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DAMAGES TO TIMBER HOUSES CAUSED BY SOUTH-HYOGO EARTHQUAKE AND FEASIBILITY OF STRUCTURAL DESIGN CRITERIA

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ABSTRACT

The South-Hyogo Earthquake on January 17, 1995 caused serious damages to timber houses built by the traditional Japanese construction method. The damages were mainly characterized by 1) soft first story and 2) overall collapse due to torsion. In this paper, the current Japanese Building Standard Law is first introduced and its characteristics are explained. Then, a simple method to evaluate the horizontal strength considering the effect of torsion is discussed , and it is applied to a sample timber house to demonstrate the strength reduction due to torsion. The paper concludes that the effect of torsion is not negligible.

KEYWORDS

South-Hyogo Earthquake; timber houses; soft-story; torsional deformation; Building Standard Law; horizontal strength; center of rigidity; strength reduction.

INTRODUCTION

The South-Hyogo Earthquake on January 17, 1995 caused disastrous damages to timber houses built by the traditional Japanese method of construction. The magnitude of the Earthquake was 7.2, the maximum acceleration observed at central Kobe city was 830 *gal*, and the velocity was up to 138 *kine* (Fujiwara *et al.*, 1995). The seismic coefficient was possibly as high as about 0.8. The total number of deaths estimated on March 17, 1995, was 5,459, and 88 % of the total deaths was caused by the crash of collapsing buildings. Most of them must be caused by the collapse of timber houses, since the Earthquake occurred early in the morning, while most people were in bed. It was reported that 54,949 timber houses were seriously damaged, and 31,789 were damaged. This is equivalent to 10 % of the number of total dwelling houses of the district (Fujiwara *et al.*, 1995).

Photo. 1

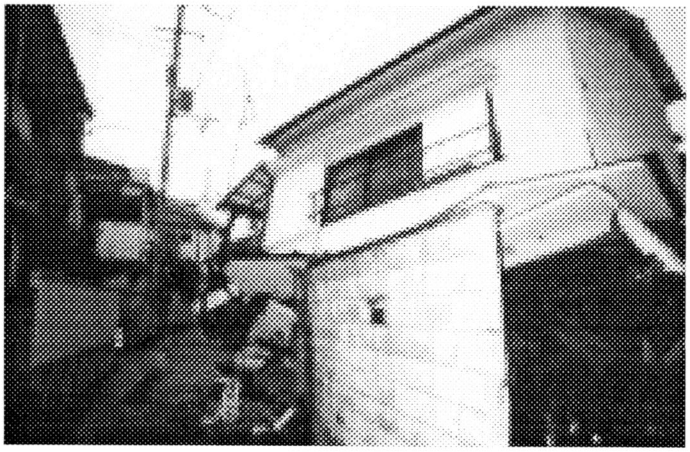

Photo. 2

The damages to timber houses are characterized as follows: 1) soft first story of the two-story buildings due to the lack of sufficient amount of earthquake-resistant structural elements (**Photo. 1**), 2) overall collapse with torsional deformation due to unbalanced arrangement of structural elements (**Photo. 2**), and 3) fracture and falling of furnishing members such as window glasses, clay tile roof and exterior mortar walls.

Objectives of the paper are to explain the outline of the current design method of timber houses according to Japanese Building Standard Law, to discuss its feasibility of the application to the real practice, and to indicate several points of attention considered from the structural and architectural aspects, which should be paid in the course of the design of timber houses.

JAPANESE TRADITIONAL TIMBER STRUCTURE

Historical Background

Japanese traditional timber structure is a system which is developed from the traditional method of construction for vernacular dwellings. The drawing by E. Morse (**Fig. 1**) shows a traditional Japanese dwelling in Tokyo around 1880 (Morse, 1886). This drawing clearly presents the absence of structural elements, such as braces or shear walls, which would resist the horizontal force.

From this reason, timber houses and their district constantly suffered serious damages from every earthquake and typhoon. Through these lessons, the Building Standard Law was enacted in 1950, and the installation of braces or shear walls was prescribed. Since then, partial amendments were made on the Law as shown in **Table 1**, and the current method of design and construction has been developed through the process. **Figure 2** shows a typical structural composition in which braces are set within the traditional timber frame.

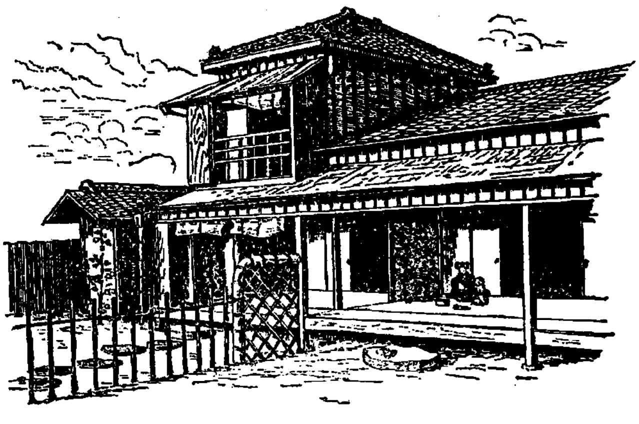

Fig.1. Japanese traditional dwelling

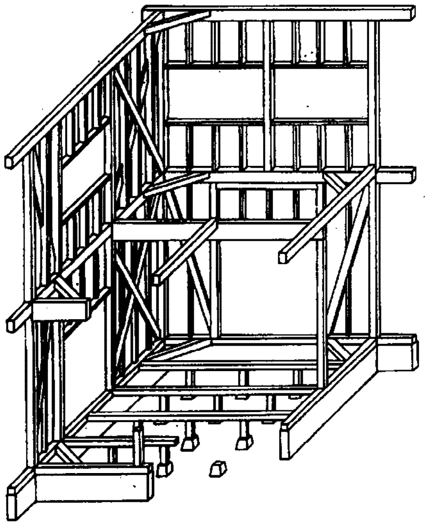

Fig. 2. Typical structural composition

Table 1. Chronological chart of major earthquakes and legal actions on timber structures

Year	Major earthquakes and legal actions
1948	*Fukui Earthquake*
1950	Enactment of the Building Standard Law (prescription of usage of braces for timber structures)
1959	Revision of the Building Standard Law (prescription of minimum wall ratio)
1964	*Niigata Earthquake*
1968	*Tokachi-oki Earthquake*
1971	Revision of the Building Standard Law (revision of the minimum wall ratio)
1975	*Ohita Earthquake*
1978	*Miyagi-ken-oki Earthquake*
1981	Revision of the Building Standard Law (revision of the minimum wall ratio)
1995	*South-Hyogo Earthquake*
?	?

The Design Method Based on the Japanese Building Standard Law

The horizontal resisting force capacity provided by the earthquake-resistant structural elements is calculated about each axis of the frame as follows:

$$Q = 130 \, \Sigma \, \alpha \, L \tag{1}$$

where

Q : horizontal resisting force of the frame (kgf)

130 : horizontal resisting force per unit length of structural element (kgf / m)

α : effective multiplier (see **Table 2**)

L : length of structural element (m)

The design horizontal load acting on the frame is calculated as follows:

$$\overline{Q} = 0.8 \times w \times A \times c \tag{2}$$

where

$\overline{Q}$: design horizontal force (kgf)

0.8 : ratio of horizontal force carried by the frame

w: total design gravity load per unit floor area (kg / m^2)

A: floor area (m^2)

c : seismic coefficient

The check has to be done by

$$Q \geq \overline{Q} ; \qquad 130 \times \Sigma \, \alpha \, L \geq 0.8 \times w \times A \times c ; \quad \Sigma \, \alpha \, L \geq R_W \; A \tag{3}$$

where

$$R_W = \frac{0.8 \times w \times c}{130}$$

The parameter R_W in Eq. (3) is called the wall ratio. The value of R_W are plotted against arguments of w in **Fig. 3**. The minimum value of R_W is specified in the Building Standard Law as shown in **Table 3**. Therefore, these minimum values are commonly used as criteria for ordinary design.

Table 2. Values of effective multipliers according to the specification of shear walls
(from Table 1 of the Article 46 of the Building Standard Law Enforcement Order)

	Specification of the shear wall	Effective multiplier
(1)	Shear walls with earth-plaster or with wooden lath or the like, nailed to one side of columns and studs	0.5
(2)	Shear walls with wooden lath or the like, nailed to both sides of columns and studs	1
	Shear walls with braces of timber 1.5 *cm* in thickness and 9 *cm* in width or with steel bar braces 9 *mm* in diameter or the equivalent	
(3)	Shear walls with braces of timber 3 *cm* in thickness and 9 *cm* in width or the equivalent	1.5
(4)	Shear walls with braces of timber 4.5 *cm* in thickness and 9 *cm* in width or the equivalent	2
(5)	Shear walls with braces of timber 9 *cm* square or the equivalent	3
(6)	Shear walls with "X" braces shown in any of items (2) through (4)	Double each value of items (2) through (4)
(7)	Shear walls with "X" braces shown in item (5)	5
(8)	Other shear walls specified by the Minister of Construction as having such strength as equivalent to that of the shear walls shown in one of items (1) through (7)	A value to be specified by the Minister of Construction within the range between 0.5 and 5
(9)	Shear walls shown in item (1) or (2) plus braces shown in one of items (2) through (6)	The sum of the value of item (1) or (2) and that of one of items (2) through (6)

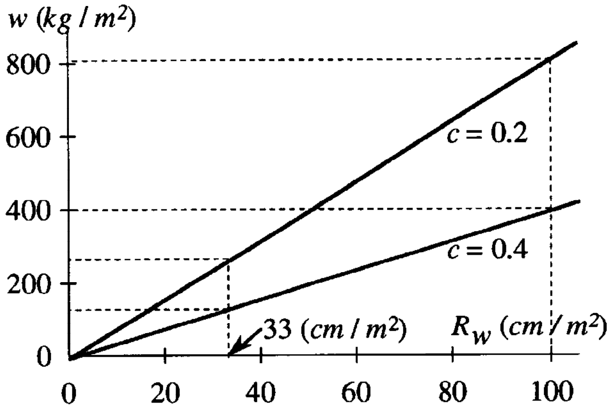

Fig. 3. R_w - w relations

Table 3. Values of the minimum wall ratio
(from Table 2 of the Article 46 of the Building Standard Law Enforcement Order)

Buildings		Minimum wall ratio (unit : cm/m^2)					
		One-story buildings	First story of two-story buildings	Second story of two-story buildings	First story of three-story buildings	Second story of three-story buildings	Third story of three-story buildings
(1)	Buildings whose roofs are covered with light materials such as metal sheets or the like	11	29	15	46	34	18
(2)	Buildings other than those in item (1)	15	33	21	50	39	24

The Characteristics of the Design Method

The design method of the Building Standard Law indicated by Eq. (3) with **Tables 2** and **3** is very simple. It is suitable for the simple and plain way of design conducted by Japanese carpenters who have a through knowledge of woodwork details but have less about sophisticated structural theory. However, the collapse characteristics presented in the Earthquake seem to tell us that the current method contains several insufficient points as indicated below.

The Absence of the Consideration on Live Load. Horizontal force caused by an earthquake is in proportion to the gravity load, which is constituted from dead load and live load. The minimum value of R_w, appeared in **Table 3**, was derived from the estimation of the live load to be 60 kg/m^2 on the second floor (Sugiyama *et al.*, 1983). But this value can easily fall short of today's actual situation and closely depends on the dweller's way of life. In addition, the minimum values of R_w are given uniformly, although it is essentially a function of w and c, and the structural effect of the live load is hardly considered by carpenters.

Generally, the live load of Western style rooms is greater than those of Japanese rooms, and those of storages than those of living rooms. Such eccentricity of live load forms one of the possibilities of the torsion.

The Absence of the Consideration on Torsion. Equation (1) determines the force under the assumption that only pure sway deformation occurs in the frame, but does not care about the torsional deformation. The Article 46 of the Building Standard Law Enforcement Order contains a description that "...... *either walls or braces shall be* ***properly arranged*** *on each floor in both the span and ridge directions so that the buildings will be safe against horizontal force in any direction.*" This may be read as a caution to the problem, but not enough to warn the carpenters who have to estimate the effect of torsion through their experience and imagination.

Structural theory tells us that torsional force is caused by the eccentricity between center of gravity and center of rigidity. Carpenters often arrange relatively big rooms on the south side, and small rooms or utilities to the north. This makes the center of rigidity shift to the north. In addition, center of gravity has a tendency to shift to the south, because set back arrangement of the upper floor at the north is often necessary to conform to the legal regulation about the height of the building.

ANALYSIS OF ULTIMATE STRENGTH OF A FRAME FAILING IN TORSION

In the South-Hyogo Earthquake, many examples of the failure due to excessive torsion were observed in two-story timber dwelling frame. This failure was mainly caused by two reasons as indicated before: soft first story, and large eccentricity between the center of gravity and the center of rigidity. This section of the paper introduces a simple evaluation method for the strength reduction due to torsion (Wakabayashi et al., 1985), and indicates the necessary design considerations.

Model Frame

Figure 4 shows the rectangular plan of l_x times l_y of the model frame, which is composed of (n+1) earthquake-resistant elements in y-direction, and two elements in x-direction, and subjected to the earthquake force Q_T in y-direction acting at the center of gravity **G**. K_j denotes the lateral stiffness of the j-th element in y-direction located at the distance from the origin x_j. Two elements in x-direction are arranged at $y = \pm\, l_y / 2$, and they have the same stiffness equal to half the total stiffness in y-direction, $K_y = \Sigma K_j / 2$. The center of rigidity (shear center) **S** locates at x_S, and y_S and ϕ denote the displacement at **S** in y-direction and the torsional angle (clockwise positive), respectively.

Strength of Model Frame

The displacement y_j and lateral shear resistance Q_j of the j-th element in y-direction are given as follows:

$$y_j = y_S - (x_j - x_S)\phi \tag{4}$$

$$Q_j = K_j\, y_j = K_j\, \{y_S - (x_j - x_S)\phi\} \tag{5}$$

The total resistance is in equilibrium with Q_T, and thus

$$Q_T = \sum_{j=1}^{n+1} Q_j = y_S \sum_{j=1}^{n+1} K_j - \phi\left(\sum_{j=1}^{n+1} K_j\, x_j - x_S \sum_{j=1}^{n+1} K_j\right) \tag{6}$$

Due to the torsional rotation, the displacements in x-direction, $\phi\ (\pm\, l_y / 2\,)$ occur in two elements at $y = \pm\, l_y / 2$, and they provide anti-clockwise torsional resistance around **S**. Then, the torsional equilibrium around **S** leads to

$$\Sigma\, Q_j\, x_j - K_y\, \frac{l_y}{2}\, \phi\, l_y = 0 \tag{7}$$

Substituting Eq. (6) into (7) leads to

$$y_S\, \Sigma K_j\, x_j - \phi\left\{\Sigma\, K_j\, x_j^2 - x_S \Sigma K_j\, x_j + \frac{l_y^2}{2} K_y\right\} = 0 \tag{8}$$

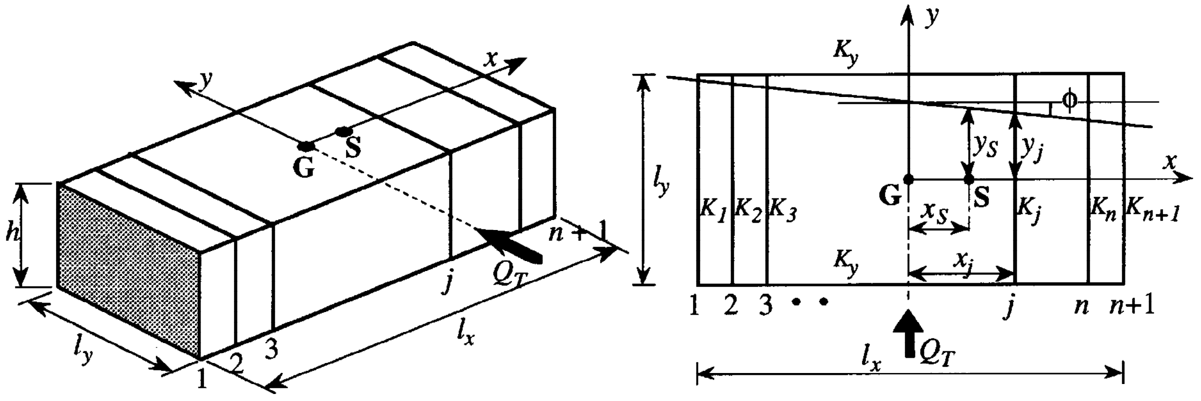

Fig. 4. Model frame

The eccentricity between the centers of gravity and rigidity is defined as

$$x_S = \frac{\Sigma K_j x_j}{\Sigma K_j}\,;\quad \Sigma K_j x_j - x_S \Sigma K_j = 0 \tag{9}$$

In order to define the torsional stiffness of the overall model frame, consider the application of a torsional moment $M_{\phi S}$ at the center of rigidity which causes a unit torsional angle, as shown in **Fig. 5**. The equilibrium in torsion is obtained from Eq. (8) in view of Eq. (9), $y_S = 0$ and $\phi = 1$, as follows:

$$M_{\phi S} - \left\{ \Sigma K_j\, x_j^{\,2} - x_S \Sigma K_j\, x_j + \frac{l_y^2}{2} K_y \right\} = 0 \tag{10}$$

$$\therefore\ M_{\phi S} = \Sigma K_j\, x_j^{\,2} - x_S \Sigma K_j\, x_j + \frac{l_y^2}{2} K_y \equiv K_{\phi S}$$

Equation (10) gives the definition of the torsional stiffness. Finally, two independent equations of equilibrium are obtained from Eqs. (6) and (8) in view of Eqs. (9) and (10), as follows:

$$\begin{bmatrix} \Sigma K_j & 0 \\ 0 & K_{\phi S} \end{bmatrix} \begin{Bmatrix} y_S \\ \phi \end{Bmatrix} = \begin{Bmatrix} Q_T \\ Q_T x_S \end{Bmatrix} \tag{11}$$

Torsion constant r_e, parameter often used in the seismic design, is defined as follows:

$$r_e = \sqrt{\frac{K_{\phi S}}{\Sigma K_j}} \tag{12}$$

Now consider the strength of the model frame Q_T when the maximum displacement of the outermost element at $x = -\,l_x / 2$ become a limiting value y_l. That is,

$$y_S - \left(-\frac{l_x}{2} - x_S\right)\phi = y_l\,;\quad \phi = \frac{y_l - y_S}{\dfrac{l_x}{2} + x_S} \tag{13}$$

Substituting ϕ of Eq. (13) into Eq. (11) and eliminating y_S lead to

$$Q_T \left\{ \frac{K_{\phi S}}{\Sigma K_j} + x_S \left(\frac{l_x}{2} + x_S \right) \right\} = y_l\, K_{\phi S} \tag{14}$$

Suppose that there is no eccentricity and only translating displacement y_l occurs, then the strength Q_{T0} under such a situation is derived from Eq. (11) as follows:

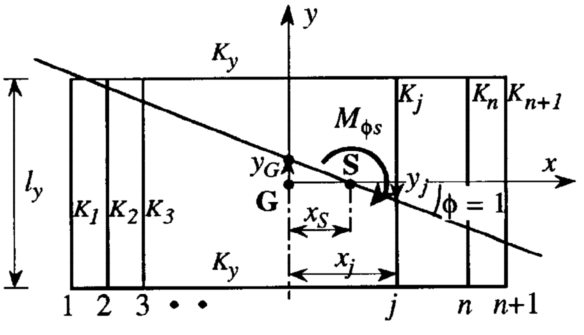

Fig. 5. Frame subjected to unit torsional angle

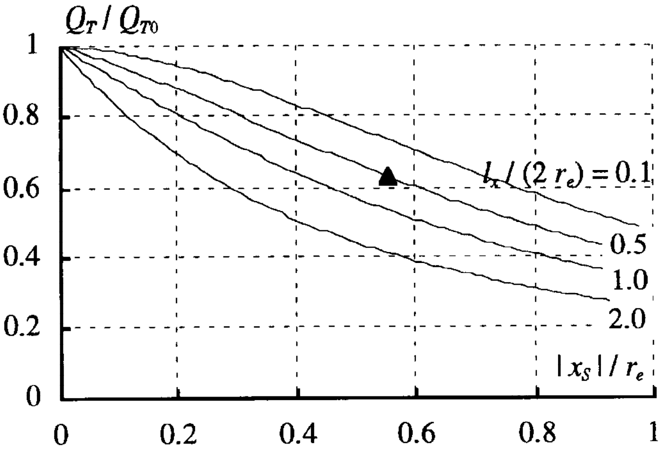

Fig. 6. Q_T / Q_{T0} - $|x_S| / r_e$ **relations**

$$Q_{T0} = y_l \, \Sigma K_j \tag{15}$$

Equation (15) is considered as the strength when the displacement of each element reaches to y_l without taking the effect of torsion into account. Dividing Eq. (14) by Eq. (15) leads to

$$\frac{Q_T}{Q_{T0}} = \frac{\dfrac{K_{\phi S}}{\Sigma K_j}}{\dfrac{K_{\phi S}}{\Sigma K_j} + x_S\left(\dfrac{l_x}{2} + x_S\right)} \tag{16}$$

Strength Reduction Due to Torsion

Equation (16) is written in view of Eq. (12) in the following form:

$$\frac{Q_T}{Q_{T0}} = \frac{1}{1 + \dfrac{x_S}{r_e}\dfrac{l_x}{2\,r_e} + \left(\dfrac{x_S}{r_e}\right)^2} \tag{17}$$

The relation between Q_T / Q_{T0} and eccentricity ratio x_S / r_e given by Eq. (17) is illustrated in **Fig. 6** with the parameter l_x / r_e. The horizontal line, $Q_T / Q_{T0} = 1$, indicates the strength without considering the torsion. Note that the greater eccentricity ratio causes the larger strength reduction, and the greater value of the parameter $l_x / (2\,r_e)$ causes the greater reduction. Note that if the maximum displacement occurs at $x = \pm\, l_x / 2$, the sign of the second term of the denominator of Eq. (17) becomes negative.

Equation (17) can be written in a different form for a simple frame shown in **Fig. 7**, in which the model frame has only two earthquake-resistant elements in both x- and y-directions. The stiffness of the elements located at $x = \pm\, l_x / 2$ are denoted by K_1 and K_2, respectively, where $K_1 > K_2$, and the stiffness of both elements at $y = \pm\, l_y / 2$ is given by $(K_1 + K_2) / 2$. The torsional stiffness $K_{\phi S}$ in Eq. (10) for the frame in **Fig. 7** becomes as follows:

$$K_{\phi S} = (K_1 + K_2)\left\{\left(\frac{l_x}{2}\right)^2 - x_S^2 + \left(\frac{l_y}{2}\right)^2\right\} \tag{18}$$

Then, Eq. (16) becomes

$$\frac{Q_T}{Q_{T0}} = \frac{1 - \left(\dfrac{2\,x_S}{l_x}\right)^2 + \left(\dfrac{l_y}{l_x}\right)^2}{1 + \dfrac{2\,x_S}{l_x} + \left(\dfrac{l_y}{l_x}\right)^2} \tag{19}$$

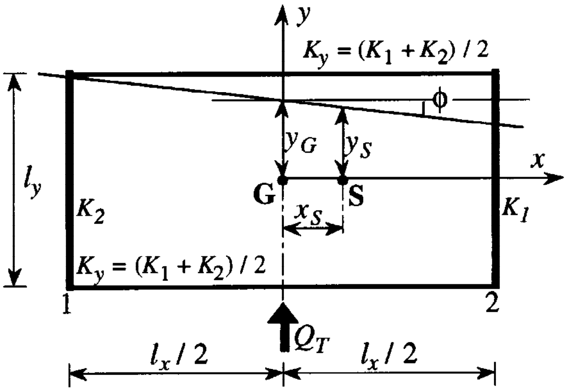

Fig. 7. Simple frame example

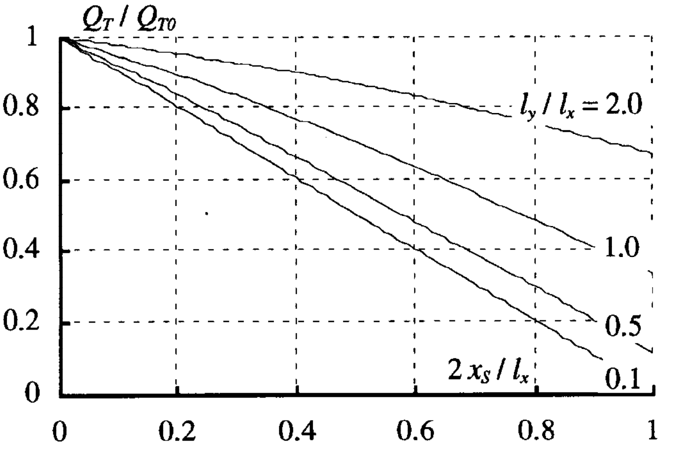

Fig. 8. Q_T / Q_{T0} - $2\,x_S / l_x$ relations

Figure 8 illustrates the relation between the strength reduction due to torsion and the eccentricity given by Eq. (19) with the aspect ratio l_y / l_x. Note that the larger eccentricity ($2\,x_S / l_x$) decreases the value of Q_T / Q_{T0}, and the smaller aspect ratio (l_y / l_x) causes the greater strength reduction.

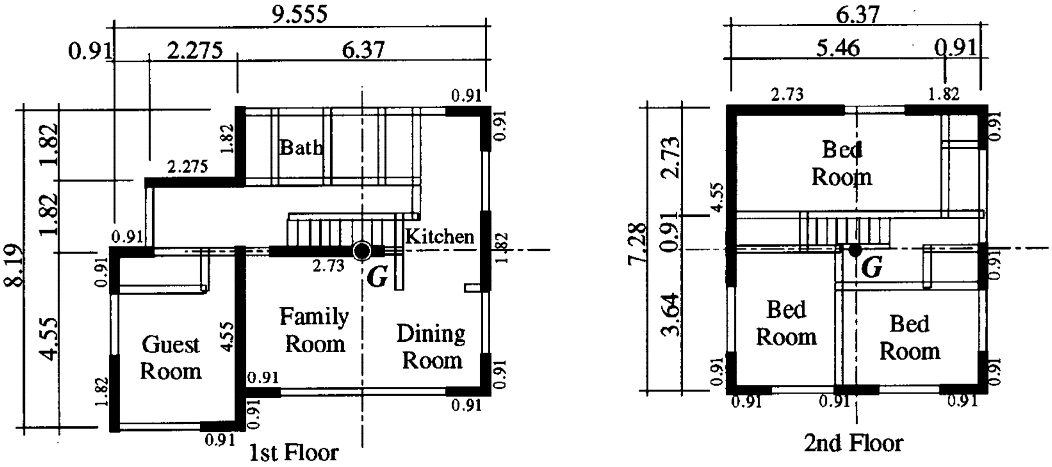

Fig. 9. Floor plan of a typical dwelling house for sample calculation

A sample calculation is carried out using a typical two-story house designed based on the current Japanese Building Standard Law as in **Fig. 9**. Solid black walls indicate the shear walls, and the center of the gravity load carried by the 1st floor is shown as **G**. The eccentricity ratio of the 1st floor is calculated as follows:

$$\frac{x_S}{r_e} \fallingdotseq -0.554$$

and then the value of Q_T / Q_{T0} is calculated by Eq. (17) as follows:

$$\frac{Q_T}{Q_{T0}} \fallingdotseq 0.637$$

This point is shown in **Fig. 6** by a black triangle. This indicates that the strength of this frame reduces about 36 % by the torsional effect. Therefore, the strength reduction caused by the torsion is not negligible.

CONCLUDING REMARKS

Disastrous damages to traditional Japanese timber houses caused by the South-Hyogo Earthquake on January 17, 1995 raised the questions about the feasibility of the simple design method based on the minimum wall ratio specified in Japanese Building Standard Law, that is, mainly the questions about the lack of considerations on the intensity of live load and the effect of torsion. The required amount of shear walls is determined by the intensity of the gravity load and shear coefficient, and the live load estimated from the value of the minimum wall ratio specified by the Law seems to be too small to cover the design of timber houses associated with today's westernized life style in Japan. As to the effect of torsion, sample calculation of the strength reduction due to torsion using a typical two-story dwelling house designed by the concept of minimum wall ratio reveals that the effect of torsion must not be neglected, and it is strongly suggested that the Law should amend a quantitative provision to prevent the torsional collapse of timber dwelling houses.

REFERENCES

Building Guidance Division and Urban Building Division, Housing Bureau, The Ministry of Construction. ed. (1986). *The Building Standard Law of Japan*, The Building Center of Japan.
Fujiwara, T. *et al.* (Mar. 1995). *The Survey of the Disaster Caused by The Great South-Hyogo Earthquake, 1995.* [in Japanese], p. 120, p. 423.
Morse, E. S. (1886). *Japanese Homes and Their Surroundings*, Boston. quoted from Japanese ed. (1979), p. 74. Kajima Publ., Tokyo.
Sugiyama, H., Kamiyama, Y. and Imaizumi, K. (1983). *The Design of Wooden Structure* [in Japanese], A New Comprehensive Series of Architectural Studies, vol. 39, pp. 226-227. Syokokusya, Tokyo.
Wakabayashi, M. *et al.* (1985). *Advanced Theory of Steel Structures* [in Japanese], pp. 59-61. Maruzen, Tokyo.