Seismic Performance Evaluation of Shear Wall Retrofitted with FRP

You-sun Yi, and Sung-gul Hong

Abstract—The study was performed to verify the effect of FRP in retrofitting shear wall by evaluation of energy dissipation capacity of the member. Energy dissipation capacity of member is determined by reinforcement’s strain variation from cyclic behavior. Based on the previously developed method, it is modified by the effect of vertical or horizontal FRP sheet and verified by the comparison with experimental results in this study.

Keywords—Energy Dissipation, FRP, Retrofitting, Shear wall

I. INTRODUCTION

Since earthquake zone is being enlarged around the globe lately, seismic design code provisions have been revised several times. Buildings that built after revision are safe for earthquake; however, existing buildings that was built before revision are not safe for severe earthquake. Since they have to be retrofitted to satisfy new seismic design code provisions, lots of methods for retrofitting have been developed and studied. Although lots of methods have been developed for retrofitting, there exists almost no methods for seismic performance evaluation of retrofitted structural member. This condition may cause the problems about degree of retrofit for members. Therefore, not only retrofitting methods, also methods for evaluating seismic performance are important. This study suggests an evaluation method of seismic performance of shear walls retrofitted by FRP sheet by energy dissipation contribution, which has been derived for ordinary reinforced members.

II. EVALUATION OF ENERGY DISSIPATION CAPACITY

Previous studies about determination of energy dissipation of RC members suggested how to evaluate those of components for flexural members. There are 3 basic assumptions used in this research.

• The strain distribution is linear in the section.
• The steel is assumed to be a perfectly elasto-plastic material. (Bauschinger effect is considered)
• To calculate compressive stress, equivalent rectangular stress block is applied, and tensile strength of concrete is negligible.

Based on these three assumptions, the previous study identifies some behaviors causes energy dissipation in the shear wall section.

• Since concrete is rarely contribute to the energy dissipation of reinforced concrete member, shear wall’s energy dissipation capacity is determined by the cyclic behavior of reinforcement.
• Energy dissipation in the reinforcement can be calculated from its maximum and minimum strain value during its cyclic behavior. It is shown in Fig 1.

Fig. 1 Energy dissipation occurs in the reinforcement

Fig. 2 Energy dissipation occurs in the section during one load cycle

Fig. 3 Shear wall section

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During one cyclic behavior, there occurs one large energy dissipation at the reinforcement of end region, and two small energy dissipation at the reinforcement of center region. It is shown in Fig 2.

Considering these behaviors, the previous study suggested an equation for evaluating shear wall’s energy dissipation capacity.

\[
e_{D1} = 4Ra\rho f_y \phi_y h^2 t \left[ \gamma \left( 1 - \gamma - 2 \frac{\varepsilon_y}{\phi_y h} \right) \right]
\]

\[
e_{D2} = 2Ra\rho_w f_y \phi_y h^2 t \left[ \left( 1 - \frac{\varepsilon'_r}{h} - 2 \frac{\varepsilon'_r}{\phi_y h} \right) + \left( \frac{\varepsilon'_r}{h} \right)^2 \right]
\]

\[
e_D = e_{D1} + e_{D2}
\]

where \( \varepsilon_y \) and \( f_y \) are yield strain and yield strength of reinforcement, respectively. \( \phi_y \) is ultimate curvature of shear wall, and \( c'_r \) is revised neutral axis depth considering \( e_{Dr} \) strain value when curvature of the shear wall is zero.

(1) is contribution of concentrated reinforcement at the end section, and (2) is contribution of web reinforcement uniformly distributed in the section. By using this suggested equation, this study applies it to shear wall retrofitted by FRP sheets, and classify validity.

III. APPLICATION OF FRP RETROFITTING EFFECT

A. Energy dissipation of FRP sheet

Compared to the case of mild steel has obvious plastic part, FRP sheet behaves like perfectly elastic body. It is shown in Fig. 4. Since this study assumed that the cyclic behavior does not affect FRP sheet’s elastic behavior, energy dissipation due to FRP sheet is neglected in retrofitted shear wall’s behavior. Therefore, the contribution of FRP sheet in energy dissipation of shear wall has to be considered in different way. FRP retrofitting revises the c value, depth of neutral axis of the section, and it revises energy dissipation of shear wall section according to the proposed energy dissipation equation from the previous study. Therefore, this study proposes the method for applying FRP retrofitting effect to proposed energy dissipation equation.

B. Retrofitted in vertical direction

Vertically retrofitted FRP shear wall revises the neutral axis depth by inducing vertical force to end of the section. This force is affected by the number of the ply of FRP sheet, its area, and its strain value which depends on the location of FRP sheet. Therefore, this study proposes the equation for evaluating FRP force applied to the shear wall section.

\[
F_f = nE_f \varepsilon_f l_f t_f
\]

where \( n \) is the number of ply, \( E_f \) and \( \varepsilon_f \) are Young’s modulus of FRP sheet and strain of FRP sheet, respectively. \( l_f \) is the length of FRP sheet in horizontal direction, and \( t_f \) is the FRP sheet.

C. Retrofitted in horizontal direction

Horizontally retrofitted FRP shear wall can give confining effect to concrete of shear wall section. Since unconfined concrete strength \( f'_{cc} \) is increased to confined concrete strength \( f'_{cc} \). This contribution can change the c value, depth of the neutral axis. Confined concrete strength value \( f'_{cc} \) can be derived from the (4) and (5). (ACI 440.2R-02 for FRP-wrapped column)

\[
f_f = \frac{\kappa_a \rho_f E_f \varepsilon_{fe}}{2}
\]

\[
f'_{cc} = f'_c \left( 2.25 \sqrt{1 + 7.9 \frac{f'_c}{f'_{cc}} - 2 \frac{f'_c}{f'_{cc}} - 1.25} \right)
\]

where \( f_f \) is confining stress, \( \kappa_a \) is effectiveness coefficient, and \( \rho_f \) is FRP sheet ratio. \( \varepsilon_{fe} \) is effective strain and its value is 0.004.

However, this value from the ACI code cannot be used directly, since this code is based on the column section’s dimension, \( \kappa_a \) value. Considering that \( \kappa_a \) value is 1 for circular column, this study uses \( \kappa_a \) value as 0.5 for shear wall section.

IV. VERIFICATION OF PROPOSED RETROFITTING EFFECTS

To verify proposed methods of applying retrofitting effect to the energy dissipation equation, this study uses experimental results of S. Hiotakis, D. T. Lau, and N. Londono’s thesis. The specimens tested in this experiment are 1500mm wide, 100mm thick. The flexural reinforcement consists of six pairs of reinforcing bars spaced at 280mm, providing a reinforcement ratio of 0.8%. The shear steel reinforcement consists of five pairs of reinforcing bars spaced at 400mm for a reinforcement ratio of 0.5%. Details of the steel
reinforcement of the specimen are shown in Fig. 5. Retrofitted specimens are strengthened by carbon fiber reinforcement polymer (CFRP) sheets. The CFRP sheets are bonded externally on the face of the shear wall by an epoxy matrix. Carbon fiber sheets have a tensile modulus of 230 GPA, a tensile strength of 3,480 MPa, and an ultimate strain of 1.5%. The first strengthened wall (wall No.1) was strengthened with one vertical ply of carbon fiber sheets. The second strengthened wall (wall No.2) was strengthened with two vertical plies of carbon fibers and one in the horizontal direction. Test results are shown in Fig.6.

![Fig. 5 Details of specimen](image)

![Fig. 6 Test results of retrofitted shear walls](image)

![Fig. 6 Ultimate deformation cycle's dissipated energy](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Wall No.1</th>
<th>Wall No.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{max}}$</td>
<td>30mm</td>
<td>50mm</td>
</tr>
<tr>
<td>Plastic length ($l_p$)</td>
<td>750mm</td>
<td>750mm</td>
</tr>
<tr>
<td>Test result ($U_{U2}/U_{U0}$)</td>
<td>12.8 kN</td>
<td>21.0 kN</td>
</tr>
<tr>
<td>Analytical result ($\varepsilon_{\text{U0}}$)</td>
<td>12.6 kN</td>
<td>23.7 kN</td>
</tr>
</tbody>
</table>

This study assumed plastic length as $h/2$, then section’s energy dissipation can be calculated from the last load cycle’s area of load-deformation graph according to the ATC-40, and FEMA-273. (See Fig. 8) The comparison of experimental and analytical results are shown in Table I.

V. CONCLUSIONS

- The proposed methods for applying FRP retrofitting effect can evaluate FRP-retrofitted shear wall’s energy dissipation capacity by using the proposed energy dissipation equation derived from the previous study.
- By this equation, it is possible to evaluate retrofitting effectiveness of shear wall numerically. It makes easy to determine and compare effectiveness of retrofitting methods for the shear wall by comparing energy dissipation capacity.
- Similar to this study, energy dissipation equation derived from the previous study can evaluate retrofitted shear walls with other strengthening materials like steel plate, concrete jacketing and etc. by using revised $c$ value and additional dissipated energy from strengthening materials.

However, this study also has a limitation of using ACI code for column in the case of horizontally retrofitted shear wall by FRP sheet. Therefore, the code for shear wall is needed for more accurate result. Moreover, anchorage of FRP sheet also have to be considered to avoid debonding of FRP sheet. Therefore, this area have to be studied in future study.

REFERENCES