TOWARDS A NEW APPROACH TO DESIGN ACCELERATION-SENSITIVE NON-STRUCTURAL COMPONENTS

E. Miranda¹ A.K. Kazantzi² and D. Vamvatsikos³

ABSTRACT

Nonstructural components often represent the largest portion of the investment in new commercial buildings, typically accounting for 70 to 85% of the total construction cost. Furthermore, damage to nonstructural components can lead not only to serious injuries and even casualties, but can lead to partial or total temporary loss of use of the building and to large economic losses. Nonstructural components are often subjected to seismic motions that are completely different both in amplitude and in frequency content than ground motions. Floor motions are characterized by being narrowband motions that produce extremely large accelerations on nonstructural elements whose frequencies of vibration coincide with those of one of the modal frequencies of the building in which they are mounted. The purpose of this paper is to propose a new approach in which bracing elements of nonstructural elements are designed and detailed to work as fuses that limit forces acting not only in the nonstructural elements but also those acting on the attachments to the structure and on the attachment(s) to the nonstructural element. It is shown that the proposed approach not only results in reductions in design forces but can also result in important reductions in deformation demands, especially for components that are tuned to modal periods of the building in which they are mounted on.

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ABSTRACT

Nonstructural components often represent the largest portion of the investment in new commercial buildings, typically accounting for 70 to 85% of the total construction cost. Furthermore, damage to nonstructural components can lead not only to serious injuries and even casualties, but can lead to partial or total temporary loss of use of the building and to large economic losses. Nonstructural components are often subjected to seismic motions that are completely different both in amplitude and in frequency content than ground motions. Floor motions are characterized by being narrowband motions that produce extremely large accelerations on nonstructural elements whose frequencies of vibration coincide with those of one of the modal frequencies of the building in which they are mounted. The purpose of this paper is to propose a new approach in which bracing elements of nonstructural elements are designed and detailed to work as fuses that limit forces not only in the nonstructural elements but also those acting on the attachments to the structure and on the attachments to the nonstructural element. It is shown that the proposed approach not only results in reductions in design forces but can also result in important reductions in deformation demands, especially for components that are tuned to modal periods of the building in which they are mounted on.

Introduction

Nonstructural components often represent the largest portion of the construction investment in commercial buildings, typically accounting for 70 to 85% of the total construction cost [1]. Furthermore, since damage to nonstructural components is typically triggered at smaller levels of ground motion intensity than those required to initiate structural damage, hence nonstructural damage contribute to a percentage of economic losses even greater to the percentage of the construction cost previously mentioned [2-7]. Economic losses. In addition to being the main

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contributor to economic losses in buildings, damage to nonstructural components can lead not only to serious injuries and even casualties, but can lead to partial or total temporary loss of use of the building. The latter being particularly detrimental in the case of critical facilities such as hospitals [8-10].

Nonstructural components are typically at the end of a long and complicated set of events. As schematically illustrated in figure 1, their seismic response and performance depends not only on the magnitude, location and faulting mechanism of the earthquake but are also affected by the wave propagation and diffraction from the source to the site, possible basin effects in the vicinity of the site, site effects on shallow soil deposits, soil-structure interaction effects that further modify and then, of course, are strongly affected by the seismic response of the structure in which the nonstructural component is mounted on, and on the characteristics of not only the nonstructural component itself but also on the characteristics of the bracing and attachments systems. This long and complicated number of factors give rise to large uncertainties on the estimation of force and deformation demands on nonstructural components during earthquakes which in most cases are even larger than those involved in estimating the response of the building itself greatly complicating how they should be designed and installed these elements in seismic regions.
Current design provisions for nonstructural components are typically based on the use of equivalent static forces computed using simplified equations. Unfortunately, these equations do not take into account the main factors that control the amplitude and frequency content of force and deformation demands on nonstructural components and therefore they may result in large overestimations or large underestimation of seismic demands.

The objective of this paper is to summarize an alternate novel approach being proposed by the authors which recognizes that nonstructural components are rarely actually designed by structural engineers and where bracing elements are allowed to act as fuses during severe earthquake ground motions particularly for nonstructural components whose frequencies of vibration coincide with modal frequencies of the structure in which they are mounted on or suspended from.

**Shortcomings of Current Design Provisions for Nonstructural Components**

In current design provisions, nonstructural components and systems, bracings and attachments are typically designed to resist an equivalent lateral force \[ F = (A_x + A_y) \times \gamma \times T \]. The amplitude of this force is computed as a function of the level of seismicity at the site, the height within the structure in which it is installed and the type of component. Examples of these type of components are shown in figure 2. An important and rapidly growing number of studies have pointed out the many shortcoming in current design provisions. For example, the equivalent static force is amplified as a function of the height to the base of the structure in which the nonstructural component will be located relative to the total building height. In U.S. provisions the variation of forces is determined by an amplification factor varying from 1.0 at the base of the structure to 3.0 at roof level, but this factor is the same regardless of the height of the structure (e.g. the same amplification factor is applied for structures on one-story buildings than of 50 story buildings) and regardless of the lateral-resisting system in the building. However, both analytical and empirical (based on motions

![Figure 3. Examples of ground (bottom) and floor (middle and top) 5%-damped floor spectra of motions recorded in four instrumented buildings in California.](image-url)
recorded during earthquake on instrumented buildings) have shown that such amplification of peak floor accelerations (PFA) is strongly influenced by the fundamental period of the structure and also influenced, but to a lesser extent of the lateral resisting system and damping ratio of the building [12-17]. These studies have shown that amplifications of PFAs may vary by more than a factor of four as a function of the characteristic of the supporting building. Independent studies have corroborated those results and conclusions [18-23].

Unless, the nonstructural component is nearly rigid and it is rigidly attached to the structure, its acceleration demand will differ to that of the floor in which they are mounted on or suspended from. In current provisions, this is taken into account by applying a component amplification factor $a_p$, which is equal to either 1.0 or 2.5, regardless of the frequency of vibration or damping of the component or of those of the supporting structure [11]. However, floor motions may greatly differ to ground motions not only in amplitude but also in frequency content. In particular, the supporting structure will filter the ground motion to amplify the amplitude for frequencies at or close to modal frequencies of the structure and deamplify others. An example is shown in figure 3 which shows floor spectra computed from records obtained in 4 instrumented buildings. It can be seen that floor spectral ordinates can be significantly larger than PFAs or PGAs by values very different than those in current seismic provisions. There is no rational basis for the factor $a_p$, in ASCE provisions and the 2.5 value was decided as a compromise between smaller and larger values proposed by members of the code committee [24]. Various studies have suggested that these factors could vary by more than a factor of 20 depending on the frequency of vibration or damping of the component and those of the supporting structure [15-17].

We have known for many years, that components whose frequency coincide with those of modal frequencies of the supporting structure, that is that they are tuned, can experience very large dynamic amplifications. For example, almost 50 years ago Jennings and Kuroiwa [25] conducted forced vibration tests on a 9-story building and noted “During the vibration tests in the N-S direction, it was noticed among the roof-top machinery that the vibration of an air handling unit was much greater than that of the other pieces of equipment. The vibration amplification was measured by placing one horizontal accelerometer on the roof and another on the top of the air handling unit” and “It was found that the acceleration measured on the top of the air handling unit was about 8.5 times the acceleration of the roof”.

Figure 4. Response of a tuned 5% damped SDOF system to a harmonic motion.
To gain understanding of these large dynamic amplifications consider the response of a 5%-damped single-degree-of-freedom system (SDOF) subjected to a harmonic motion whose frequency coincides to that of the system. As illustrated in figure 4, the secondary system would experience a very rapid buildup of response and reach 90% of the amplitude of the ten-fold amplification of the steady-state vibration after only seven cycles of vibration. Now, building floor motions are not harmonic motions, but as shown in figure 3 tuned systems will exhibit smaller amplifications. These is due on one hand on the finite durations of floor motions where the amplitude does not remain constant in time and on the other because of the presence of input motion at other frequencies. The first effect is illustrated in figure 5, where a tuned 5%-damped SDOF system is subjected to an MP pulse/wavelet in which a harmonic motion is time-modulated by a harmonic function [26]. As shown in the figure, even if the duration of the wavelet is only equivalent to eight times the period of vibration and the mean amplitude is much smaller than in the harmonic motion, the system experiences a six-fold dynamic amplification after only four cycles of vibration. A comparison of the normalized floor response spectra from the motions presented in the previous two figures is shown in figure 6. While these large amplification may not pose a problem to very light systems can lead to very large forces in the case of heavier nonstructural components. Current code further reduce design forces by the use of component reduction factors, $R_p$, which vary as a function of the type of component, but again their values do not have any rational basis [24].

Figure 5. Response of a tuned 5% damped SDOF system to time-modulated harmonic motion, MP pulse, with a duration of eight times the period of the SDOF.

Figure 6. Comparison of 5%-damped floor response spectra to a harmonic and a time-modulated harmonic motion, MP pulse/wavelet.
In most cases, nonstructural components are not designed by structural engineers. Typically, structural engineers only design the bracing of these elements and the attachments of the bracing to the supporting structure and to the nonstructural component. Furthermore, the engineer/firm designing these elements in often not the same designing the supporting structure. Hence, a better approach is to focus the design on those elements, such as those indicated on figure 7, that the structural engineering will be dealing with and to try to reduce the dependence of the seismic forces on the characteristics of the supporting structure.

In the proposed approach, the bracing elements, would be explicitly allowed to undergo a nonlinearity that would limit the force not only in the bracing element to a force known to the engineer designing the element, but would also limit the force in the nonstructural component and

Figure 7. Examples of nonstructural components and their corresponding bracings and attachments [27].

Toward a New Better Design Approach

Figure 8. Normalized floor spectra computed for 2%-damped systems subjected to floor motions recorded at the roof of instrumented buildings in California for: (a) elastic components (left); and (b) nonlinear components (right).
Figure 9. Inelastic displacement ratios as a function of the lateral strength of the nonstructural component normalized by the strength required to maintain the system elastic when subjected to floor motions recorded at roof level of instrumented buildings in California.

to the attachment of the bracing to the structure and to the attachment of the bracing to the nonstructural component. This bracing system would be explicitly be designed to be the weakest component of the four elements previously mentioned in which the attachments are designed using capacity design principles as a function of the probable capacity of the bracing element. The nonlinearity could be introduced by a yielding, rocking or sliding movement or a combination of these mechanisms.

It is expected that the nonlinearity would be triggered primarily for tuned components. The proposed approach is based on the observation that for floor motions which are characterized by being narrow banded processes, even allowing small levels of nonlinearity such as ductility of 1.5 or 2.0 can lead to very large reductions in design forces for systems whose frequencies are equal or close to modal frequencies of the supporting structure. This is illustrated in figure 8 which shows normalized floor spectra quantifying force amplifications in 2% damped elastic and inelastic systems subjected to floor motions recorded at roof level of instrumented buildings. It can be seen that while tuned system could experience median accelerations 7.5 larger than PFAs, these amplifications could be reduced by a factor of five by allowing a ductility of two. Furthermore, as shown in figure 9, the proposed approach can also result in smaller deformation demands for tuned nonstructural components. For example, for components designed for one fifth of the strength required to maintain the system elastic, median deformation are reduced by slightly less than half of the elastic system.

**Summary and Conclusions**

Challenges in estimating force and deformation demands on nonstructural components and their attachments to the structure in which they are mounted on or suspended from have been described and discussed. Current design provisions in most cases do not have rational basis and do not properly take into account the main factors controlling the intensity and other characteristics of
seismic demands on nonstructural components and therefore in many cases they made greatly overestimate demands while in many other cases they may greatly underestimate seismic demands.

Although conceptually it is possible to develop methods that adequately take into the characteristics of the ground motion, of the structure (lateral strength, lateral stiffness and their spatial distribution in the structure, modal frequencies, damping, etc) and of the nonstructural component (mass, stiffness, strength, modal frequencies, damping) nonstructural components are rarely included in the analytical models and more importantly very little of this information required to develop such models is typically available to the engineers in charge of designing bracing elements of nonstructural components or their attachments to the structure and to the component itself.

An alternate novel approach is proposed which recognizes that nonstructural components are rarely actually designed by structural engineers which is based on allowing the bracing elements to act as fuses during severe earthquake ground motions particularly for nonstructural components whose frequencies of vibration coincides to modal frequencies of the structure in which they are mounted on or suspended from. It has been shown that despite the large uncertainties involved has the following advantages: (1) provides a mechanism to greatly reduce and limit seismic forces on the nonstructural component and to the attachments to the bracing element and to the structure; (2) significantly reduces uncertainties on the seismic forces to the nonstructural components, bracing and attachments as these forces now depend of the strength of the bracing/fuse element which can be estimated with much smaller uncertainty; (3) force demands become far less sensitive to the ratio of vibration frequency of the component to modal frequencies of the supporting structure; and (4) can reduce deformation demands to tuned components that otherwise would undergo much larger deformations.

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