9

Floor Response of Single Degree of Freedom Systems with Metallic Structural Fuses

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Summary

The floor demands of Single-Degree-of-Freedom (SDOF) systems designed or retrofitted with metallic structural fuses are studied in this article. Floor velocity and acceleration are obtained and comparisons are made between the floor response of bare frames and the floor response of systems with metallic fuses. Furthermore, velocity and acceleration spectra are developed from the floor time history responses to assess how the behavior of nonstructural components may be influenced by the use of metallic fuses.

Introduction

In the 1964 Alaska and 1971 San Fernando earthquakes, extensive damage of nonstructural components was observed, which resulted in substantial economic losses with serious casualties and impediments to the buildings operation, although structural damage was found to be less significant (Lagorio, 1990). Consequently, since the 1970's, many research projects have focused on providing guidance to design, retrofit, and improve the seismic performance of nonstructural elements. An inventory and summary of past research, as well as comparisons of existing regulations to seismically design nonstructural components can be found in Filiatrault et al. (2002), where, as part of the study, recommendations are made for the development of rational research plans to investigate the seismic performance of nonstructural building components.

In Vargas and Bruneau (2004), the structural fuse concept was investigated as a way to protect primary moment frame structures from experiencing inelastic behavior of beams and columns, by concentrating all damage on easily replaceable elements. Furthermore, limiting story drift indirectly allows mitigation of damage to nonstructural components that are sensitive to lateral deformations (i.e., elements that are generally attached to consecutive floors). However, many nonstructural elements are only attached to one floor, which makes them vulnerable to shifting or overturning. Damage to the internal components of sensitive equipment may also occur due to severe floor vibrations. In order to protect these components, floor acceleration and, in some cases, floor velocity (e.g., in the case of toppling of furniture) should be kept under certain limits.

This article studies the floor velocity and acceleration response of SDOF systems designed with metallic dampers acting as structural fuses. Comparisons are made between the floor response of bare frames and the floor response of systems with metallic fuses. Furthermore, velocity and acceleration spectra are developed from floor time history responses to assess how the behavior of nonstructural components may be affected by the use of metallic fuses. Finally, an equivalent sine-wave floor acceleration response is proposed to generate acceleration and velocity spectra, that may be used to seismically design nonstructural components.

Floor Response

A parametric study was conducted to obtain floor accelerations and velocities for SDOF systems with metallic fuses, using the set of parameters previously considered in Vargas and Bruneau (2004). Figures 1a and 1b show an example of the results obtained from the parametric study for floor acceleration, S_a, and floor velocity, S_v, respectively. The solid line in both figures corresponds to the NEHRP elastic design spectrum, and every curve corresponds to a different value of the strength ratio, η. Note that as structures become more flexible (i.e., $T \geq 2.0$ s), floor spectral accelerations progressively approach those obtained for elastic SDOF systems. Figure 1b shows, as expected, that the relative velocity is close to zero for short period systems. Like in the case of acceleration, floor velocity increases with η values, and for long period systems all the curves approach the NEHRP elastic design spectrum for $T \geq 2$ s.

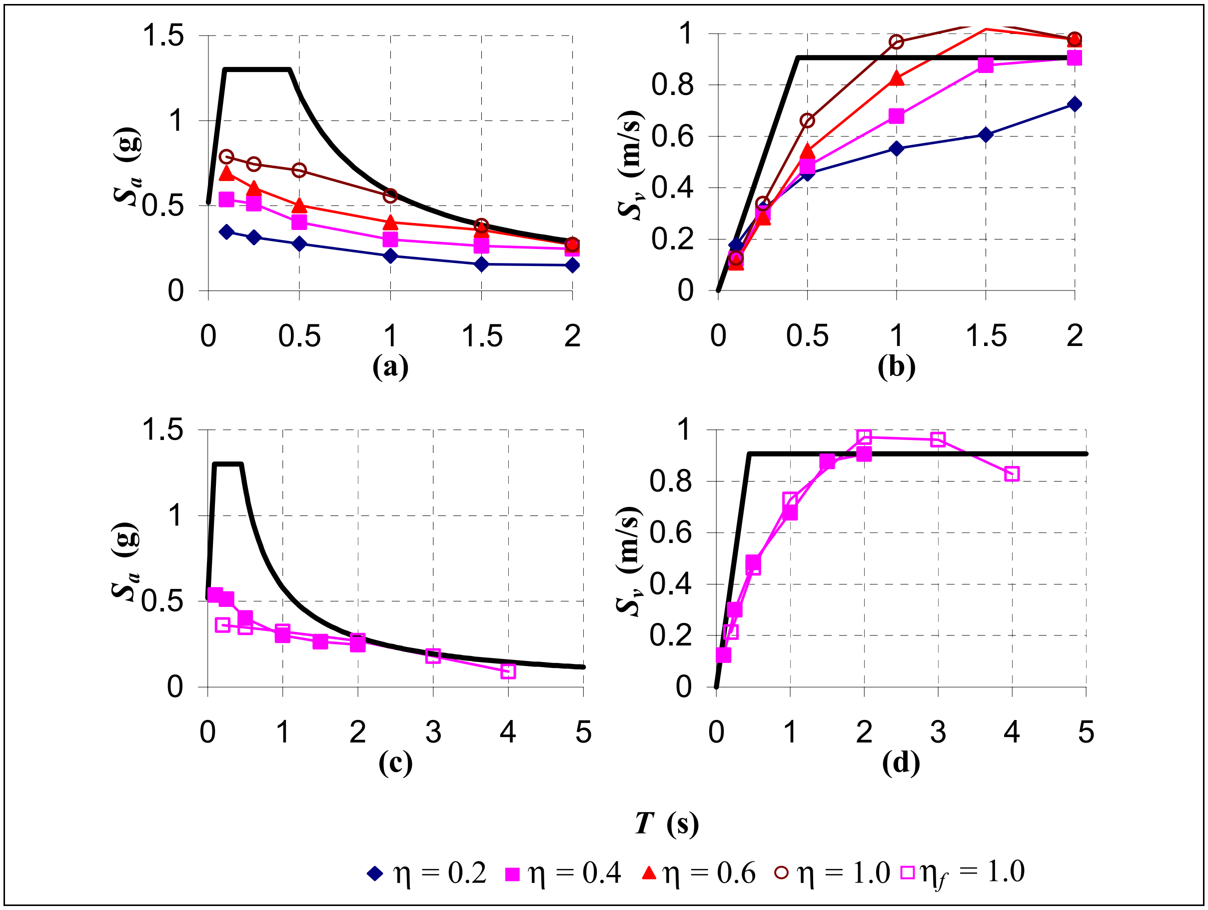

Figure 1. Floor Response; (a) Floor Acceleration, (b) Floor Velocity, (c) Floor Acceleration of Structural Fuse System and Bare Frame, (d) Floor Velocity of Structural Fuse System and Bare Frame

To analyze how metallic fuses modify the floor response, comparisons between the response of bare frames and the response of structural fuse systems were made, in terms of acceleration and velocity. Figure 1c shows an example of the floor acceleration of structural fuse systems, along with the floor acceleration of the corresponding bare frame (i.e., without metallic dampers). Note that when metallic fuses are added to the system, the period of the system shortens. When comparing bare frame and retrofitted system response in Figure 1c, one cannot directly read up from the horizontal axis, but should rather compare the results point-by-point for the six cases considered (alternatively, the figures could have been plotted as a function of the bare frame period on the horizontal axis, but it was felt worthwhile to also visually see the shift in period corresponding to each case). Figure 1c also shows that, in most of the cases, floor acceleration is increased by adding metallic fuses to the system. Furthermore, Figure 1d shows the floor response, in terms of velocity, for bare frames and structural fuse systems. In this case, the periods are also "shifted" to lower values. Unlike acceleration, velocity either decreases or remains equal in most of the cases, which implies that adding metallic fuses do not seem to change the velocity response of the systems.

As a case study to illustrate in more details the above results, a SDOF system designed with unbonded braces to satisfy the structural fuse concept was selected. The frame is a single-story one-bay structure composed of W14 x 211 columns and a W12 x 190 beam, with unbonded braces made of rectangular plates (57 x 25 mm) in a chevron configuration. General properties for this example are: L = 4877 mm, H = 3810 mm, m = 0.35 kN·s^2/mm, F_{yf} = 345 Mpa, and T = 0.53 s. In this case study, results obtained from time history analysis (or directly read from Figures 1c and 1d) indicate that floor spectral acceleration, S_a, and floor spectral velocity, S_v, are 0.40 g and 484 mm/s, respectively. Prior to adding the unbonded braces, properties of the system were η_f = 0.52 and T_f = 1.04 s. Figures 1c and 1d also show that S_a and S_v on the bare frame are respectively 0.32 g and 728 mm/s. In this particular example, it may be noted that adding unbonded braces to the system result in an increase of 25% in the floor acceleration, and a reduction of 33% in the floor velocity.

Floor Spectra

Floor acceleration response histories of SDOF systems have been taken as the input signal to generate elastic floor acceleration and velocity spectra, to analyze the response of nonstructural components attached to the floor of bare frame systems, and structures designed with metallic fuses. A damping ratio of 5% was selected for this study.

Figures 2a and 2b show an example of the floor acceleration spectra, S_{anc}, and the floor velocity spectra, S_{vnc}, respectively, for the selected structural fuse systems, and their corresponding bare frame systems, where the subscript "nc" denotes "nonstructural component." In these plots, the horizontal axis corresponds to the elastic period of the nonstructural components, T_{nc}, since floor spectra were built to analyze the response of secondary elements attached to the floor of the primary structure. Note that, even though peak floor acceleration was found to increase in most of the cases, in floor acceleration spectra, two regions are defined by the critical period of the nonstructural component, T_c, where both spectra intersect. Nonstructural elements with a period shorter than this critical period are subjected to acceleration demands greater in structural fuse systems, than in the corresponding bare frame; whereas for components with a period longer than critical, the acceleration demand decreases for structural fuse systems. Approximately, the critical period, T_c, may be determined as the average between the period of the bare frame, T_f, and the period of the structural fuse system, T.

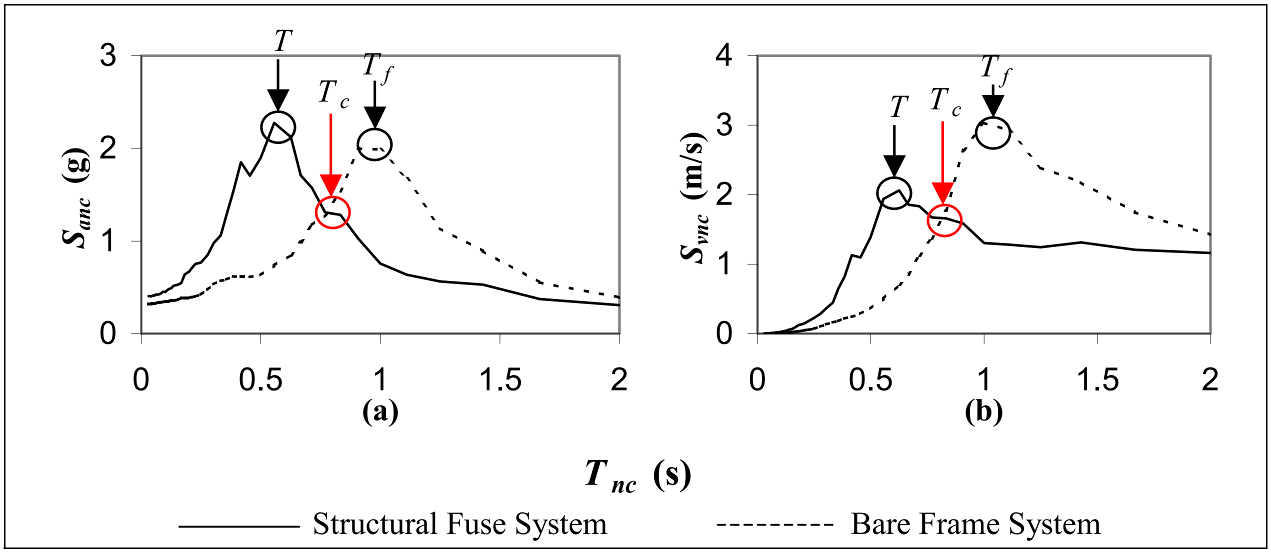

Figure 2. Floor Spectra; (a) Floor Acceleration Spectra, (b) Floor Velocity Spectra

Figures 2a and 2b demonstrate that, in a retrofit situation, the seismic behavior of the nonstructural components may (or may not) be improved with the addition of metallic dampers to the structural system. Positive or negative results may be obtained, depending on the dynamic characteristics of the nonstructural elements, relative to the properties of the retrofitted system. For example, for the case study described in the former section, the critical period is approximately equal to 0.83 s (see Figures 2a and 2b). In this case, nonstructural components with an elastic period less than 0.83 s would experience an increase in acceleration and velocity by the addition of metallic dampers. On the other hand, components having a period greater than 0.83 s are more likely to be subjected to lower levels of acceleration and velocity when metallic dampers are added.

Equivalent Sine-wave Floor Spectra

This section investigates whether an equivalent sine-wave floor acceleration response history could be used as a simplified way to generate acceleration and velocity spectra for that purpose. The dynamic response of a nonstructural component attached to the floor of a structural fuse system can be obtained through the following expression:

$$m_{nc}\,\ddot{u}_{nc} + c_{nc}\,\dot{u}_{nc} + k_{nc}\,u_{nc} = -\,m_{nc}\,\ddot{u}_{F} \tag{1}$$

where, again, the subscript "*nc*" denotes "nonstructural component", and $\ddot{u}_F$ is the floor acceleration (i.e., the input signal exciting the nonstructural component). Substituting an equivalent harmonic sine-wave motion for $\ddot{u}_F$ gives, after arranging terms:

$$\ddot{u}_{nc} + \left(\frac{4\pi\,\xi_{nc}}{T_{nc}}\right)\dot{u}_{nc} + \left(\frac{4\pi^2}{T_{nc}^{\;2}}\right)u_{nc} = PFA_{eff}\,\sin\left(\frac{2\pi t}{T}\right) \tag{2}$$

where ξ_{nc}, T_{nc}, are the damping ratio and the period of the nonstructural component, respectively, and PFA_{eff} is the effective peak floor acceleration, defined here as the average of the absolute values of the peaks of the floor acceleration response history, between the first and last exceedances of a threshold acceleration (arbitrarily set at 25% of the maximum floor acceleration in this study). Results for effective peak floor acceleration using this procedure, indicate that PFA_{eff} may be conservatively determined as 50% of the peak floor acceleration (i.e., $PFA_{eff} \approx 0.50\ S_a$). Figure 3 shows the first 15 seconds of an actual floor acceleration response history, and its equivalent sine-wave floor acceleration response history generated per the above procedure.

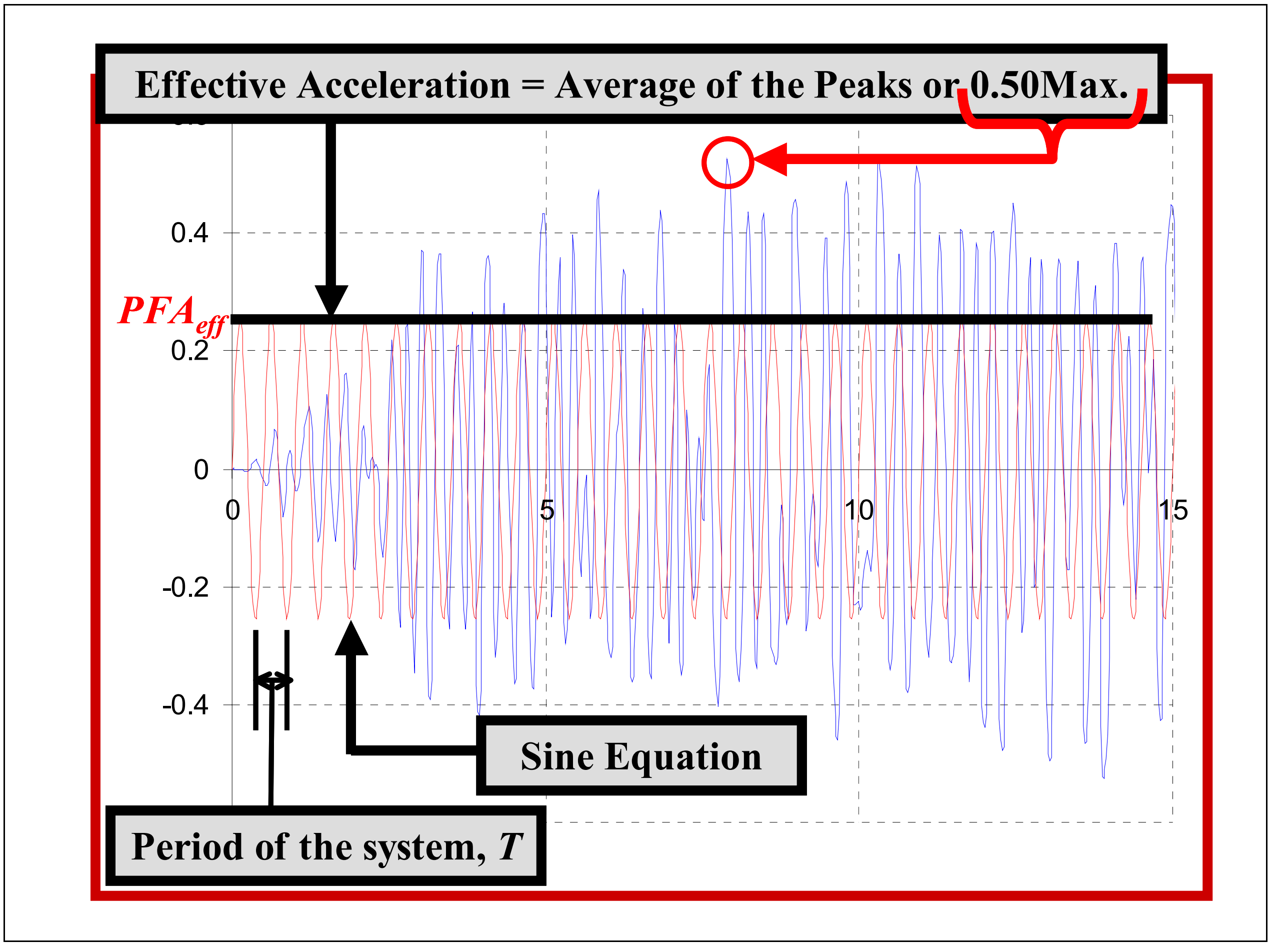

Figure 3. Equivalent Sine-Wave Floor Acceleration Response History of a SDOF System with Metallic Fuses

Closed form solutions for the spectral acceleration, S_{anc}, and velocity, S_{vnc}, of nonstructural components for the equivalent sine-wave floor acceleration may be obtained from Equation (2). Figures 4a and 4b show an example of actual acceleration and velocity spectra, respectively, along with the sine-wave response obtained from Equation (2), assuming a damping ratio of 5% for the nonstructural components (i.e., $\xi_{nc} = 5\%$).

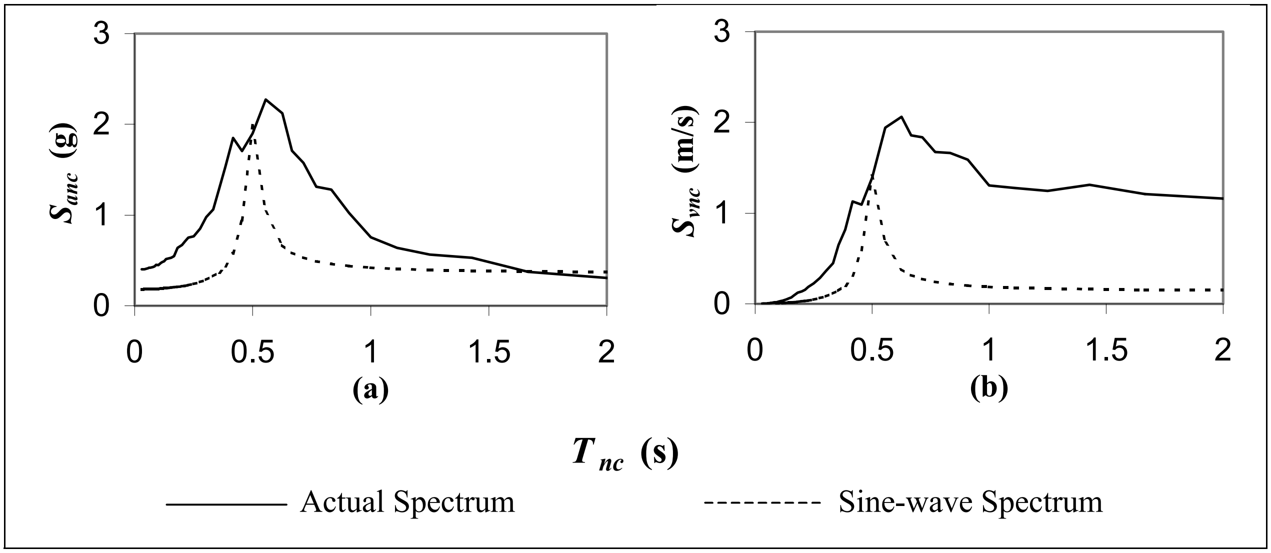

Figure 4. Actual and Sine-wave Response Spectra; (a) Acceleration Spectra, (b) Velocity Spectra

As an example, the case study from former sections will be subjected to a peak floor acceleration of 0.40 g at the roof level (Figure 1a). Conservatively, taking an effective peak floor acceleration of 0.50 S_a, and assuming a damping ratio of 5% (i.e., PFA_{eff} = 0.20 g, and ξ_{nc} = 5%), a nonstructural component located at the roof level of the building, may be conservatively designed to resist an acceleration, S_{anc} = 2.2 g, and a velocity, S_{vnc} = 1.56 m/s. These results are corroborated by Figures 4a and 4b.

Conclusions

Floor accelerations and velocities for SDOF systems with metallic fuses have been studied in this chapter through a parametric analysis. It was found that, in most of the cases, floor acceleration increases when using metallic fuses.

It was also found that the critical period, T_c, is an useful indicator to identify when using metallic fuses can increase or decrease the dynamic acceleration and velocity response of nonstructural components. It was observed that nonstructural elements having a period shorter than T_c may be susceptible to greater acceleration (which would increase their likelihood of sliding on their support if unrestrained, for example), and greater velocity (which would for example increase their probability of overturning) when metallic fuses are added. On the other hand, it was found that retrofit works may improve the seismic behavior of flexible nonstructural components that have a period longer than T_c; however, adequate judgement must be exercised in retrofitting these elements.

Furthermore, using the equivalent sine-wave criterion, it is also possible to determine spectral acceleration and velocity to conservatively design nonstructural components and/or their anchorages. This criterion may be applied to multi-degree of freedom systems assuming a linear variation of floor acceleration over the building height.

Acknowledgements

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