Seismic Retrofit Work of School Buildings

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1999 Chi-Chi Earthquake

$M_L = 7.3$

Sept. 21, 1999

Vertical Rupture = 9.0m

Tai-Chung County

Taipei County

GiGi-Earthquake : EW-Component, PGA (gal)

Longitude, E
Seismic Deficiency of School Buildings

If earthquake happened at school hours, death toll could have been much more
Typical Characteristics of School Buildings

- Most vulnerable category of buildings
- Similar in structural system
- Directivity: vulnerable along the corridor
- First story is most critical
- Strong-beam-weak-column
- Poor Concrete strength

Seismic performance depends on columns and walls along the corridor at first story
Column Failures at First Floors
Non-ductile Detailing for Columns

(a) Widely Spaced Hoops

(b) 90° Hooks for Hoops

(c) Splices within Plastic Zones
Magnitude of the Problem

Number of schools for compulsory education (elementary and junior high schools) is larger than 3,000

Number of school buildings for compulsory education is larger than 15,000

collapse or severe damaged

\[ \frac{293}{496} \approx \frac{1}{2} \]
Current Actions

- **Governmental mandate** – all essential public buildings are mandatory to go through the process of seismic evaluation and retrofit.

- **Ministry of Education** promised to allocate a budget of **US $600 millions (NT $20 Billions)** in a time span of **5 years**.
Strategy for School Upgrading

- Screening and prioritization
- Simple
- Reliable
- Systematic
- Cost-effective
Stages for School Upgrading

- Screening...
  - Simple Survey
  - Preliminary Evaluation
  - Detailed Evaluation and Retrofit Design

- Evaluation/Design...
  - Peer Review
  - Yes

- Construction...
  - Inspection
  - Yes
  - Construction
  - END

Data Bank and Networks
Stages for School Upgrading

- **Simple Survey** by school administration through internet
- **Preliminary Evaluation** by P.E.’s through filling templates
- **Detailed Evaluation and Retrofit Design** by P.E.’s
cost effective methods are verified
Auxiliary Measures

- Detailed Evaluation and Retrofit Design conducted by same P.E.
- Peer Review for detailed evaluation and retrofit design
- Inspection for retrofit construction
- Data Bank and Information Networks for survey, evaluation and retrofit
Preliminary Evaluation

- Templates filled by P.E.
- Capacity-to-demand ratios
- **Capacity**: dimensions of columns and walls
- **Demand**: weight and location of buildings
Preliminary Evaluation

Assumptions

◆ Failure along corridor
◆ Dead load 900 kg/m²
◆ Compressive strength 160 kg/cm²
◆ Yield strength of steel reinforcement 2800 kg/cm²
Preliminary Evaluation

- **Capacity**: dimensions of columns and walls
  - $A_{RCC}$ reinforced concrete columns
  - $A_{RCW}$ reinforced concrete walls
  - $A_{BW4}$ four-side bounded brick walls
  - $A_{BW3}$ three-side bounded brick walls

- **Demand**: weight and location of buildings
  - $A_f$ floor area above first floor
  - $Z$ factor for seismic zones
3-side and 4-side bounded walls
Shear Capacity

Three-side bounded brick walls
\[ \tau_{BW3} = 1.5 \text{kg/cm}^2 \]

Four-side bounded brick walls
\[ \tau_{BW4} = 3.0 \text{kg/cm}^2 \]

Reinforced-concrete columns
\[ \tau_{RCC} = 15.0 \text{kg/cm}^2 \]

Reinforced-concrete walls
\[ \tau_{RCW} = 24.0 \text{kg/cm}^2 \]
Fundamental Seismic Performance

\[
E = \frac{\text{Capacity}}{\text{Demand}} = \frac{0.5A_{BW3} + A_{BW4} + 5A_{RCC} + 8A_{RCW}}{10ZA_f}
\]
Modification factor

\[ Q = q_1q_2q_3q_4q_5q_6 \]

- Regularity
- Soft and weak story
- Crack, corrosion and leakage
- Differential settlement
- Redundancy
- Short columns
Seismic Performance Index

\[ I_s = EQ = q_1 q_2 q_3 q_4 q_5 q_6 \left( \frac{0.5 A_{BW3} + A_{BW4} + 5 A_{RCC} + 8 A_{RCW}}{10 Z A_f} \right) \]

- \[ I_s < 80 \]
  - Seriously damaged or collapsed
  - Higher priority for detailed evaluation

- \[ 80 \leq I_s \leq 100 \]
  - Damaged
  - Lower priority for detailed evaluation

- \[ I_s > 100 \]
  - Not seriously damaged
  - No action taken
Simple Survey

- Simplified from the preliminary evaluation method
- Template filled out by school administrators
- Submitted through internet
- All walls are considered as three-side bounded brick walls
Fundamental Seismic Performance

\[ E = \frac{\text{Capacity}}{\text{Demand}} = \frac{0.5A_w + 5A_c}{10Z \Lambda_f} \]

Modification Factor

\[ Q = q_1q_2q_3q_4q_5q_6 \]

Seismic Performance Index

\[ I_s = EQ = q_1q_2q_3q_4q_5q_6\left(\frac{0.5A_w + 5A_c}{10Z \Lambda_f}\right) \]
Simple Survey

\( I_s < 80 \)

Seriously damaged or collapsed
Higher priority for preliminary evaluation

\( 80 \leq I_s \leq 100 \)

Damaged
Lower priority for preliminary evaluation

\( I_s > 100 \)

Not seriously damaged
No action taken
Simple Survey

- 3419 out of 3497 schools (97.77%) completed the simple survey
- 11060 out of 12650 buildings’ data (87.43%) are valid
Floor Plan of Typical School Buildings

- Brick Wall
- Corridor
- Classroom
- Length
Simple Survey (11060 buildings)

Mean = 52.9 m

Building Length (m)
Simple Survey (11060 buildings)

Mean = 11.5 m

Building Depth (m)
Simple Survey (11060 buildings)

No. of Stories

Mean = 2.8

No. of Buildings
Simple Survey (11060 buildings)

Floor area of 1st floor (m²)

Mean = 616 m²

No. of Buildings

一樓樓地板面積（平方公尺）

佔總校舍數之比例（%）
Simple Survey (11060 buildings)

Mean = 4.0 m

No. of Buildings

Column Span (m)
Simple Survey (11060 buildings)

Year of Construction (%)

- **Before 1982**
  - 民國71年之前: 4329 (39%)
  - 民國71 ~ 民國86: 4569 (41%)

- **1982 - 1997**
  - 民國86年之後: 1637 (15%)
  - 其他: 525 (5%)

- **After 1997**
  - unknown: 187 (unknown)
Simple Survey (11060 buildings)

<table>
<thead>
<tr>
<th>No. of Buildings</th>
<th>0 ~ 15</th>
<th>15 ~ 30</th>
<th>30 ~ 45</th>
<th>45 ~ 60</th>
<th>60 ~ 75</th>
<th>75 ~ 90</th>
<th>90 ~ 105</th>
<th>105以上</th>
</tr>
</thead>
<tbody>
<tr>
<td>柱量比（平方公分／平方公尺）</td>
<td>0.78%</td>
<td>16.93%</td>
<td>27.61%</td>
<td>22.57%</td>
<td>13.14%</td>
<td>6.91%</td>
<td>4.34%</td>
<td>7.73%</td>
</tr>
</tbody>
</table>

Mean = 57.0 cm²/m²
Simple Survey (11060 buildings)

Fundamental seismic performance $E$

<table>
<thead>
<tr>
<th>E值</th>
<th>校舍數 (棟)</th>
<th>佔總校舍數之比例 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ~ 20</td>
<td>17</td>
<td>0.15%</td>
</tr>
<tr>
<td>20 ~ 40</td>
<td>485</td>
<td>4.89%</td>
</tr>
<tr>
<td>40 ~ 60</td>
<td>1945</td>
<td>17.59%</td>
</tr>
<tr>
<td>60 ~ 80</td>
<td>2460</td>
<td>22.24%</td>
</tr>
<tr>
<td>80 ~ 100</td>
<td>1990</td>
<td>17.99%</td>
</tr>
<tr>
<td>100 ~ 120</td>
<td>1279</td>
<td>11.56%</td>
</tr>
<tr>
<td>120 ~ 140</td>
<td>1909</td>
<td>9.45%</td>
</tr>
<tr>
<td>140 ~ 160</td>
<td>1157</td>
<td>5.78%</td>
</tr>
<tr>
<td>160 ~ 180</td>
<td>738</td>
<td>3.61%</td>
</tr>
<tr>
<td>180 ~ 200</td>
<td>464</td>
<td>2.23%</td>
</tr>
<tr>
<td>200 ~ 220</td>
<td>266</td>
<td>1.26%</td>
</tr>
<tr>
<td>220 ~ 240</td>
<td>196</td>
<td>0.93%</td>
</tr>
<tr>
<td>240 ~ 260</td>
<td>131</td>
<td>0.64%</td>
</tr>
<tr>
<td>260 ~ 280</td>
<td>94</td>
<td>0.45%</td>
</tr>
<tr>
<td>280 ~ 300</td>
<td>74</td>
<td>0.36%</td>
</tr>
<tr>
<td>300以上</td>
<td>48</td>
<td>0.23%</td>
</tr>
<tr>
<td>300以上</td>
<td>212</td>
<td>1.05%</td>
</tr>
</tbody>
</table>

Mean = 104

44%, $E < 80$

18%, 80 $< E < 100$

38%, 100 $< E$
Simple Survey (11060 buildings)

Modification factor Q

No. of Buildings

Q值 佔總校舍數之比例（%）

校舍數（棟）

0.72 0.85 0.95

0.725 ~ 0.75 0.75 ~ 0.775 0.775 ~ 0.8 0.8 ~ 0.825 0.825 ~ 0.85 0.85 ~ 0.875 0.875 ~ 0.9 0.9 ~ 0.925 0.925 ~ 0.95

No. of Buildings

37 295 647 743 4101 37.08% 2377 21.49% 1955 17.68% 1552 14.03%
Simple Survey (11060 buildings)

Seismic performance index $I_S$

- 55%, $I_S < 80$
- 16%, $80 < I_S < 100$
- 29%, $100 < I_S$

No. of Buildings

校舍數（棟）

佔總校舍數之比例（%）

55%, $I_S < 80$
16%, $80 < I_S < 100$
29%, $100 < I_S$
Annual Budget for Repair/Reconstruction of School Buildings (Ministry of Education)

Budget (Billion, NT)

Year

02' 03' 04' 05' 06' 07' 08'

0.6 2.0 1.5 3.5 4.6 6.2 6.4

0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0
Test Setup
Failure mode: Shear failure of captive columns

$V_{\text{prototype}} = 48.2 \text{ t}$
Retrofit by adding Wing Walls
Test Result(2) – Wing Walls

Failure Modes:
- Beam – Flexural Failure
- Joint – Shear Failure

$V_{\text{retrofit}} = 63.1 \text{ t}$

$V_{\text{prototype}} = 48.2 \text{ t}$
Retrofit by using Steel Jacketing
Test Result(3) – Steel Jacketing

V_{retrofit} = 52.8 \text{ t}

V_{prototype} = 48.2 \text{ t}

Failure Modes:

- Beam – Shear Failure
- Joint – Shear Failure
Retrofit by using RC Jacketing
Test Result(4) – RC Jacketing

Failure Mode: Interior column – Flexural Failure

V_{retrofit} = 88.23 \text{ t}

V_{prototype} = 48.2 \text{ t}