Seismic Performance of RC Frame Retrofitted by Steel Plate Slit Damper

Sang-Hoon Oh, Researcher, Research Institute of Industrial Science and Technology (RIST)
Waon-Ho Yi, Professor, Kwangwoon University
Won-Jik Yang, Research Professor, Kwangwoon University
Dae-Eon Kang, Research Professor, Kwangwoon University
Jung-Han Lee, Ph.D. Candidate, Kwangwoon University

Structural Engineering

Damping
Seismic
Shear

2004

CTBUH 2004 Seoul Conference

1. Book chapter/Part chapter
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

© Council on Tall Buildings and Urban Habitat / Sang-Hoon Oh; Waon-Ho Yi; Won-Jik Yang; Dae-Eon Kang; Jung-Han Lee
Seismic Performance of RC Frame Retrofitted by Steel Plate Slit Damper

Waon-Ho Yi\textsuperscript{1}, Sang-Hoon Oh\textsuperscript{2}, Won-Jik Yang\textsuperscript{3}, Dae-Eon Kang\textsuperscript{3}, Jung-Han Lee\textsuperscript{4}

\textsuperscript{1}Professor, Division of Architecture and Architectural Engineering, Kwangwoon University
\textsuperscript{2}Researcher, Steel Structure Research Laboratory, Research Institute of Industrial Science and Technology
\textsuperscript{3}Research Professor, Division of Architecture and Architectural Engineering, Kwangwoon University
\textsuperscript{4}Ph.D. Candidate, Division of Architecture and Architectural Engineering, Kwangwoon University

Abstract
The objectives of this study are 1) to find out the shear behavior and the shear capacity of RC bare frames, and damper-retrofitted RC frames, 2) to evaluate the equation of the shear capacity of RC frames by comparing the Japanese Standard equations and Modified equations adopting the test results for the seismic performance evaluation of low rise RC structures in Korea, 3) to analyze and compare the hysteretic behavior under the lateral loads using the analysis models such as the D-Tri model and the Bi-Linear model. The main variables are the presence of steel plate slit damper. The test results show that the shear capacity of specimen DF-4.2 is 2.8 times as high as that of the specimen BF-4.2 and it presents the fact that the retrofitting effect and the possibility of RC frame reuse with changing the slit damper is verified. A comparison of the results obtained by the Japanese Standard equations and the Modified equations to the test data indicates that the Modified equations are compatible with the test results. And according to the comparison results of the experiment and the analysis show that the D-Tri model and the Bi-Linear model is compatible to analyze the RC bare frame and the damper retrofitted RC frame.

Keywords: RC Bare Frame, Brick-Infilled RC Frame, Damper-Retrofitted RC Frame, Shear Behavior, Shear Capacity

1. Introduction
The crustal activity does not affect directly to the Korea different from the Japan and there is no experience of destructive earthquakes in the past. Also, countermeasures against earthquake disasters such as the seismic capacity evaluation and the seismic retrofitting techniques of low rise RC buildings have not been fully performed However, with more than four hundred earthquakes with medium intensity that centered on off-coastal and inland areas of Korea during the past 25 years, and due to the great earthquakes which occurred recently in neighboring countries, such as the 1995 Hyogoken-Nambu Earthquake with more than 6,500 fatalities in Japan and the 1999 Chi-Chi Earthquake with more than 2,500 fatalities in Taiwan, the importance of the future earthquake preparedness measures is highly recognized in Korea. Most of low rise buildings such as the school and government office buildings utilized for a shelter against disasters are commonly constructed with reinforced concrete moment resisting frame. Since low rise buildings have not adopted seismic designs and have not enough strength against the lateral forces, a critical damage is expected with an earthquake.\textsuperscript{1)}

To prevent the damages, lots of retrofitting techniques are developed in many researches. As mentioned above, Korea is not situated in a high seismic region as China and Japan, retrofitting techniques with the economical efficiency and suitable to the domestic situation are needed.

The primary purpose of this investigation is to find out the shear behavior and the shear capacity of RC bare frames, and damper-retrofitted RC frames and to evaluate the equation of the shear capacity of the specimens, BF-4.2 and DF-4.2 by comparing the Japanese Standard equations\textsuperscript{3)} and Modified equations\textsuperscript{1)} adopting the test results for the seismic performance evaluation of low rise RC structures in Korea and to analyze the hysteretic behavior of the RC frame retrofitted steel slit damper under the lateral loads using the analysis models such as the D-Tri model and the Bi-Linear model.

2. Experimental Investigation
Description of Test Specimen
Test specimens are shown in Table 1 and Fig. 1. Test specimens which are composed of RC bare frame, damper-retrofitted RC frame are manufactured full scale and tested in the laboratory unit.
Table 1. Specimen List

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Longitudinal reinforcement</th>
<th>Hoop</th>
<th>Dimension of Column Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-4.2</td>
<td>8-D22</td>
<td>D10-@300</td>
<td>400×400mm</td>
</tr>
<tr>
<td>DF-4.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BF: RC Bare Frame
DF: Damper Installed RC Frame,
4.2: Span

(1) BF-4.2 Specimen
To calculate the shear capacity and shear behavior mode of the BF-4.2 specimen, Japanese Standard equations⁵) and Modified equations¹) are adapted.

\[ M_{UL} = 0.8 \cdot \alpha \cdot \sigma_{y} \cdot D + 0.5 \cdot N \cdot D \left( 1 - \frac{N}{b_{D}F_{c}} \right) \]

\[ Q_{SU} = 2 \times M_{UL} \frac{h_{o}}{b_{o}} = 16.33 \text{tf} \]

\[ Q_{SU} = \frac{0.053p_{o}^{23}(180+F_{j})}{M/(Q-D)+0.12} + 2.7\left( p_{o} \cdot \sigma_{y} + 0.1\alpha \right) \cdot b \cdot j = 21.73 \text{tf} \]

\[ \text{Japanese Standard}^{5} \]

\[ Q_{SU} = \frac{0.042p_{o}^{23}(180+F_{j})}{M/(Q-D)+0.12} + 2.7\left( p_{o} \cdot \sigma_{y} + 0.1\alpha \right) \cdot b \cdot j = 20.09 \text{tf} \]

\[ \text{--- Modified Equation}^{1} \]

where, \( M_{UL} \): ultimate bending strength (tf-m)
\( Q_{SU} \): ultimate shear strength (tf)
\( \alpha \): dimension of tension reinforcement (cm²)
\( N \): axial force (kgf)
\( \sigma_{y} \): Axial Stress (kgf/cm²)
\( b \): width of column section (cm)
\( D \): depth of column section (cm)
\( P_{t} \): tension reinforcement ratio (%)
\( M/Q \): \( h_{o}/2 \)
\( d \): \( D-5 \text{cm} \)
\( j \): 0.8D (cm)

From the calculation result that \( Q_{SU} \) is lower than \( Q_{SU} \), the BF-4.2 specimen is governed by predominant flexural yielding. The shear capacity can be calculated to 32.66 tf (16.33×2, as two columns).

(2) DF-4.2 Specimen
Prediction of shear behavior mode of steel slit damper is performed by formulas of H. Akiyama and S. H. Oh⁶) for predicting the stiffness and ultimate strength of the steel slit damper. To determine the shear capacity of steel slit damper, 85% of frame yield strength is selected and the slit damper strut is assumed to be governed by predominant flexural yielding.

\[ P_{s} = \left( \frac{t \cdot b \cdot \sigma_{y}}{2H} \right) n = 11.87 \text{tf} \]

\[ P_{s} = \left( \frac{2}{3} \frac{t \cdot b \cdot \sigma_{y}}{\sqrt{3}} \right) n = 22.80 \text{tf} \]

where, \( t \): thickness of the strut
\( b \): width of the strut
\( \sigma_{y} \): yield strength of the strut
\( n \): number of the strut
\( H \): height of the strut
From the calculation result that $\sigma_y$ is lower than $\sigma_P$, the steel slit damper (SS400) is governed by predominant flexural yielding. Generally, ultimate stress of steel is about 2 times higher than yield stress, ultimate strength of the steel slit damper is calculated to 47.46tf, considering ultimate stress of steel (4.11 tf/cm²) after material test and two dampers. Consequently, the ultimate strength of the DF-4.2 specimen can be calculated to 80.12tf by summation of the shear capacity of RC bare frame.

**Materials**
To evaluate the material properties, two kinds of tests are carried out and test results are as follows.

**Table 2.** Tensile Test of Reinforcements  
<table>
<thead>
<tr>
<th>Type</th>
<th>Elastic modulus (tf/cm²)</th>
<th>Yield strength (tf/cm²)</th>
<th>Yield strain ($\times 10^{-6}$)</th>
<th>Tensile strength (tf/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL12t(SS400)</td>
<td>1,975</td>
<td>2.06</td>
<td>2,286</td>
<td>4.11</td>
</tr>
<tr>
<td>D22(SD40)</td>
<td>1,813</td>
<td>4.82</td>
<td>2,656</td>
<td>6.11</td>
</tr>
<tr>
<td>D13(SD40)</td>
<td>1,746</td>
<td>4.28</td>
<td>2,450</td>
<td>6.36</td>
</tr>
<tr>
<td>D10(SD40)</td>
<td>1,870</td>
<td>4.31</td>
<td>2,303</td>
<td>5.96</td>
</tr>
</tbody>
</table>

**Table 3.** Compressive Test of Concrete  
<table>
<thead>
<tr>
<th>Type</th>
<th>Compressive strength (kgf/cm²)</th>
<th>Height (cm)</th>
<th>Area (cm²)</th>
<th>Elastic Modulus (tf/cm²)</th>
<th>Slump (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{ck}=210$ (kgf/cm²)</td>
<td>211</td>
<td>20.2</td>
<td>78.6</td>
<td>103</td>
<td>18</td>
</tr>
</tbody>
</table>

**Test Procedure**
During testing, the specimens are bedded vertically in a steel reaction floor and the loading beam is placed on top of the specimen (Fig. 2). The constant axial force corresponding to 79tf is applied to the top of the loading beam over the each column. To prevent the out-of-plane failure, lateral support beams with rollers are installed on both sides of steel frames. Lateral load is applied using a 300 tf of servo-hydraulic actuator under the displacement control. The first step of lateral loading, $\delta_1$, is set 0.125% of the specimen height. The direction of loading is then reversed. The loading history is shown in Fig. 3.

**Test Results**
The test results including the maximum load and the maximum displacement are listed in Table 5. The shear capacities of the DF-4.2 specimen are 2.8 times as high as that of the BF-4.2 specimen.

**Cracking Patterns and Load Deflection Curve**
Fig. 4 shows crack patterns of each specimen at failure and Fig. 5 shows the load-deflection curve of each specimen. Each specimen undergoes the same loading history. The BF-4.2 specimen showed the maximum strength at 24 cycle (rotation angle: 1/67) and sustained the load until 28 cycle (rotation angle: 1/57). On the other hand, the DF-4.2 specimen showed high stiffness and strength different from those of the BF-4.2 specimen. Moreover, the shear strength is sustained until the slit dampers were cut off in 40mm (19 cycles, rotational angle: 1/80).
The ability of a member to dissipate energy is perhaps the most important aspect of structural performance under seismic loadings. The "energy dissipated" is taken as the area enclosed by the load-deflection curve. In this study, to calculate the energy dissipation capacity more precisely, the hysteretic load-displacement curve is dissolved with the Skeleton part and the Bauschinger part as shown in Fig 6.

The BF-4.2 specimen and the DF-4.2 specimen are both different from the maximum load and the maximum displacement, and to make the criterion of the evaluation of the effect of retrofitting, only the cycles at which the main deformed bar of the column is in yield point are considered in the computation of the dissipated energy $E$. The yield point of the each specimen is presented in Fig. 7, and Fig. 9. As shown in Fig. 7 and Table 6, the BF-4.2 specimen is yielded at 34.82mm(17 cycle, rotational angle; 1/90), and the DF-4.2 specimen is yielded at 46.71mm(23 cycle, rotational angle; 1/67). Especially, in case of the DF-4.2 specimen, the yield state of the main re-bar of the column is appeared after the slit damper is cut off.

And the energy dissipation values based on this criterion are presented in Fig. 10 and table 6.
Fig. 6 Dissolution of Load-Displacement Curve

Fig. 7 Strain Curve of Each Specimen

Fig. 8 Skeleton and Bauschinger Curve of Each Specimen at the Yield State
As shown in Table 6, the DF-4.2 specimen using steel slit dampers as a retrofitting method are outstanding in energy dissipation capacity.

### Table 6. Energy Dissipation Capacity at Yield Point

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield Point Load (tf)</th>
<th>Yield Point Disp. (mm)</th>
<th>Energy Dissipation Capacity at Yield Point ($W_S$, $W_B$, $W_T$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-4.2</td>
<td>28.83</td>
<td>34.82</td>
<td>1,352, 2,739, 4,091</td>
</tr>
<tr>
<td>DF-4.2</td>
<td>38.01</td>
<td>46.71</td>
<td>3,858, 49,750, 53,608</td>
</tr>
</tbody>
</table>

### Comparison of Test Results and Analysis Results

The experimental hysteretic behavior of the BF-4.2 specimen and DF-4.2 specimen is compared with analytical results. To predict and analyze the hysteretic behavior, D-Tri Model is adopted with the bare frame, and Bi-Linear Model is adopted with the steel plate slit damper. In case of the DF-4.2 specimen, both analytical models are simply accumulated. The comparison results as shown in Fig 9 show that the D-Tri model and the Bi-Linear model are compatible with the prediction of RC frame retrofitted with the steel slit damper.

### Conclusion

Based on the test results and the analytical results of these specimens, the following conclusions can be drawn:

1) The shear capacity of the DF-4.2 specimen is 2.8 times as high as that of the BF-4.2 specimen
2) The retrofitting effect and the possibility of RC frame reuse with the slit damper is verified.
3) According to the experimental and analytical results, the D-Tri and Bi-Linear model are compatible to analyze the RC bare frame and steel slit damper retrofitted RC frame.

### References