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Control of Wind-Induced Acceleration Response of 46-Story R.C. Building Structure Using Viscoelastic Dampers Replacing Outrigger System

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Abstract
The purpose of this study is to evaluate the performance of viscoelastic dampers (VED) practically used for enhancing the serviceability of a 46-story reinforced concrete residential building structure. Considering that bracing system for the installation of VED is not appropriate for residential building because it occupies large interior space, a method for installing VED at midspan of horizontal beam connecting the core and exterior columns is proposed. These VED control the total structural response in a similar way to general outrigger system. The results from numerical analysis indicate that VED are effective for reducing not only mean components but also fluctuating ones of wind induced responses by providing additional damping as well as stiffness.

Keywords: viscoelastic damper, outrigger, vibration control, high-rise building

1. Introduction
High-rise residential building is increasing in Korea, owing to the rise of the land value and the progress in the construction technology. The development of the new structural system and material makes it possible to design light and slender structures satisfying economical and architectural requirements. However, such structures are vulnerable to the vibration problems induced by the wind load. Especially, the residential building has stricter serviceability criteria on the human discomfort due to the wind-induced vibration the office building, because human behaviors in the former type of building require relatively still residential environment. Usually, engineers try to solve this kind of problem by structural design. However, in some cases, structural design is not able to satisfy the serviceability requirement by itself, and the use of supplementary vibration control devices is considered as a supplementary solution.

Up to the present, most research in the field of structural control has been focused on the analysis and design of control system and the development of the device. However, studies on the problems faced in the practical applications are few in contrast to the increasing number of the buildings with vibration control devices. One of the representative problems is the confliction between the space planning and the place for the installation of control devices. Another problem is on the transportation and construction of the large scale devices. This paper presents a new configuration and construction procedure of the viscoelastic dampers (VED) to solve those problems, which are applied to the Galleria Palace, the high-rise residential building located in Seoul constructed by Samsung Engineering and Construction.

Another feature of this study is the use of the VED in order to supplement the outrigger system, which is one of the well-known structural systems to control the displacement of the high-rise building induced by lateral loads. The outrigger system has limitations in placement similarly to the damper installed between floors, and lengthens construction term resulting into the high cost. Also, the more outriggers are used, the less effect the addition of outrigger has. On the other hand, the VED reduces both displacement and acceleration response effectively by increasing damping capacity of the structure. [1] Generally, the acceleration response is more sensitive to the damping than the stiffness of the structure. Therefore, the use of the VED is able to replace the outrigger system and reduce consequent construction cost, which is demonstrated by the numerical study.

2. Description of the building structure
The structure under consideration is the building ‘B’ that belongs to a housing development located in...
Seoul, Korea. It is a 46 story 149.5 meter reinforced concrete (RC) building composed of a RC core and RC frame, and has outrigger beams with a section of 1.5m × 2.5m in the 15-th floor. [2] The section of the building is presented in Fig. 1. Those outrigger beams connect the core and the wide beams which tie exterior columns. Another outrigger system was planned at the 42-th floor, but decided to be removed in the final design due to the low efficiency in the displacement control and the increase of the construction term. Instead, it was taken into account to utilize supplemental vibration control devices for the purpose of additional reduction of displacement and acceleration induced by wind loads. Particularly, the damping capacity of the device was considered the important characteristics because effective acceleration response control can be achieved by the increase of damping rather than stiffness.

The maximum acceleration of the top floor predicted by the wind tunnel test for the wind loads of 5-year return period is 11.4 mg. The natural frequency of the first structural mode obtained by the eigenvalue analysis is 0.2459 Hz. For this frequency, the peak acceleration limit for serviceability is 14.9 mg according to the ISO 6897. [3] Therefore, the serviceability condition was satisfied. However, the building under consideration had an acceleration level higher than the other buildings in the same housing development due to its relatively large slenderness ratio. To provide equal level of serviceability with occupants in the housing development, it was decided to install VED's in the building 'B'. The objective level of acceleration is 10 mg and the corresponding reduction ratio is 12.28 %.

One of the most well-known and widely-used structural control devices for the high-rise building is the tuned mass damper (TMD). TMD has been applied successfully to many high-rise buildings, but it has several shortcomings such as large installation area, large amount of floor system reinforcement and the dependency on the tuning accuracy. But, the VED is free from such problems because it utilizes neither inertia force of the device nor resonance effect. Also, the VED is cheap and easy to manufacture and install in various forms.

3. Configuration of VED

There are many configurations for the VED, as shown in the Fig. 2. Most of them utilize the relative displacement between two adjacent story diaphragms. To reproduce this relative displacement in the VED, a brace or wall is used as a connection between the structure and damper. However, these types of the connection restrict flexible space planning so that careful examination is required on the stage of design. Also, shear deformation may not be the main structural behavior for certain structural systems. In this case, configurations in Fig. 2 are ineffective.

The part of the considered building above 15-th floor with outrigger system deforms like a moment frame & shear wall system of which general deformation shape is like Fig. 3. As shown in this figure, the rotation angles at both ends of the girder have the same direction. If two deep beams are connected to the core wall and the exterior column, respectively, as represented by the dotted line in Fig. 3, large deformation can be produced between two free ends of both beams due to the rotation in the same direction.

Since the VED dissipates energy in proportion to its deformation, this deformation is appropriate for the effective configuration of the VED. Particularly, if these beams are constructed close to the slab of the

![Fig. 1. Section of the Building 'B'](image1)

![Fig. 2. conventional VED configuration](image2)

![Fig. 3. behavior of the moment frame & shear wall system](image3)
upper floor, flexible space planning is made possible without dividing the interior space.

The mechanisms of the conventional VED configuration using axial deformation of the bracing and the proposed configuration are presented in Fig. 4 (a) and (b), respectively. Horizontal shear deformation of the VED can be neglected since the slab with large in-plane stiffness works as a diaphragm.

![Fig. 4. mechanism of the VED configuration](image)

Also, torsional shear deformation of the VED is neglected because, at the VED location, both beams rotate in the same direction. As a result, the VED was designed as a one-dimensional damper. The maximum bending moment is produced at the joint of the beam and column. Although the large bending moment at the joint requires large beam section and rigid joint, the overall cost does not increase much owing to the relatively cheap value of the steel beam compared to the VED.

4. Optimal placement and number of VED

The placement of the VED can be determined by various optimization criteria and methods. [4,5,6,7] However, the placement and number of the VED should be determined considering not only optimal control performance but also practical and economical points of view. In this chapter, the optimal placement and number of VED is investigated in view of control performance and practicability.

4.1 Control performance

The equivalent damping ratio of structure with VED can be approximately obtained using modal strain energy method as follows [8].

$$\ddot{x}_{S,i} = \ddot{x}_{C,i} + \frac{(\eta_D - 2\ddot{x}_{C,i})}{2} \frac{\phi_i^T K_C \phi_i}{\phi_i^T K_C \phi_i} + \frac{(\eta_D - 2\ddot{x}_{C,i})}{2} \frac{1 - \omega_{S,i}^2}{\omega_{C,i}^2}$$

$$= \ddot{x}_{C,i} + \frac{(\eta_D - 2\ddot{x}_{C,i})}{2} \sum_{j=1}^{N} k_{D,j}(\phi_i^T e \phi_j)$$

(1)

Where $\ddot{x}_{C,i}$ and $\ddot{x}_{S,i}$ are the $i$-th modal damping ratios of the building without & with VED; $\eta_D$ is the loss factor of the VED; $\omega_{C,i}$ and $\omega_{S,i}$ are the $i$-th natural frequencies of the building without & with the VED; $K_C$, $K_S$, $K_D$ are stiffness matrices of the building without & with the VED and stiffness matrix of only VED, respectively; $\phi_i$ is the $i$-th mode shape of the building without the VED; $\phi_{ij}$ is the $i$-th mode shape vector corresponding to only $j$-th VED-related DOF's; and, finally,

$$\mathbf{e} = \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$$

The sensitivity of the equivalent damping ratio, $\ddot{x}_{S,i}$, in Eq. (1) to the stiffness of the VED is as follows

$$\frac{\partial \ddot{x}_{S,i}}{\partial k_{D,i}} = \frac{\eta_D - 2\ddot{x}_{C,i}}{2\phi_i^T K_C \phi_i} \frac{\sum_{j=1}^{N} k_{D,j}(\phi_i^T e \phi_j)}{2\phi_i^T K_C \phi_i}$$

(2)

Since $k_{D,j} = 0$ for the structure without VED, the above sensitivity can be expressed as

$$\frac{\partial \ddot{x}_{S,i}}{\partial k_{D,i}} = \frac{\phi_i^T e \phi_j}{\phi_i^T K_C \phi_i}$$

(3)

Eq. (3) indicates that connecting the VED between the nodes of which relative modal deformation is largest provides the most significant increase of the modal damping ratio. If the control performance is evaluated by the increase of damping ratio, optimal placement of the VED can be obtained directly.

In this study, the first mode shape was considered for finding optimal placement of the VED. Eigenvalue analysis was performed using SAP2000 and obtained mode shape is shown in Fig. 5.

![Fig. 5. The shape of the first mode](image)

It is observed from Fig.5 that upper stories have larger
relative rotation between core and exterior column than lower stories, and the 38-th floor has the largest relative rotation. However, since the variation of relative rotation is very small over 38-th story, optimal placement is determined considering practicability in following section.

4.2 Practical and economical consideration

The VED for controlling responses of building structure is generally installed at a machinery room for practical consideration of space planning and architectural design requirement. Considered building structure, however, do not have any floor for machinery rooms, which forces residential room to be used for the installation of the VED. The operating mechanism of VED proposed in this study requires beams with large depth, which occupies larger interior space. The 15-th and 42-th floors, for the installation of outrigger system, were designed to have relatively higher story height than other floor. Accordingly, these two floors were preferentially considered as a place for the VED, and then the installation placement was finally determined based on the results from dynamic analysis. Final structural design is to install the outrigger at 15th floor and the structural damping is assumed for all modes to have 2% damping ratio. As an input dynamic load, a harmonic load shown in Fig. 6 was used as a concentrated force at top floor for exciting the first modal resonant response. Although actual wind loads are not harmonic, the harmonic load is used for the convenience of analysis under the assumption that the response reduction ratio under both wind and harmonic loads is similar. The VED for the analysis has shear loss modulus $G_v = 3.221 \text{MPa}$ and loss factor $\eta = 1.250$, according to the spec provided by the Unison Co. in Korea. The VED size is assumed to be $400 \times 600 \times 40 \text{mm}$. The numerical analysis was performed using SAP 2000 and Kelvin model was used for representing the VED. Five cases’ with varying installation placements and girder sections were considered in the analysis.

In order to verify that the target acceleration level 10 mg. significantly in spite of installing VED at both 15-th and 45-th floors, which indicates that Case-E is not so desirable from a practical and economical points of view. This is because the relative rotation between the core and the exterior column is small at the 15-th floor. Also, the performance comparison between Case-B and Case-C, and between Case-D and Case-E, indicates that the effect of VED is strongly dependent on the size of transfer beam section and it is important to design and realize transfer beam with sufficient section stiffness and rigid connections. Consequently, Case-C is selected as a final design because it is practical and provides more response reduction ratio than 12.28% necessary for achieving target acceleration level 10 mg.

Table 1 shows the reduction ratio of the top floor acceleration of the structure with the VED. If the identical transfer beam (H-900×300×18×34) and the VED are used, Case-C which installs VED at 42-th floor provides much larger response reduction ratio than Case-A which installs VED at 15-th floor. Cases-B does not enhance the performance of Case-C significantly in spite of installing VED at both 15-th and 45-th floors, which indicates that Case-E is not so desirable from a practical and economical points of view. This is because the relative rotation between the core and the exterior column is small at the 15-th floor. Also, the performance comparison between Case-B and Case-C, and between Case-D and Case-E, indicates that the effect of VED is strongly dependent on the size of transfer beam section and it is important to design and realize transfer beam with sufficient section stiffness and rigid connections. Consequently, Case-C is selected as a final design because it is practical and provides more response reduction ratio than 12.28% necessary for achieving target acceleration level 10 mg.

### Table 1. Top floor acceleration reduction ratio

<table>
<thead>
<tr>
<th>Case</th>
<th>Floor</th>
<th>Beam Section (mm)</th>
<th>Acceleration Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15</td>
<td>H-900×300×18×34</td>
<td>3.18</td>
</tr>
<tr>
<td>B</td>
<td>42</td>
<td>H-600×300×20×40</td>
<td>8.19</td>
</tr>
<tr>
<td>C</td>
<td>42</td>
<td>H-900×300×18×34</td>
<td>15.09</td>
</tr>
<tr>
<td>D</td>
<td>42</td>
<td>H-600×300×20×40</td>
<td>11.29</td>
</tr>
<tr>
<td>E</td>
<td>42</td>
<td>H-900×300×18×34</td>
<td>17.83</td>
</tr>
</tbody>
</table>

5. The planar placement of VED

In the initial design for planar placement of the VED, eight VED’s were supposed to be installed at 42-th floor as illustrated in Fig. 7(a). However, the VED cannot be placed at the place where the vertical facility lines or the transfer girder exist. Accordingly, final design installs five VED’s as illustrated in Fig. 7(b)

In order to verify that the target acceleration response reduction ratio 12.28% in spite of using less VED’s than initially planned, numerical analysis was performed using harmonic load for both X-direction and Y-direction. The analysis results are listed in Table 2 and 3. It is observed from these tables that the effects of the VED’s installed at the same floor are varying according to the direction of placement and the increment of response reduction ratio is decreasing with increasing number of VED. The placements denoted by 1, 2, and 4 in Fig. 7(b) show good control efficiency while installation of the 5-th VED does not bring so much enhancement of control performance. However, for a conservative design, it was finally determined to install five VED’s. Also, additional significant reduction of Y-directional acceleration can be achieved although Y-directional acceleration of the structure without the VED is smaller than the target performance level.
6. Practical Considerations for Construction

The most emphasized consideration in the design procedure was to provide sufficient stiffness with the connection from the transfer beam to the core or the exterior column. This is very important to guarantee the performance expected from the analysis. All steel connections were designed using high-strength bolts considering the field construction as shown in Fig. 8.

![Fig. 8. Supporting beams and connection design](image)

The design of the connection between the steel connection beams and the RC shear wall and column was difficult because of the difference in material and designed using embedded plate, which was anchored by the anchor bolts to obtain sufficient anchorage length and better practicability and represented in Fig. 9. Also, field setting of Embedded plate is presented in Fig. 10. [2]

![Fig. 9. Embedded plate design](image)

![Fig. 10. Embedded plate in setting](image)

During the install process, the most significant difficulty existed in placing the VED and transfer beams at the installation height, since the floor height of the 42-th floor is 4.2m, which is considerably high for lifting heavy steel beam. Because the slab system

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**Table 2.** X-directional control performance

<table>
<thead>
<tr>
<th>Place</th>
<th>Maximum Acceleration (mg)</th>
<th>Reduction Ratio (%)</th>
<th>Increment of Reduction Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o damper</td>
<td>11.40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>10.48</td>
<td>8.07</td>
<td>8.07</td>
</tr>
<tr>
<td>1+2</td>
<td>9.94</td>
<td>12.81</td>
<td>4.74</td>
</tr>
<tr>
<td>1+2+3</td>
<td>9.88</td>
<td>13.33</td>
<td>0.52</td>
</tr>
<tr>
<td>1+2+3+4</td>
<td>9.49</td>
<td>16.73</td>
<td>3.40</td>
</tr>
<tr>
<td>1+2+3+4+5</td>
<td>9.58</td>
<td>15.98</td>
<td>-0.75</td>
</tr>
</tbody>
</table>

**Table 3.** Y-directional control performance

<table>
<thead>
<tr>
<th>Place</th>
<th>Maximum Acceleration (mg)</th>
<th>Reduction Ratio (%)</th>
<th>Increment of Reduction Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o damper</td>
<td>9.83</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>8.57</td>
<td>12.79</td>
<td>12.79</td>
</tr>
<tr>
<td>3+4</td>
<td>7.90</td>
<td>19.65</td>
<td>6.86</td>
</tr>
</tbody>
</table>
was designed against the gravity load of residence building, it was prohibited to put a machine of excessive weight on the 42-th floor slab. To overcome this obstacle, small holes were punched on the slab at the 1/4 span location and a hoist placed on the 43-th floor lifted the VED and transfer beams to the placement height. The distance between the core and the exterior column was measured after stripping the forms. Considering the measured distance, the length of the supporting beams was adjusted.

The final configuration of the VED system is represented in Fig. 11

![Fig. 11. Final configuration of the VED system](image)

7. Conclusion

A new VED configuration for the high-rise building with outrigger system was proposed for the improvement of the serviceability against wind loads. The VED controls the acceleration response by adding damping capacity, while outrigger system controls the displacement response by increasing stiffness. Most of all, the cooperation between the VED and outrigger can reduce the required number of outrigger system and the resulting construction cost. The analysis results turned out that sufficient bending stiffness of the transfer beam is important to activate full capacity of the VED.

In the non-structural point of view, the proposed configuration of the VED enables flexible space planning. However, during the construction, it was required to adjust the number and location of the VED’s to minimize confliction with the building facility lines and transfer girders. The initial design was modified successfully without loss of control performance. Finally, construction procedure without additional reinforcement of the floor system and increase of the construction term was proposed to facilitate the installation of the VED.

As a result, this study could be a practical reference to the similar building projects. Also, future research should be carried out on the maintenance program and performance evaluation of the VED system using measurement system and.

References

3) International Standard 6897 (1984) Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion (0.063 to 1 Hz), International Organization for Standard