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The influence of vertical ground motion on the seismic behavior of RC frame with construction joints

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Abstract. The aim of this study is to investigate the effect of vertical ground motion (VGM) on seismic behavior of reinforced concrete (RC) regular frame with construction joints, and determine more proper modeling method for cast-in-situ RC frame. The four-story RC frames in the regions of 7, 8 and 9 earthquake intensity were analyzed with nonlinear dynamic time-history method. Two different methods of ground motion input, horizontal ground motion (HGM) input only, VGM and HGM input simultaneously were performed. Seismic responses in terms of the maximum vertex displacement, the maximum inter-story drift distribution and the plastic hinge distribution were analyzed. The results show that VGM might increase or decrease the horizontal maximum vertex displacement depending on the value of axial load ratio of column. And it will increase the maximum inter-story drift and change its distribution. Finally, proper modeling method is proposed according to the distribution of plastic hinges, which is in well agreement with the actual earthquake damage.

Keywords: seismic behavior; vertical ground motion (VGM); RC frame; construction joint; nonlinear time-history analysis; numerical model

1. Introduction

Based on the strength design for structural members, the objective of seismic design for RC structures is to ensure the overall bearing capacity margin and deformation capacity of the structures, and increase their redundancy and integrity. It should be able to provide effective measures to obtain a reasonable yielding mode, create multiple seismic resistant systems and improve its collapse-resisting performance.

For RC frame structures, it is widely agreed that the "strong column-weak beam" (SCWB) failure mode is an ideal failure mode, as seen in Fig. 1(a). However, the preferred SCWB mode has not been observed in most RC frame structures in the Wenchuan earthquake (Zhao *et al*. 2009). While the "weak column-strong beam" (WCSB) failure mode was developed in almost all collapsed frame structures, as seen in Figs. 1(b)-(c). And the typical earthquake damage photos are shown in Fig. 2. Interestingly, RC structures, which are designed according to the code provisions (GB50011-2010, "Chinese Code" for short), also suffered WCSB damage although theoretically

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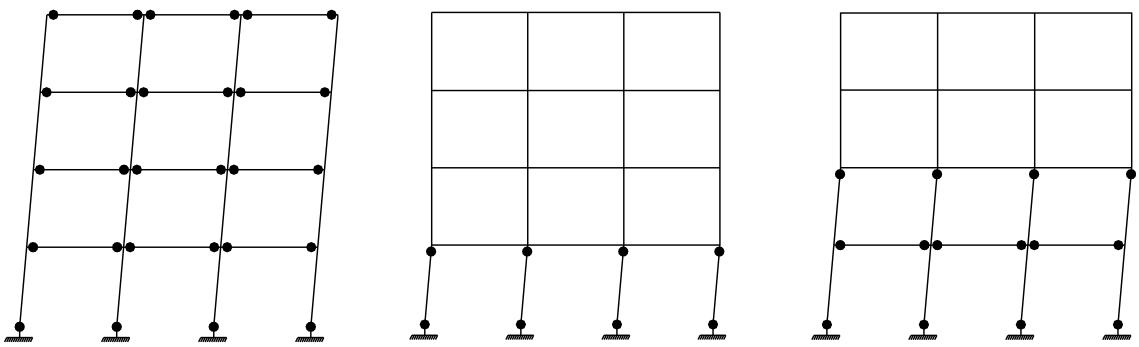
possessing beam hinge failure mode. It is necessary to find causes of the contrast. One of the most possible reasons is that the theoretical model does not match with the actual building.

As is known to all, continuous casting of concrete is not available during construction of a cast-in-situ RC structure. When the casting time interval exceeds the initial setting time of the concrete, construction joints are formed. Construction joints typically occur in the column ends of the frame structure where large forces and key connected structural members exist. Most of the observed structural failure has generally been initiated by damage or failure in the beam-column joints as known from literatures (Lu *et al*. 2012, Zhou and Zhang 2014). And numerous research has been carried out to study the complex mechanism and the behavior of joints under seismic loadings (Hwang and Lee 2000, Kim *et al*. 2007, Sharma *et al*. 2011, Unal and Burak 2012). They all agree with the opinion that joints are often the greatest risk parts in a structural system. Some believe that the working stresses mainly concentrated within the joints due to the larger dimensions than the members joined, while others believe that the weakest part lies in the link. But almost all the research objects are the monolithic structure.

The most typical mechanical property of concrete with construction joint is that its tensile strength and shear strength are much lower than the ones of integral casting concrete (Clark and Gill 1985, Jensen 1975, Monks 1974, Waters 1954). Test results show that construction joint can reduce the cracking load of structural member. Obvious stress concentration is observed in the joint surface. The shear dislocation along the joint will increase the shear deformation and the longitudinal bar slip at the bottom of the column, resulting in concentrated failure area and reduced length of plastic hinge (Isao *et al*. 1998, Mattock and Alan 1981). The reality is that almost all of the modeling analysis of the RC frame is based on the continuous casting structure, and the influence of construction joint is neglected.

Research (Di Sarno *et al*. 2011, Kikuchi *et al*. 2000, Kim and Elnashai 2008) shows that the VGM has a great influence on the axial load of the columns, while the axial load ratio (marked as R_c) is the main factor affecting the seismic behavior, and it may decrease the shear capacity of the structure. Assumed the axial load of column as F_c, the axial load ratio R_c is defined as $R_c=F_c/A\cdot f_c$, where A is the section area of the column; f_c is the design value of concrete prismatic compressive strength, for C30, f_c=14.3 N/mm^2. VGM may magnify vertical dynamic responses of structures, or cause serious damage (Bas and Kalkan 2016, Farsangi *et al*. 2015, Wang *et al*. 2015). If large VGM occurs in a strong earthquake, it is reasonable to assume that the construction joint first



(a) ideal beam hinge failure mode (b) inter-layer column hinge failure mode (c) mixed hinge failure mode

Fig. 1 Failure modes of RC frame

Fig. 2 Photos of the seismic damage of RC frame in Wenchuan Earthquake Region

cracks due to poor tensile strength, then it relies on the weak shear strength to resist horizontal earthquake action. There is a great possibility to form plastic hinges here, which will affect the failure mode of the structure. These assumptions will be demonstrated in this paper.

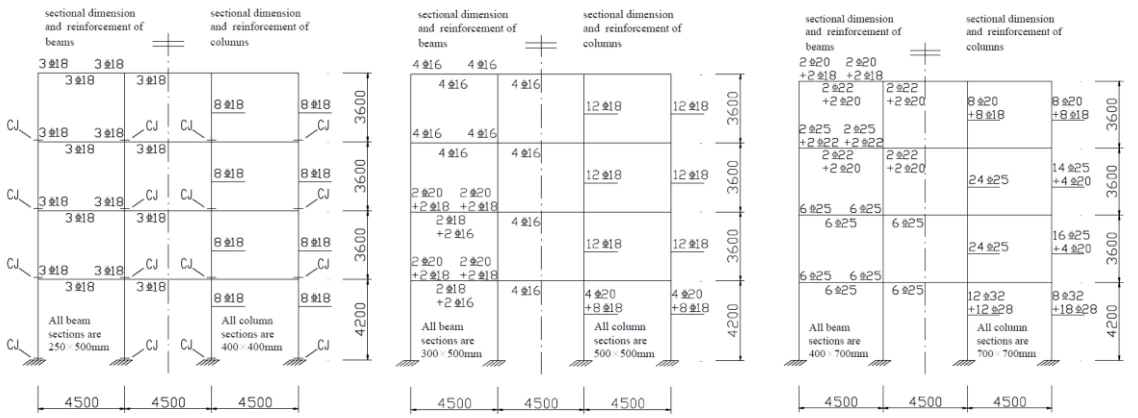
In this study, two numerical models, "monolithic frame" (formed by continuous casting of concrete) and "jointed frame" (formed by interval casting of concrete), are established based on regular RC frame structures in the regions of 7, 8 and 9 earthquake intensity ("Intensity Region" for short) for nonlinear time-history analysis (NTHA). Two different methods of ground motion input, HGM input only, VGM and HGM input simultaneously were performed in NTHA. The influence of VGM on the seismic behavior of RC frame is studied through comparison. Finally, proper modeling method is suggested according to the distribution of plastic hinges, which are in well agreement with the actual earthquake damage.

2. Analytical models

Four-story RC frames in Intensity Regions 7, 8 and 9 were designed according to the Chinese Code. The reason for selecting four-story frame is that it is the most common type in the earthquake damage, and the seismic design details are moderate level in accordance with the Chinese Code. Information about the sectional dimension of the component and the reinforcement is shown in Fig. 3. The used materials include HRB400 longitudinal bars (marked as Φ, characteristic value of reinforcement yielding strength f_{yk}=400 N/mm^2) and HRB335 stirrups (f_{yk}=335 N/mm^2) for beams and columns. The strength of concrete is C30 (characteristic value of concrete prismatic compressive strength f_{ck}=20.1 N/mm^2, characteristic value of concrete tensile strength f_{tk}=2.01 N/mm^2), and the thickness of floor slab is 120 mm.

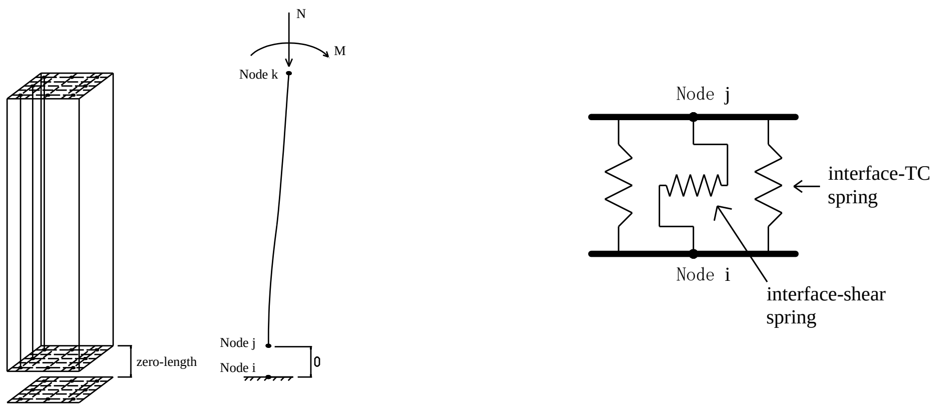
Two types of numerical models are adopted for the same frame structure. One is the "jointed frame" (marked as "-j" in Table 3), with construction joint model attached to the column bottom of all stories (i.e., the elevation of beam top surface), as shown in Fig. 3(a), the construction joints are marked as "CJ". The other is the "monolithic frame" (marked as "-m" in Table 3), which is a conventional method for modeling frame structures, as shown in Fig. 3(b) or (c). The calculation was completed on the OpenSEES (open system for earthquake engineering simulation) platform (Mazzoni *et al*. 2009). Beams and columns are simulated using non-linear beam-column elements, while floor slabs are simulated through assumption of rigidity.

As for construction joint model, both normal tensile or compressive behavior and tangential shear behavior are taken into account. Since the construction joint is of zero length in the axial direction, shown as zero between node *i* and node *j* in Fig. 4(a). The normal mechanical properties



(a) frame in the Intensity Region 7, marked as FR7 (b) frame in the Intensity Region 8 (FR8) (c) frame in the Intensity Region 9 (FR9)

Fig. 3 Sectional dimensions of the component and the reinforcement of frames



(a) combination of construction joint model and column (b) construction joint model

Fig. 4 The construction joint model

are modeled by “interface-TC spring” and the tangential mechanical properties are modeled by “interface-shear spring”, as shown in Fig. 4(b). The derivation and verification of such models are shown in the literature (Li *et al*. 2011).

3. Ground motion input

3.1 Ground motions selected

Selecting input ground motions are essential to NTHA. The Chinese Code requires the ground motions selected statistical significance match case with the design spectrum. In this calculation, seven ground motions were selected for each frame, including five real ground motion records (3

Table 1 Ground motions selected

No.	Earthquake	Occurrence time	Recording station	Direction	Magnitude
USA05	NORTHWEST CALIFORNIA	1951.10.7	City Hall, Ferndale, CA	N46W	6.0
USA74	HELENA MONTANA	1935.10.31	Montana Carroll College	S90W	6.0
USA98	NORTHRIDGE	1994.1.17	Catskill Ave, Carson, CA	S90E	6.7
USA97	NORTHRIDGE	1994.1.17	Water st, Carson, CA	S00W	6.7
AF1~6	Several artificial ground motions fitting class Ⅱ site in Intensity Regions 7, 8 and 9				
PRC03	TANGSHAN,CHINA	1976.7.27	Beijing hotel, China	V	7.8
USA96	SAN FERNANDO	1971.2.9	Wilshire blvd, Losangeles, CA	V	6.6
USA89	SAN FERNANDO	1971.2.9	South hill st, Losangeles, CA	V	6.6
USA26	NORTHRIDGE	1994.1.17	Saturn st, Losangeles, CA	V	6.7
Result	FR7, horizontal: USA05, USA74, USA98, AF1, AF2; vertical: PRC03, USA96 FR8, horizontal: USA05, USA74, USA98, AF3, AF4; vertical: PRC03, USA96 FR9, horizontal: USA97, USA74, USA98, AF5, AF6; vertical: USA89, USA26				

horizontal, 2 vertical) and two artificial ground motions. The ground motions were selected according to the input ground motion scheme for two frequency domains of response spectra in accordance with the design spectra in a statistical sense (Yang *et al*. 2000). The two frequency domains correspond to the flat range of design spectra and the nature period of structure. The ground motions selected are listed in Table 1.

3.2 Combination rules of the VGM and HGM

Since the VGMs and HGMs are selected separately, they may not necessarily come from the same earthquake and the same recording station, so the combination rules should be addressed (Elnashai and Di Sarno 2008).

Take frame FR7 as an example, five HGMs and two VGMs are combined respectively and evaluated. The maximum inelastic seismic responses of frame FR7 were estimated as realistically as possible by simultaneously applying vertical and horizontal components. Then, the accuracy of the above-mentioned combination rule and others, in the estimation of the seismic response, was evaluated. The seismic response is expressed in terms of vertex displacement (i.e., the displacement of the top floor of the structure), vertex acceleration (i.e., the acceleration of the top floor of the structure), and the response of the bottom section (i.e., force-displacement hysteretic curves) of column at the ground floor. They are not shown because of lack of space. The results show that different combination rules will greatly affect the values, but do not affect the regularity.

In the following calculations, two artificial ground motions shall be adopted in the horizontal direction (considered to have statistical sense), while two real ground motions be adopted in the vertical direction. Then combined them respectively and the average values of seismic responses are analyzed.

3.3 The maximum value of the VGM

Another important question is the maximum value of the VGM. There is still no agreement on it. As stipulated in the Chinese Code, the vertical effect coefficient can be 65% of the horizontal

Table 2 Horizontal and vertical MVD under different seismic inputs (unit: m)

ground motion records combination	Input 1		Input 2		Input 3	
	D_h^*	D_v^*	D_h	D_v	D_h	D_v
AF1+PRC03	0.162	-0.041	0.165	-0.057	0.180	-0.132
AF1+USA96	0.247	-0.039	0.257	-0.059	0.122	-0.149
AF2+PRC03	0.182	-0.042	0.188	-0.057	0.160	-0.087
AF2+USA96	0.216	-0.038	0.262	-0.058	0.119	-0.149
Mean value	0.202	-0.040	0.218	-0.058	0.145	-0.129

*D_h -horizontal maximum vertex displacement; *D_v -vertical maximum vertex displacement

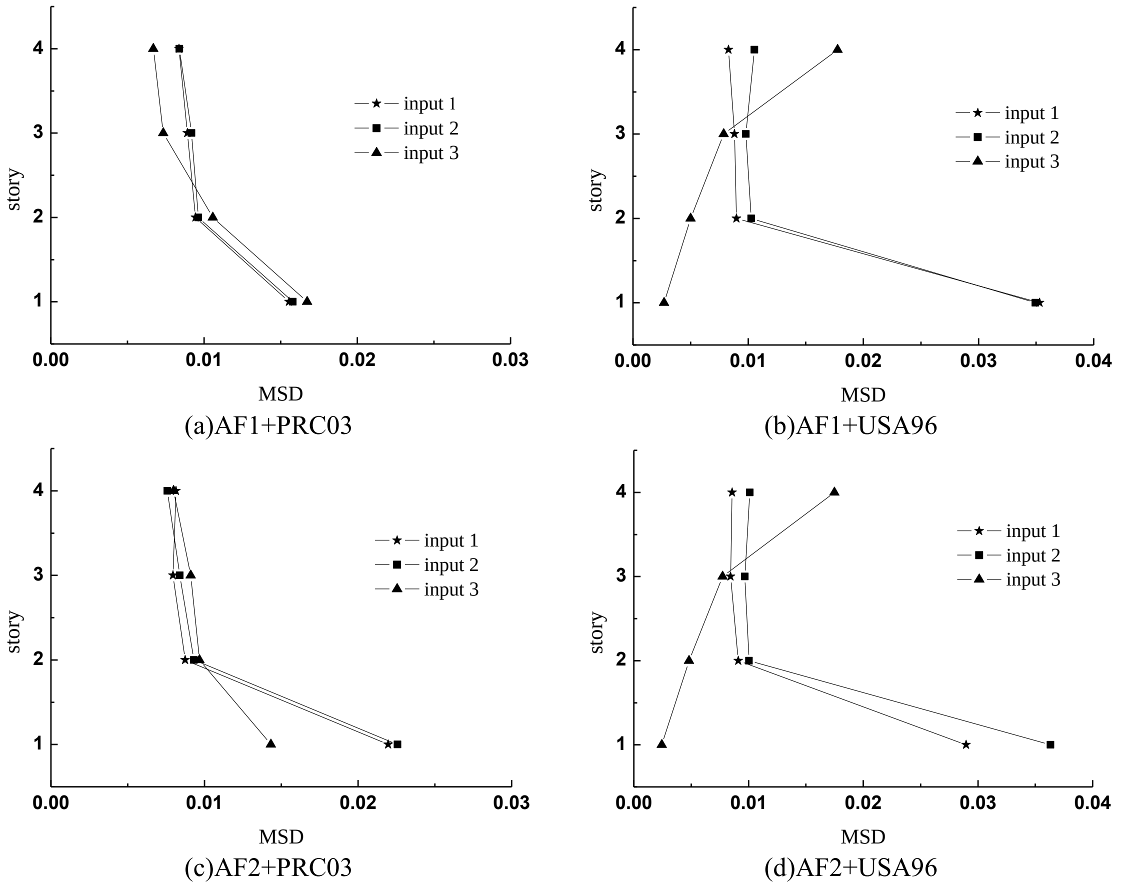


Fig. 5 The maximum inter-story drifts distributions under different inputs

one. Consequently, in most NTHA, the maximum value of VGM was determined 65% of the HGM. However, this rule is controversial. The actually detected maximum value of the VGM may surpass the horizontal one, or even more than 1.0 g.

Take frame FR7 as an example, the maximum value of the VGM be valued in three ways, i.e., 65% of the maximum value of the HGM (denoted as "Input 1"); the same as the maximum value of the HGM (denoted as “Input 2”); and 1.0 g (denoted as “Input 3”). The maximum inelastic seismic response of frame FR7 are estimated as realistically as possible by applying these three inputs. Then, the difference of the above-mentioned inputs is evaluated. The seismic response is expressed in terms of maximum vertex displacements (MVD), maximum inter-story drift distribution (MSDD).

The MVDs of the structures under different seismic inputs are listed in Table 2. It can be seen that there is no obvious difference between Input 1 and Input 2. The vertical MVD is much smaller than the horizontal one, which is about 1/5 of the horizontal one. It deserves to be specially noted that the calculation is always not converged under Input 3 due to large deformation, so corresponding values of Input 3 in Table 2 are the maximum values selected from limited calculation data instead of the entire time history. For example, the calculation stopped on 2.72 s due to convergence failure, under Input 3 of the combination of AF1 and USA96 ground motions. So the value of horizontal MVD, 0.122 mm, is the maximum value in 2.72 seconds. However, a valuable conclusion is that the vertical MVDs are largest under Input 3, and may exceed the horizontal MVD. Thus, the RC frame structure is very vulnerable to tensile or compression failure.

The MSDDs of the structures under different seismic inputs are shown in Fig. 5. It can be seen that the MSDDs of Input 1 and Input 2 follow the same rules, and the values show little difference. Nevertheless, the MSDDs of the Input 3 is quite irregular due to that calculation stopped at a certain moment as mentioned above.

From the analysis above, the maximum value of the VGM has relatively great impact on the results. But the effect shows the same regularity when it is less than the maximum value of the HGM. To keep consistent with the Chinese Code, the maximum value of the VGM is set to be 65% of that of the HGM in the following calculation.

4. Numerical results and analysis

NTHA has been performed by building numerical models of RC frames in Intensity Regions 7, 8 and 9 and applying the above defined ground motion inputs. The impact of VGM on seismic behavior of RC frames with construction joints are described through comparing the parameters as MVD, MSDD and plastic hinge distribution. To consider the impact of random factors, the average values of multiple ground motion inputs are taken as the final results for every parameter.

4.1 The maximum vertex displacements (MVD)

MVD could reflect the comprehensive response of structure in the earthquake. For comparison, two different ground motion inputs were performed, one is HGM only (*one-way* in short, marked as “-1” in Table 3), the other is VGM and HGM simultaneous (*two-way* in short, marked as “-2” in Table 3). The calculation results are shown in Table 3. It can be seen that the MVD of jointed frames always larger than that of monolithic frames. And the vertical MVDs of frames are zero when there is only *one-way* input.

As can be seen from the data, the influence of VGM on the horizontal MVD is different in Intensity Regions 7, 8 and 9. The horizontal MVD is increased by about 30%, decreased by about 2%, increased by up to 110%, respectively. To explain this phenomenon, the values of R_c of bottom columns were traced in the history analysis process, and the time-history curves of them are shown in Fig. 6. Axial load imposed on the column at a specific moment is assumed to be

Table 3 Horizontal and vertical MVD under different inputs (unit: m)

	FR7-m-1*	FR7-m-2	FR7-j-1	FR7-j-2*	FR8-m-1	FR8-m-2	FR8-j-1	FR8-j-2	FR9-m-1	FR9-m-2	FR9-j-1	FR9-j-2
D_h	0.105	0.151	0.152	0.202	0.099	0.073	0.103	0.101	0.060	0.068	0.063	0.134
D_v	0	0.013	0	-0.040	0	0.019	0	-0.061	0	0.040	0	-0.090

*"FR7-m-1"refers to "monolithic frame in the Intensity Region 7 in *one-way* input"; "FR7-j-2"refers to "jointed frame in the Intensity Region 7 in *two-way* input"; The following marks are the same; The vertical MVD, i.e., D_v , is positive in the upward direction and negative in the downward direction

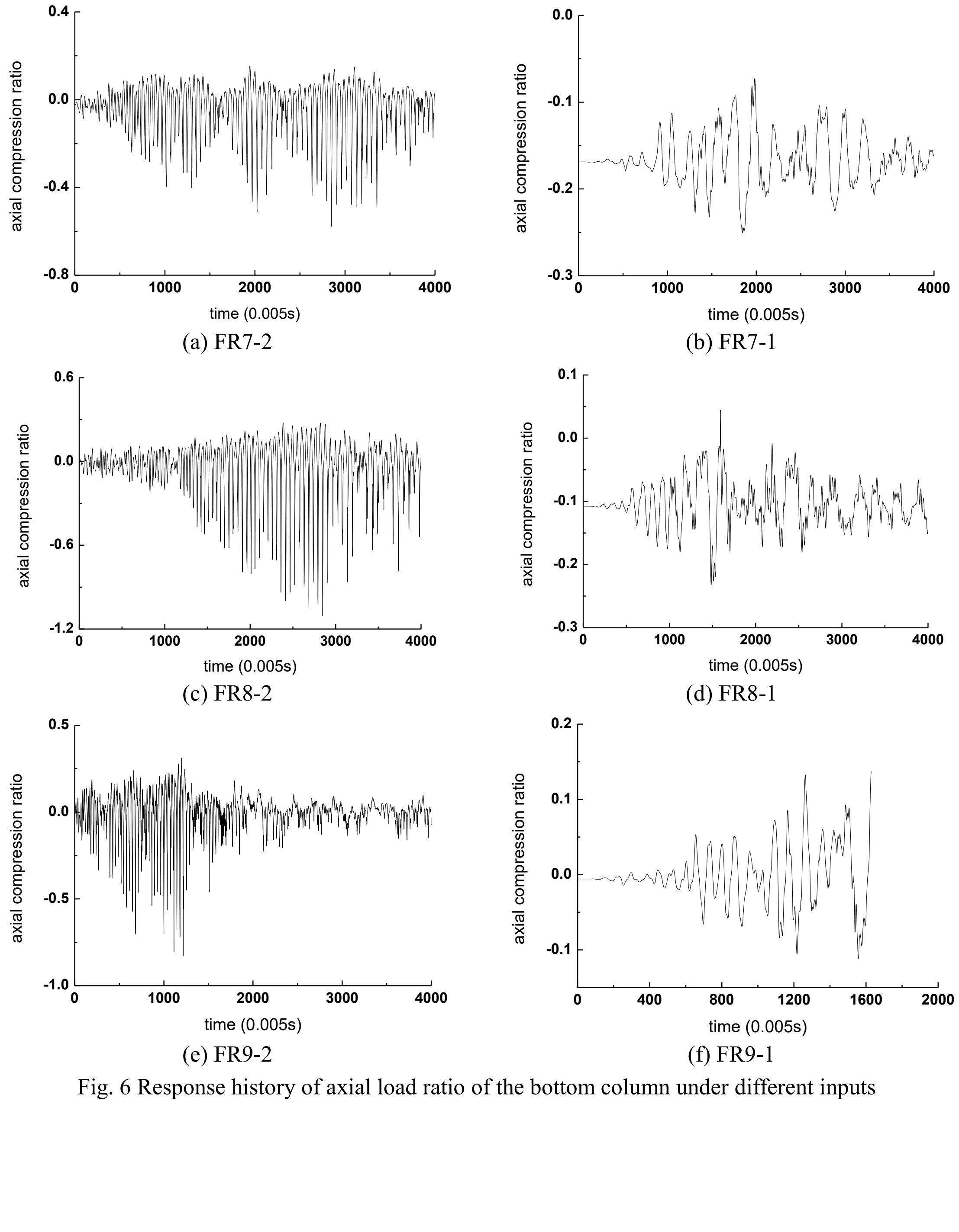


Fig. 6 Response history of axial load ratio of the bottom column under different inputs

positive (tensile force) or negative (compressive force).

It can be seen that the frequencies are obviously different between curves of *one*-*way* input and *two*-*way* input. The magnitude of the latter is larger. In the Intensity Region 7, the maximum R_c are -0.58 and 0.15 respectively in *two*-*way* input, while the value is always negative and the maximum is -0.25 in *one*-*way* input. This indicates that the effects of the VGM can be found in two aspects: produce tensile stress, increase compressive stress. These are harmful to the structural seismic resistant.

In the Intensity Region 8, the maximum R_c are -1.10 and 0.28 respectively in *two*-*way* input, while the values are -0.23 and 0.04 respectively in *one*-*way* input. When the R_c exceeding -1.0, theoretically, the column was subjected to compressive failure. While the R_c exceeds 0.2, the stiffness and strength of the column declined rapidly, and the tensile failure is easy to occur. The structural ductility decreases due to large R_c caused by VGM. Therefore, the horizontal MVD are smaller than that in *one*-*way* input.

In the Intensity Region 9, the maximum R_c are -0.83 and 0.31 respectively in *two*-*way* input, while the values are -0.11 and 0.14 respectively in *one*-*way* input. It can be seen that the VGM increases the value of R_c significantly, and it may exceed the limit value (i.e., -0.7) specified in the Chinese Code. This leads to a significant increase in the MVD, no matter in horizontal and vertical direction.

It can be concluded from above analysis that the influence of VGM on the MVD of frames in Intensity Regions 7, 8 and 9 is not uniform. It mainly depends on the R_c of bottom column. The other responses also follow this rule, as described below.

4.2 The maximum inter-story drift distribution (MSDD)

MSDD could reflect the weak parts of the structure. Three specific moments were selected in the calculation. One is the moment of MVD reaching the maximum, recorded as "t1"; the second is the largest inter-story drift reaching the maximum, recorded as "t2"; the third is the inter-story drift of each story reaching the maximum, recorded as "t3". And the MSDDs of frames in Intensity Regions 7, 8 and 9 excited by different ground motion inputs are shown in Fig. 7.

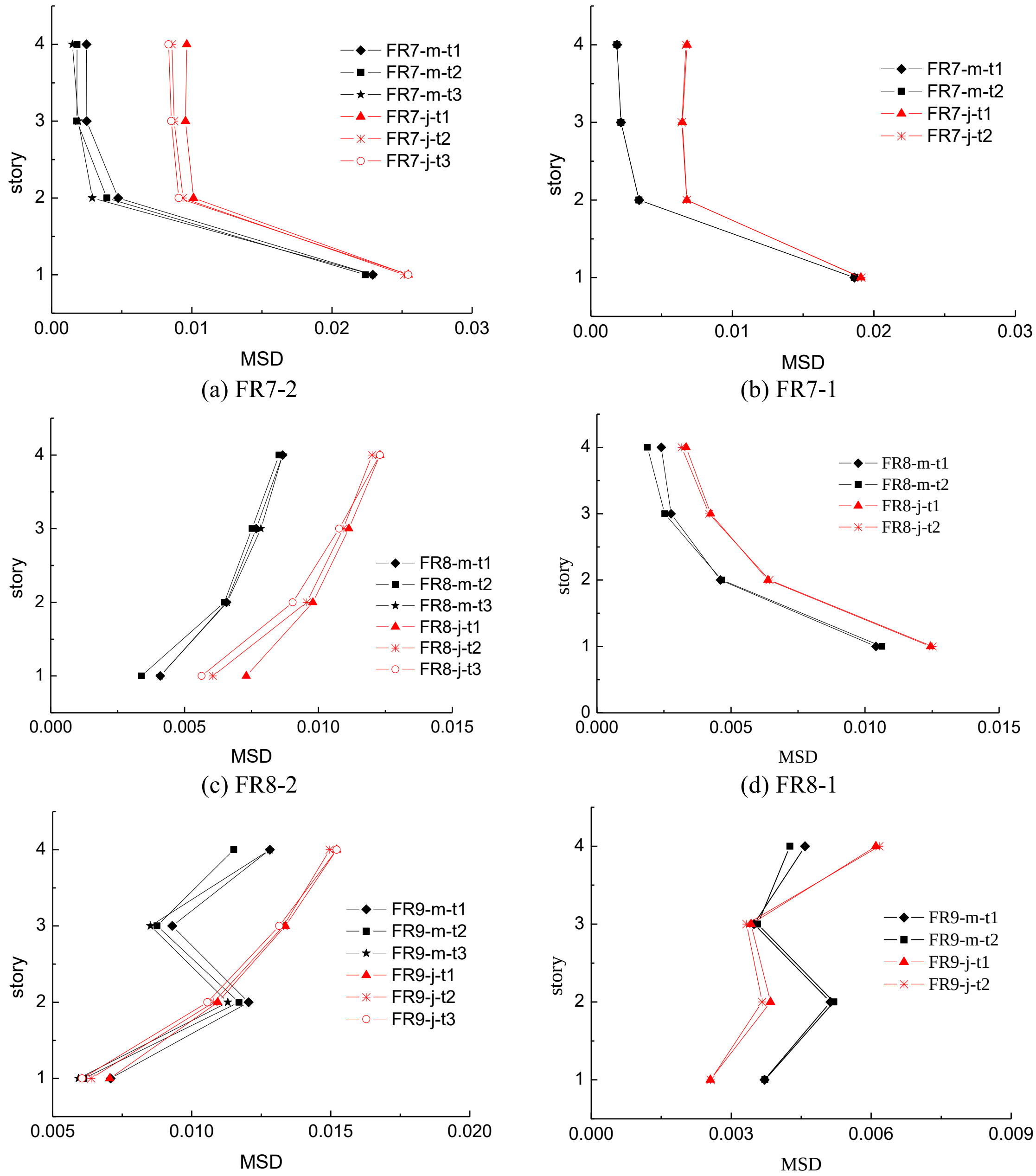
It can be seen that in the Intensity Region 7, the maximum inter-story drift (MSD) of monolithic frame and jointed frame are 1/44 and 1/39 respectively, in *two*-*way* input. Both exceed the limit value (i.e., 1/50) specified in the Chinese Code. And the MSDs of two types of frames are 1/54 and 1/52 respectively, in *one*-*way* input. The VGM increases the MSDs of frame, but the MSDDs are uniform.

In the Intensity Region 8, the MSDDs of frames are different between *one*-*way* input and *two*-*way* input. And the MSDs of jointed frame are larger than that of monolithic frame in the same input. For example, the MSD of jointed frame is 1/82, while the MSD of monolithic frame is 1/111, in *two*-*way* input, both are within the limit value.

In the Intensity Region 9, the MSDDs of jointed frames are different between *one*-*way* input and *two*-*way* input, while the monolithic frames show uniform. The influence of VGM on jointed frame is more obvious. Similarly, the MSDs of jointed frame are larger than that of monolithic frame in the same input. It should be noted that the impact of construction joint is very significant, which not only increases the MSD of frame, but also changes the MSDD.

The influence of VGM on the MSDD of frames in Intensity Regions 7, 8 and 9 is not uniform. It could increase the MSD, or change the MSDD, or both. In addition, the effect of construction joints can be seen from the calculation results. It will generally increase the MSD, or change the

MSDD. If a structure is designed according to the traditional analysis method without considering the influence of VGM and ignoring the effect of the construction joints, it would bring great risk when subjected to strong earthquake. That is one of the reasons that some structures designed according to the Chinese Code were damaged in the Wenchuan earthquake.



(a) FR7-2 (b) FR7-1

(c) FR8-2 (d) FR8-1

(e) FR9-2 (f) FR9-1

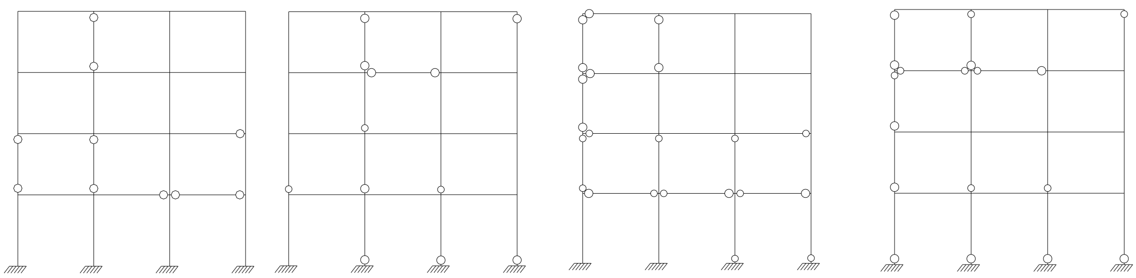
Fig. 7 The MSDDs of frames excited by different ground motion inputs

4.3 Plastic hinge distribution

Plastic hinge distribution reflects the failure mode of structure. From the sequence in which the members enter the yielding stage, it can be found whether the seismic resistant system in design are at work or not. In the NTHA, by tracing the response history of the key fibers on the control section, the stress-strain time-history curves could be output. Then we can identifying whether the plastic hinge is formed here by judging the yield of the outermost steel bar fiber. By numbering the order in which all members of frame yielding, the yielding sequence is obtained, and the distribution of plastic hinges are provided.

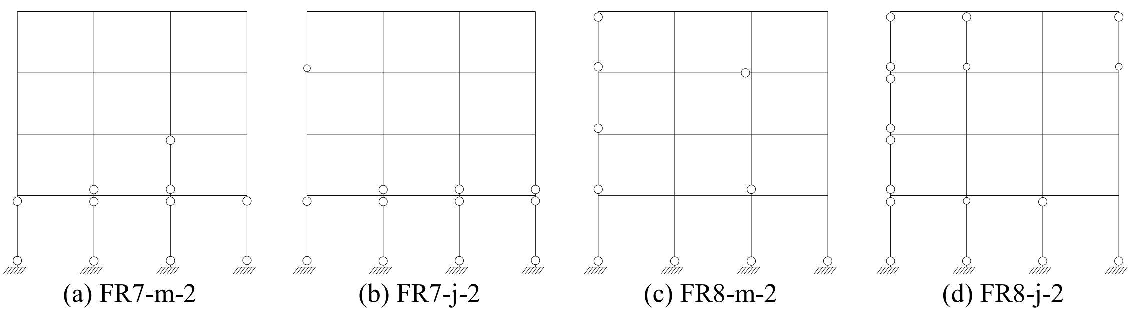
The results in the following figures are taken from a set of ground motions which cause the largest combination effect, i.e., the plastic hinges formed sufficiently. Plastic hinge distribution of frame in the Intensity Region 9 under different ground motion inputs are shown in Fig. 8 (the hollow circle represents the plastic hinge, and the NO. of ground motions are shown in the brackets). It can be seen that the *two-way* input causes the structure to form more plastic hinges. Structures in other intensity regions also showed this rule. In addition, the hinge failure mode of jointed frame is different from that of monolithic frame. Due to the existence of construction joints, plastic hinges are more likely to appear in the column ends, and less likely to appear in the beam ends. This is in well agreement with the real earthquake damage.

Frames in Intensity Regions 7 and 8 almost show the same rule, as seen in Fig. 9. Plastic hinges are observed at the column ends of both types of frames. The difference is that the existence of construction joints leads to earlier appearance of plastic hinges in column ends, and make it easier to appearance in the column ends instead of the beam ends. Take frame FR7-j-2 as example,



(a) FR9-m-1 (AF6) (b) FR9-j-1 (AF6) (c) FR9-m-2 (AF6+USA26) (d) FR9-j-2 (AF6+USA26)

Fig. 8 Plastic hinge distribution of frames in the Intensity Region 9 under different ground motion inputs



(a) FR7-m-2 (AF1+PRC03) (b) FR7-j-2 (AF1+PRC03) (c) FR8-m-2 (AF3+USA96) (d) FR8-j-2 (AF3+USA96)

Fig. 9 Plastic hinge distribution of frames in Intensity Regions 7 and 8 under *two-way* input when NTHA was carried out to 2.62 s, the first plastic hinge appears at the lower end of the bottom column. In contrast, for frame FR7-m-2, the first plastic hinge appears at the lower end of bottom column at 4.12 s. Once the inter-layer column hinge failure formed, there is no new plastic hinges appeared, as seen in Fig. 9(a)-(b).

For frames in the Intensity Region 8, it could be seen from Fig. 9(c)-(d) that construction joints bring more plastic hinges in column ends, none in the beam ends, and plastic hinges are formed at both ends of the column, which are in well agreement with the actual earthquake damages. The results above show that the numerical model of "jointed frame" is more reliable and practical.

5. Conclusions

In this paper, NTHA of regular RC frames in different intensity regions were carried out, two types of numerical model, i.e., with or without construction joints, excited by two types of ground motion inputs, i.e., with or without vertical ground motion, were analyzed and compared. Conclusions are as follows:

- The vertical ground motion could produce vertical MVD, and the values of vertical MVD are in ascending order in Intensity Regions 7, 8 and 9. While the influence of vertical ground motion on the horizontal MVD are not uniform in different intensity regions. It will increase the horizontal MVD by about 30% in the Intensity Region 7, while decrease the value by about 2% in the Intensity Region 8, and increase the value by about 110% in the Intensity Region 9. These mainly depends on the axial load ratio of the bottom column. The vertical ground motion could produce tensile stress and increase compressive stress in the column.
- The construction joints could increase the MVDs of frames in three intensity regions, no matter it is in *one-way* or *two-way* input. It increases the horizontal MVD by about 34%, 38% and 97%, for frames excited by *two-way* input in the Intensity Region 7, 8 and 9, respectively. The situation is somewhat different when the frame is subjected to *one-way* input. Only the values of frame in the Intensity Region 7 increase significantly, by about 45%, while the values of frames in the other two regions show relatively little change. In addition, the construction joints could increase the vertical MVD significantly in *two-way* input.
- The vertical ground motion could increase the MSDs of frame, i.e., in the Intensity Region 7, or change the MSDD of frame, i.e., in the Intensity Region 8, or both, i.e., in the Intensity Region 9. It is worth noting that the vertical ground motion could make MSDs of frames in the Intensity Region 7 exceed the limit value in the Chinese Code. The values of jointed frame and monolithic frame are 1/39 and 1/44 respectively. While the values of both frames are 1/52 and 1/54 in *one-way* input.
- The construction joints could increase the MSDs of frames in three intensity regions by about 13%, 35% and 25% respectively. More importantly, the construction joints could change the MSDD of frame in the Intensity Region 9. This means that it may alter the failure sequence of structure.
- The vertical ground motion causes the structure to form more plastic hinges, which could more fully estimate the structural damage in the earthquake. Due to the existence of construction joints, plastic hinges are more likely to appear in the column ends, and less likely to appear in the beam ends. The hinge failure modes are in well agreement with the actual earthquake damages.
- It is very important to fully estimate the possible damages of structure in the earthquake. The vertical ground motion has much effect on seismic behavior of RC frame so that it can't be

ignored. By comprehensive comparison, the numerical model of "jointed frame" is more reliable and practical.

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