Assessment of Viscous Damper Placement as Passive Energy Dissipation on High-rise Building, a Numerical Study

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Abstract. The methods to reduce the impact of earthquake loads is using a damper, namely passive control, active control, and semi-active. One of the advantages of passive control is because of its simplicity in design, installation, and especially in its maintenance. Viscous Fluid Damper (VfD) is one type of dampers which has been widely applied. A numerical analysis of the seismic response of VfD on the ten-story reinforced concrete (RC) frame that receives lateral loads as earthquake loads already compared to conventional RC frame. Displacement and acceleration are an earthquake response parameter which is a direct impact on the structure. The results of numerical time history analysis with the excitation of the Kobe-X earthquake record show that the presence of structural passive control has succeeded in reducing displacement on the top floor and also on the floors below. On the roof floor, for the X longitudinal direction, there was a reduction up to 7.721 percent. Whereas on the 6th, 4th and 2nd floors the smaller reduction occurred by around 6.624% to 2.932%. Likewise, with the acceleration parameters, generally able to reduce acceleration. For frames with placement of VfD in 1st – 2nd floor can reduce acceleration to 10.293 percent whose data is taken at the top of the building. For further, need an experimental laboratory program to validate the numerical analysis to ensure the prediction behaviour of the structural design.

1. Introduction
Conventional design methods in improving seismic performance in buildings are by placing concrete shear walls or steel bracing, this method cannot be applied to several buildings because it requires expensive and time-consuming foundation work. Two methods and devices have been proposed, tested numerically to improve building performance. Installation of Passive energy dissipation devices into a structure will dissipate some of the incoming energy, thereby reducing the load received by primary structural elements and being able to reduce the possibility of structural damage. An analysis of the use of viscous dampers on reinforced concrete frameworks has been carried out by reviewing the parameters of absolute acceleration, absolute displacement, and absolute speed by showing the results that the installed device is able to rise the value of energy dissipation in the structural system. Installing a damper device as a seismic energy dissipation system effectively can reduce the structural response of framed structures during earthquake excitation. [1].

To improve the performance of structures especially in the seismic response, in recent years, damping devices have been developed [2, 3]. The purpose of designing structures is to get
structures that meet the requirements of strength and comfort. In designing earthquake resistant structures, the stiffness requirements are implemented in the form of permissible lateral deviation restrictions. This restriction is required to minimize non-structural damage to buildings.

One solution that is done conventionally by planners to reduce the amount of lateral deviation to meet the requirements in general is to reinforce the structure, namely by enlarging the dimensions of the structure that has been designed based on the strength criteria. By increasing the dimensions of the structure like this, the structure becomes heavier, and the costs incurred are more expensive.

Another way to do this is to reinforce structures that have been designed based on strength criteria by installing bracing. The mechanism of action of bracing is to resist the lateral tensile forces that occur in structures due to dynamic excitation. Even this solution also tends to add weight to the structure and overall costs.

2. Literature Review

The use of passive energy dissipation devices in a structure to absorb most of the seismic energy has been started by Kelly in 1972 [4] both conceptually and experimentally.

Seismic performance of middle-rise building structures equipped with dampers and without dampers has been investigated by [5]. An attempt was made to find a reduction in earthquake response from a structure modeled with a passive energy dissipation device.

The structural element deformations can be reduced by passive control devices. That is become basic principle of damper application. A simple single-degree-of freedom (SDOF) can represent the system of passive and active control. \(-m \ddot{x}_g(t)\) is a dynamic load that is a load which is a function of time. The symbols \(m\), \(c\) and \(k\) are respectively mass, damping coefficient of damper and stiffness of spring. This system is subjected to an earthquake load where \(g(t)\) is ground acceleration. The excited model responds with a lateral displacement \(x(t)\) relative to the ground, this is satisfying the equation of motion [6].

\[
m \ddot{x} + c \dot{x} + k x = -m \ddot{x}_g(t)
\]  

After the installation of passive energy dissipation device, the equation becomes,

\[
m \ddot{x} + c \dot{x} + k x + \Gamma x = -(m + m) \ddot{x}_g(t)
\]

where \(m\) is the device mass and \(\Gamma\) is the force of device.

Installing Damper is an effective way for the retrofitting approach for reinforced concrete frames. The displacement responses of the reinforced concrete frame can be reduced significantly. The acceleration responses and the base shear of the reinforced concrete frame were reduced also [7].

Three building models simulate with ETABS with excitation of dynamic characteristics for the current conditions. The performance and effectiveness of the retrofit construction under study namely the Viscous-Fluid-Spring Damper (VFSD) system was proposed as an "optimal" solution for buildings. VFSD, was chosen because it combines a relatively compact size and minimally invasive construction. Numerical analysis with the Base Earthquake Design 475-year return period, and three historical pairs of representative earthquake ground motion time scales to match this DBE. The proposed scheme reduces the maximum inter-floor drift ratio of buildings from 5.4% to around 1% [8].

The 12-story steel structure performance is modeled in three dimensions with the addition of viscoelastic damping applications. the analysis of the structure of time history shows that the acceleration and displacement at the top of the building has decreases [9].

The effect of viscous energy dissipation bracing on stress performance has been investigated, especially on the connection of concrete frames both with and without a damper in the effect
of earthquake action using SAP2000 software. The results of the analysis prove that the dampers installed increase the ability of energy dissipation at the connection, and produce stress concentrations in the connection area. Internal strength is able to increase and the floor shift angle, floor displacement and floor shear are significantly reduced. The seismic capacity of the concrete framework and the seismic performance of the structure increases [10].

Several types of damper devices are used, namely hysteretic dampers, friction dampers and viscoelastic dampers. Finite element method modeling is done to observe the behavior of the structure. Three concrete building prototypes (3, 5 and 10 Story) with the same damper placement position were analyzed by the time history method. with different properties, an analysis is carried out and the response of the building model is measured in terms of displacement, base shear and floor acceleration parameters. It was found that viscous and viscoelastic dampers were more effective for 3 & 5 story buildings while friction and hysteresis dampers were effective for 10 floors [11].

In buildings with moderate height, which is the most built type, an increase in the performance that causing of the application of dampers can be proven with the displacement, damping ratio and acceleration parameters [12]. Kasai [12] did on shaking table that are realistic three-dimensional tests were conducted for full-scale 5-story building specimens with steel damper, oil damper, viscous damper and viscoelastic dampers compare to building without damper.

Simplification of design procedure of viscous dampers application can formulate by Weng [13]to predict and repair the existing building that damaged because of earthquake excitation. Shin Hwang [14] succeeded in demonstrating the effectiveness of supplemental viscous dampers to structures by carrying out several alternative damper installation systems. His research proved that an efficient mounting mechanism is a toggle-brace-damper system, effective with a relatively small story drift to the structural seismic response.

Viscous dampers have better to dissipate energy by control the displacement parameter [7]. They have three types of dampers that designed with maximum damping force under moderate earthquake. From the curve of force-displacement data seen very full amount of energy that can dissipate by the dampers.

Dehghan [15] showed that viscous dampers can decrease the effect of seismic. The energy Dissipation effective increasing on the structure when compared to the structure without damper. They have better capability damping force up to 30% so it can be an alternative as a damper device.

The response of the displacement by the research of Gordan [16]showed the maximum displacement reduction demonstrate at experiment laboratory of structure with and without damper devices. The value of displacement reduction of the structure with viscous damper up to about 50%, so it can improve the performance of building structures.

Lower seismic design loads are expected to be applied to buildings by placing viscous damper at different levels of floors. Over strength, ductility, and response modification factors become a parameter to evaluate the impact of viscous dampers application on structure with different damping coefficients through an equivalent statistical analysis. The analysis showed that viscous damper devices have better performance on the parameters than the structures without viscous damper devices [17].

The structural response strongly influenced by the positioning of dampers. The best drift reduction happens when the dampers placed in the first level of the building. The distribution of the damper in the uniform model has become one of the best placements for the frame structures at Tovar research [18]. For the wall structure, placing the dampers in the lower stories of the building is the best arrangement.
3. Building Properties

The building (Figure 1) is a ten-story reinforced concrete (RC) frame and following are the properties of the FC frame. Six models of concrete frame consist of RC frame without VfD, RC frame with VfD at 1st-2nd floor, RC frame with VfD at 3rd-4th floor, RC frame with VfD at 5th-6th floor, RC frame with VfD at 7th-8th floor, and RC frame with VfD at 9th-10th floor. The building properties are shown in Table 1.

4. Damper Properties

This paper presents the results of a numerical building design case study that aims to study the effectiveness of placement of Viscous Fluid Damper (VfD) in absorbing vibrational energy caused by earthquake loads in concrete frame structures. The case study is carried out by implementing a high-rise structure design that uses the criteria of strength, stiffness, strength plus bracing, and strength plus VfD.

Viscous Fluid Dampers (VfD) devices have begun to be developed, including viscous walls developed by the Sumitomo Construction Company (Figure 1), which consists of plate elements that move in thin steel shrouds filled with VfD. VfD damper generally consists of a piston in a chamber filled with silicon material or similar to oil, and on the piston, there are a number of small holes through which liquid can pass from one side of the piston to the other side, which are called orifices.

VfD provide the optimal method for reinforcing historic and important buildings. Because of the importance of these buildings, these structures must be preserved and need to meet seismic performance requirements during an earthquake.

The excitation of the ground motion spectrum affects the behavior of the velocity and internal...
Figure 2: Design, Hysteresis behaviour and Material model of VfD (Tsuji & Nakamura, 1996)

Table 2: Viscous fluid damper properties

| $F_{bracing}$ (%) | $F_{bracing}$ (kN) | $\alpha$ | V   | C     | K       |
|-------------------|---------------------|----------|------|-------|---------|
| 100               | 1660                | 1        | 4.378| 379.17| 3791685.7|
| 80                | 343.36              | 1        | 4.378| 303.33| 2275011.4|

force of the structural element. The behavior of velocity and internal force element will affect the behavior of stiffness $K$ and damping $C$ according to the formula $F = CV\alpha$ where the ratio of $K$ to $C$ is 10,000 (Table 2). Data of the velocity take it from the analysis of frame without bracing element. Data of the internal force element of bracing take it from the analysis of the frame with the bracing element.

5. Loading
In general, there are two types of structural analysis of earthquake loads, namely equivalent static load analysis and dynamic analysis. Equivalent static load analysis is a method of structural analysis where the effect of an earthquake on a structure is considered a horizontal static load obtained by only calculating the response of the first motion range, and usually, this force distribution is simplified as an inverted triangle. Dynamic analysis is a structural analysis in which the dividing of earthquake shear forces at all levels is obtained by taking consideration of the dynamic influence of ground motion on the structure. Two ways to do the dynamic analysis first is the analysis of the range of response spectrum where the total response is obtained through the superposition of the response of each vibrating range. The second is time history analysis, which is a dynamic analysis in which the structural model is given a record of earthquake records and the response of the structure is calculated step by step at certain intervals.

Dynamic analysis for the design of earthquake-resistant structures is carried out if a more accurate evaluation of the earthquake forces on the structure is needed, and to determine the behavior of the structure due to earthquake effects. Dynamic analysis is carried out on the design of high-rise building structures or structures with irregular shapes or configurations. Dynamic analysis can be done either elastic or inelastic. In an elastic way, it is divided into Time History Modal Analysis where it is necessary to record earthquake acceleration and Response Spectrum Analysis where the maximum response of each motion range that occurs is obtained from
Figure 3: E-W direction of time history Acceleration Graph at Kobe Earthquake motion PGA 0.80g

the Response Spectrum Design Spectra. Elastic dynamic analysis is used to obtain structural responses due to the effect of a very strong earthquake by direct integration (Direct Integration Method). This elastic dynamic analysis is used more often because it is simpler. The dynamic analysis aims to determine the division of the level of shear force due to ground motion by the earthquake and can be done by analyzing the variety of response spectra. The dividing of the shear force is to replace the dividing of the basic shear load due to an earthquake along with the height of the building in the analysis of equivalent static loads.

In the initial stages of the study, a ground motion analysis was conducted sourced from https://peer.berkeley.edu (Figure 3). Analysis of structural dynamics using earthquake load input was taken from the 1923 Kobe earthquake record in the direction of the E-W with a PGA of 0.80 taken from Peer Berkeley website.

6. Results and Discussion
The displacement at six models of RC frame structure can be seen from Table 3 and Figure 4. The data shows that five models of the frame with VID at any placement can perform better than frame without VID in the displacement parameter.

On the 10th floor, a comparative analysis was carried out for the displacement parameters between frames without VID and frames with VID on floors 1st - 2nd (Figure 5). In the displacement parameter, there is a decrease in value on each floor for five frame models with different damper placement (Table 2). Of the five frames, it appears that variations in VID placement on floors 1st - 2nd provide the best response with a decrease in value up to 7,721% followed by frames with placements placed on floors 7th - 8th of 6,624%. While the worst displacement value occurs when VID is placed on the 5th - 6th floor, which is the position in the middle of the elevation or height of the building. In this position, the damper was only able to reduce the highest displacement of up to 2,932% (Table 4).

The effect of damper placement affects the seismic performance of the building structure. It can be seen in table 3, figure 5 and table 4 the differences in structural response characteristics of the 1956 KOBE earthquake were seen in terms of displacement that occurred in the structure. According to SNI 1726-2012 provision 7.6.2 regulates the structure of a building permitted to
Table 3: Maximum displacement at each floor with different placement of VfD

| Floor | without Dumper | 1st-2nd | 3rd-4th | 5th-6th | 7th-8th | 9th-10th |
|-------|----------------|---------|---------|---------|---------|----------|
| 1     | 49.462         | 35.025  | 44.657  | 46.7    | 40.135  | 41.563   |
| 2     | 107.509        | 81.985  | 109.65  | 97.201  | 92.123  | 102.923  |
| 3     | 161.259        | 132.62  | 160.735 | 154.891 | 143.472 | 150.972  |
| 4     | 205.548        | 171.281 | 192.136 | 197.754 | 181.613 | 200.849  |
| 5     | 210.115        | 185.445 | 201.726 | 208.007 | 194.674 | 210.943  |
| 6     | 198.645        | 177.514 | 184.344 | 189.631 | 180.603 | 191.716  |
| 7     | 201.415        | 179.973 | 178.788 | 180.913 | 188.644 | 190.761  |
| 8     | 208.208        | 198.708 | 192.903 | 193.559 | 206.42  | 207.559  |
| 9     | 247.974        | 238.771 | 237.625 | 240.556 | 233.099 | 243.215  |
| 10    | 289.382        | 267.038 | 277.606 | 280.896 | 270.213 | 280.118  |

Figure 4: Displacement at each floor of RC frame without and with VfD at 1st – 2nd floor

Figure 5: Displacement at 10th floor of frame without and with different placement of VfD
Table 4: Comparison of displacement at 10th floor without and with different placement of VfD

| VfD placement | Displacement at 10th floor (mm) | Comparison to w/o VfD (%) |
|---------------|---------------------------------|--------------------------|
| w/o VfD       | 289.38                          | -                        |
| 1st-2nd       | 267.04                          | 7.721                    |
| 3rd-4th       | 277.61                          | 4.069                    |
| 5th-6th       | 280.90                          | 2.932                    |
| 7th-8th       | 270.21                          | 6.624                    |
| 9th-10th      | 280.18                          | 3.180                    |

Figure 6: Time history response of displacement at 10th floor without and with VfD at 1st – 2nd floor

Figure 7: Time history response of acceleration at 10th floor without and with VfD at 1st – 2nd floor

deform horizontally, table 3 seen that all the frame structure has not yet reached the maximum permissible limit.

Figure 6, seen the response seismic of frame structure displacement which given from Kobe earthquake record 1956 at stations 0.1.1. This response located at the top of the structure that moving to the horizontal direction. The graph describes the pattern of wave response at 10th floor not really change definitely, but the displacement is changing following the treatment of the structure’s models.

Acceleration is dynamic, as is structural response. Dynamic time history analysis can represent the dynamic nature of earthquake acceleration and structural response, so that this analysis method can provide more complete information on structural behavior and response.
Figure 7 is the acceleration of data in terms of the time history of the analysis, namely the response on the roof of the building or peak on the 10th floor. More details in figure 6 can be read that in the frame without VfD at 2.13 seconds the highest acceleration occurs at the top of the building is 106.2695 m/s². Compared to the frame with VfD on floors 1st – 2nd, it can be seen that at 2.596 seconds the maximum acceleration at the top of the building is 95.3316 m/s². From these data, there was a decrease in the value of acceleration at the top of the building by 10.293%, which means the value of the building’s performance increased along with the decrease in the value of acceleration.

7. Conclusion
Numerical analysis on six concrete frame models without and with viscous fluid dampers produce several conclusions:
1. The method of installing damper is effective to upgrade the performance of building.
2. Viscous fluid dampers can reduce displacement and acceleration at the top of the building.
3. Relatively, placement of VfD at first and second floor can obtain lower displacement and acceleration compared to other placement method and can meet code requirements.

The recommendation for future research are:
1. Further numerical analysis for existing buildings with recommended placement of dampers is needed for more application purposes.
2. Need an experimental laboratory program to validate the numerical analysis to ensure the prediction behavior of the structural design.
3. Comparison between different methods needs to be further investigated to get a definite conclusion. The application of the methods to the existing building also needs to be investigated.

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