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Seismic response of nonstructural components considering the near-fault pulse-like ground motions

Chang-Hai Zhai[*1,2], Zhi Zheng[1a], Shuang Li[1,2], Xiaolan Pan[1] and Li-Li Xie[1,3]

[1]School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
[2]Key Lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Heilongjiang, Harbin, 150090, China
[3]Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China

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Abstract. This paper investigates the response of nonstructural components in the presence of nonlinear behavior of the primary structure considering the near-fault pulse-like ground motions. A database of 81 near-fault pulse-like ground motions is used to examine the effect of these ground motions on the response of nonstructural components. For comparison, a database of 573 non-pulse-like ground motions selected from the PEER database is also employed. The effects of peak ground velocity (PGV), maximum incremental velocity (MIV), primary structural degrading behavior and damping of nonstructural components are evaluated and discussed statistically. Results are presented in terms of amplification factor which quantifies the effect of inelastic deformations of the primary structure on subsystem responses. The results indicate that the near-fault pulse-like ground motions can significantly increase the amplification factors of nonstructural components with primary structural period and the magnitude of increase can reach 17%. The effect of PGV and MIV on amplification factors tends to increase with the increase of primary structural ductility. The near-fault pulse-like ground motions are more dangerous to components supported by structures with strength and stiffness degrading behavior than ordinary ground motions. A new simplified formulation is proposed for the application of amplification factors for design of nonstructural components for near-fault pulse-like ground motions.

Keywords: floor response spectra; nonstructural components; near-fault pulse-like ground motions; inelastic seismic behavior; seismic design

1. Introduction

In the near-fault conditions, due to the effects of forward rupture directivity, most of the seismic energy in ground motion is concentrated in a single pulse of motion at the beginning of the record (Somerville *et al*. 1997). These ground motions, referred as "near-fault pulse-like ground motions", may result in high seismic demands for buildings. Many investigations have studied the effects of the near-fault pulse-like ground motions on the various structures (Hall *et al*. 1995,

*Corresponding author, Professor, E-mail: zch-hit@hit.edu.cn
[a]Ph.D. Student, E-mail: zhengzhi.hit@qq.com

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Sehhati *et al.* 2001, Alavi and Krawinkler 2004, Phan *et al.* 2007, Trifunac 2009, Jalali *et al.* 2012, Karalar *et al.* 2012, Mazza and Vulcano 2012, Ghahari and Khaloo 2013, Ismail *et al.* 2013, Lu and Hsu 2013, Park 2013). The results in these investigations demonstrated that the near-fault pulse-like ground motions can induce more severe damage of structures than the non-pulse-like ground motions (referred as "ordinary ground motions" here). However, the preceding researches have not caused enough attention on the effects of near-fault pulse-like ground motions on the nonstructural component responses. The near-fault pulse-like ground motions may have disadvantageous effects on nonstructural components. Since the failure to nonstructural components during earthquakes constitutes a major portion of economic losses (McKevitt *et al.* 1995, Naeim 2000, Filiatrault *et al.* 2002, Taghavi and Miranda 2003, Myrtle *et al.* 2005), it is necessary to consider the effects of near-fault pulse-like ground motions in the seismic design and performance evaluation of nonstructural components. To date, although some references such as (Kennedy *et al.* 2006, Sankaranarayanan and Medina 2006, Kanee *et al.* 2013) have demonstrated the relationship between the near-fault pulse-like ground motions and the nonstructural components established on the inelastic supporting structure, they established the relationship only by scaling the intensity of ground motions, which is similar to the strength reduction method. The relationship between the target primary structural ductility and component responses has not been developed for near-fault pulse-like ground motions. Also, the characteristics of near-fault pulse-like ground motions and primary structural hysteretic behavior have not been thoroughly investigated. Most importantly, such an understanding will aid the development of performance-based seismic design and evaluation of nonstructural components.

In the seismic design of nonstructural components, amplification factors, defined as the floor response spectrum (FRS) for an inelastic primary structure normalized by the FRS for an elastic primary structure, is a particularly appealing approach to obtain the design floor response spectrum from conventional linear elastic floor response spectrum accounting for yielding of the supporting structure without having to perform inelastic analysis. Many investigations have been conducted to study the characteristics of the amplification factors (Bumpus *et al.* 1980, Wesleyand Hashimoto 1981, Lin and Mahin 1985, Singh *et al.* 1993, Kennedy *et al.* 2006, Sankaranarayanan and Medina 2007, Oropeza and Favez 2010). Bumpus *et al.* (1980) used a parameter denoted as factor of conservatism that is similar to the amplification factor to investigate the effect of structural nonlinearity on equipment under the seismic safety margins research program (LLNL 1980). Wesley and Hashimoto (1981) found that structural nonlinearity often caused increases in the high frequency region of the spectra through a comparison of inelastic to elastic FRS at various locations of the structure. Lin and Mahin (1985) conducted a parametric study on the influence of structural nonlinearity on the amplification factor primarily with SDOF elastic equipment mounted on a SDOF structure. Kennedy *et al*. (2006) used a FRS ratio factor which is equivalent to the amplification factor to evaluate a typical MDOF Pressurized Water Reactor auxiliary building modelled with a series of lumped masses and beam elements considering soil-structure interaction effects. Sankaranarayanan and Medina (2007) employed simple structural models to investigate the effect of location of components, periods of components and buildings, damping of components and level of inelasticity of building on the *R*acc factor which is the inverse of the amplification factor. Additionally, other works such as Chen and Soong (1988), Gupta (1990), Soong (1994), Phan and Taylor (1996), Villaverde (1997, 2004), Chauduri and Villaverde (2008), Politopoulos (2010) and Vukobratović and Fajfar (2015) presented more details on the different methods of analysis for nonstructural components. Hence, based on the above researches, this study focuses on the effects of near-fault pulse-like ground motions on the amplification factors for the seismic design and performance evaluation of acceleration-sensitive nonstructural components.

This paper studies the amplification factors (AFs) based on primary structural ductility factor with 81 near-fault pulse-like ground motions and three hysteretic models. The influences of peak ground velocity (PGV), maximum incremental velocity (MIV), primary structural degrading behavior and damping of nonstructural components are evaluated and discussed statistically. A new simplified formulation is established for the application of amplification factors with primary structural ductility due to near-fault pulse-like ground motions. It should be noted that this study does not consider the nonlinearity of the component and is valid for light components that do not offer dynamic feedback to the primary structure, i.e., interaction effects between nonstructural components and primary building are not considered.

2. Amplification factors for design of nonstructural components

The inelasticity of a building modifies the floor motions and the forces to which acceleration-sensitive nonstructural components are subjected to. At present, there is less clear understanding as to how the near-fault pulse-like ground motions may affect a FRS. Hence, this study focuses the effects of near-fault pulse-like ground motions on the FRS. In this study, a parameter denoted as amplification factor (AF) is used to quantify the effect of structural nonlinearity on the peak acceleration demands of nonstructural components. The AF factor is defined as the FRS for an inelastic primary structure normalized by the FRS for an elastic primary structure (Eq. (1)). The terms 'elastic' and 'inelastic' in this equation refer to the behavior of the supporting structure

$$\mathrm{AF} = FRS_{\mathrm{inelastic}} / FRS_{\mathrm{elastic}} \tag{1}$$

where AF is the amplification factor, $FRS_{\mathrm{inelastic}}$ is the floor response spectrum when the inelastic structure suffers damage from a ground motion, FRS_{elastic} is the floor response spectrum when the elastic structure is excited by the same ground motion.

In this investigation, amplification factors are computed for single-degree-of-freedom (SDOF) systems with viscous damping ratio ξ=5% for the primary structure. Fig. 1 shows the diagram for the computation of the amplification factor AF. It should be noted that the absolute accelerations of the primary structure with target structural ductility are calculated by gradually reducing the applied strength of SDOF system from the corresponding elastic strength demand until the specified μ is achieved within a tolerance (1% is used in this paper).

In order to investigate the influences of the levels of structural nonlinearity, structural hysteretic behavior and damping of nonstructural components ξ_c on the amplification factor, five primary structural ductility factors μ=2, 3, 4, 5 and 6 are selected to consider the different damage performances; five damping values of nonstructural components ξ_c=0.01, 0.05, 0.1, 0.15 and 0.2 are utilized to consider the different damping of components. As for the hysteretic behavior, three different hysteretic models are used in this paper: (i) Elastic-Perfectly-Plastic (EPP) model, representing the non-degrading systems; (ii) Modified Clough (MC) model, simulating the flexural behavior that exhibit stiffness degradation at reloading; and (iii) Stiffness Strength Degradation (SSD) model based on the three parameter model (Kunnath *et al.* 1990, Kunnath *et al.* 1992), representing global behavior of systems exhibiting stiffness degradation and strength deterioration during reloading branches. A total of 81 near-fault pulse-like ground motions are selected to conduct the analyses of SDOF systems for which primary structural periods T_P range from 0.3 s to

1.8 s with an interval of 0.3 s. The periods of nonstructural components T_C increase from 0.03 s to 6 s by 60 equally spaced points in logarithmic space.

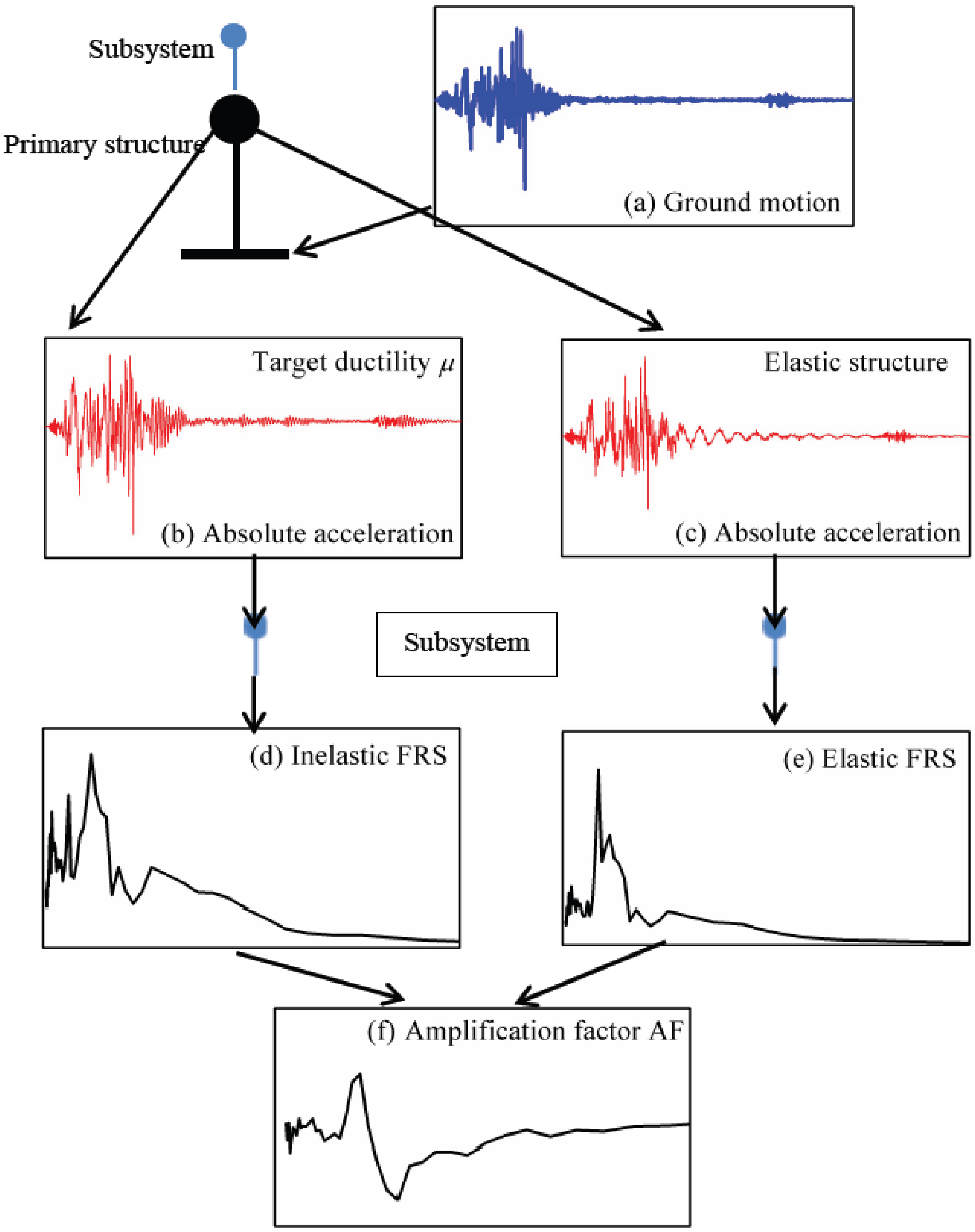

Fig. 1 The diagram for the computation of the amplification factor AF (a): 81 near-fault pulse-like ground motions; (b): Absolute acceleration (response) of the inelastic primary structure; (c): Absolute acceleration (response) of the elastic primary structure; (d) and (e): The obtained accelerations (b) and (c) are considered as ground motions for the subsystem and obtain the corresponding FRS; (f) Obtained final results plotted in terms of $FRS_{inelastic}/FRS_{elastic}$ vs. T_C/T_P

3. Ground motions

In Ref. (Baker 2007), Baker proposed a quantitative classification procedure of pulse-like ground motions, and 91 ground motions with large-velocity pulses in the fault-normal component of records were selected from the approximately 3500 ground motions in the Next Generation Attenuation (NGA) project ground motion library. It is well known that, for the near-fault pulse-like ground motions, the pulse-like signals of fault-normal component are generally more pronounced than fault-parallel component (Somerville *et al.* 1997, Zhai *et al.* 2013). Therefore, 81 fault-normal ground motions are selected from Ref. (Baker 2007) by excluding the ground motions whose Joyner-Boore rupture distance (Joyner and Boore 1981) is beyond 30 km. These ground motions selected here have the following characteristics: (a) magnitudes of most ground motions range from 5.7 to 7.6; (b) peak ground velocities are greater than 30 cm/s. It should be noted that the epicentral distance is used to estimate the Joyner-Boore rupture distance, when the Joyner-Boore rupture distance of a given ground motion is unavailable.

4. Statistical analyses

4.1 Mean amplification factors

A total of 2,187,000 amplification factors (AFs) are computed for 81 near-fault pulse-like ground motions, 6 primary structural periods, 60 vibration periods of components, 5 structural ductility factors, 3 hysteretic behaviors and 5 damping of components. Mean AFs are then calculated by averaging the results of 81 near-fault pulse-like ground motions for each primary structural period, each component period, each structural ductility factor, each hysteretic behavior and each component damping.

For the brevity of the paper, mean AF values of EPP system corresponding to ξ_c=0.05 are used to study in this section. Fig. 2 shows the mean AFs of EPP system for 6 primary structural periods and 5 structural ductility factors. The component periods are represented by the component period (T_C) normalized by the primary structural period (T_P), which is widely utilized in preceding studies. It can be seen that, in general, the mean AFs show the same general trend regardless of primary structural periods. In the short period region (for the T_C smaller than $0.5T_P$ in this work), mean AFs keep constant in most of the regions and tend to increase with the increase of the primary structural period. In this region, mean AFs are close to 1.0, meaning the inelastic behavior of the structure has a negligible effect on the FRS for the components. In the fundamental period region ($0.5T_P \le T_C \le 1.5T_P$), the period of the nonstructural component is close to the period of the primary structure. In this region, a substantial decrease in AFs is seen in the vicinity of the T_C/T_P equal to 1.0, but after the T_C/T_P equal to 1.0, the AFs begin to increase. In the long period region ($1.5T_P \le T_C \le 3.5T_P$), mean AF values increase slightly with the increase of the component period and appear to be larger than one in some of the cases (e.g., Fig. 2(a)), implying that the FRS values for inelastic primary structures may be higher than those for elastic primary structures in the long period region. Amplification occurs in this region because the structure softens with higher structural ductility factors and the fundamental period of vibration lengthens.

For each of six primary structures in Fig. 2, mean AF values almost overlap for different primary structural ductility factors in the short period region, indicating that structural nonlinearity has a negligible effect on the component responses in this region. For the fundamental and long period regions, mean AFs decrease with the increase of structural ductility factor. Take the mean AFs for primary structural period equal to 0.3 s as an example, the AF for μ=2 is 0.77 while the AF for μ=6 is 0.56 when the T_C/T_P value is equal to 1.0.

4.2 Dispersion of amplification factors

It is significant to quantify the level of dispersion in amplification factors, because the dispersion can reflect the diversity and uncertainty of the selected ground motions. The coefficient of variation (COV), which is defined as the ratio of the standard deviation to the mean, is a common and effective parameter to quantify the dispersion.

The COVs of AFs of EPP system corresponding to ξ_c=0.05 are given in this section. Fig. 3 illustrates the COVs of AFs for six primary structures. It is clear from Fig. 3 (a) that most COVs of

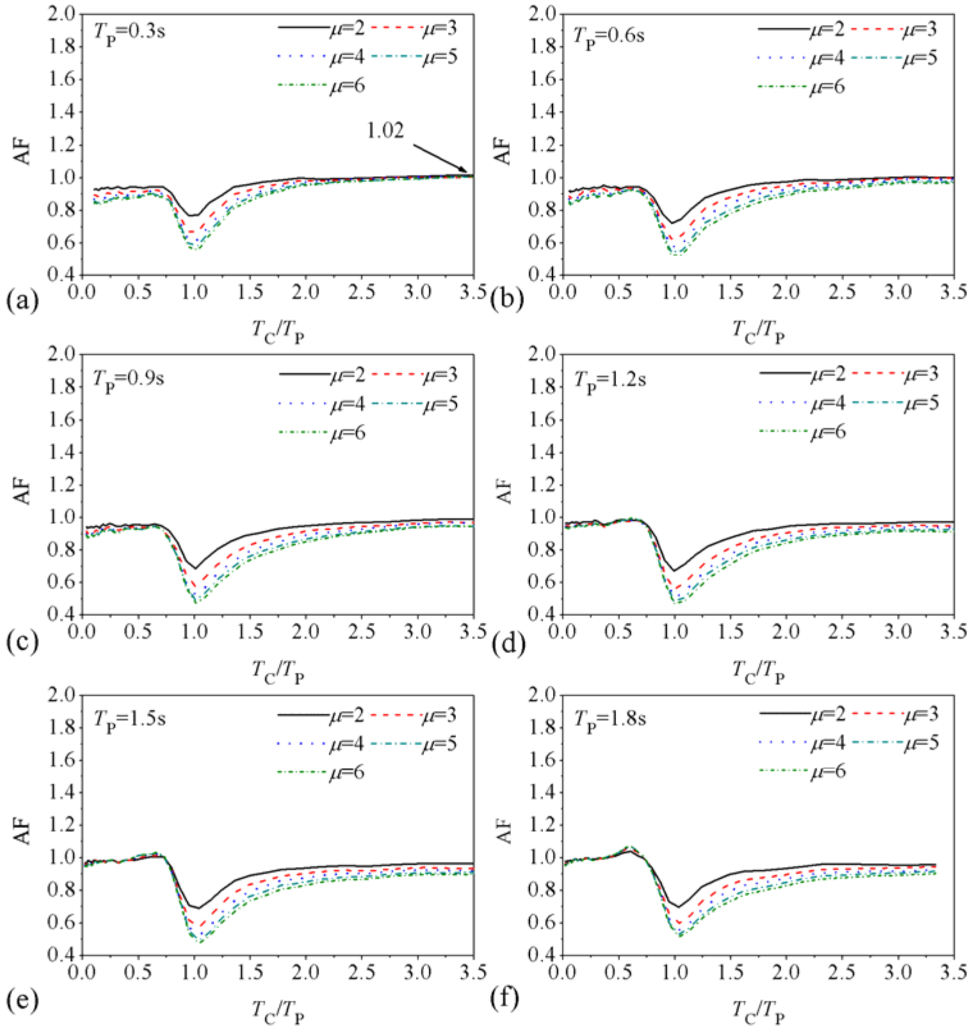

Fig. 2 Mean AFs of EPP system

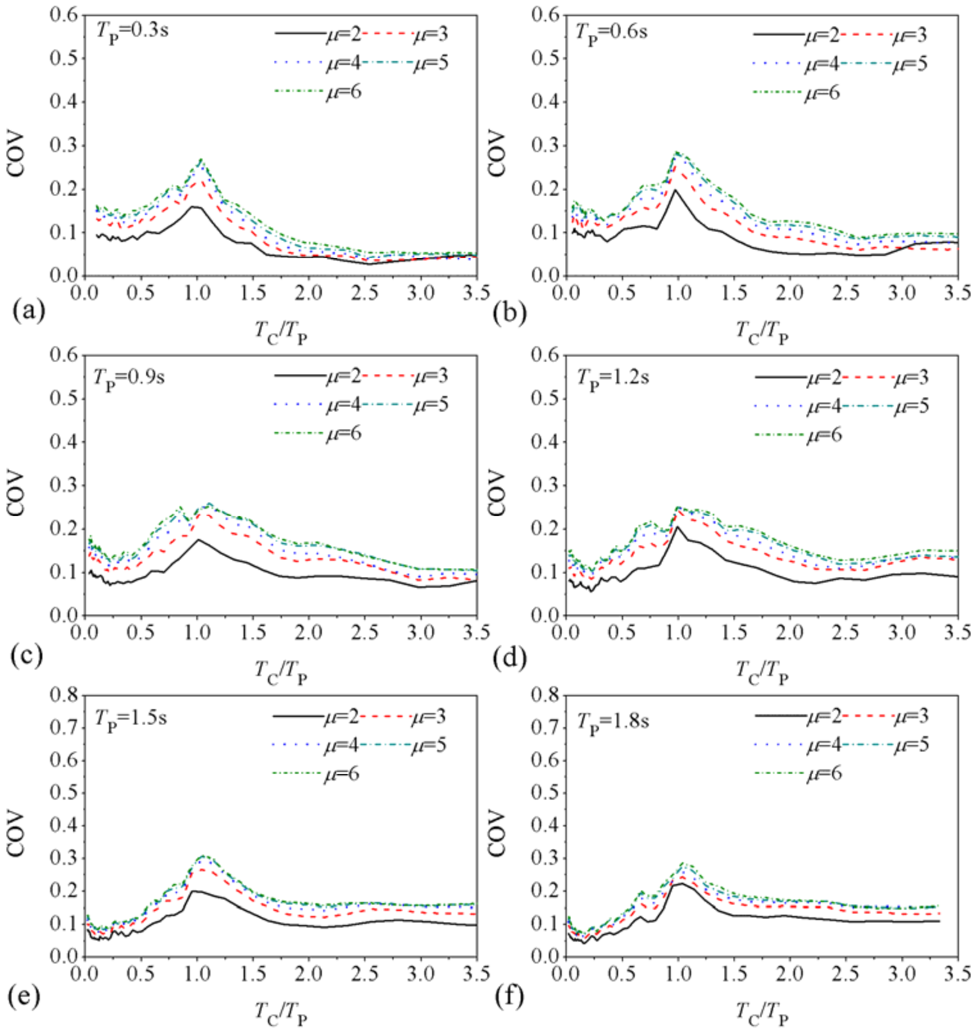

Fig. 3 COVs of AFs for EPP system

AFs increase with the increase of the T_C/T_P values for the T_C/T_P values smaller than 1.0 while decrease with the increase of the T_C/T_P values for the T_C/T_P values greater than 1.0. The peaking COVs of AFs occur in the vicinity of the T_C/T_P equal to 1.0, indicating that the COVs are approximately period dependent. It is obvious that the COVs are relatively sensitive to the μ and increase with the increase of μ. For example, as is shown in Fig. 3(a), the COV for μ=2 is about 0.16 when the T_C/T_P value is about 1.0 while it increases to 0.27 for μ=6.

4.3 Comparison with the ordinary ground motions

In order to quantitatively study the effects of near-fault pulse-like ground motions on the AFs, a total of 573 ordinary ground motions recorded in 38 earthquakes in the world with magnitudes ranging from 5.7 to 7.8, and rupture distances ranging from 0.1 to 180 km, are selected to make a comparison in this paper. These ground motions are obtained from the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation (NGA) relationships database (http://peer.berkeley.edu/nga/), and involve different site conditions (according to the United States Geological Survey (USGS) classification). The numbers of ground motions for site class A, B, C and D are 111, 195, 180 and 87 respectively. All the ground motions selected here have the following characteristics: (1) recorded on accelerographic stations where enough information about the geological and geotechnical conditions at the site is available; (2) recorded on free field stations or in the first floor low-rise buildings where the soil-structure interaction effects are negligible; (3) containing no distinct pulses in velocity-time histories. Then, the ratios of mean AFs of 81 near-fault pulse-like ground motions to the mean AFs of 573 ordinary ground motions are computed.

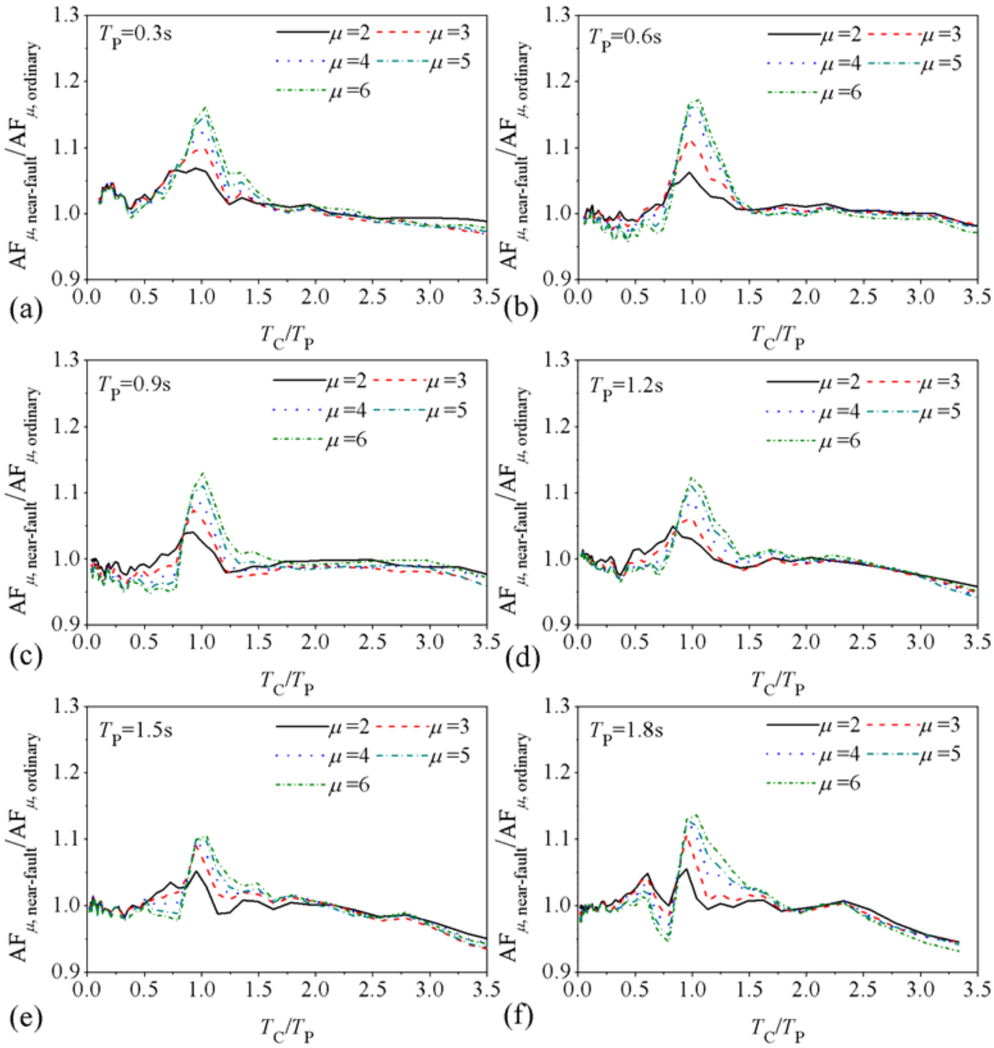

Fig. 4 The ratios of mean AFs of 81 near-fault ground motions to the mean AFs of 573 ordinary ground motions for EPP system

Table 1 The number of ground motions in each PGV and MIV range

Parameters	Range (cm/s)	Number of ground motions
PGV	0-50	39
	50-80	21
	80-191	21
MIV	0-55	26
	55-80	20
	80-322	35

Fig. 4 presents the ratios of mean AFs of 81 near-fault pulse-like ground motions to the mean AFs of 573 ordinary ground motions for EPP system. The ratios of mean AFs with different μ values are very close to 1 in the short and long period regions for six primary structures, indicating that near-fault pulse-like ground motions do not have a significant effect on the AFs in those regions. In the fundamental period region, the ratios of mean AFs increase to more than 1 and the ratios of mean AFs tend to increase with the increase of μ. Take the 0.6 s building for an example, the maximum ratios for μ=2, 3, 4, 5 and 6 are 1.06, 1.11, 1.15, 1.16 and 1.17 respectively, indicating that the near-fault pulse-like ground motion would increase AF and the magnitude of increase can reach about 17 %.

4.4 Effect of peak ground velocity

Several investigations (Zhai *et al*. 2007, Baez and Miranda 2000) have demonstrated that peak ground velocity (PGV) and maximum incremental velocity (MIV) are important ground motion parameters to characterize the near-fault pulse-like ground motions. It is necessary to investigate the effects of PGV and MIV on the AFs. In this section, the ground motions are divided into three groups according to the different PGV ranges, and the numbers of ground motions in each PGV range are summarized in Table 1. Fig. 5 shows the ratios of mean AFs in each PGV range to the mean AFs of 81 near-fault pulse-like ground motions for four primary structures of the EPP system. It is clear that in Fig. 5(a), (b), (e) and (f), the ground motions with larger PGVs tend to induce greater AFs than the ground motions for which PGVs are relatively smaller, particularly in the fundamental period region. By contrast, Fig. 5(c), (d), (g) and (h) do not show the similar trend. It can also be found that the differences between the ratios of mean AFs for different PGV ranges tend to increase when the primary structures suffers more severe damage from ground motions. The ratios of mean AFs for different PGV ranges and μ values vary within interval [0.9 1.09], indicating that the effect of PGV on AF is within 10%.

4.5 Effect of maximum incremental velocity

In this section, the ground motion dataset is divided into three groups according to the different MIV ranges. The numbers of ground motions in each MIV range are summarized in Table 1. Fig. 6 presents the ratios of mean AFs in each MIV range to the mean AFs of 81 near-fault pulse-like ground motions for four primary structures of EPP system. In general, the effect of maximum incremental velocity shows the similarity with the trend of PGV. It is clear that in Fig. 6(a), (b), (e) and (f), the ground motions with larger MIVs tend to induce greater AFs than the ground motions for which MIVs are relatively smaller, particularly in the fundamental period region while Fig. 6(c), (d), (g) and (h) do not show the similar trend. It can also be found that higher seismic intensity would induce larger differences between the ratios of mean AFs for different MIV ranges. The ratios of mean AFs for different MIV ranges and μ values vary within interval [0.92 1.08], indicating that the effect of MIV on AF is within 8% and the effect of MIV on AF is very similar to PGV.

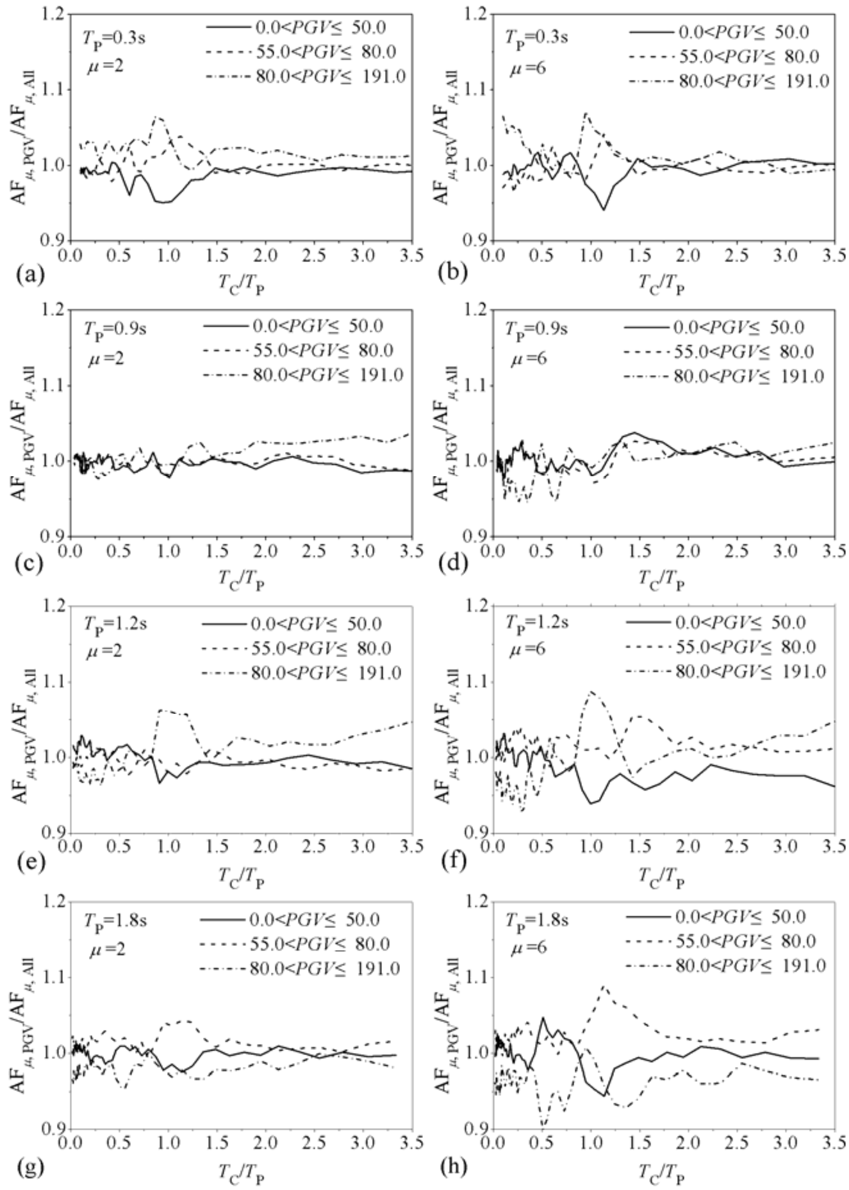

Fig. 5 The ratios of mean AFs in each PGV range to the mean AFs of 81 near-fault pulse-like ground motions for EPP system

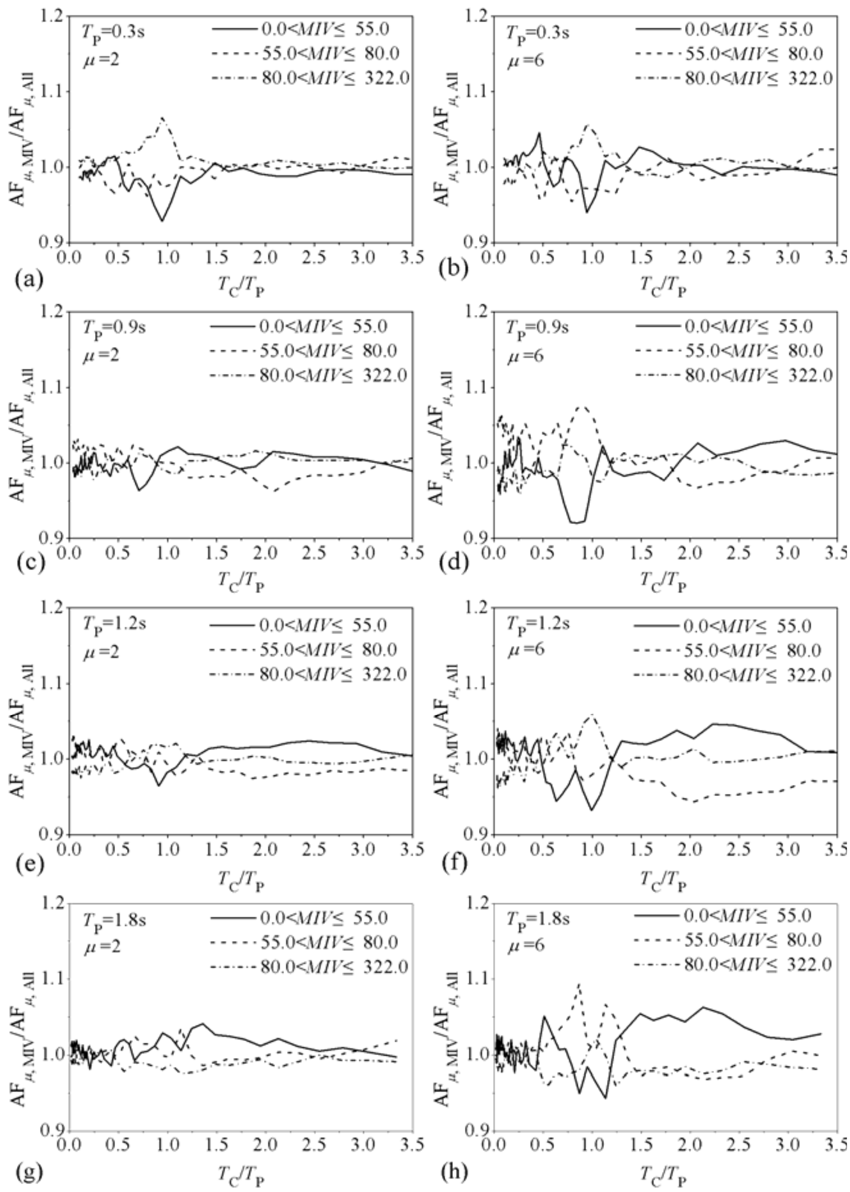

Fig. 6 The ratios of mean AFs in each MIV range to the mean AFs of 81 near-fault pulse-like ground motions for EPP system

4.6 Effect of structural hysteretic behavior

In this section, the influences of stiffness degradation and strength deterioration are investigated by considering the MC and SSD models. The difference of AFs between near-fault pulse-like ground motions and ordinary ground motions is also researched in this part. The mean ratios of AFs of MC and SSD systems to the AFs of EPP systems are calculated for each ground motion, each component period, each primary structural ductility factor, each component damping and each primary structural period.

Fig. 7 presents the mean ratios of AFs of MC and SSD systems to the AFs of EPP systems for the 81 near-fault pulse-like ground motions and 573 ordinary ground motions. For μ=2 case, negligible difference can be found in the short and long period regions between the near-fault pulse-like ground motions and ordinary ground motions. The mean ratios of AFs for the MC and SSD systems are close to 1.0 and the values tend to keep constant in those regions. In the fundamental period region, a substantial decrease in the mean ratios of AFs can be observed for the MC and SSD systems for the ordinary ground motions and near-fault pulse-like ground motions. However, for the near-fault pulse-like ground motions, the mean ratios of AFs are significantly greater in the fundamental period region in comparison with ordinary ground motions. For example, for the 1.8 s building, the mean ratio of AF due to near-fault pulse-like ground motions is 0.86 for MC and SSD models when T_C/T_P being 1.0 while it has only 0.74 for ordinary ground motions. For μ=6 case, the mean ratios of AFs for the two degrading systems and two types of ground motions almost overlap in the short period region. In the fundamental period region, the

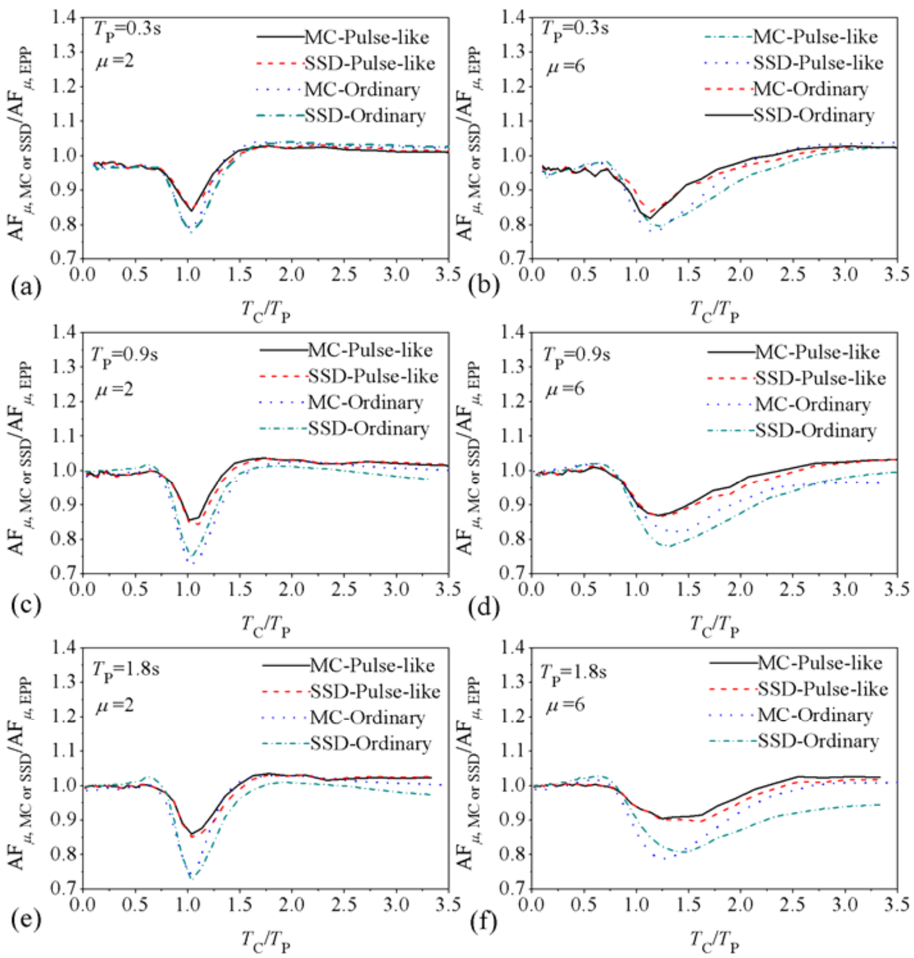

Fig. 7 Mean ratios of AFs of MC and SSD systems to the AFs of EPP systems for the 81 near-fault pulse-like ground motions and 573 non-pulse-like ground motions

mean ratios of AFs for the degrading systems experience a substantial decrease, with the ratios increasing gradually in the long period region. It should be noted that near-fault pulse-like ground motions result in larger mean ratios of AFs than ordinary ground motions for degrading systems, particularly in the fundamental and long period regions. For example, for the SSD model, the mean ratios of AFs due to ordinary ground motions for T_P=0.3 s, 0.9 s and 1.8 s are 0.80, 0.78 and 0.81 respectively when the T_C/T_P is equal to 1.25. By contrast, the ratios for near-fault pulse-like ground motions increase to 0.86, 0.87 and 0.90. The values for near-fault pulse-like ground motions are about 7.5%, 11.5% and 11.1% larger than the ordinary ground motions. This phenomenon indicates that the near-fault pulse-like ground motions are more dangerous to components mounted on structures with degrading behavior than ordinary ground motions.

4.7 Effect of damping of nonstructural components

In this section, the effect of damping of nonstructural components ξ_c on the AFs is investigated. The AFs of EPP system are computed corresponding to ξ_c=0.01, 0.1, 0.15 and 0.2 respectively,

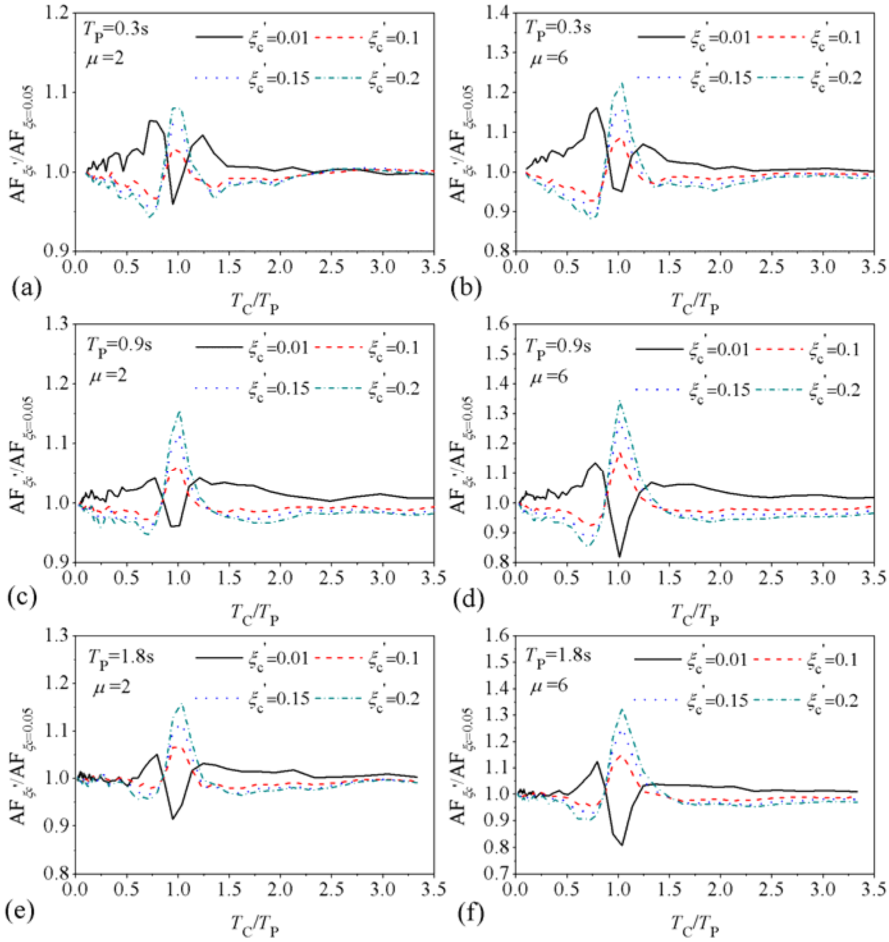

Fig. 8 Mean ratios of AFs of ξ_c=0.01, 0.1, 0.15 and 0.2 to the AFs of ξ_c=0.05 for EPP system

then the ratios of AFs of ξ_c=0.01, 0.1, 0.15 and 0.2 to the AFs of ξ_c=0.05 are computed for each ground motion, each component period, each structural ductility factor and each primary structural period.

Fig. 8 presents the mean ratios of AFs of ξ_c=0.01, 0.1, 0.15 and 0.2 respectively to the AFs of ξ_c=0.05 for EPP system. For ξ_c=0.01 and μ=2, for the T_C/T_P smaller than 0.75, the mean ratios of AFs increase with the increase of the T_C/T_P, peaking at the T_C/T_P equal to 0.75. After that, it is clear that the valley values occur in the vicinity of the T_C/T_P equal to 1.0 for ξ_c=0.01. Then, the mean ratios of AFs decrease slightly and gradually when the T_C/T_P is larger than 1.25. This is just opposite to the cases having other ξ_c values. For μ=2 case, the effect of ξ_c on AFs is within the interval [0.95 1.05] for different primary structures in the short and long period regions, indicating that the effect of ξ_c on AFs is negligible in those regions. In the fundamental period region, the effect of ξ_c on AFs varies within the interval [0.9 1.16] and this effect is moderate for the seismic design of nonstructural components. It is also noted that the effect of damping of components becomes more significant when the level of primary structural ductility increases. Take the 0.3 s building with ξ_c=0.01 for an example, the ratio of AF for μ=2 reaches 1.05 when the T_C/T_P is 0.75 while the value for μ=6 has 1.14. From Fig. 8, the effect of ξ_c on AFs is within the interval [0.81 1.34]. Therefore, the damping of components can have a significant effect on component responses.

5. Predictive model

It is necessary and desirable to propose a predictive model of the mean AFs for the near-fault pulse-like ground motions. Based on the statistical results in Section 4, the predictive model to estimate the mean AFs for the near-fault pulse-like ground motions is developed and related parameters are established

$$\mathrm{AF} = a + b\cdot(T_C/T_P) + c\cdot(T_C/T_P)^2 + d\cdot(T_C/T_P)^3 + e\cdot(T_C/T_P)^4 + f/\mu \qquad (T_C/T_P \le 1) \tag{2}$$

$$\mathrm{AF} = a + b/(T_C/T_P)^2 + c\cdot\ln(\mu) \qquad (T_C/T_P > 1) \tag{3}$$

where T_C is the vibration period of component, T_P is the primary structural period, μ is the primary structural ductility factor, a, b, c, d, e and f are independent constants. Parameters a, b, c, d, e and f are computed by a nonlinear least-square regression analysis using the Levenberg-Marquardt method (Bates and Watts 1988) for each hysteretic model. The resulting values of these parameters for T_P=0.9 s and different ξ_c values are summarized in Table 2. Fig. 9 shows the comparison of mean AFs computed using Eqs. (2) and (3) with the statistical results in this study for EPP system and all 81 ground motions.

The comparison of the results of Eqs. (2) and (3) and the actual AF dataset of near-fault pulse-like ground motions, which includes the dispersion of AF, is investigated with the similar error measures as defined in FEMA 440 (2005). These error measures consist of sample mean error E_T and the standard deviation of the error σ_T, and are defined as

$$E_T = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{\tilde{\mathrm{A}}\tilde{\mathrm{F}}}{(\mathrm{AF})_i}\right] \tag{4}$$

$$\sigma_T = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left[\frac{\tilde{A}\tilde{F}}{(\mathrm{AF})_i} - E_T\right]^2} \tag{5}$$

where $\tilde{A}\tilde{F}$ is the AF computed using Eqs. (2) and (3), $(\mathrm{AF})_i$ is the AF of *i*th near-fault pulse-like ground motion computed by the nonlinear response history analysis, n is the number of near-fault pulse-like ground motions. The E_T can provide the average bias of Eqs. (2) and (3) and the σ_T can provide the measure of the dispersion of the errors, when the Eqs. (2) and (3) are used to estimate the AF. Fig. 10 presents the error measures of Eqs. (2) and (3) for three structural systems under the near-fault pulse-like ground motions. It can be seen that the values of E_T vary within the interval [0.9 1.1], indicating that the mean error is less than 10% for seismic estimation of nonstructural components. Although the values of σ_T can reach 0.4 and 0.5 for EPP system and degrading systems respectively, the values are generally within 0.2, showing the low dispersion. Generally, the Eqs. (2) and (3) can provide the well estimate of AF for near-fault pulse-like ground motions.

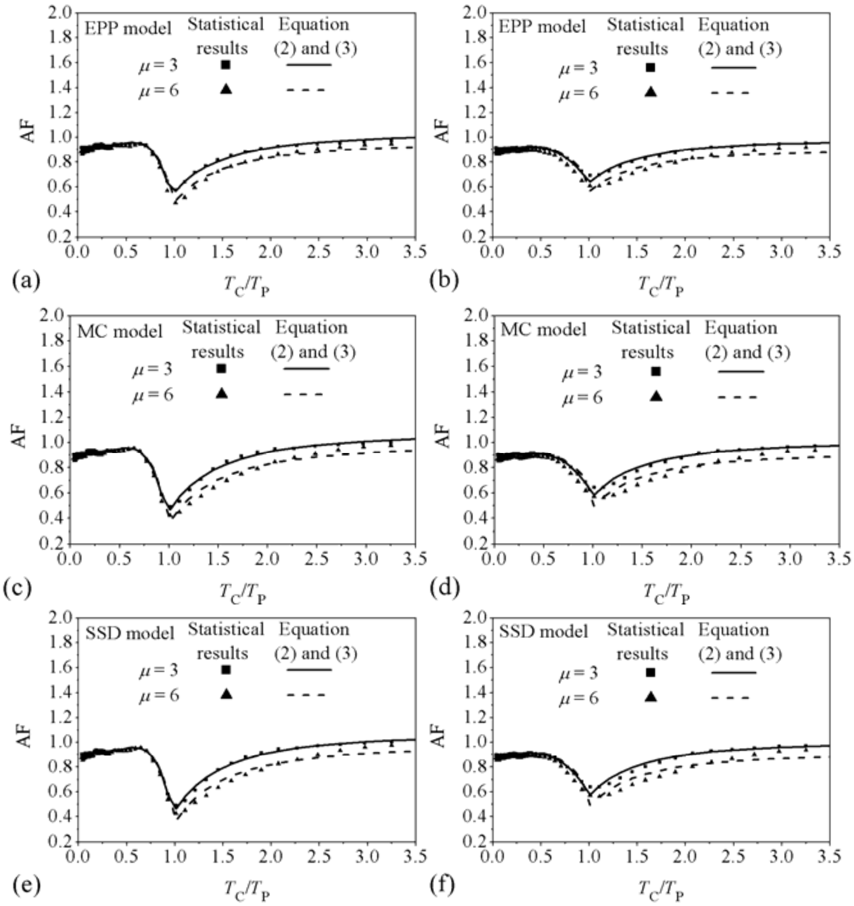

Fig. 9 Comparison of mean AFs computed using Eqs. (2) and (3) with the statistical results in this study for EPP system and all 81 ground motions: (a, c, e) ξ_c=0.05; (b, d, f) ξ_c=0.15

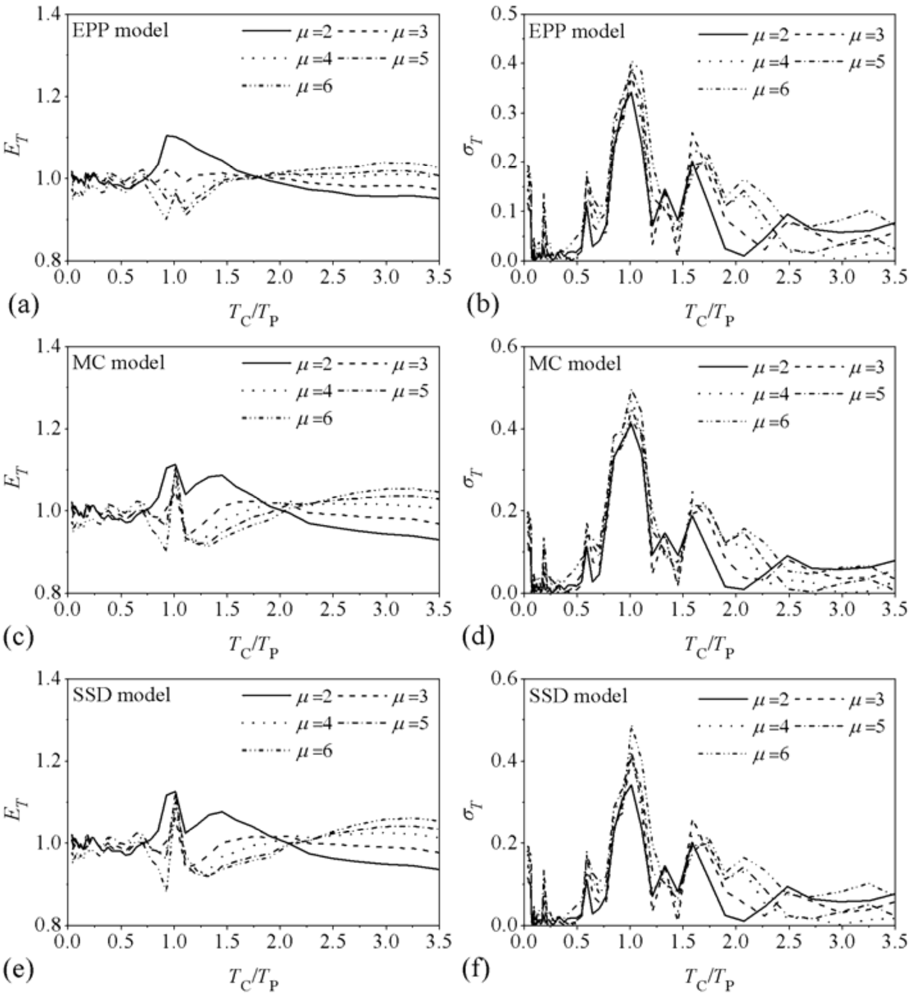

Fig. 10 The error measures of Eqs. (2) and (3) for three structural system with ξ_c=0.05 under the near-fault pulse-like ground motions: (a, c, e) mean error; (b, d, f) standard deviation of error

Table 2 Parameters to be used in Eqs. (2) and (3) for T_P=0.9 s

Hysteretic model	Parameter	Damping of nonstructural component ξ_c									
		ξ_c=0.01		ξ_c=0.05		ξ_c=0.1		ξ_c=0.15		ξ_c=0.2	
		T_C/T_P		T_C/T_P		T_C/T_P		T_C/T_P		T_C/T_P	
		<1.0	>1.0	<1.0	>1.0	<1.0	>1.0	<1.0	>1.0	<1.0	>1.0
EPP	a	0.84	1.18	0.84	1.16	0.84	1.13	0.84	1.10	0.84	1.09
	b	1.18	-0.50	0.54	-0.48	0.14	-0.41	0.00	-0.35	-0.15	-0.30
	c	-5.88	-0.11	-2.54	-0.11	-0.40	-0.11	0.34	-0.11	0.98	-0.11
	d	11.81		5.36		1.06		-0.57		-1.73	
	e	-7.72		-3.86		-1.15		-0.05		0.68	
	f	0.09		0.14		0.17		0.19		0.20	

Table 2 Continued

Hysteretic model	Parameter	Damping of nonstructural component ξ_c									
		ξ_c=0.01		ξ_c=0.05		ξ_c=0.1		ξ_c=0.15		ξ_c=0.2	
		T_C/T_P		T_C/T_P		T_C/T_P		T_C/T_P		T_C/T_P	
		<1.0	>1.0	<1.0	>1.0	<1.0	>1.0	<1.0	>1.0	<1.0	>1.0
MC	a	0.82	1.29	0.83	1.23	0.84	1.18	0.83	1.15	0.83	1.13
	b	1.48	-0.76	0.59	-0.62	0.15	-0.52	0.00	-0.44	-0.14	-0.38
	c	-7.67	-0.13	-2.85	-0.13	-0.44	-0.13	0.33	-0.13	1.01	-0.12
	d	15.66		6.15		1.24		-0.52		-1.83	
	e	-10.26		-4.46		-1.36		-0.14		0.71	
	f	0.07		0.13		0.16		0.18		0.20	
SSD	a	0.82	1.29	0.84	1.23	0.84	1.18	0.84	1.15	0.83	1.13
	b	1.49	-0.76	0.60	-0.63	0.16	-0.52	0.02	-0.44	-0.13	-0.38
	c	-7.74	-0.14	-2.90	-0.14	-0.46	-0.13	0.29	-0.13	0.98	-0.13
	d	15.81		6.24		1.26		-0.48		-1.83	
	e	-10.36		-4.52		-1.37		-0.15		0.72	
	f	0.06		0.12		0.15		0.17		0.19	

6. Conclusions

This paper investigates the amplification factors for design of acceleration-sensitive nonstructural components based on primary structural ductility factor for the near-fault pulse-like ground motions. Amplification factors are computed with 81 near-fault pulse-like ground motions, and the corresponding statistical studies are presented. The following conclusions are drawn from this investigation:

• The primary structural nonlinearity can result in reductions of the FRS in most period regions, indicating that the primary structural nonlinearity has an advantageous effect on component acceleration responses. The mean AF values decrease with the increase of structural ductility factor, particularly in the fundamental period region.

• In comparison with the ordinary ground motions, the near-fault pulse-like ground motions can significantly increase the AFs with the primary structural period, and magnitude of increase can reach about 17%.

• Coefficients of variation (COVs) change significantly with the variation of the T_C/T_P values in the whole period region. The peak COVs of AFs occur in the vicinity of the T_C/T_P equal to 1.0 and the COVs on both sides of the peak values decrease gradually with the distance from the T_C/T_P equal to 1.0, indicating that the COVs are approximately period dependent. COVs are relatively sensitive to the structural ductility factor and increase with the increase of μ.

• Larger PGVs or MIVs not necessarily induce greater AFs than the ground motions for which PGVs or MIVs are relatively smaller. The differences between the ratios of mean AFs for different PGV and MIV ranges tend to increase when the primary structure suffers more severe damage from ground motions. The ratios of mean AFs for different PGV ranges vary within the interval [0.9 1.09] and the values for different MIV ranges are within the interval [0.92 1.08].

• The near-fault pulse-like ground motions induce larger mean ratios of the AFs of degrading systems to the AFs of EPP system than the ordinary ground motions, meaning that the near-fault pulse-like ground motions are more dangerous to components mounted on structures with degrading behavior than ordinary ground motions.

• In comparison with ξ_c=0.05, the AF values can be amplified for ξ_c=0.01 when the T_C/T_P is close to 0.75 and become greater for ξ_c=0.1, 0.15 and 0.2 when the T_C/T_P is in the vicinity of 1. The effect of the damping of components on the AFs becomes more significant in the presence of higher primary structural nonlinearity and the mean ratios of AFs are within the interval [0.81, 1.34].

• In order to facilitate the application of amplification factors, a new simplified formulation is proposed and related parameters corresponding to the predictive model for the near-fault pulse-like ground motions are established in this study. The parameters in the equation are dependent on the period ratio (T_C/T_P), primary structural ductility factor μ, primary structural period T_P and damping of components ξ_c.

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