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An Equivalent Design Method to Improve Seismic performance of Step-terrace RC Moment Frames by Viscous Dampers

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Abstract

Step-terrace RC moment frame, which foundations are not at same elevation level, is one of typical structures in mountain cities and its seismic behavior is different from conventional regular ones under earthquake action. It is necessary to study on how to improve its seismic performance using viscous dampers because many research works are focused on the conventional regular frames at present. In this paper, an equivalent seismic design method is proposed that the Step-terrace frame is firstly simplified into regular one according to equal stiffness, then the locations and parameters of diagonal viscous dampers are determined by traditional seismic design method. In order to verify this approach's availability, structural dynamic analyses are conducted for frames with different configurations subjected to different level earthquake excitations. The results show that the proposed method is available. However, its applicable scope is related to total number of floors and spans of step-terrace part. Meanwhile, the dampers setup scheme which damping coefficients are proportional to story shear force is better than equal along building height. It's also found that structural seismic performance is not significantly influenced whether dampers are set at step-terrace floors of the structure. And the weak part of structures is located at upper embedding floor although viscous dampers are used.

Keywords: Step-terrace frame; equivalent model; viscous damper; upper embedding end

1. Introduction

The step-terrace RC moment frame, which foundations are not at same elevation levels as shown in Fig.1, is one of most typical structures in mountain cities. Due to its vertical irregularity, there are greater shear force at upper embedding end than lower one under earthquake. It was also found by tests that plastic hinges or failure of beams and columns occur numerously at upper embedding floor earlier than other floors [1]. Thus it's particularly important for step-terrace RC frames to find some measures to improve their seismic performance.

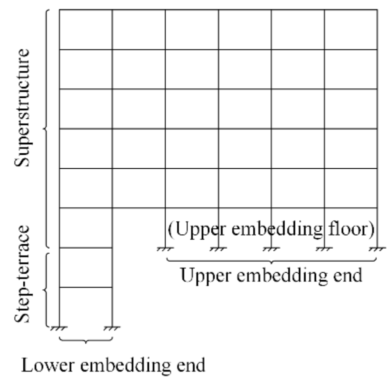


Fig.1 Elevation of step-terrace RC frame

Many research results show that it is one of effective seismic methods to set some dampers in the structures. For example, energy dissipating braces were used by Ding Kun [2] and Lin [3] to substitute rigid ones in cantilever truss at story with outriggers or belt members. And then earthquake energy is dissipated by these energy dissipating braces and dynamic response of structure is reduced. The parameters such as location and number of dampers are analyzed and an optimized design method for high-rise structure with viscous energy-dissipation story are proposed.

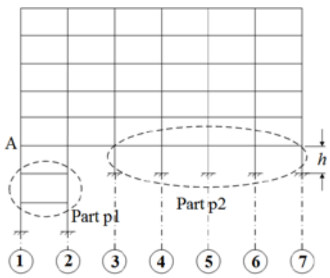
Comparing response of structures with different configurations of viscous dampers and lead-viscoelastic dampers, the efficiency of energy dissipation special story to reduce whole structural response for high-rise building structures under wind and earthquake excitation was proved by Wang Dayang [4]. To satisfy various demands and objectives at different earthquake risk levels, another practical design procedure was proposed by Weng Dagen [5] for structures with additional viscous dampers. Wang Zhihao [6] and Zhou Yun [7] improved the connecting method of dampers between different floors and applied this new method for design of high-rise buildings.

At present, many research results of seismic energy-dissipation design using dampers are mainly focused on regular building structures whose column feet are at the same elevation level. But step-terrace RC frames have unique mechanical behavior due to different base elevation level. In other word, displacements at two sides of the frame in same elevation level may be different. For instance, the upper embedding ends have no displacement, while other ends in the same elevation have. So further research is needed to select reasonable value of structural vibration modes in order to determine the damping factor along the height of the structure. Meanwhile, there is still no research work of discussing whether existing seismic design methods are able to apply directly to step-terrace RC frames. Equivalent lateral stiffness of bottom columns in step-terrace frames is determined by He Ling [8] considering effect of rotation of column ends between adjacent floors. Therefore, equivalent height formulas of columns is also derived.

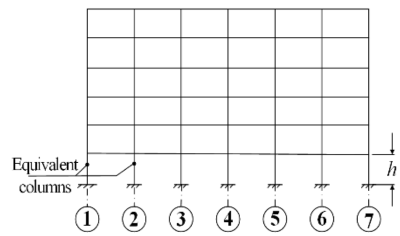
In order to investigate seismic behavior of step-terrace RC frames, several examples with different configuration are designed. Then they are converted into regular RC frames using equivalent model so as to calculate the damping factor and determine the number and location of dampers. Finally, the applicability of proposed method is verified by structural dynamic nonlinear analysis results.

2. Equivalent model of step-terrace RC frames

In order to obtain an equivalent model for step-terrace frame (shown in Fig. 2), the columns connecting with lower embedding ends are simplified into equivalent ones (Part p1 in Fig. 2a). Then lateral stiffness of these columns are calculated. Assumed that the height of all bottom columns is *h*, thus dimension of columns were derived according to equal lateral stiffness.



(a) Step-terrace RC frame



(b) Equivalent frame model

Fig.2 Stiffness-equivalent model for step-terrace RC frames

According to the literature [8], the stiffness of frame above upper embedding floor have an effect on lateral stiffness of bottom column, but this effect can be neglected if amount of superstructure story is more than 2. So, a substructure is take apart from whole structure as part just including upper embedding floor and step-terrace floor in the paper. Then the stiffness of Part p1 and p2 was calculated by applying horizontal concentrated force at point A in Fig. 2a. Therefore, the dimensions of columns were determined according to equal lateral stiffness using D-value method.

3. Construction of structural models

3.1 Moment frame examples

The parameters of 2-Dimension moment frames were selected as follows: the basic design acceleration of ground motion is 0.15g. Site classification is D as defined according to FEMA450. Each frame has 6 spans and each span is 6 meters. The superstructure has 6 floors, while story number of step-terrace part are 1, 3 and 5, respectively. Span numbers of step-terrace part are 1, 2, 3 and 4, respectively. All of story height is assumed 3.6m. Therefore, 12 examples were designed shown in Table 1. Herein these examples are named according to total number of step-terrace floors and spans. For example, the structure in Fig 2a is named Model D2-1, which means the number of step-terrace floors and spans are 2 and 1, respectively. The design compressive strength of concrete is 14.3MPa, and the design tension strength of longitudinal bars and stirrups is 360Mpa. Dimension of all beams is 250mm×600mm. As shown in table 1, dimensions of columns were determined to exactly meet minimum requirements of China codes.

Table 1 Dimensions of columns

Model number	Floor number	Dimension/mm
D1-1、D1-2、D1-3、D1-4	-1, 1	600×600
	2, 3, 4, 5, 6	500×500
D3-1、D3-2、D3-3、D3-4	-3, -2, -1, 1	600×600
	2, 3, 4, 5, 6	500×500
D5-1、D5-2、D5-3、D5-4	-5, -4, -3, -2, -1, 1	650×650
	2, 3, 4, 5, 6	500×500

3.2 Analytical model

The nonlinear analytical model of step-terrace RC moment frame was implemented in the SAP2000 software. In the model, column base is a fixed constraint and beam-column connections are assumed rigid. Frame element is adopted to simulate behavior of beam and column components. The beam plastic hinge, M3 in main direction, and the column plastic hinge, P-M2-M3 combining axial and bending direction is located at its ends. The length of each plastic hinge is 5% of member length. The deformation curve of plastic hinge represents three important performance points in accordance with FEMA356, i.e. IO(immediately open), LS(life safety), CP(collapse prevent), respectively. Considering the influence of cast-in-place floor slab, the beam stiffness amplification coefficient is taken as 2.0 to calculate its section inertia moment. The mean tensile strength of reinforced steel is 455.7Mpa and its elastic modulus is 2.0×10^5MPa, and the mean compressive strength of concrete was 28.0MPa and its elastic modulus is 3.0×10^4MPa [9].

The viscoelastic Maxwell model was used to simulate behavior of nonlinear viscous dampers in software SAP2000 [12]. The nonlinear viscous dampers brace whose damping factor is 0.3 was set diagonally between columns in adjacent floors. It was assumed that additional damping ration of structure is 15% [10~11]. Damping factors of each floor were calculated by equivalent model. In the paper, D3-2 Model was taken as an example to illustrate the damping factors at each floor. As shown in Table 2, Method 1 and 2 represent damping factors are uniform and proportional to story shear force along building height, respectively.

Table 2 Damping factor determined for Model D3-2

Floor	**1st mode**	**Damping factor *C* /kN.s.m^{-1}**	
		Method 1	Method 2
6	1.000	311.21	125.01
5	0.923		212.02
4	0.788		277.33
3	0.598		329.81
2	0.372		370.99
1	0.128		392.05

The structural response are compared in the paper with three setup configurations of dampers, which are ST0 (no damper was set in structure), ST1 (2 dampers were set on every floor and damping factor was calculated by Method 1), ST2 (2 dampers were set on every floor and damping factor was calculated by Method 2). The main purpose is to study energy dissipation effect and applicability of equivalent frame model.

4 Response analysis of step-terrace RC frames

According to GB50010-2010, Code for Seismic Design of Buildings [9], the energy dissipated structures should be designed higher than ordinary ones under earthquake, thus the seismic fortification objectives for this type of structure is ‘no damage under moderate earthquake and repairable under rare earthquake’ and the corresponding limited vale of story drift is 1/550 and 1/240, respectively.

Two natural ground motion records, USA02347 and USA03005, and one artificial ground motion record, ACC1, were selected which match design response spectrum of China current code. Their acceleration response spectra were shown in Fig. 3. The nonlinear dynamic analysis of the step-terrace RC frames were conducted under moderate and rare earthquake level. The average value of results by three motions was used to verify accuracy of proposed equivalent model and investigate structural seismic behavior.

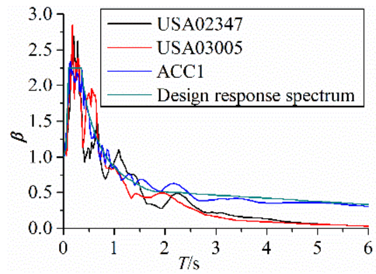


Fig. 3 Acceleration response spectra of selected ground motions

4.1 Seismic response of structures under moderate earthquake

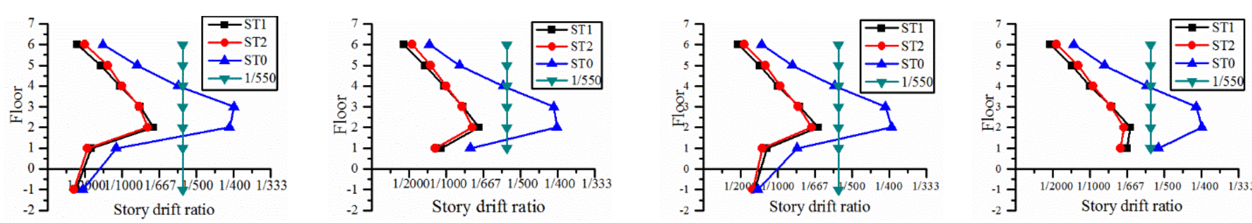
The maximum drift ratio of structural models under moderate earthquake are shown in Table 3.

Table 3 Maximum drift ratio under moderate earthquake

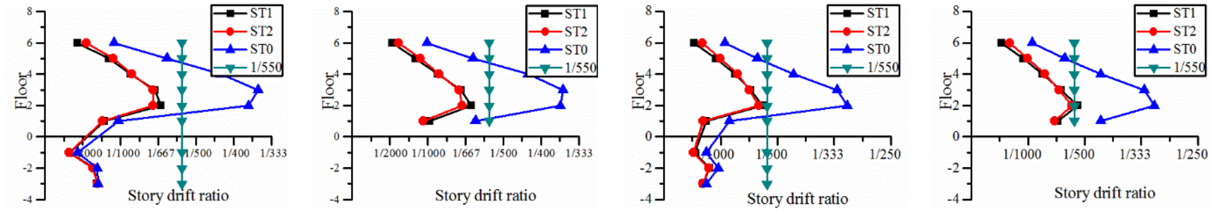
Model number	θ_{max}		
	ST0	ST1	ST2
D1-1	1/402	1/696	1/739
D1-2	1/399	1/685	1/728
D1-3	1/399	1/674	1/721
D1-4	1/398	1/647	1/688
D3-1	1/358	1/636	1/685
D3-2	1/345	1/599	1/637
D3-3	1/309	1/535	1/565
D3-4	1/291	1/471	1/496
D5-1	1/356	1/567	1/604
D5-2	1/330	1/542	1/576
D5-3	1/305	1/481	1/509
D5-4	1/240	1/431	1/431

The story drift ratio of some of structures along height under moderate earthquake are plotted in Fig 4. It can been found in Table 3 and Fig 4 that the efficiency controlled by viscous dampers reduces when span number of step-terrace part increases. The maximum drift ratio is almost at 2nd or 3rd floor.

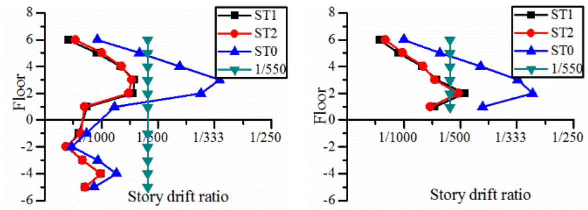
The maximum response of step-terrace RC frames with dampers is less than frames without dampers. Meanwhile, seismic performance of frames with dampers setup configuration ST2 is better than ST1.



(a) Model D1-1, axis 1 (b) Model D1-1, axis 7 (c) Model D1-4, axis 1 (d) Model D1-4, axis 7



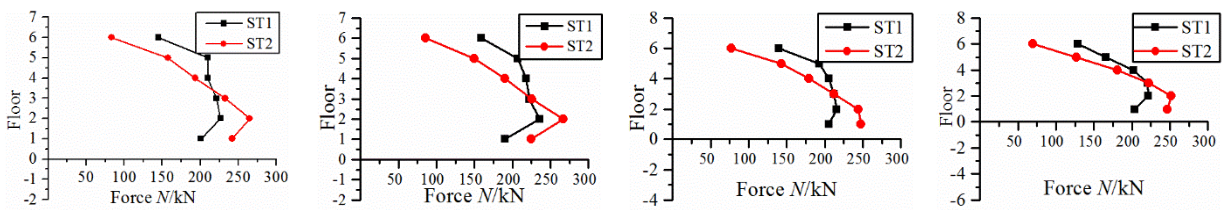
(e) Model D3-1, axis 1 (f) Model D3-1, axis 7 (g) Model D3-3, axis 1 (h) Model D3-3, axis 7



(i) Model D5-3, axis 1 (j) Model D5-3, axis 7

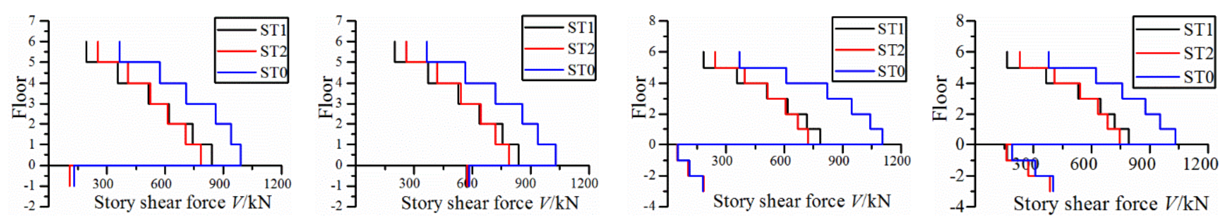
Fig.4 Story drift ratio under moderate earthquake

Due to greater shear force at the bottom of frames caused by earthquake, demand for axial force or energy dissipation of dampers is also higher which depends on damping factor and story deformation. So distribution of damping axial force at each floor are investigated shown in Fig.5 for some of frames. It is found that the distribution is usually as same as of maximum drift ratio. The dampers configuration ST2 had greater difference of damper axial force between floors compare with ST1.

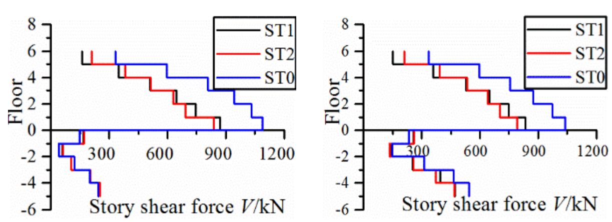


(a) Model D1-1 (b) Model D1-4 (c) Model D3-3 (d) ModelD5-3

Fig.5 Distribution of damper force under moderate earthquake



(a) Model D1-1 (b) Model D1-4 (c) Model D3-1 (d) Model D3-3



(e) Model D5-1 (f) Model D5-3

Fig.6 Distribution of story shear force under moderate earthquake

The distribution of story shear force along height of frames is plotted in Fig 6. It is found that the shear force of superstructure reduces effectively when viscous dampers are set except step-terrace floors because their shear force almost keep constant. Meanwhile, the reducing coefficient of story shear force of ST2 is more significant than ST1.

To sum up, the structures can meet seismic performance objectives of Code, i.e. no damage under moderate earthquake when they are in accordance with following requirements, a) Floor number of step-terrace is 1 and span number is no more than 4; b) Floor number of step-terrace is 3 and span number is no more than 3; c) Floor number of step-terrace is 5 and span number is no more than 2. Others cannot meet seismic performance objectives.

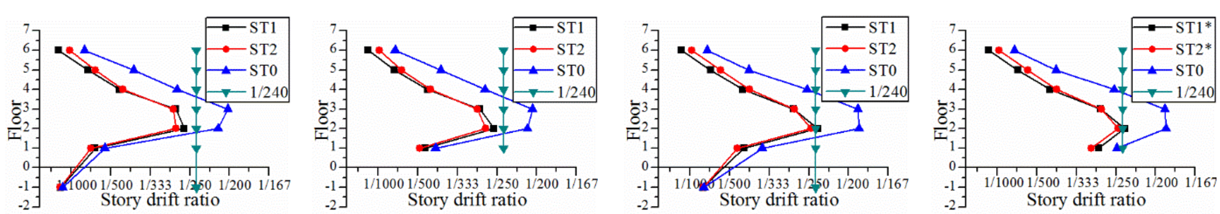
4.2 Seismic response of structures under rare earthquake

The maximum drift ratio of structural models under rare earthquake are shown in Table 4.

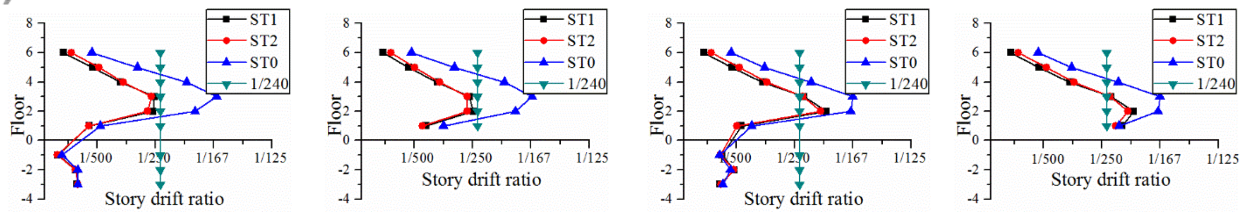
Table 4 Maximum drift ratio under rare earthquake

Model number	θ_{max}		
	ST0	ST1	ST2
D1-1	1/204	1/255	1/269
D1-2	1/203	1/254	1/267
D1-3	1/198	1/246	1/258
D1-4	1/190	1/241	1/247
D3-1	1/166	1/249	1/261
D3-2	1/160	1/238	1/248
D3-3	1/167	1/197	1/204
D3-4	1/151	1/145	1/155
D5-1	1/178	1/236	1/245
D5-2	1/156	1/224	1/231
D5-3	1/145	1/192	1/196
D5-4	1/107	1/134	1/145

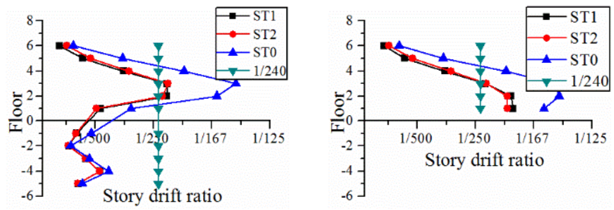
The distribution of drift ratio is provided in Fig 7. It is found that the structural response regularities under rare earthquake are almost same as moderate earthquake. The maximum drift ratio of structures increases when total number of step-terrace floors increases. The dampers configuration ST2 have better control effect on structural seismic response than ST1.



(a)Model D1-1, axis 1 (b) Model D1-1, axis 7 (c) Model D1-4, axis 1 (d) Model D1-4, axis 7



(e) Model D3-1, axis 1 (f) Model D3-1, axis 7 (g) Model D3-3, axis 1 (h) Model D3-3, axis 7



(j) Model D5-3, axis 1 (k) Model D5-3, axis 7

Fig.7 Story drift ratio under rare earthquake

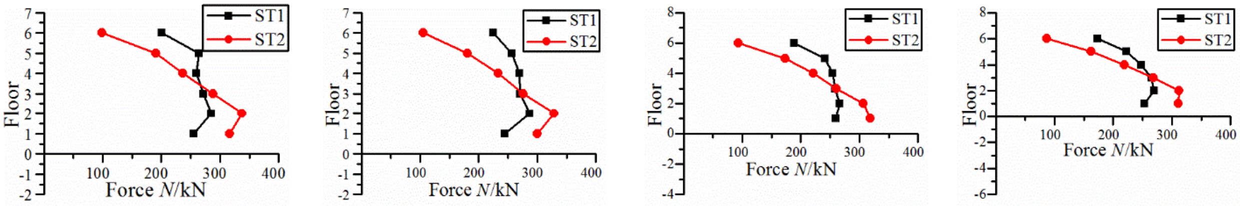
As shown in Table 4 and Fig.7, the maximum drift ratio of structures without dampers exceeds 1/240. Meanwhile, whether the structures with dampers meet the performance objectives, 'repairable under rare earthquake', depends on amount of floors and spans of step-terrace part. Only the following structures satisfy seismic performance objectives under rare earthquake: a) Total number of step-terrace floors is 1 and span numbers is not greater than 4; b) Total number of step-terrace floors is 3 and span numbers is not greater than 2; c) Total number of step-terrace floors is 5 and span numbers is not greater than 1. Others cannot meet seismic performance objectives.

Table 5 provides average reduction coefficient of story shear force of ST1/ST0 and ST2/ST0 respectively. It is found that the coefficient become greater with the increasing of total number of step-terrace part.

Table 5 Average reduction factor of story shear force

Model number	**Moderate earthquake**		**Rarely earthquake**	
	ST1	ST2	ST1	ST2
D1-1	0.706	0.733	0.820	0.856
D1-2	0.706	0.734	0.832	0.879
D1-3	0.705	0.736	0.833	0.877
D1-4	0.719	0.748	0.842	0.889
D3-1	0.626	0.646	0.822	0.852
D3-2	0.639	0.664	0.822	0.869
D3-3	0.662	0.688	0.823	0.863
D3-4	0.671	0.700	0.823	0.861
D5-1	0.652	0.671	0.839	0.877
D5-2	0.637	0.659	0.841	0.882
D5-3	0.677	0.701	0.826	0.882
D5-4	0.691	0.733	0.801	0.870

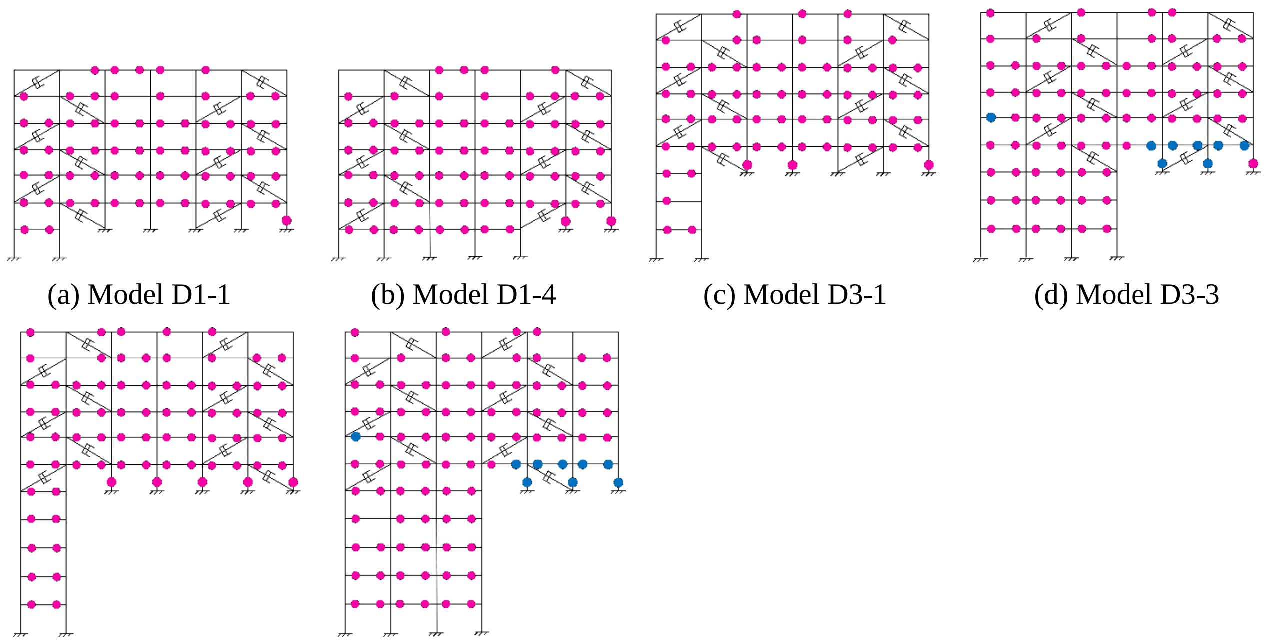
Fig.8 show distribution of damper axial force along the floors of frames under rare earthquake. And it is obviously that its distribution law is almost consistent with situation under moderate earthquake.



(a) Model D1-1 (b) Model D1-4 (c) Model D3-3 (d) ModelD5-3

Fig.8 Damper force under rare earthquake

The distribution of plastic hinges of step-terrace RC frames models with dampers configuration ST1 under rare earthquake ACC1 is shown in Fig. 9. Noted that blue color ones in the drawings mean the deformation state of plastic hinges is less than IO, the pink color ones mean the deformation state of plastic hinges is between IO and LS. As shown in Fig. 9, the plastic hinges always appear in the column base at upper embedding ends. And with the increasing of total numbers of step-terrace floors and spans, the total numbers of columns and beams plastic hinges in upper embedding floor increase and its plastic state becomes more seriously.



(a) Model D1-1 (b) Model D1-4 (c) Model D3-1 (d) Model D3-3

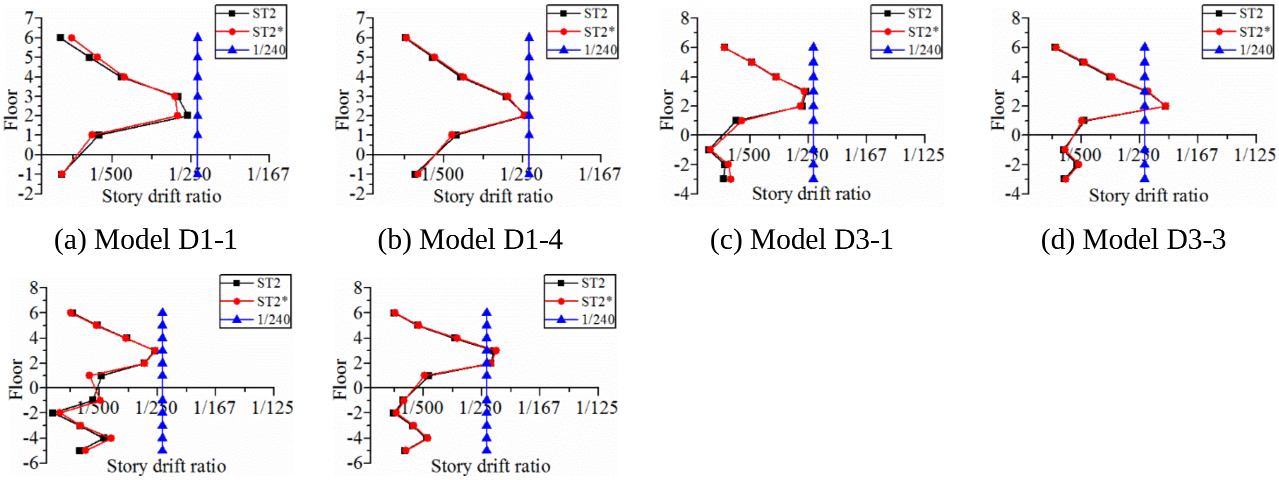
(e) Model D5-1 (f) Model D5-3

Fig.9 Distribution of plastic hinges in structures under rare earthquake

For frames which total number of step-terrace floors is 3 or 5 and spans is more than 3, severe damage occurs at end of columns in upper embedding floor although dampers are implemented. In other words, the method proposed in the paper is suitable for structures with less total number of step-terrace floors and spans.

4.3 discuss on location of dampers

Above analysis results and conclusions are gotten in condition of implementing dampers in floor of superstructure. It is needed to study how the dampers set in step-terrace floors affect structural behavior under earthquake action. Another configuration ST2* is designed that dampers setup in floors of superstructure are same as ST2, while two additional dampers are implemented in each step-terrace floors. Fig. 10 illustrates that comparison of story drift ration of ST2 with ST2*. It is found that the effect of dampers setting in step-terrace floors can be negligible because the story drift ration of configuration ST2* is almost same as ST2.



(a) Model D1-1 (b) Model D1-4 (c) Model D3-1 (d) Model D3-3

(e) Model D5-1 (f) Model D5-3

Fig.10 Story drift ratio under rare earthquake

5 conclusion

In the paper, an equivalent Model is proposed which step-terrace frames are firstly simplified into regular one according to equal stiffness, and then the damping factors of every floor are determined by traditional seismic design method. The proposed equivalent method was verified by dynamic analysis process. It is found that its accuracy depends on total number of step-terrace floors and spans which advised value is not greater than 3 floors and 1/3 of the total span numbers of the frame, respectively.

The damper configuration ST2 which damping factors are proportional to the story shear force is better to improve seismic performance. So it is recommended to select it to design the damper parameters and locations.

The weak stories of step-terrace RC frames are usually located at upper embedding floor where plastic beams and columns hinges occurs. The plastic extent of structures would reduce when viscous dampers are implemented in frames. While there are not any effect when dampers are implemented at step-terrace floors.

6. Acknowledgements

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