Seismic Assessment and Strengthening Method of Existing RC Buildings in Response to Code Revision

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ABSTRACT

This paper summarized the results of a research program, which aimed at providing effective methods to upgrade the seismic resistance capacity of existing RC buildings to accommodate the current code requirements in Taiwan. The first part of this paper is the research findings of the seismic performance of steel shear panels made of low yield strength steel. The second part is the experimental studies of four prototype RC frames strengthened by the buckling inhibited bracing members. And the third part of this paper is the study of the mitigation methods for seismic pounding of adjacent structures.

INTRODUCTION

The 1995 Huogoken-Nanbu Earthquake caused tremendous lost of human lives and properties. The buildings suffered serious damage or collapse were mostly built before 1981, especially before 1971. This indicates that the old building regulation and design code do not properly regulate the earthquake load and the structural ductility. The 1999 Chi-Chi Earthquake in Taiwan also caused severe damage or collapse of many buildings. Again, these buildings damaged or collapsed were mostly designed and built before 1983, the year the seismic design codes were first released. After the 1999 earthquake, the seismic zoning factors were raised in most area of Taiwan. For example, the earthquake acceleration in Taichung area was increased from 0.23g to 0.33g. As a result, almost all of the buildings in Taichung need to be strengthened according to the new design codes. The objective of this project is to investigate this problem and to work out several effective strengthening measures to improve the seismic resistance capacity of the existing RC buildings. This project consists of three sub-projects, including the understanding of the degree of improper seismic resistance of the existing RC
buildings and the seismic pounding problem of the nearby buildings induced from their excessive lateral displacements, and the development of the two new energy dissipation devices, such as steel shear panel and bucking inhibited braces, to improve the seismic resistance of the structures.

SEISMIC CHARACTERISTICS OF LOW YIELD STRENGTH LYP STEEL SHEAR PANEL

Due to its high strength and stiffness, steel shear walls have been used as the primarily seismic resistant system in the design of new buildings and the strengthen of existing buildings [1,2]. However, thin steel plate is prone to buckle and therefore limit the energy dissipation capacity of the steel plate. Recently, the advancement of metal production technology has made a new type of steel plate available. This type of steel has lower yield strength but higher elongation capacity and is able to deform and hence absorb much energy before it breaks. Another important feature is the low yield ratio, which is beneficial to the spreading of plastic area, and provide better capacity of stress redistribution. The steel shear panel made of LYP steel is able to absorb and dissipate great amount of seismic energy. However, the structural behavior of this type of shear panel is affected by the strain rate. A total of nine specimens were tested to examine its behavior under different loading protocol. Figure 1 shows the design of the specimen. Figure 2 shows the test set-ups. The width-to-thickness ratio of the panel is 50. The boundary flange element is shaved in order to prevent fracture of the connection between flange plate and base plate. This is to avoid the stress concentration and shift the plastic area to the pre-selected position as suggested in a previous research. In this study, the effect of loading history of steel shear panel is examined. Three loading speeds of 2.5, 50 and 100mm/second are selected to investigate the effect of strain rate. The specimen is loaded with gradually increased cyclic loading representing the recursion of seismic load. For each loading speed, three different displacement increment of $\delta y$, $2\delta y$, and $3\delta y$ are adopted in the cyclic loading test.
program. Structural test was stopped when the strength decrease to below 80% of the ultimate strength. Table 1 shows the experimental results.

Discussion of Test Results

Figure 3 shows the typical hysteresis behavior of the shear panel. From experimental study, it is found that the steel shear panel is able to achieve a drift angle more than 5%, which far exceed the required drift angle. It is usually assumed that a story drift angle about 2.5% is close to the collapse stage of the structure. With the deformation of surrounding elements, and with reserve deformation capacity, the drift angle of 5% is believed to be sufficient for the shear panel. Obviously, almost all the specimen tested have a drift angle exceeding 5%, as shown in Table 1. It is found that the difference on the ultimate strength of LYP steel shear panel loaded with slow speed and high speed is less than 16%. With the same loading increment, the effect of the loading rate on the total energy dissipation capacity can be ignored. From Fig. 3 it is also found that the shear panel tested has demonstrated stable and reliable energy dissipation capacity and is insensitive to loading speed or variation of displacement amplitude. The shear panel is proven to be able to dissipate energy efficiently under random seismic loading cycle.

![Fig. 1 Test setups](image1)

![Fig. 2 Design of LYP steel shear panel specimen](image2)

Table 1 Summary of experimental results of LYP steel shear panels

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\omega$ (rad/sec)</th>
<th>$V$ (mm/sec)</th>
<th>Increment of displacement (mm)</th>
<th>Ultimate strength (kN)</th>
<th>Average of ultimate strength (kN)</th>
<th>Drift angle (1/1000)</th>
</tr>
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<tbody>
<tr>
<td>PL1</td>
<td>0.01</td>
<td>2.5</td>
<td>$\Delta y$</td>
<td>203.55</td>
<td>205.45</td>
<td>60</td>
</tr>
<tr>
<td>PL2</td>
<td>0.01</td>
<td>2.5</td>
<td>$\Delta y$</td>
<td>194.25</td>
<td>191.4</td>
<td>60</td>
</tr>
<tr>
<td>PL3</td>
<td>0.01</td>
<td>2.5</td>
<td>$3\Delta y$</td>
<td>186.85</td>
<td>223.08</td>
<td>75</td>
</tr>
<tr>
<td>PL4</td>
<td>0.2</td>
<td>50</td>
<td>$\Delta y$</td>
<td>220.75</td>
<td>228.6</td>
<td>60</td>
</tr>
<tr>
<td>PL5</td>
<td>0.2</td>
<td>50</td>
<td>$2\Delta y$</td>
<td>212</td>
<td>208</td>
<td>70</td>
</tr>
<tr>
<td>PL6</td>
<td>0.2</td>
<td>50</td>
<td>$3\Delta y$</td>
<td>212</td>
<td>222</td>
<td>75</td>
</tr>
<tr>
<td>PL7</td>
<td>0.4</td>
<td>100</td>
<td>$\Delta y$</td>
<td>189.7</td>
<td>202.59</td>
<td>50</td>
</tr>
<tr>
<td>PL8</td>
<td>0.4</td>
<td>100</td>
<td>$2\Delta y$</td>
<td>207.46</td>
<td>220.87</td>
<td>70</td>
</tr>
<tr>
<td>PL9</td>
<td>0.4</td>
<td>100</td>
<td>$3\Delta y$</td>
<td>214.5</td>
<td>232.26</td>
<td>75</td>
</tr>
</tbody>
</table>
The load-deformation characteristics of shear panel are strongly affected by the shear buckling of relatively thin steel plate. Usually, the strength will gradually decrease after shear buckling occurred. The ultimate deformation capacity of the shear panel is also affected by the width-to-thickness ratio of steel panel. From previous study, it is found that if the ratio is kept under 60, stable deformation characteristics can be obtained [5]. In this study, the width-to-thickness ratio of the specimen tested is 50, and the onset of shear buckling is found at a drift angle above 4%. The deferment of shear buckling not only increases the deformation capacity of the shear panel but also reduce damage of the non-structural elements that may attached to the shear panel.

Figure 4 shows the accumulated energy of all the panel tested. It is found that the total energy dissipation is not significantly affected by the loading speed or the displacement increment. Since the seismic excursion is of random nature, this study also showed the insensitivity of the loading protocol, this is beneficial to the application of shear panel as a seismic damper. The steel panel can be effectively used in the retrofit of existing buildings. Experimental studies of RC frame strengthened by the steel shear damper are explained in the next section.
SEISMIC STRENGTHENING OF BUILDINGS USING LOW YIELD BIBS AND SHEAR WALL

Buckling Inhibited Brace (BIB)

Previous experiences show that buildings not designed and constructed according to modern specifications can be seismically insufficient and vulnerable to strong earthquakes. In Taiwan, those buildings are mostly RC buildings, and they need to be rehabilitated to improve their seismic resistance. Buckling Inhibited Brace (BIB) [6] and steel shear wall [5] have been proved to possess characteristics of high strength, high ductility, and stable hysteresis loops. BIB is consisted of load-carrying element and lateral support element. The axial load of the brace is carried by the load-carrying element, while the lateral support element provides lateral support to the load-carrying element to prevent that element from buckling. Shear wall usually uses low yield strength steel as shear carrying element, and when it is properly designed, it will behave satisfactorily as a seismic resistance element. In this study, BIB and steel shear wall are used to strengthen the RC frames, the effectiveness of BIB and steel shear wall are investigated experimentally.

Experimental Program

Focus identical prototype RC frames with a scale factor of 0.8 are constructed. Figure 5 shows the details of the RC frame. One RC frame was tested without any strengthening, and was designated as MRF. The second one was strengthened with a BIB using LYP100 steel as load-carrying element, and was designated as BIB-LYP. The third one was strengthened with a BIB using A36 steel as load-carrying element, and is designated as BIB-A36. The fourth one was strengthened with a steel shear wall with wall plate made of LYP100 steel, and was designated as SSW-LYP. The details of the BIB of BIB-LYP are shown in Fig. 6. The axial yield strength of BIB of BIB-A36 was the same as BIB-LYP. The details of the steel shear wall used are shown in Fig. 2, and the yield strength of the steel shear wall was about the same as BIB-LYP.

Fig. 5 Details of RC frame

Fig. 6 Details of BIB with LYP
Each strengthening member, such as BIB and steel shear wall, was connected to a steel frame made of 4 H200 × 200 × 8 × 12 shapes, as shown in Fig. 7. The minor axis of the H is in the plane of the frame. A flange of the H shape was cut off, as shown in Fig. 8. Shear studs were welded to the web of the H shapes in the plant. The BIBs and steel shear wall along with steel frames were fabricated in the plant. Figures 4 and 5 show the details of the interface of RC frame and the steel frame. The mechanical properties of the steel used are listed in Table 2, and the compressive strength of the concrete at the time of loading test was 21.8MPa, 20.7MPa, 25.0MPa, and 23.7MPa respectively for MRF, BIB-LYP, BIB-A36, and SSW-LYP. Cyclic loading was applied to each test frame at the center of the beam, and Fig. 9 shows the test setup of the frame. Prestress bars were used to transfer applied load, and the beam was always loaded under axial compression.

Test Results and Discussion

Figures 10 ~ 12 shows the crack pattern of BIB-LYP, BIB-A6, and SSW-LYP, respectively, at a story drift angle about 2.5%. The added diagonal brace of BIB-LYP and BIB-A36 introduce large axial force to the column both in tension and in compression. Consequently, cracks were developed mainly in the columns. The SSW-LYP experienced a unsymmetrical deformation of steel shear wall. When loading was applied to the right, the bottom of the vertical stub produced a significant opening between steel beam and RC beam due to the bending moment at the bottom of the stub. Figure 13 shows the load vs. roof

![Fig. 7 Interface of RC frame and steel frame](image)

![Fig. 8 Details of interface](image)

![Fig. 9 Test set-up](image)

Table 2 Steel mechanical properties

<table>
<thead>
<tr>
<th>Steel</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYP (16mm)</td>
<td>98.6</td>
<td>247</td>
<td>48.6</td>
<td>BIB-LYP</td>
</tr>
<tr>
<td>LYP (5.1mm)</td>
<td>95.7</td>
<td>275</td>
<td>45.2</td>
<td>Steel shear wall</td>
</tr>
<tr>
<td>A36 (16mm)</td>
<td>321</td>
<td>457</td>
<td>28.0</td>
<td>BIB-A36</td>
</tr>
<tr>
<td>#6 bar</td>
<td>433</td>
<td>665</td>
<td>22.0</td>
<td>RC frame</td>
</tr>
<tr>
<td>#3 bar</td>
<td>418</td>
<td>601</td>
<td>23.0</td>
<td>RC frame</td>
</tr>
<tr>
<td>4mm bar</td>
<td>259</td>
<td>358</td>
<td>31.0</td>
<td>Spiral</td>
</tr>
</tbody>
</table>
displacement hysteresis loops of the test frames. Compared to the MRF, the stiffness and strength of all strengthened frames are dramatically enhanced. Figure 14 shows the axial force vs. axial deformation hysteresis loops of the BIB in BIB-LYP and BIB-A36 frames. Figure 15 shows the hysteresis loops of shear force vs. relative horizontal displacement of the steel shear wall. The steel shear wall has an unsymmetrical response. It is recommended that a vertical member be added to the steel frame at the left-hand side of the steel shear wall. Table 3 summarizes test results.

The test results showed that buckling inhibited braces (BIB) and steel shear walls are effective in strengthening of existing frames. The stiffness, strength, and ductility of the test frames after strengthening were dramatically enhanced. The details of the interface between RC frame and steel frame used were effective for BIBs and easy to construct. BIBs were able completely develop their strength and ductility. However, the details of the strengthening frame for steel shear wall need further study.

Fig. 10 Crack pattern of BIB-LYP at 2.7% drift angle

Fig. 11 Crack pattern of BIB-A36 at 2.7% drift angle

Fig. 12 Crack pattern of SSW-LYP at 2.4% drift angle

Fig. 13 Hysteresis loops of test frames
Mitigations Methods for Seismic Pounding Between Adjacent Buildings

During the 1985 Mexico City Earthquake, structural pounding was found to be the major cause of many severe damaged or collapsed buildings [7]. In Taiwan, although the building codes of 1982 have been enhanced to incorporate the minimum seismic separation, there are still many existing buildings without proper seismic separations [8]. During the 921 Chi-Chi earthquakes, many tall buildings also suffer pounding damage and hence the mitigation methods are in urgent need.

Numerical Study of Pounding Mitigation Methods

There are many possible strategies for mitigating the structural pounding, such as:

(1) Strengthening individual structures, such as adding shear walls or dampers to the structures to decrease the vibration and pounding of a structure. This method usually increases the seismic resistance capacity of the structure but might cause some space rearrangement of the building.

(2) Adding pounding preventing mechanism between adjacent structures such as rigid links or viscous damping links (shock absorber) [9]. There is no interfering with the space arrangement of the building. But the interaction forces between the two adjacent structures might cause one of the structures suffering larger seismic dynamic force than it originally designed for.

(3) Enlarging the separation between adjacent structures. This is rarely an option for most structures.

(4) Strengthening the impact area to

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Table 3  Test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$P_y$ (kN)</th>
<th>$\Delta_y$ (mm)</th>
<th>$P_{peak}$ (kN)</th>
<th>$\gamma_y'$ (%)</th>
<th>SF (%)</th>
<th>DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRF</td>
<td>116</td>
<td>21.3</td>
<td>163</td>
<td>1.51</td>
<td>100</td>
<td>1.66</td>
</tr>
<tr>
<td>BIB-LYP</td>
<td>324</td>
<td>3.9</td>
<td>798</td>
<td>0.48</td>
<td>490</td>
<td>5.21</td>
</tr>
<tr>
<td>BIB-A36</td>
<td>328</td>
<td>5.4</td>
<td>797</td>
<td>0.66</td>
<td>490</td>
<td>3.79</td>
</tr>
<tr>
<td>SSW-LYP</td>
<td>322</td>
<td>7.7</td>
<td>631</td>
<td>0.75</td>
<td>390</td>
<td>3.33</td>
</tr>
</tbody>
</table>
reduce the damage. This is only valid for light pounding.

This study [10] investigates the first two type of pounding mitigation methods. The previous studies concentrated on the mitigation effects of the viscoelastic dampers and Metallic dampers [11]. In this study, pounding mitigation effects for the following four methods are studied: (1) stiffening, (2) viscous damper, (3) rigid links and (4) viscous damper links.

Two adjacent structures with the same height are first modeled as two SDOF systems. Different period ratios and mass ratios between the two systems are studied. Adjacent structures with different heights are also investigated. Fifteen individual earthquake records are adopted to investigate the averages seismic responses of the adjacent structures with the previous mentioned mitigation strategies; the seismic response of the original structures with 5% damping ratios are used as baseline to demonstrate the effectiveness of these methods. The minimum separation to avoid pounding, the story shear of the structure, and the interaction force between structures are the major parameters investigated. Structural parameters such as height ratio, period ratio, and mass ratio between adjacent structures are discussed.

Discussion of Results

The results are summarized as follows. The detailed results discussions are referred to Refs. 3 and 4.

(1) Among the four methods studied, the viscous damper links and the viscous damper, both provide additional damping to the system therefore reduce the overall seismic response of the system. On the other hand, the stiffening and the rigid links methods both increase the seismic responses of the system and additional strengthen are needed; therefore, they are less desirable.

(2) Viscous damper links (shock absorber) are very effective for pounding mitigation.

1. The optimum damping ratios for the damper links are 5% ~ 10% (r = 1~2).

2. For the cases most likely to cause severe pounding damage to adjacent structures (adjacent structures with large difference in periods, story masses difference, or different heights), the mitigation by damper links is most effective. The reason was that in these cases the large relative velocity between adjacent structures caused large energy dissipation in the damper links.

3. For adjacent structures with different story height, pounding at the middle of the higher structure was known to increase the story shear above the pounding location. However, in this study, it is found that the overall structure responses (including the upper story shear) are reduced after implementing the damper links.

(3) Adding dampers to the two individual adjacent structures are found to reduce the seismic response and promote in phase motion of the structures, therefore reduce the separation requirement and pounding damage.

(4) Rigid links could force the two connected adjacent structure to vibrate in phase therefore eliminate the need for separation. However, when the difference of the period of the adjacent structures is large, the
interaction force between adjacent structures through the links is large comparing to the base shear; also, the upper story shear of the taller adjacent structure could be amplified. Therefore, this method should be adopted with caution.

(5) Stiffening the adjacent structures could reduce the structural periods and hence reduced the seismic displacements and separation requirements.

(6) All of the four methods could be implemented to reduce the separation requirements to 20 ~ 30cm for most existing tall adjacent buildings at Taipei according to limited cases studied.

**SUMMARY AND RECOMMENDATIONS**

This research program investigates methods for strengthening RC structures, so as to upgrade their seismic resistance capacity to meet the increased seismic zoning factor after the 921 Chi-Chi Earthquakes. The LYP steel panels, the BIBS bracing members and several pounding mitigation schemes are studied for strengthening RC structures. These devices and schemes will become the effective means in the retrofit of RC frames.

**LYP Steel Panel**

(1) The yielding strength and ultimate strength of LYP steel is affected by the strain rate. The ultimate strength of shear panel made of LYP steel is also affected by the loading speed. In this study, the difference of ultimate strength of LYP steel shear panel loaded with slow speed and high speed is about 16% in difference.

(2) With proper design and fabrication, the steel shear panel made of LYP steel is able to achieve a story drift ratio of 5% and dissipate large amount of energy.

(3) Under in-plane gravity load, the shear panel will yield first, and with the increase of in-plane load, shear buckling will occur and resulted in tension field action. After the shear panel yield completely, the boundary plate element will participate in dissipating energy at final stage. The whole device will participated in the energy absorption and dissipation.

**BIBS Bracing System**

(1) Test results showed that buckling inhibited braces (BIB) and steel shear walls are effective in the strengthening of existing frames. The stiffness, strength, and ductility of the test frames after strengthening were dramatically enhanced.

(2) The details of the interface between RC frame and steel frame used in this study were effective for BIBs and easy to construct. BIBs were able to completely develop their strength and ductility. However, the details of the strengthening frame for steel shear wall need further study.

**Pounding Mitigation Scheme**

(1) For large building, which was divided into two similar structures, a small (eg. 15cm) separation is recommended. For building which was divided into two dissimilar structures (such as with different heights), they should be considered as regular adjacent structures and designed with the minimum seismic separation as specified in codes.

(2) There exist many uncertainties in pounding mitigation design, such as uncertainties in periods and period's
ratio of adjacent structures, which could significantly influence the outcome of design. Engineers should make necessary assumptions based on engineering judgments.

3) There are many existing adjacent buildings without proper seismic separation in Taipei city. To prevent the loss of lives and property in the future earthquakes, mitigation measures for these structures are in urgent need.

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REFERENCES