOF) systems (further validated by [20]) that is capable of considering the effect of
inelasticity in the supporting structure and various levels of elastic damping. More recently a
proposal has been made [21] to extend the method to deal with linear multiple degree of freedom
(MDOF) supporting structures. With this in mind, this paper investigates the applicability of this
recently proposed approach for the estimation of floor acceleration demands in multi-storey
buildings.

**Code Methods for the Prediction of Acceleration Demands**

Current seismic codes contain provisions to help engineers rationalize the preliminary design of
non-structural elements. To this extent, most suggestions involve the employment of an
equivalent static method where the seismic force acting on a component is computed as a
function of the peak acceleration that the component experiences throughout the seismic event
and the component mass. The acceleration demand is classically calculated as a function of the
peak ground acceleration, the location of the non-structural element up the height of the primary
structure and the component period of vibration in relation to the fundamental period of vibration
of the primary system. However, because of differing assumptions about the best formulation,
predictions of the floor acceleration demand on the same component according to different
international codes can vary by a factor of more than two [22], and there is no certainty as to the
best methodology since no approach has shown consistently better performances. Furthermore,
[19] pointed out that available codes do not properly address important aspects such as the
inherent damping of the non-structural element and the effects of the higher modes of vibration
of the supporting structure.
The elastic damping of the non-structural element has a very strong influence on the peak
acceleration demands, as shown in Fig. 1 where acceleration spectra atop a 20-storey building
are shown for two different values of elastic damping (2% and 5%), and therefore should be
considered in seismic assessment. In addition, higher modes can significantly affect the floor
spectra. This second point can be seen from the curves presented in Fig. 1 which are
characterized by the presence of three acceleration peaks; the main peak is associated with
amplification of demands at the 2nd period of vibration of the supporting structure, the peak at
shorter periods is related to amplification due to resonance with the 3rd mode of vibration of the
building whereas the peak associated with a period of approximately 2.5s is related to the
amplification due to resonance with the fundamental period of the main system. It is evident
from this figure that floor spectra which are constructed considering only the effects of the
fundamental period of vibration of the main supporting system are therefore likely to provide
poor estimates of the actual seismic demand on non-structural elements.
Figure 1. Comparison of roof level acceleration spectra at 2% damping (left) and 5% damping (right) as predicted via different code approaches and from non-linear time-history analyses of a 20-storey case study building (adapted from [19]).

**Approximate Method for SDOF Supporting Structures**

As mentioned in the introduction, an innovative approach to construct floor response spectra atop single-degree-of-freedom (SDOF) systems has been recently proposed [19]. In the approach, the acceleration spectrum on SDOF supporting systems can be computed using the following equations:

\[
\begin{align*}
    a_m &= \frac{T}{T_y} \cdot [a_{max}(DAF_{max} - 1)] + a_{max} & T < T_y \\
    a_m &= a_{max}DAF_{max} & T_y < T < T_e \\
    a_m &= a_{max}DAF & T > T_e
\end{align*}
\]  

(1)

where \(a_m\) is the acceleration spectral coordinate for a supported element of period \(T\), \(a_{max}\) is the maximum acceleration of the mass of the supporting structure (obtained for SDOF systems by dividing the structure’s lateral resistance by the seismic mass), \(T_y\) is the natural (elastic) period of the supporting structure (the subscript \(y\) is provided to emphasize that this period is expected up until yield), \(T_e\) is the effective period of the supporting structure (which will be dependent on the earthquake intensity), \(DAF\) is the dynamic amplification factor from Eq. 2 with \(\beta = T_e/T\), and \(DAF_{max}\) is the maximum expected dynamic amplification factor obtained employing Eq. 3:

\[
    DAF = \frac{1}{\sqrt{(1 - \frac{1}{\beta})^2 + \xi}}
\]  

(2)
\[
\begin{aligned}
DAF_{\text{max}} &= \frac{c_1}{(c_3 + \frac{T_a}{TB}c_2)} \quad \text{if } 0 \leq T_a < TB \\
DAF_{\text{max}} &= \frac{c_1}{\xi c_2} \quad \text{if } T_a \geq TB
\end{aligned}
\]  

(3)

where \( C_1 = 1.0 \), \( C_2 = 0.5 \), \( C_3 = 1.79 \) and \( TB = 0.3s \). Note that Eq. 3 is an adaptation of the equation originally proposed by [19], to include scenarios in which the supporting structure falls in the short period range (i.e. lower than 0.3 seconds).

### Extension to MDOF Supporting Systems

#### Conceptual Considerations

The approach summarized in the previous section has been shown ([19] and [20]) to effectively address aspects such as non-linear response of the supporting system and inherent damping of the non-structural elements. However, the procedure does not account for the effects of the higher modes. This simplification can lead to inaccurate evaluation of the risks associated with components characterized by periods of vibration in the vicinity of higher mode periods, because for taller buildings higher modes will have a strong influence on acceleration floor spectra. It should also be noted that the relevance of higher modes could increase as the main structure undergoes inelastic deformations. For instance, while the engagement of a plastic mechanism caps the effects of the first mode in RC wall structures, it generally provides little beneficial action on the effects of higher modes (see [7], [23] and [24] amongst others).

In general, predicting acceleration spectra at various levels of a structure should recognize the following points [21]:

- Higher modes can strongly affect acceleration floor spectra, even in cases where the participating mass associated with those modes is low;
- Higher modes can substantially affect the peak floor acceleration;
- Higher modes can substantially affect the shape and intensity of floor response spectra;
- The influence of a mode with respect to the floor acceleration at a specific level, is somewhat proportional to the modal coordinate of that level, in that mode;
- Individual mode acceleration floor spectra, combined in line with standard combination rules (e.g. SRSS), produce very good approximations of the “exact” floor spectra when the supporting structure responds elastically.

### Methodology

One of the most commonly adopted means of designing structures for earthquakes in line with code legislation is to use response-spectrum analysis, also referred to as multi-modal analysis, in order to obtain estimates of structural response both in terms of design forces and displacements. Normally, modal response spectrum analyses can be useful for the design of the main structural system but because non-structural elements are not typically modeled when undertaking eigenvalue analyses, the approach does not identify relevant demands for their design and instead, can only be used to identify peak accelerations of the floors themselves.
Extending on what was introduced in the previous sections, it has recently been proposed [21] that the basic approach for floor spectra atop SDOF supporting systems [19] can be combined with concepts of response spectrum analysis to permit evaluation of floor spectra within MDOF supporting systems. The approach, explained in detail in [21], proposes that the floor spectra over the upper storeys of a MDOF structure can be obtained from the following few steps:

1. A linear dynamic analysis of the main structure is carried out;
2. Once the modal properties (periods of vibration, mode shapes etc.) are known, the peak floor acceleration of each level is obtained for each of the modes being considered;
3. The floor response spectra associated with each mode can be constructed according to Eq. 1, following the approach described earlier, and subsequently combined in line with SRSS method or analogous to obtain the final spectrum.

The floor spectra expected at the lower levels of the building (i.e. between the ground level and the mid-height of the structure) are obtained as a curve that envelopes the floor spectra constructed as described above and the ground response spectrum. This recommendation is made in reflection of the limited filtering that occurs to the ground motion over the lower levels of a structure. The reader is invited to refer to [21] for further discussion on the topics treated in this section.

Performance of the Method

In order to investigate the performance of this method, Eq. 1 is used to estimate acceleration spectra at all levels of the 20-storey case study structure schematized in Fig. 2. The lateral load resisting system in the building is provided by a series walls in both directions. For the purposes of this study, only the response in the X-direction is examined.

Figure 2. Illustration of the case study RC wall structures partial side and plan view.
The materials employed are typical of construction practice and the structural layout is considered analogous to a hotel or apartment building in which RC walls act as both partitions and structural elements. This type of structural configuration was selected as it will tend to be stiffer than other types of buildings and should be expected to have higher floor accelerations.

Design of the structure was done in accordance with Eurocode 8 for the EC8 type 1 spectrum with a ground acceleration of 0.4 g and soil type C. The standard wall is 10 m long and 0.25 m wide. The axial load at the base of the wall is 8800 kN the seismic mass is 90 ton per floor. The nominal flexural strength at the base of the structure is 63070 kNm which translates in a longitudinal reinforcement content of 0.5%. The reinforcement detailing for the walls is not shown here but it is assumed that good detailing would be provided in line with the EC8 recommendations to ensure ductile response under rare earthquake events. Models of the RC structures are developed for 2D non-linear time-history (NLTH) analyses in Ruaumoko (refer [25]) and are provided with Takeda-thin hysteretic properties following recommendations in [7]. The structure is subject to a series of 7 real accelerograms (taken from [19]) that were scaled to be spectrum compatible with the EC8 type 1 spectrum on soil type C, reported in Fig. 6. The analyses are run at three different intensity levels corresponding to a peak ground acceleration demand of 0.1g, 0.2g and 0.4g but in all cases the response was seen to be elastic owing to the large number of walls in the building.

Figure 3. Acceleration response spectra at 5% elastic damping for the selected accelerograms, scaled to be spectrum compatible with the EC8 type 1 spectrum for soil type C and a PGA = 0.4g.

Figure 4 compares the peak floor accelerations obtained from the time-history analyses with those predicted by the simplified approach. The comparison is very good, indicating that the simplified approach described earlier can provide accurate estimates of the peak floor acceleration estimates over the full height.
Figure 4. Ratio of peak floor acceleration to the peak ground acceleration along the height of the 20-storey case study structure.

Acceleration spectra at all the levels were also obtained and comparisons are reported here for acceleration spectra developed at 2% and 5% elastic damping. The curves shown in Figs. 5 and 6 are relative to the tenth and the second floor level spectra respectively. The tenth floor case is representative of a scenario where the floor spectra are a result of a floor acceleration that is substantially different from the ground motion as a consequence of the filtering action provided by the supporting system. The second floor on the other hand, is located in the lower portion of the building, where the filtering action provided by the supporting system is weak. The floor acceleration recorded at this level is seen to be practically identical to the ground motion record and the floor spectra are shaped accordingly.

Figure 5. Mean 10th floor acceleration spectra obtained for the case study structure via NLTH analyses compared with those predicted using Eq. 1 combined with response spectrum analysis, for 2% (left), and 5% (right) elastic damping.
Note that the acceleration spectra are predicted quite well at both levels (being only slightly non-conservative at the second mode acceleration spike) and that the approximation of using the maximum between the ground spectrum and the proposed floor spectra to estimate the lower storey floor spectra appears satisfactory. Results have only been shown for the 2\textsuperscript{nd} and 10\textsuperscript{th} floors but note that the predictions obtained for all levels of the structure were of the order of accuracy of the ones reported in Figs 5 and 6.

Figure 6. Mean 2nd floor acceleration spectra obtained for the case study structure via NLTH analyses compared with those predicted using Eq. 1 combined with response spectrum analysis, for 2\% (left), and 5\% (right) elastic damping.

Also included in Figures 5 and 6 are the floor spectra predicted according to the ASCE and EC8 procedures. The comparison suggests that the newly proposed methodology is very promising, providing considerably superior performance to existing code methods, particularly for systems with low elastic damping.

Conclusions

There is general agreement on the fact that the seismic performance of structures can only be guaranteed if both structural and non-structural elements are properly designed. In regards of components that are sensitive to seismic accelerations, it has been shown that, while simplified methods of predicting acceleration spectra are quite appealing, there is the need to improve on existing recommendations. This is particularly true for non-structural elements characterized by an elastic damping ratio that is not equal to 5\% critical damping. As such, this paper has presented a simplified means of predicting floor level acceleration spectra for multiple-storey buildings. At the moment, the procedure is only applicable to multiple-storey buildings that respond in the linear range, but it is able to be adjusted for a wide range of elastic damping values. The procedure has been validated in this paper by comparing spectra obtained from the approach and those obtained from non-linear time-history analyses of a 20-storey building subject to seven ground motions scaled to various levels of intensity. The results have
demonstrated that the simplified approach for estimating floor acceleration spectra at various levels of a building works well and the possibility of extending it to non-linear systems should be explored as part of future research.

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