Case Study of Combination Ways of Timber and Steel in Japanese Buildings

Hiroshi Isoda 1, Naohito Kawai 2 and Mikio Koshihara 3

ABSTRACT: Some mixed members and structure consisting of timber and steel have been developed recently. As one of the background, revision of the Building Standards Law in 2000 allowed the construction of timber-based buildings four stories or taller with fire-resistance performance. Some examples of combination ways of timber and steel member are presented in the paper. They are not only members but also connections and structures. These hybrid structures may lead to new utilization of steel material.

KEYWORDS: mixed structure, steel, mid-rise building, large-scale building, earthquake, fire-proof

1 INTRODUCTION

Steel is key materials and members in new timber buildings as well as in retrofitted old buildings. In new buildings, connections such as nails, bolts, plates and so on are made of steel and steel member such as plate and bar also used. The purpose of utilization of steel is mainly reinforcement of stiffness and strength of timber members. Photo 1 is a mid-rise timber wood frame apartment in the US with steel construction of the base. The weight of steel connections including tie-down system which is used for resisting uplift of the building is about 10% in woodframe story. Recently, steel begins to be used for fire resistance in timber-based members. This method and member will be discussed in the next chapter. In retrofit measurement of timber old buildings, various kinds of steel members and structures are used to enhance the performance against vertical force and horizontal force. Figure 1 is an example of reinforcement against vertical load in famous hall of the Great Buddha in Todai-ji Temple (height: 46.8m, area: 2878m²). As mentioned above Steel plays an irreplaceable role in timber buildings.

This paper describes a state of the art of hybrid building system of timber and steel. It consists of three parts. First, the national project of hybrid timber structure is introduced [1][2]. Second, five story steel and wood composite structure is shown [3]. Third, seismic distribution for mid-rise timber with steel or R/C structure on the bottom is described.

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2 R/D PROJECT OF TIMBER-BASED HYBRID STRUCTURE

The effective utilization of timber is urged from the point of preservation of natural resources and global environment also in Japan. And the effective composite of timber and other materials is expected to extend the possibility of building structures because of the possibility to realize high performance in both structural safety and fire safety. The Building Standard Law (BSL) of Japan was revised in June 1998 and the potential to accept large-scale and high-rise timber buildings was added with provisions of performance-based code.
Before the revision, only large scale buildings such as dome and gymnastic hall have been able to be constructed under special approval of ministry. Structurally effective composite systems also have been used in dome and gymnastic hall constructions. After the revision, the composite system began to be used for the purpose of both fireproof measurement and high structural performance.

According to the current BSL of Japan, the main structural members such as columns, beams, floors and walls for buildings with more than four stories are required 1 hour performance in fireproof. Table 1 briefly shows the requirements of fireproof performance for members in accordance with the stories of the building. According to the BSL, five stories building is required 2 hour fireproof performance at the first story and 1 hour performance at from the second to the fifth story. For considering the fireproof performance of timber base members, some fire tests were executed. Based on the testing method under the BSL to confirm the 1 hour fireproof performance of members with combustible materials, members are exposed to the fire for 1 hour and left in the furnace for 3 hours and confirmed that they can support the load even after the test, it means, they can support the load during the test and there is no fear to lose the ability by re-ignition, progress of char, or a rise of temperature after the test. In case of members with 2 hour performance in fireproof, 1 hour is replaced by 2 hours and 3 hours is replaced by 6 hours in the above explanation.

As the results of some tests, floors and walls with covering of gypsum boards or other non-combustible materials with some construction methods were revealed as 1 hour or 2 hour fireproof performance member. The examples are shown in photo2 which has 2 hour fireproof performance in woodframe construction which is so called as “2x4 construction” in Japan and a major construction method in the US. Some walls and floors with 1 hour fireproof performance have been developed and the details between them have been examined and tested. Now a manual for woodframe construction with fireproof performance is published and the buildings can be built only with test result certifications. Table 2 shows the number of buildings with fireproof performance surveyed by the Japan 2x4 home builder association.

Table 2: Number of Woodframe Construction with fireproof performance (update September 2009)

<table>
<thead>
<tr>
<th>Number of floors</th>
<th>Number of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>184</td>
</tr>
<tr>
<td>3</td>
<td>859</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

*Fire proof performance is required with all stories building in fire protection area

![Figure 2: Examples of members whose fireproof performance was confirmed](image)

Table 1: Requirement of property to withstand the heat under BSL

<table>
<thead>
<tr>
<th>Parts of buildings</th>
<th>Stories of buildings</th>
<th>Uppermost story, and second to fourth stories from the uppermost story</th>
<th>Fifth to fourteenth stories from the uppermost story</th>
<th>Fifteenth story or more from the uppermost story</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Walls</td>
<td>Partition walls</td>
<td>1 hour</td>
<td>2 hours</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td>External walls</td>
<td>1 hour</td>
<td>2 hours</td>
<td>2 hours</td>
</tr>
<tr>
<td>Columns</td>
<td></td>
<td>1 hour</td>
<td>2 hours</td>
<td>3 hours</td>
</tr>
<tr>
<td>Floors</td>
<td></td>
<td>1 hour</td>
<td>2 hours</td>
<td>2 hours</td>
</tr>
<tr>
<td>Beams</td>
<td></td>
<td>1 hour</td>
<td>2 hours</td>
<td>3 hours</td>
</tr>
<tr>
<td>Roofs</td>
<td></td>
<td>30 minutes</td>
<td>30 minutes</td>
<td>30 minutes</td>
</tr>
<tr>
<td>Stairs</td>
<td></td>
<td>30 minutes</td>
<td>30 minutes</td>
<td>30 minutes</td>
</tr>
</tbody>
</table>

More than 1000 buildings have completed since the revision.

For columns and beams construction, two member types are found to be solutions of fireproof members with using timber based material. One is the type of members with covering of gypsum boards or other non-combustible material, but this type dose not fascinate designers and owners because the same texture and space are achieved using steel members which are cheaper than timber and easy to use. Another is the type of members with shape steel inserted. This type members have, if made with some special construction specifications, the self-extinguish property. They are burnt when exposed to the fire but the progress of char stops while left in the furnace after the exposure to the fire. Figure 2 shows examples of members whose 1 hour fireproof performance was confirmed in the tests.

For the multi-story timber building, the first and/or second story are used for shops, parking lot normally. Main construction material of their stories is a reinforced concrete and a steel frame. They are also effective to anchor the uplifting load and to support inside steel member of composite column.
3 Five story post and beam timber based composite building

The five-story Kanazawa M Bldg shown in photo 3 (height: 14.237 m, area: 6.195 m x 12.100 m) was constructed in Kanazawa City, Ishikawa Prefecture. The first story has a reinforced concrete structure and the second to fifth stories have a timber based composite structure with built-in steel materials as shown in Figure 3. The floor plan and elevation are shown in Figure 4. The building mainly uses the structural members to satisfy the requirements for vertical load performance and seismic performance. So this building is also required fire resistive construction, and structural elements are required 1 hour fire resistive period.

Photo 3: M-Bldg.

Figure 3: Cross section of column beam and brace

Figure 4: Plan and elevation
Similar to ordinary timber buildings, a five stories timber based composite structure requires verification of its safety against self weight, live load, vertical load by snow coverage, and horizontal load under a horizontal force, such as an earthquake or wind. Fire resistive buildings are also required to maintain building integrity in the event of a fire. Based on these structural performance requirements, the following structural verification was conducted (Koshihara)

3.1 Vertical Load

The timber and steel frame function together as a structural member in the second to fifth stories of a timber based composite structure. To clarify the function of the timber and the steel frame about each member, the joint was designed as follows:

(1) Beam
Since the vertical deformation is equal between the timber and the steel beam, vertical load should be shared depending on their ratio of flexural rigidity, EI. The flexural rigidity ratio $\frac{E_1}{\Sigma E_1}$ is shown in Table 3. The timber and steel frame of the beam are joined at a beam edge using drift pins to transmit the load from the timber to the steel frame, so the steel frame supports all the shear force at the edge. The gusset plate from the steel bar of the column and the steel plate of the beam are joined with high tension bolts. The holes in the side of the timber beam are filled with timber after high tension bolts are clamped. Snow load stress on both the timber and steel frame of the beam are designed not to exceed the short-term allowable limit, even in the very rare case of a snow load with a vertical depth of 1.2 m.

(2) Column
Vertical load is transmitted to the steel bar of a column through a gusset plate, and vertical loading of the timber is avoided through a 2.5 mm clearance, which is essential for combining the timber with the steel frame. The column also supports vertical load only using the steel frame, and when the timber collides against the bearing plate, the vertical frame. The timber has a bearing plate of the column, and the steel beam of the beam are joined by a 2.5 mm clearance. The holes in the side of the timber beam are filled with timber after high tension bolts are clamped. Snow load stress on both the timber and steel frame of the beam are designed not to exceed the short-term allowable limit.

3.2 Horizontal Load

The structural planning of the building is different from each direction. A timber based composite beam is suspended laterally and supported by columns of identical material, and the longitudinal beam is built in a reinforced concrete slab. Seismic force at the damage limit produces greater horizontal force than the load exerted by very rare wind, as prescribed in the BSL, so horizontal resisting elements are braces the lateral roof face and the longitudinal plywood walls.

| Table 3: Flexural rigidity ratio of timber and steel frame |
|-------------|-----------|---------------|----------------|-------------|
|             | $E_1$ (N/mm) | $I_1$ (mm$^4$) | $E_1I_1$ (Nmm$^2$) | $E_1/\Sigma E_1$ |
| Timber frame | 1.05x10$^6$ | 5.55x10$^8$ | 0.583x10$^{12}$ | 0.366 |
| Steel frame  | 2.05x10$^7$ | 4.95x10$^9$ | 1.01x10$^{13}$ | 0.634 |

A lateral timber based composite structure meets the safety requirements. The steel column produces a reaction force of braces during an earthquake. The column does not buckle when the steel column yields to axial force. Vertical shear force is transmitted from the plywood shear wall to the column through the vertical frame. The column has a bearing plate of the steel plate (PL-19) at both ends of the column, and the column is clamped against the bearing plates. Axial force is transmitted to the steel frame of the column. Therefore, during an earthquake, the timber functions as a buckling restraint.

(3) Brace
A brace bears axial force during a lateral earthquake. Only one steel frame (PL-22x65), at the center, contributes to the structure as the steel frames. Buckling of the brace is not observed under significant plastic deformation of the steel frame by compression axial force.

(4) Plywood shear wall
Plywood shear walls resist horizontal force during a longitudinal earthquake, and consists of structural plywood (thickness: 24 mm), screws (diameter: 8 mm) and both vertical and horizontal frames of laminated timber arranged around the plywood. Shear force is transmitted from the structural plywood to both the horizontal frame and the downstairs plywood shear wall through anchor bolts (M16) embedded in the reinforced concrete slab.

After Fire

(1) Beam
Only the steel frame supports vertical load on the assumption that the timber had burnt completely. Although timber actually stops burning, the remaining timber cannot be used as a structural member under current BSL. The vertical load is assumed to be the same as before a fire, and for safety reasons, the steel frame stress should not exceed the long-term allowable limit.

(2) Column
The column also supports vertical load only using the steel frame, and the stress applied should not exceed the long-term allowable limit for buckling.

(3) Brace
Timber of a brace is also assumed to have completely burned. The wind pressure, at the maximum momentary wind velocity of 15 m/s, is set as the constant wind load, and both brace tension and beam bending resist the lateral horizontal force. The frame stress is prevented from exceeding the short-term allowable limit.
(4) Plywood shear wall
Plywood shear walls are assumed to have completely burned out.
(5) Longitudinal RC beam
A reinforced concrete slab has a built-in reinforced concrete beam in the longitudinal direction of the edge. The rigid frame structure composed by the RC beam and the steel par of the column resists the longitudinal horizontal force produced by the constant wind.

4 SEISMIC DISTRIBUTION

4.1 SRSS Analysis

Seismic force distribution of story shear coefficients according to the vibration characteristics of building is calculated using "Ai distribution" defined in Japanese Building standard law notification No.1793 as shown in the following equation.

\[ Ai = 1 + \left( \frac{1}{\sqrt{\alpha_i}} - \alpha_i \right) \cdot \frac{2T}{1 + 3T} \]  

(1)

\( \alpha_i \) : the value obtained by dividing the sum of the seismic vertical load of the parts supported by the height which is used to calculate for Ai of the building by the sum of the seismic vertical load of the building above ground, T: the fundamental natural period of building in seconds obtained by following equation.

\[ T = h(0.02 + 0.01\alpha) \]  

(2)

\( h \) : the height of the building in meters, \( \alpha \) : the ratio of the total height of stories of steel construction and wood construction of the building

In case of timber based composite structure composed of stiff and heavy structure at the bottom and soft and light weight timber structure on the top story, Ai distribution based on BSL can be used but following equation, which is called as the SRSS analysis, recommended.

\[ A_i = \left( \sum_{j=1}^{N} \left( \sum_{m=1}^{N_m} W_m \cdot \beta_j \cdot u_{w,m} \cdot R(\tilde{T}) \right)^2 \right)^{1/2} / \sum_{m=1}^{N_m} W_m \]  

(3)

\( N \): the number of stories, \( W_m \): the weight of m story, \( \beta_j \cdot u_{w,m} \): Participation vector in j-th mode, \( R(\tilde{T}) \) : the design spectral coefficient in natural period \( \tilde{T} \)

Numerical result of two cases for timber based composite structure to confirm the applicability of Ai distribution will be described below.

3.2 CASE STUDY 1

The SRSS analysis is conducted to evaluate the seismic distribution in composite structure. Table 4 shows the parameter of the seismic weight of the structure. In this case study, five stories building with reinforced concrete first story is assumed because the building can built with 1 hour fireproof members and it is practical. The weights of M1 and M2 are extremely lighter than the reinforced concrete structure, because it is not necessary to consider the fire-proof measurement. M3 is assumed as the structure consisting of members with fire proof performance. The weight of the steel structure is the same as the wooden structure and the stiffness of the steel moment resisting structure is also the same as the wood. Bracing structure is regarding as the stiff structure in the same weight. Table 5 show the combination of the story drift under the Ai seismic distribution defined by the BSL. The stiffness at each story is calculated from combination of mass and shear force.

Figure 5 shows the result of the SRSS analysis. Ai distribution is also put in the same figure in natural period calculated from both equation (2) (To) and modal analysis(To). In this analysis \( R(\tilde{T}) \) is assumed as 1.0. Ai distribution from To is reasonable for 4 and 5 story building but it underestimates for 3 story building. Natural period calculated from modal analysis is reasonable for 3 story building.

<table>
<thead>
<tr>
<th>Table 4: Combination of seismic mass (kNm²)</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Roof</td>
</tr>
<tr>
<td>Normal</td>
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<tr>
<td>R/C Floor</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5: Combination of story drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Timber</td>
</tr>
<tr>
<td>R/C</td>
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</tbody>
</table>

4.2 CASE STUDY 2

The SRSS analysis and time history analysis are conducted for the seven stories structure of NEESWood project. Seven ground motions which are 1940 El Centro, 1994 Canoga part, Rinaldi, 1995 JMA Kobe JR Takatori, 2003 k-net Ojiya, and BCJ artificial wave were used in elastic time history analysis for lumped mass model. Figure 6 shows the result of the SRSS analysis in bracing steel first story and six story building without steel story. Ai distribution without steel story expresses from the second story to compare the case of with/without steel. The shear force of second story which is the bottom story is 20% higher than that of the first story without steel bracing story. Figure 7 show the result of time history analysis. The SRSS analysis is reasonable in this case.
5 CONCLUSIONS

The hybrid structures of timber and steel have the potential to produce fascinating architectures [4]. And they also have the potential to reinforce timber member and joint and enhance a fire safety. But they are still unique because of the lack of understanding and information of their performance and design method.

ACKNOWLEDGMENT

The authors would like to thank all the members of research committees, sub-committees and working groups under the project on timber-based hybrid building structures. Thank you also members of committee of collection and analysis of new hybrid buildings at JSSC. Thank you for providing photos from Dr Kamiya of former researcher of FFPI and Saito Mokuzai co.

REFERENCES