Seismic Diagnosis and Structural Performance Evaluation of Existing Timber Houses in Tokyo

Part 3 Case Study on Low-Rise Apartment Houses

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Abstract
This paper presents the case study of seismic diagnosis and structural strengthening repair work conducted on low-rise timber apartment houses in the downtown district of Tokyo (Sumida Ward, Kyojima). The investigated timber apartment houses are one- to two-story low-rise timber apartment houses built in the middle of the 20th century. The investigated area is known for its densely populated small timber houses and is estimated to be one of the most vulnerable regions against earthquakes in Tokyo. The results of on-site investigations and a seismic diagnosis of three timber apartment houses revealed that the horizontal load carrying capacity of the houses was far below the required values in Japan’s Building Standard Law. The authors conducted structural reinforcement repair work on two of the apartment houses in collaboration with the Center for Urban Development of Kyojima. The structural repair under financial and technological restrictions is discussed together with the need of preserving the cultural background of downtown Tokyo.

1. Introduction
Studies of the structural performance and structural reinforcement repair work of existing timber houses has been increasing slowly. Although the existing timber apartment houses suffered heavy damage by earthquakes, no study has yet been conducted. In a previous investigation, the evaluation of structural performance was a seismic diagnosis based on the result of investigations; however, it was difficult to determine the detailed specifications of the foundations and walls and to confirm the deterioration of a structure. Most of the existing timber apartment houses are old; therefore, their specifications are different from those of today and deterioration of hidden members probably exists.

There are numerous timber apartment houses in areas with densely packed wooden housing. The Kyojima area is one of these areas. The map of 3-chome, Kyojima is shown in Fig.1. There are low-rise timber apartment houses shown as Photo 1. Useful information is obtained through investigations and reinforcement repair work. By examining this information, the structural characteristics of existing timber apartment houses can then be estimated in other areas. This paper presents the results of the investigation and reinforcement work on the structural problems of three existing apartment houses, and discusses the financial and technological problems of the reinforcement work.
2. Methods of Study
(1) On-site Investigation
To detect the materials and deterioration of the walls and roofs, a non-destructive investigation by measurement and observation was conducted. In addition, another investigation was conducted by interviews with the landlords and residents.

(2) Seismic Diagnosis
Based on the results of the investigations, a seismic diagnosis was conducted. House N was evaluated by a general diagnosis. Conversely, houses K1 and K2 were evaluated by a general diagnosis and a detailed diagnosis. The two diagnoses have different ways of calculating the horizontal load carrying capacity of the building. The two calculations for horizontal load carrying capacities \( P_d(Q_d) \) are given in Eq. (1) and (2).

General diagnosis: \[ P_d = P \cdot E \cdot D \quad (1) \]

where \( P \) is the strength, \( E \) is the reduction by the arrangement of structural elements, and \( D \) is the reduction by deterioration.

Detailed diagnosis: \[ Q_d = (Q_{wn} + Q_{ww}) \times F_s \times F_e \quad (2) \]

where \( Q_{wn} \) is the strength of the walls, \( Q_{ww} \) is the strength of the walls with openings, \( F_s \) is the reduction by the stiffness ratio, \( F_e \) is the reduction by the eccentricity. In the detailed diagnosis, \( Q_{wn} \) and \( Q_{ww} \) include the reduction by deterioration.

(3) Reinforcement Repair Work
Reinforcement repair work was conducted on two of the apartment houses. Detailed investigations accompanied by partial destruction of the members were conducted.

3. Results of Investigation and Seismic Diagnosis
Table 1 shows an outline of the apartment houses investigated. The north part of house K2 was not investigated because the resident was very old. House K1 is a popular two-story timber apartment house in Kyojima. House K2 is also a typical one-story timber apartment house in Kyojima. House N is not in the same area. However, the floor space and the specifications of the roof and walls are the same as those of house K1. In some places in Kyojima, tinplate roofing is used instead of tile. The specification of the walls is mainly mud in all three houses. Therefore, this structural element is mainly mud wall. The plans and results of the general diagnosis are shown in Fig. 2. Each result of the general diagnosis is described as follows.
Table 1. Investigated Timber Apartment Houses in Tokyo

<table>
<thead>
<tr>
<th>Location</th>
<th>House K1</th>
<th>House K2</th>
<th>House N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of Construction</td>
<td>Sumida, Tokyo</td>
<td>Sumida, Tokyo</td>
<td>Taito, Tokyo</td>
</tr>
<tr>
<td>Floor Space (m²)</td>
<td>1F 52.9 2F 39.7</td>
<td>1F 75.9</td>
<td>1F 59.6 2F 56.3</td>
</tr>
<tr>
<td>Spec. of roof</td>
<td>Tile-roofing, partly tinplate</td>
<td>Tile-roofing</td>
<td>tinplate</td>
</tr>
<tr>
<td>Spec. of wall</td>
<td>outer wall, Mud wall, partly board wall</td>
<td>outer wall, Mud wall</td>
<td>outer wall, Mud wall, partly tinplate</td>
</tr>
</tbody>
</table>

Table 2. The Judgment of Structural Performance

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Judgment</th>
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<tbody>
<tr>
<td>1.5 ~</td>
<td>Safe</td>
</tr>
<tr>
<td>1.0 ~ 1.5</td>
<td>Low Possibility of Collapse</td>
</tr>
<tr>
<td>0.7 ~ 1.0</td>
<td>Possibility of Collapse</td>
</tr>
<tr>
<td>~ 0.7</td>
<td>High Possibility of Collapse</td>
</tr>
</tbody>
</table>

(1) House K1: The evaluation in both directions was under 0.7, and the judgment was “High Possibility of Collapse”. (Table 2) The evaluation was low because the shear walls were not adequate in both directions. Because the reduction of eccentricity was 0.45 in the X direction, the evaluation was 0.13. It is far below the other direction. There was an earthen floor along the road on the east side. The earthen floor did not have a wall in the X direction at all and all the facades along the road were openings. Therefore, the shear walls of the east side did not add enough support and the eccentricity occurred. Also, the strength of the walls had the reduction of connections because the connections had no metal fastener (Photo 2).
(2) **House K2:** The foundation is categorized into three classes according to the specifications. Table 3 shows the three classes of the foundation. The specification of the foundation of house K2 was not clear; therefore, a diagnosis was made by the specifications for Foundation 2 and Foundation 3. Figure 2 shows the evaluation for Foundation 3. The evaluation in the X direction was 0.55, and the judgment was “High Possibility of Collapse”. The evaluation in the Y direction was 0.81, and the judgment was “Possibility of Collapse”. The evaluation in the X direction was low because the shear walls were not adequate in the X direction. The Y direction has the reduction by eccentricity. The strength of the walls had the reduction of connections because the specification of the foundations was stone and the connections had no joint metal (Photo 3).

(3) **House N:** The evaluation in the X direction was 0.32, and the judgment was “High Possibility of Collapse”. The evaluation was low because the shear walls in the X direction were not adequate. The evaluation in the Y direction was 0.94, and the judgment was “Possibility of Collapse”. The evaluation was nearly 1.0 because the outer walls and the walls on the boundary of the dwelling unit were adequate. Because the rot of the column and the damage of the wall were found by on-site investigation, a reduction by deterioration occurred.

<table>
<thead>
<tr>
<th>Table 3. Specification of Foundation</th>
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<tbody>
<tr>
<td><strong>Foundation 1</strong></td>
</tr>
<tr>
<td><strong>Foundation 2</strong></td>
</tr>
<tr>
<td><strong>Foundation 3</strong></td>
</tr>
</tbody>
</table>

**Photo 2. Column Base (K1)  Photo 3. Column-Beam Connection (K2)**

### 4. Results of Reinforcement Repair Works

We conducted two reinforcement repairs. This section reports the plan and a description of the work on house K2.

#### 4.1 Plan

There is a resident in the dwelling unit on the north side. The dwelling unit on the south side is used as a nursing care center several times per month. We made a plan to conduct the repair work on only the unit on the south side as the first step of step-by-step repair work. The places of reinforcement were determined with attention to the following points: 1) the Japanese-style room in which a senior citizen resides was reinforced, 2) the places of reinforcement are arranged equally in a plane. Figure 3 shows the places of reinforcement. During the planning of the reinforcement repair work, the landlord hoped to leave the atmosphere as it was and avoid darkening the Japanese-style room. Therefore, No. 2 and No. 4 in Fig. 3 were reinforced by structural plywood with uncovered columns and No. 5 was reinforced by a brace of stainless steel. We conducted the reinforcement on the openings where the sliding door was not usually used (No. 1, No. 3, No. 5). After the reinforcement repair work, the existing foundation was not able to resist the pull-out force of the columns. Therefore, it was replaced with a new reinforced concrete foundation (Fig. 4).
4.2 Detailed investigation
We dismantled the floor of house K2 and investigated underneath prior to the reinforcement repair work. We found that the foundation was concrete. But, it was too old; therefore, it was removed and a new foundation was added. Also, the sill was decayed intensely; therefore, it was also replaced with a new one.

4.3 The enforcement of the reinforcement work
The main work projects are as follows.

(1) Foundation work: After the existing foundation and sill were removed, a foundation of reinforced concrete and sill, to which a disinfectant was applied, was added.

(2) Reinforcement by structural plywood: In No. 1 and No. 6, structural plywood was nailed on the columns and horizontal members. Whereas, in No. 2, No. 3 and No. 4, structural plywood was fixed on the columns and horizontal members through the member nailed them. A column would show on the surface of the wall by doing this. In addition, work was conducted to maintain Nageshi, horizontal pieces of timber in the frame of Japanese-style houses. For example, opening was replaced with structural plywood in No.1 and mud wall was replaced with structural plywood with uncovered column in No.2 (Fig. 5, Photo 4). Consequently, the atmospheres did not change.
(3) **Openings of reinforcement by brace**: In No. 5 the reinforcement was a brace φ 9 mm of stainless steel, which does not darken a room. After cutting only the reinforced part of the spandrel wall and locating the column, the brace was installed. The brace touched the existing sash; therefore, the sash was removed. It was fixed on the frame, which was nailed on the column from the outside again (Fig. 6). In addition, the paper sliding door, which became unnecessary by the reinforcement in No.1, was nailed from the inside (Photo 5).

(4) **Reinforcement by wooden brace**: In No. 7 the wooden brace was added (Photo 6). The finish of the outer wall was the wood siding using calcium silicate board.

![Fig.6. Detailed Section of Stainless Steel Brace](image)

![Photo 5. Paper Sliding Door (No.5)](image)

![Photo 6. Reinforcement by Wooden Brace (No.7)](image)

### 4.4 The evaluation after the reinforcement work

Table 4 shows the evaluation of the detailed diagnosis after the reinforcement repair work. The evaluation did not change due to the result of the detailed investigation. However, by using structural plywood for the repair of the external wall on which there was intense damage, the evaluation in the Y direction rose.

<table>
<thead>
<tr>
<th></th>
<th>Before Reinforcement</th>
<th>Plan</th>
<th>After Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>0.52</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>Y</td>
<td>0.70</td>
<td>0.98</td>
<td>1.13</td>
</tr>
</tbody>
</table>

### 5. Discussion

#### 5.1 The characteristics of the building

Compared with the evaluations of the span direction (Y), the evaluations of the ridge direction (X) were low for all three apartment houses from the result of the seismic diagnosis of each building. The apartment houses have openings in the ridge direction and did not have partitions (Photos. 7 and 8). The evaluation of the span direction (Y) will change depending on whether there is an opening or not in the external wall. In other words, the ridge direction (X) needs to be reinforced in these apartment houses. However, because there are few existing walls, there will be many cases in which there are not enough strength if they are reinforced. Therefore, it is necessary that new structural elements are built in openings which have not been used and on the earthen floors.
5.2 Deterioration of the member
Detailed investigations by partial destruction of the members were conducted. The surface of the column bases visible on the outside had deteriorated. Most sections of some column bases had termite damage and decay (Photo 9). In addition, the sills decayed in houses K1 and K2 (Photo 10). The height of the beam for the foundation was low; therefore, the sills were decayed from ground moisture. In contrast, the column tops and the horizontal members were not decayed. In a building similar to these, the partial loss of sections by deterioration, which influences the structural performance, may occur in the hidden members. Therefore, the investigation by breaking part into a floor and a wall or using a fiberscope has to be conducted to evaluate their seismic performance correctly.

5.3 The existing foundation
Table 5 shows the foundation of the investigated houses. In cases in which the surface of foundation deteriorated and is buried underground, it is difficult to investigate their material. The specification of the foundation is important to make the reinforcement plan. Therefore, it was investigated carefully.

<table>
<thead>
<tr>
<th>House</th>
<th>Specification of Foundation</th>
<th>Method of Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>Stone (oyaishi)</td>
<td>Observation and Partial destruction</td>
</tr>
<tr>
<td>K2</td>
<td>Concrete</td>
<td>Observation and Partial destruction</td>
</tr>
<tr>
<td>N</td>
<td>Concrete</td>
<td>Observation</td>
</tr>
</tbody>
</table>

5.4 The reinforcement repair work
To show the effect of the reinforcement on which there is no foundation means building a new foundation. However, the foundation work greatly influences the time and work cost. The reinforcement to the earthen floor for where there is no floor and no place needs to jack up the building was easy to carry out. Namely, it would reduce time and cost. Therefore, it is necessary to consider the simple reinforcement techniques. The
frames were reinforced by structural plywood mainly. Most structural plywood touched the orthogonal walls and beams; therefore, it was nailed through the members or part of the plywood was cut. The horizontal strength of the reinforcement by structural plywood in this case should be evaluated in detail. In the reinforcement by structural plywood with uncovered columns where mud walls were removed, a large quantity of dust resulted. Therefore, it was necessary to devise how to do the work if a resident was living there. In the case that new structural elements were built, e.g., as reinforcement to the earthen floor in K1 (Photos 11 and 12) and reinforcement by brace to the opening in K2 (Photo 13), the designer should determine the place of reinforcement in consultation with the resident about directions for use. These reinforcements are effective for apartment houses that have a long frontage.

6.Conclusion
We conducted investigations on three timber apartment houses. In addition, we conducted detailed investigations and structural reinforcement repair work on two of these houses. The seismic performance in the ridge direction of the existing timber apartment houses was generally below the required values in the Building Standard Law. The deterioration of structural members was found by detailed investigation. We needed to evaluate the seismic performance to evaluate the degree of deterioration. The foundation work was conducted with reinforcement of the frames. The reinforcement in the ridge direction was conducted by reinforcement of the openings and earthen floors. The financial and technological problems were understood. In the future, we need to quantify the deterioration found by our detailed investigations and verify the seismic performance and the reinforcement in the ridge direction in these cases.

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