Structural analysis of a school building with viscous dampers applied

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Abstract. Viscous damper, as a type of energy-dissipating device, is applied in the 3-story school building. To investigate the function of viscous dampers, seismic nonlinear analysis is performed on the FE model with viscous dampers simulated in. The analysis is done for both minor earthquake and severe earthquake. The analysis results show that the viscous dampers start to dissipate energy in minor earthquake input and dissipate more energy in severe earthquake. Therefore, application of viscous dampers significantly reduce the seismic response of the building and effectively protect the structure building from severe damage or collapse.

1. Introduction
In recent years, with the developing investigations, the energy-dissipating and seismic isolation technics are widely applied in the high severity seismic zones [1]. Some engineering structures with such technics have shown better seismic performance in the earthquake events, such as Wenchuan earthquake or Lushan earthquake. As illustrated by the facts, the energy-dissipating and seismic isolation technics can effectively reduce the seismic response of the buildings and therefore improve their earthquake resistance abilities [2]. Among these technics, viscous damper, as a type of energy-dissipating device, is widely applied in the engineering structures due to its stable technical features and easy applications [3] [4]. To investigate the function of viscous dampers in the low-rise buildings, the FE model of a 3-story school building with viscous dampers is simulated and seismic analysis is performed on it.

2. Viscous Dampers

2.1 Principal of energy dissipation of viscous dampers
As shown in figure 1, viscous damper is generally made up of the cylinder, piston and viscous liquid. The viscous liquid inside the cylinder is silicone oil or other viscous liquid; and there is a small hole in the piston. When the piston moves in the cylinder, the liquid will go through the small holes in the piston and therefore prevent the relative movement between the piston and cylinder. In this way, the kinetic energy is dissipated to some extent and therefore the seismic response of structures is reduced.
2.2 Restoring force characteristics of viscous damper
As shown in figure 2, the viscous damper will develop a stable spindle shape loop when dissipating
the kinetic energy, and it is clearly seen that the viscous damper is of good energy absorption capacity.

2.3 The advantages of viscous damper
The viscous damper has following advantages:
(1)Viscous dampers in other fields already have a long history of application and have been proven
to be of good feasibility and stability. So it is reliable to extend its application to civil structural
buildings.
(2)For ordinary dampers, maintenance such as check or repair is often required. But for viscous
dampers, such maintenance is rarely needed. The viscous dampers aren’t damaged even after the
low to medium seismic event and they are easily replaced while after severe seismic event.
(3)As a type of energy dissipating device, the energy dissipating process will cause the temperature
to rise or decline. But the temperature change doesn’t have much impact on its energy
dissipating function.
(4)Viscous damper is a type of velocity - dependent damper. It doesn’t add stiffness to the structure,
therefore it only increases the structural damping ratio without reducing the vibrating periods,
which effectively reduces the structural seismic response (displacement, velocity, and
accelerations).

2.4 The arrangement pattern of viscous dampers
The viscous dampers are usually arranged as follows: Wall-embedded, Lateral-braced, K-braced.
3. Application of viscous dampers in this project

3.1 Project Introduction
This project, a three-story school building, is a reinforced concrete frame structure. The seismic fortification intensity of this area is 8 degrees (0.3g). According to the requirement of the province, where the project is in, the technics of earthquake isolation or energy dissipating shall be applied in this project. By weighing the pros and cons of different technologies, the viscous dampers are finally selected as the energy dissipation parts for this project.

The seismic design goals here are: 1) under the minor earthquake, the viscous dampers will start dissipating energy and increase the damping ratio of the structure, so that the structure itself will be in the elastic stage; 2) under the medium or severe earthquake, the viscous dampers will dissipate energy to a large extent so as to reduce the seismic response of the structure.

3.2 Arrangement of viscous dampers
The arrangement of viscous dampers in plan view is shown in Figure 3; their arrangement in sectional view is shown in Figure 4.

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Figure 3. Arrangement of dampers in plan view (red part is damper, same for each story)

Figure 4. Arrangement of dampers in sectional view (red part is damper)
3.3 Connection between the viscous damper and surrounding structural members

The connection between the viscous damper and its surrounding structural members is shown in Figure 5.

4. Parameters and earthquake wave input in nonlinear seismic analysis

The structural analysis software MIDAs/gen is applied to perform the nonlinear seismic response analysis in this project.

4.1 Selection of seismic wave input

An artificial earthquake wave (RH3TG035) and two natural earthquake waves (TH079TG035 and TH082TG035) are selected in the structural analysis. The time history curves of three waves are shown in Figure 6. The characteristics of response spectra of three waves as shown in figure 7, with the design spectra drawn in the same figure.

(a) RH3TG035  
(b) TH079TG035  
(c) TH082TG035

Figure 6. Three earthquake waves applied in the seismic analysis
Table 1. Seismic coefficient on structure periodic points for different waves

| Input          | Seismic coefficient at 3rd mode (α) | difference (%) | Seismic coefficient at 2nd mode (α) | difference (%) | Seismic coefficient at 1st mode (α) | difference (%) |
|----------------|------------------------------------|----------------|------------------------------------|----------------|------------------------------------|----------------|
| Design Spectra | 0.135                              |                | 0.147                              |                | 0.156                              |                |
| RH3TG035       | 0.127                              | 5.93%          | 0.135                              | 8.16%          | 0.142                              | 8.97%          |
| TH079TG035     | 0.152                              | 12.59%         | 0.164                              | 11.56%         | 0.174                              | 11.54%         |
| TH082TG035     | 0.144                              | 6.67%          | 0.165                              | 12.24%         | 0.164                              | 5.13%          |

As shown in Figure 7 and Table 1, the difference between the response spectra of three seismic input waves and the design spectra is within 20% at the structural main vibration periods. Therefore, the selected three earthquake waves are acceptable according to the requirements in <Code for seismic design of building> GB50010-2010 (2016 Edition) [5].

4.2 Constitutive model for component settings

(1)frame beam : M-φ (Moment-rotation angle) hinge model
The max deformation of beams occurs on both ends of beams under the given loads. The plastic deformation can be simulated as plastic hinge and the moment-rotation relationship at the beam end is characterized as M-φ (Moment-rotation angle) curve of plastic hinge. Here, Modified Takeda Trilinear model, as shown in Figure 8, is applied to simulate the M-φ relationship at beam ends. In this trilinear model, stiffness degeneration rather than strength degeneration is considered; the first turning point represents the concrete crack and the second turning point represents the member yielding.

(2)columns : P-M1-M2 axial force - bi - directional bending moment hinge model
The max deformation of columns occurs on both ends of columns under the given loads. The
plastic deformation can be simulated as P-M1-M2 plastic hinge, where P represents axial loads, M1 and M2 represent moments in two directions. The model applied to simulate the PMM relationship is shown in Figure 9.

4.3 Analysis model of viscous damper
The viscous damper is simulated as a connection element (damper) in software MIDAs/gen, as shown in Figure 10.

4.4 Verification and validation of MIDAs Model
To verify and validate the structure model with MIDAs/Gen, another widely used software PKPM is applied to simulate the structure. The FE models of two software are shown in Figure 11.

To run the two FE models by inputting the minor earthquake response spectrum, the results are listed in Table 2. It can be seen that the differences of results from two models are insignificant. Therefore, the MIDAs/Gen model is deemed acceptable and is applied in the subsequent analysis.

| Item                     | PKPM       | MIDAs/GEN  | Difference |
|--------------------------|------------|------------|------------|
| **Gross mass**           | 3299.244   | 3326.156   | 0.82%      |
| Period (s)               |            |            |            |
| Mode 1                   | 0.6672     | 0.6618     | 0.81%      |
| Mode 2                   | 0.6074     | 0.6032     | 0.69%      |
| Mode 3                   | 0.5679     | 0.5613     | 1.16%      |
| Max story drift angle    |            |            |            |
| X dir                    | 1/637.     | 1/649      | 1.88%      |
| Y dir                    | 1/597.     | 1/618      | 3.52%      |
| Base Shear (kN)          |            |            |            |
| X dir                    | 3954.86    | 3970.5     | 0.40%      |
| Y dir                    | 3601.09    | 3632.3     | 0.87%      |

5. Seismic analysis of structure
Here, software MIDAs/gen is applied to perform the dynamic time history analysis in two steps:
1. time history analysis in minor earthquake
2. time history analysis in severe earthquake

The structure model with viscous dampers is shown in Figure 12.

![Figure 12. Structure FE model with Viscous Damper simulated in MIDAs](image)

5.1 Dynamic time history analysis under minor earthquakes

The maximum base shear of structure from three earthquake waves are listed in Table 3. In the same table, the base shear from the response spectra analysis is also listed for X and Y directions. As compared in Table 3, the base shear from each wave is larger than 65% of what from response spectra analysis; and the average base shear from three waves is larger than 80% of what from response spectra analysis. Therefore, the results out of time history analysis can meet the minimum safety requirement according to the specifications in <Code for seismic design of building> GB50010-2010 (2016 Edition) [5].

| Item     | RS input | RH3TG035 | TH079TG035 | TH082TG035 | Average |
|----------|----------|----------|------------|------------|---------|
| X dir    | Base shear | 3971     | 3163       | 3876       | 3413    | 3484   |
|          | Ratio     | 79.66%   | 97.61%     | 85.96%     | 87.74%  |
| Y dir    | Base shear | 3632     | 3095       | 3584       | 3122    | 3267   |
|          | Ratio     | 85.21%   | 98.67%     | 85.95%     | 89.94%  |

The maximum story drift angle in three earthquake waves are listed in Table 4. It can be seen that the max story drift angle from all three waves is 1/810, which is less than 1/550. 1/550 is the maximum requirement of story drift angle specified in <Code for seismic design of building> GB50010-2010 (2016 Edition) [5].

| Earthquake wave | Story | X dir | Y dir |
|-----------------|-------|-------|-------|
| RH3TG035 wave   | 991   | 1056  |
| TH079TG035 wave | 810   | 847   |
| TH082TG035 wave | 929   | 1013  |
| Enveloped       | 810   | 847   |

The sum of forces in the viscous dampers in each story are listed in Table 5. The total shear of each story is also listed in the same table. By comparison, it can be seen that the sum of forces in the dampers are about 1/3 of the total shear of the story. The energy dissipating curve of the viscous damper in the minor earthquake wave is shown in Figure 13.

| Earthquake wave | Story | X dir | Y dir |
|-----------------|-------|-------|-------|
| RH3TG035        | 3     | 1354.7| 562.23|
|                 |       | 1297.4| 712.53|
5.2 Time history analysis under severe earthquake

Load combination of 1.0DL+0.5LL+1.0E is applied for time history analysis under severe earthquake input. Here, DL stands for dead load, LL stands for live load and E stands for earthquake load.

5.2.1 Story drift angle and the story shear force

The maximum story drift angle and base shear force are listed in Table 6.

![Figure 13. Energy dissipation curves under minor earthquake input](image)

| Item      | RH3TG035 | TH079TG035 | TH082TG035 | Enveloped value |
|-----------|----------|------------|------------|-----------------|
| Max drift angle | X dir | 1/184 | 1/131 | 1/178 | 1/131 |
|           | Y dir  | 1/192 | 1/144 | 1/186 | 1/144 |
| Base shear (kN) | X dir | 9210.4 | 10645 | 9191.9 | 10645 |
|           | Y dir  | 8094  | 8788.3 | 7631.5 | 8788.3 |

From the data in Table 6, it can be seen that:

1) The story drift angle under wave TH079TG03 is the greatest, followed by wave RH3TG035 and then by wave TH082TG035.

2) The greatest story drift angle under each wave is 1/131 and is less than 1/50, which is the required maximum story drift angle in Code for seismic design of building GB50010-2010 (2016 Edition) [3].

3) The structure stands stably even when the large deformation effect and the 2nd order gravity effect are both considered in the analysis. That means the goal of “no collapse in severe earthquake” is obtained.

5.2.2 Damage of plastic hinges on the member ends

Under the seismic input in both X direction and Y direction, the damages of the members are as follows:

Plastic hinges occur at the ends of most of beams and at the ends of a small number of columns. The failure mode appears to be strong column and weak beams, which is the preferred by the design
requirements as specified in <Code for seismic design of building> GB50010-2010 (2016 Edition) [5].

The sum of forces in the viscous dampers in each story are listed in Table 7. The total shear of each story is also listed in the same table. By comparison, it can be seen that the sum of forces in the dampers are about 1/3 of the total shear of the story. The typical energy dissipating curve of the viscous damper in severe earthquake wave is shown in Figure 14. The viscous dampers show good capability of energy dissipating.

Table 7. Force sum of dampers and the story shear under severe earthquake (kN)

| Earthquake wave | story | Shear force | damper forces | Shear force | damper forces |
|-----------------|-------|-------------|---------------|-------------|---------------|
| RH3TG035        | 3     | 3891.3      | 1407.23       | 3471.3      | 1610.54       |
|                 | 2     | 6291.6      | 1555.76       | 5751.9      | 1655.25       |
|                 | 1     | 8711.9      | 1710.75       | 7777.7      | 1685.14       |
| TH079TG035      | 3     | 5626.5      | 1599.28       | 5416.4      | 1802.49       |
|                 | 2     | 8968.1      | 1783.85       | 8031.8      | 1955.96       |
|                 | 1     | 10795       | 1964.96       | 9082.2      | 1980.56       |
| TH082TG035      | 3     | 4401.6      | 1435.18       | 3790.2      | 1589.15       |
|                 | 2     | 7310.2      | 1669.20       | 6007.1      | 1721.58       |
|                 | 1     | 8899.5      | 1814.84       | 7139.4      | 1778.08       |

Figure 14. Hysteretic energy dissipation curve of damper under TH079TG035 wave

6. Conclusion
From the structure analysis results, the following conclusions could be drawn:

1) Under the minor earthquake input, the viscous dampers start to dissipate energy and the structure is in the elastic stage.

2) Under the severe earthquake input, the viscous dampers continue to dissipate energy to a greater extent, which reduces the seismic response of structures. Most beams and a small number of columns gradually come to yield; the failure mode of structure is strong column and weak beam.

3) The viscous dampers are a type of feasible device to reduce the seismic response in the minor or severe seismic event.

To better understand the function of viscous dampers, more investigation is expected on their application on high-rise buildings or more complicated structured buildings such as steel-concrete Composite Structures.

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