THE DESIGN AND INSTALLATION OF A FIVE-STORY NEW TIMBER BUILDING IN JAPAN

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SUMMARY

Buildings in Japan have been constructed using timber since olden times. At the same time, Japan is a country beset by earthquake and timber buildings were weak against fire. So, from 1950 to 1987 wooden buildings over 13m height were prohibited by law. Revision of the Building Standards Law 2000 allowed the construction of buildings four-story or taller with fire-resistance performance. M-Bldg. built in 2005 is the first five-storied timber building after established Building Standard Law in Japan. This paper describes the structural framing and fire resistance system for this building and details. M-Bldg. was built in Kanazawa city, Ishikawa prefecture. In this building, first-story was built in reinforced concrete construction and from 2-5 stories was built in timber-based hybrid construction. In structural framing, the performance-based design method (“Calculation of Response and Limit Strength”) was applied and some static structural experiments were conducted about the seismic performance of shearing wall and the buckling stress of timber-based hybrid column. In fire resistance system, fireproof construction was needed for this building. Three fireproof elements, column, girder and bracing, were tested for 1 hour fire resistive period. All elements could have enough properties for 1 hour fire resistance. The possibilities of middle-rise and high-rise timber buildings are extended by completion of this building.

1. INTRODUCTION

Buildings in Japan have been constructed using timber since olden times. Traditional timber temples and shrines, such as the Horyu-ji Temple, look the same as they did when constructed more than 1400 years ago. Many large-scale timber buildings were constructed during that time, and include the Hall of the Great Buddha in Todai-ji Temple (height: 46.8 m, area: 2878 m^2) and the five-story Pagoda in Toji Temple (height: 54.8 m). Even after the Meiji Era, four and five-story timber buildings were used as factories, warehouses, and inns, until the construction of large-scale timber buildings was restricted by the Urban Building Law of 1919, and the Building Standards Law of 1950 further restricted the construction of large-scale timber buildings. In 1959, the Architectural Institute of Japan carried a resolution against timber construction to prevent fire, storm, and flood damage, making it impossible to construct large-scale timber buildings. Timber building height restrictions were loosened in 1987, allowing the construction of three-story structures and buildings taller than 13 m. Eaves having a height of more 9 m were also permitted using large sections of laminated timber. Revision of the Building Standards Law in 2000 allowed the construction of buildings four stories or taller with fire-resistance performance. The present study reports the structural and fire resistance characteristics of the first timber-based hybrid structure in Japan, the five-story Kanazawa M building (Kanazawa M Bldg.), constructed in 2004.

2. OUTLINE OF THE BUILDING

The five-story Kanazawa M Bldg. (height: 14.237 m, area: 6.195 m x 12.100 m) was constructed in Kanazawa City, Ishikawa Prefecture.(Photo.1) The first story has a Reinforced Concrete structure and the second to fifth stories have a timber-based hybrid structure with built-in steel materials. Building data are listed in Table 1, and the floor plan and elevation are shown in Fig. 1 and Fig. 2.

Table 1 Building data

Architect	-architect office- Strayt Sheep
Structural Design	Kirino Structural Engineering Office
Area	$374m^2$(total floor) / $74.96m^2$(building)
Use	School
Height	14.237m
Structure	RC construction(first story) Timber-based hybrid construction(2-5 storied)

Photo.1 External view of Kanazawa M Bldg.

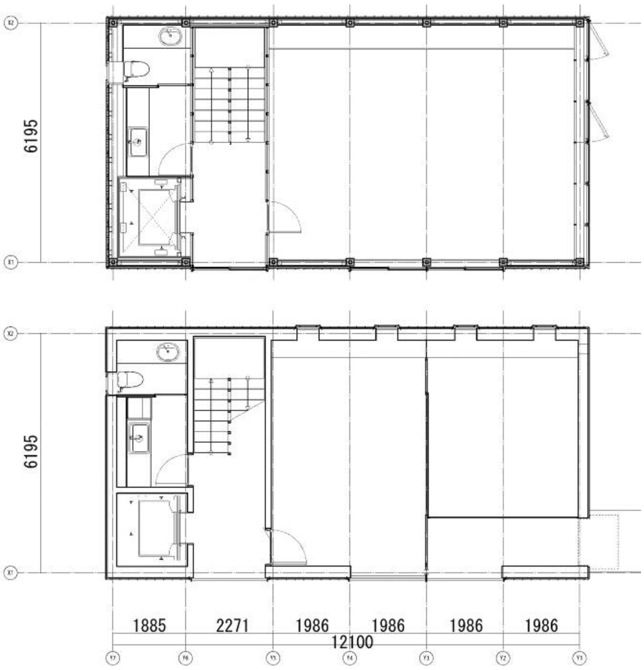


Fig. 1 Floor plan

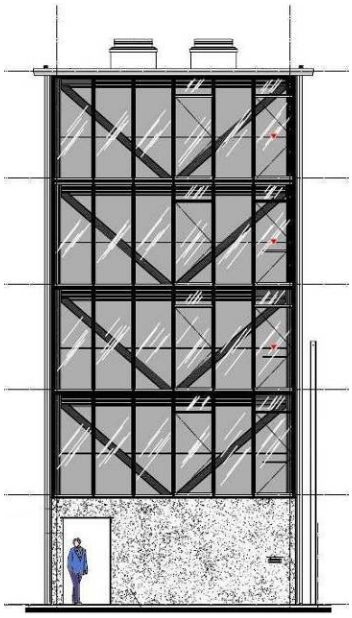


Fig.2 Elevation

Members

The building mainly uses the structural members listed below to satisfy the requirements for vertical load performance, seismic performance, and fire resistance. This building is required fire resistive construction, and structural elements are required 1 hour fire resistive period.

(1) Column, beam, and brace

The building uses laminated timber with built-in steel materials for columns, beams, and braces to satisfy the structural and fire resistance requirements of a five-story building. The cross section of each member is shown in Fig. 3.

The column is square laminated timber (larch E105-F300, 200 x 200 mm) with built-in square steel bars (SS400, 65 x 65 mm). The beam is laminated timber (200 x 330 mm) with steel plates (SS400, PL-22x300). The cross section of a brace looks identical to that of a column, which is necessary for fire resistance certification.

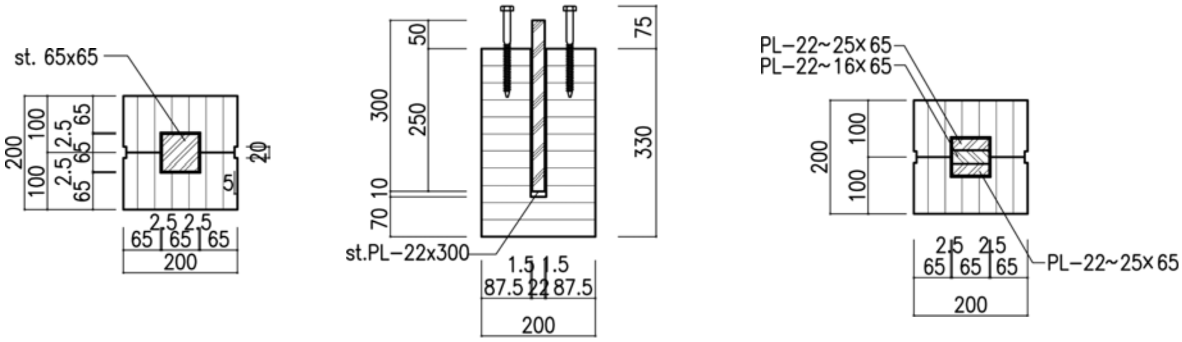
(2) Floor and roof

The floors and roofs are made of reinforced concrete slabs joined together with lag screws and steel plates built into the beams.

(3) Wall

The longitudinal walls are load-bearing and made of nailed plywood. The lateral walls are

non-load-bearing, because of setting braces.
(4) Stairs
The stairs are made of steel frames.



column beam brace

Fig.3 Cross sections of column, beam, and brace

3. STRUCTURAL PLANNING

Similar to ordinary timber buildings, a five-story timber-based hybrid 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 on the Kanazawa M Bldg.

Vertical Load

The timber and steel frame function together as a structural member in the second to fifth stories of a timber-based hybrid 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 frame, vertical load should be shared depending on their ratio of flexural rigidity, EI (E: Young's modulus, I: Geometric moment of inertia). The flexural rigidity ratio EI / ∑EI is shown in Table 2.
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 bears all the shear force at the edge. The gusset plate from the steel frame of the column and the steel frame of the beam are joined with high

Table 2 Flexural rigidity ratio of timber and steel frame

	E (N/mm^2)	I (mm^4)	EI (Nmm^2)	EI/∑EI
Timber frame	1.05×10^4	5.55×10^8	0.583×10^{13}	0.366
Steel frame	2.05×10^5	4.95×10^7	1.01×10^{13}	0.634

tension bolts for the column-beam connection. The holes in the side of the timber frame are filled with timber after high tension bolts are clamped. (Fig. 4).

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 (multiplied by 1.4).

(2) Column

Vertical load is transmitted to the steel frame of a column through a gusset plate, and vertical loading of the timber is avoided using a 3 mm clearance, which is essential for combining the timber with the steel frame. The timber of the column functions as a buckling restraint for the steel frame, and, as the structural experimentation in Chapter 4 shows, alone, the steel frame of the column buckles at about 20% of the yield stress. However, the timber-based hybrid column did not buckle when the steel frame yielded to axial force compression because the timber functioned as a buckling restraint.

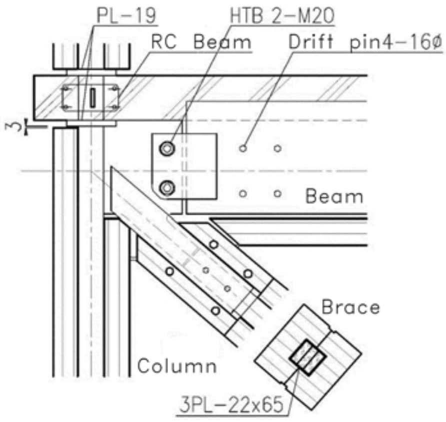


Fig.4 Joint (Lateral)

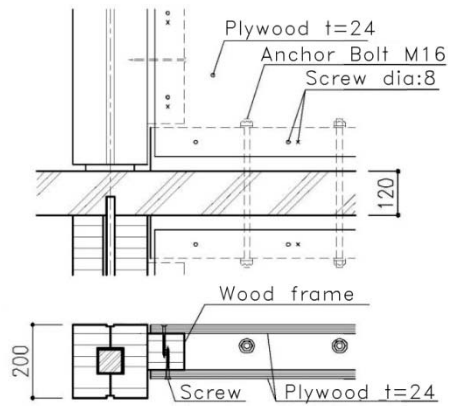


Fig.5 Joint (longitude)

Horizontal Load

The structural planning of the building is different from each direction. A timber-based hybrid beam is suspended laterally and supported by columns of identical material, and the longitudinal beam is built in a reinforced concrete slab. Damage limit seismic force produces greater horizontal force than the load exerted by very rare wind, as prescribed in the Building Standards Law, so horizontal

resisting elements are braces the lateral roof face and the longitudinal plywood (load-bearing) walls.
(1) Beam
A lateral timber-based hybrid beam bears axial force and produces a reaction force of braces during an earthquake. The steel frame bears axial force, the timber frame functions as a buckling restraint, and calculations confirmed the absence of buckling within the safety limits of applied axial force.
(2) Column
During a lateral earthquake, a timber-based hybrid column produces a reaction force of braces. This column does not buckle when the steel frame yielded to axial force compression as mentioned above.
During a longitudinal earthquake, vertical shear force is transmitted from the plywood bearing wall to the timber of the column through the vertical frame (Fig. 5). The timber has a bearing plate of the steel frame (PL-19) at both ends of the timber of the column, and when the timber collides 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 was not observed under significant plastic deformation of the steel frame by compression axial force.
(4) Plywood bearing wall
A plywood bearing wall bears 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 (Fig. 5). Vertical shear force of the plywood bearing wall is as mentioned in Section (2), and horizontal shear force is transmitted from the structural plywood to both the horizontal frame and the downstairs plywood bearing wall through anchor bolts (M16) embedded in the reinforced concrete slab.

After Fire
(1) Beam
Only the steel frame bears 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 present law. 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 bears vertical load only using the steel frame and the stress applied should not exceed the long-term allowable limit for buckling.

(3) Brace

The 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. In this case, the steel frame stress is prevented from exceeding the short-term allowable limit.

(4) Plywood bearing wall

A plywood bearing wall is assumed to have completely burned.

(5) Longitudinal RC beam

An RC slab has a built-in longitudinal RC beam, as shown in Fig. 5. The rigid frame structure, consisting of the RC beam and the steel frame of the column, resists the longitudinal horizontal force produced by the constant wind.

4. STRUCTURAL EXPERIMENTATION

According to structural planning in Chapter 3, we clarified the structural performance of each member through experimentation. More specifically, we conducted a buckling performance test on a timber-based hybrid column and a shear performance test on a load-bearing wall.

Methods and Results of Experimentation

(1) Column

According to the structural design policy described in Chapter 3, the columns support vertical load only using the steel frames, but the surrounding timber supports axial force to resist buckling during an earthquake. Therefore, the timber requires a flexural rigidity (EI) that prevents buckling up to the yield load (Py) of steel.

We conducted a full-size buckling test to verify the buckling restraint of the timber a specimen of the full length (L = 2800 mm) was monotonously pressurized on both ends as shown in Photo 2, and the load-deformation relationship is shown in Fig. 6. Rigidity decreased at an axial deformation of 5 to 10 mm, resulting in strain hardening, because the partial loss of area at the end of the steel for jig yielded. Under a load of 1000 kN, the steel also yielded and suffered from a plastic deformation of approximately 30 mm. The yield axial force calculated from the result of a material test on a square steel bar (yield stress = 284 N/mm^2) is 912 kN. The square steel bar contracted and the timber of the column made contact with the jig, producing axial force, as axial deformation reached 30 to 40 mm. The timber cracked and buckled from a further increase in the load. The buckling strength (Nk) of the laminated timber is greater than the 672 kN calculated from the standard compressive strength. Results indicate that the timber-based hybrid column did not to buckle until the short-term allowable axial force (908 kN) of the square steel bar was reached.

Photo 2 Full view of experimentation

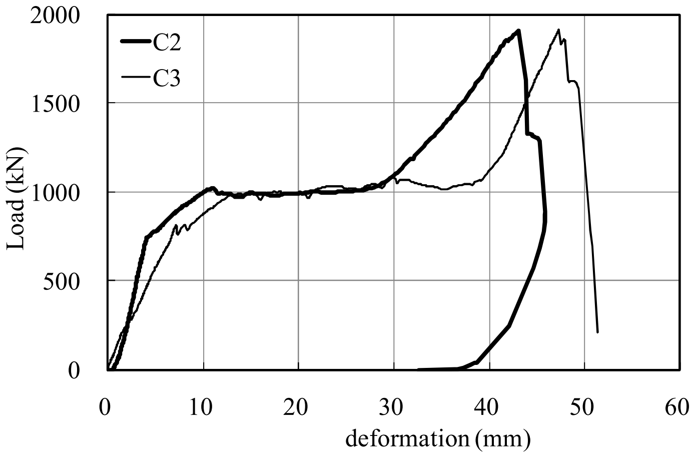
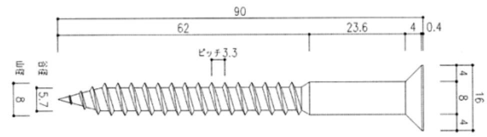


Fig.6 Column load-deformation relationship

(2) Wall

As a load-bearing wall, plywood (thickness: 24 mm) is secured on each side of a framework with screws (dia.: 8 mm) at intervals of 150 to 250 mm. The shear rigidity and shear strength of the screws securing the plywood were calculated experimentally, and are shown in Table 3.

Table 3　Performance per screw

Shear rigidity: K_1 (N/mm)	Shear strength (N)	
1300	7126	

An analytical model of the Plywood bearing wall and frame is shown in Fig. 7, and the detail of model is as follows:

1. The frame consists of square steel bar columns and RC beams, and the ends of the members form plastic hinges when yielded.
2. The load-bearing wall consists of plywood, timber column, sill, and both screws and bolts for joining the members.
3. The connectors between the plywood and the frame are modeled as a spring as screws (rigidity: K_1, Table 3).
4. The spring formed between the column timber and the square steel bar transmits shear force, received from screws colliding against the bearing plate, from the timber to the steel bar. To ensure elasticity, even during deformations

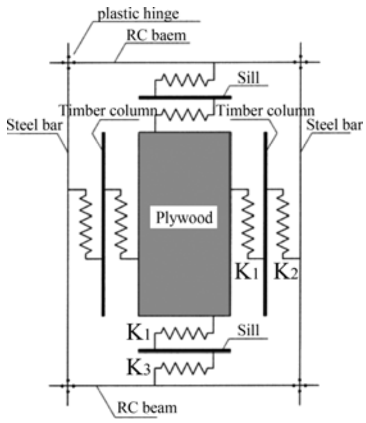


Fig.7 Plywood bearing wall model

within safety limits, K_2 is set at 11.5 N/mm. This also takes into consideration the axial rigidity of the column timber and the rigidity due to the clearance between the column timber and the bearing plate.

5. The spring formed between the sill and the RC beam transmits shear force, received from the screws through anchor bolts, from the sill to the RC beam. To ensure elasticity, even during deformations within safety limits, K_3 is set as 81.6 N/mm. this also takes into consideration the transmission of shear force between the bolt and the sill and the rigidity due to the clearance between the bolt and the sill.

If the rigidity K_1 of the plywood bearing wall is linked in series with the rigidity K_2 by the column timber or the rigidity K_3 by the sill, and K_2 and K_3 are linked in parallel, the equivalent rigidity can be calculated as follows:

$$K = 1/\ \{1/K_1+1/\ (K_2+K_3)\}$$

Using this equation, the yield strength and ultimate strength can be calculated as "analytical values" (Table 4).

Table 4 Performance of plywood bearing wall

	Analytical values	Experimental values
Rigidity (kN/mm)	2.85	2.56
Yield strength (kN)	97.5	92.3
Ultimate strength (kN)	178	182

We conducted a full-size static loading test to verify the performance of the plywood bearing wall. The specimen had a column span of 1710 mm and a height of 2740 mm as shown in Fig. 8. Reverse cycling loading was used for the static loading test, and the cyclic loading profile was controlled by apparent shear deformation angle. Loading of the same deformation profile was repeated three times, using a loading profile of ±1/600 - ±1/450 - ±1/300 - ±1/200 - ±1/100 - ±1/75 - ±1/50 - ±1/25 - ±1/15 rad. The load-deformation relationship of the plywood bearing wall is shown in Fig. 9. When the maximum strength (P_{max}) is 235 kN, the drift is 161.5 mm (1/17 rad.). A crack developed and grew along the RC part of the joint between the square steel bar column and the RC beam; resulting in the destruction of the screws by shear force and the collapse of the plywood. Performance of plywood bearing wall was investigated experimentally, and results are shown in Table 4. The experimental values are slightly greater than the analytical values.

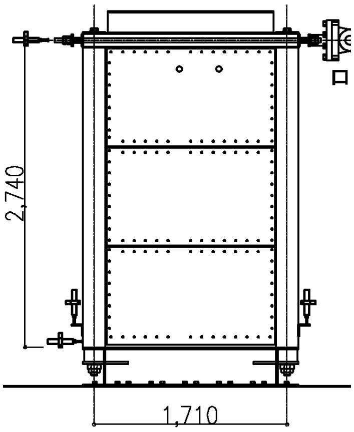


Fig. 8 Specimen of plywood bearing wall

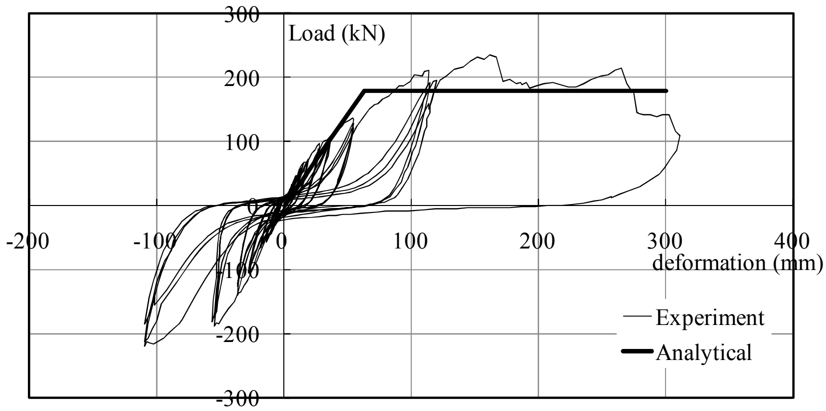


Fig.9 Wall load-deformation relationship

5. CALCURATION OF RESPONSE AND LIMIT STRENGTH

We created an analytical model of the building based on the experimental results, and verified the safety against seismic force by predicting response deformation using the performance-based design method ("Calculation of Response and Limit Strength").

Verification by Safe Limit Strength Calculation

(1) Safe limit drift angle

A safe limit drift angle of 1/50 was set for both the lateral and longitudinal directions. Since the strength of longitudinal plywood bearing wall rose to a drift angle of approximately 1/20, 1/50, as a safety margin, is more than adequate. This margin was set in accordance with the deformation tracking performance of a sash window used for an outside wall of an ordinary building.

(2) Calculation of response

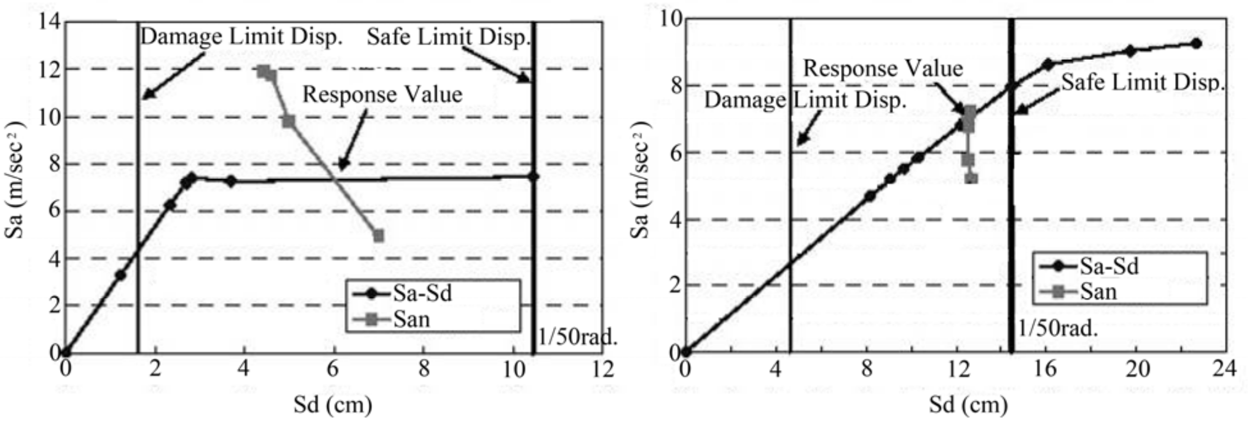
The experimental and analytical safety limit strength exceeded the required safety limit strength, and the true response value is calculated as follows:

a) Creating a relation diagram of the load-deformation curve (Sa-Sd) at the representative material point of the building

b) Calculating the acceleration (San) of input into the building at equivalent cycles by considering building attenuation at each step

c) Plotting San on a straight line connecting Sa-Sd (load deformation of the building) and the origin at the step

d) The true response value is the intersection of the San curve at each step (demand curve) and the Sa-Sd curve of the building.



lateral direction longitudinal direction

Fig.10 Prediction of responses at the time of an earthquake

Results of the calculation are shown in Fig.10. The safety against seismic force both direction was verified. In the lateral direction, strength hardly increases after the yielding of horizontal resisting elements. In the longitudinal direction, the plywood bearing wall is in an elastic area, up to 1/50 of the safe limit drift angle.

5. CONCLUSION

Besides verifying the safety against seismic force, to satisfy the fire resistance performance required for fireproof buildings, we verified fire resistance using a beam-loaded heating test, a column-loaded heating test, and a joint heating test. Based on the results of structure and fire resistance research, Japan's first building using a timber-based hybrid structure, having 1- hour fire resistance, was completed in Ishikawa Prefecture in 2005,

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