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REGIONALITY OF RESISTANT ELEMENTS AND WEIGHT IN TRADITIONAL WOODEN HOUSES IN JAPAN

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Abstract

There is one of the questions with evaluating seismic performance of traditional wooden houses in Japan that structural characteristics of them are different by region. However, the regionality of the structural characteristics of the houses has not been clear adequately, and there has been no study that tried to analyze the regionality quantitatively. The purpose of this study is to understand the differences in resistant elements and weight of traditional wooden houses among regions which is largely related to the seismic performance of houses. Our conclusions are as follows. 1) Regionality is observed for yield shear force per unit 1st floor area Q_y/A_1 and in breakdown by resistant elements. 2) The weight per unit 1st floor area W/A_1 vary from regions to compare, depending on specifications of the roofs and walls in houses. 3) There is a strong correlation in both weak and strong direction between the total length of the full walls in 1st floor per weight L_1/W and the natural frequency f and between the total length of full walls in 1st floor per unit 1st floor area L_1/A_1 and the yield base shear force per unit 1st floor area Q_y/A_1. 4) There is also a strong correlation between the natural frequency f and the yield base shear coefficients C_y except for the houses in a region where ambient vibration measurements was conducted immediately after the earthquake occurred.

Keywords: Traditional wooden houses in Japan, Regionality, Resistant elements, Weight, Natural frequency

1. Introduction

There is one of the questions with evaluating seismic performance of traditional wooden houses in Japan that structural characteristics of them are different by region. However, the regionality of the structural characteristics of the houses has not been clear adequately, and there has been no study that tried to analyze the regionality quantitatively. The purpose of this study is to understand the differences in resistant elements and weight of traditional wooden houses among regions which is largely related to the seismic performance of houses. This paper reports the results of a study concerning resistant elements and weight according to regionality based on structural surveys of traditional wooden houses conducted by the authors.

2. Target study regions and houses

2.1 Target study regions

The authors conducted structural surveys and selected total of 8 regions including 6 districts designated as the Important Preservation District for Groups of Historic Buildings (IPDGHB) by Agency for Cultural Affairs. Figure 1 shows the target study regions and appearance of typical residential structures located there. Table 1 gives specifications of roof and external wall according to the regions that were target of the study. The target study regions were, from north to south: (1) Kuroshima, Monzen-cho, Wajima-shi, Ishikawa Prefecture [1], (2) Kisohirasawa, Shiojiri-shi, Nagano Prefecture [2], (3) Narai, Shiojiri-shi, Nagano Prefecture [3], (4) Kyoto-shi, Kyoto Prefecture [4], (5) Ominato-cho, Ise, Mie Prefecture [5], (6) Gojoshinamachi, Gojo-shi, Nara Prefecture [6], (7) Yuasa-cho, Arita-gun, Wakayama Prefecture [7], and (8) Kiragawa-cho, Muroto-shi, Kochi Prefecture [8]. For the sake of simplicity, these shall hereinafter be referred to as Kuroshima, Hirasawa, Narai, Kyoto, Ise, Gojo, Yuasa and Kiragawa.

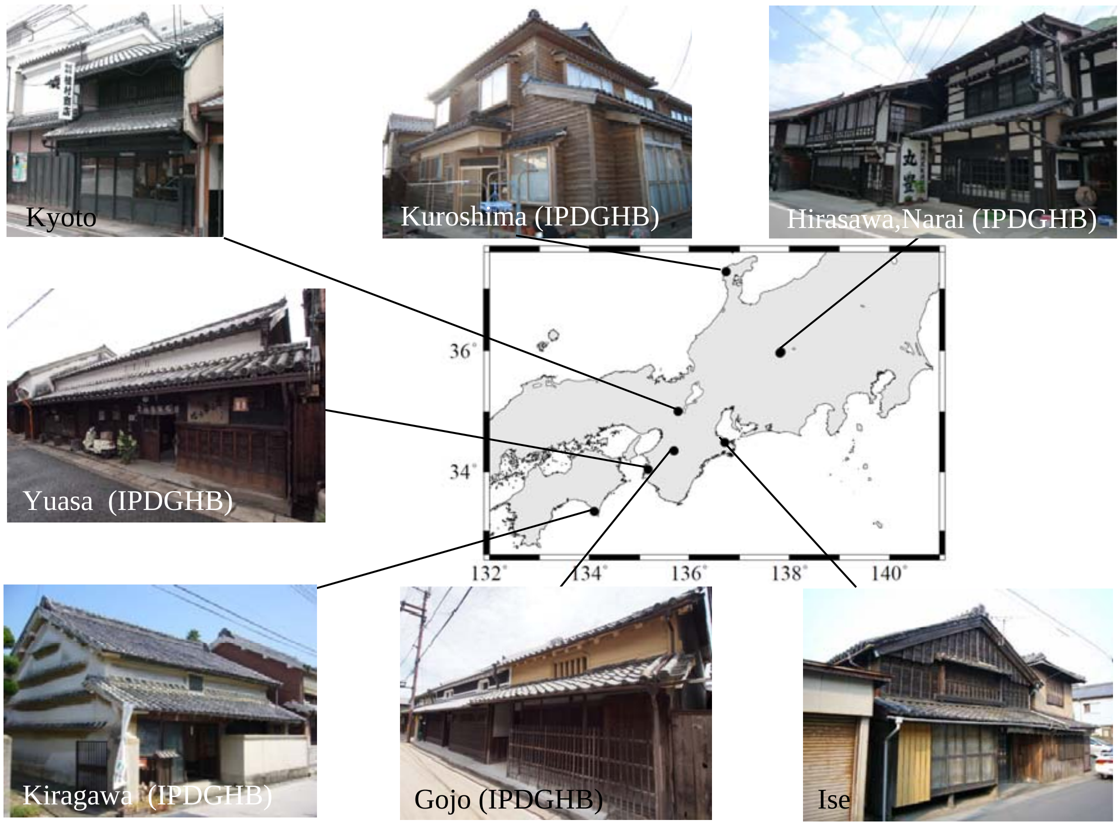


Figure 1 – Target study regions and appearance of typical residential structures located there

Table 1 – Target study regions and specifications of roof and external wall

Regions	Investigation year	Number of target study houses	Roof		External wall	
			Materials	Mud paving	Structure	Finishing
Kuroshima	2007	4	clay tiles	non	mud wall	clapboard
Hirasawa	2009	11	clay tiles, metal	paving (clay tiles)	mud wall	non
Narai	2009	9	clay tiles, metal	paving (clay tiles)	mud wall board	non
Kyoto	2007	9	clay tiles	paving	mud wall	non
Ise	2005	4	clay tiles	paving	mud wall	board,tinplate, panel
Gojo	2013	7	clay tiles	paving	mud wall	non
Yuasa	2011	7	clay tiles	paving	mud wall	board, tinplate
Kiragawa	2008	8	clay tiles	paving	mud wall	non

2.2 Target study houses

The target study houses are 2-story townhouses built using traditional Japanese construction methods. The following is a description of the structural characteristics of houses in each region.

Kuroshima:
There are 4 target study houses investigated in 2007. Houses employ clay tile roofing without mud paving and mud external walls finished with clapboard on the entire surface.

Hirasawa:
There are 11 target study houses investigated in 2009. Houses have “Kirizuma-zukuri Hira-iri*” and are long, narrow townhouses. Also, they employ clay tile roofing with mud paving or metal roofing in many cases.

Narai:
There are 9 target study houses investigated in 2009. Houses have “Kirizuma-zukuri Hira-iri*” and are long, narrow townhouses. Also, they employ clay tile roofing with mud paving or metal roofing in many cases. External walls are mud walls or boards.

Kyoto:
There are 9 target study houses investigated in 2007. Houses have “Kirizuma-zukuri Hira-iri*” and are long, narrow townhouses. Also, they employ clay tile roofing with mud paving and mud external walls.

Ise:
There are 4 target study houses investigated in 2005. Houses have “Kirizuma-zukuri Tsuma-iri**” and are long, narrow townhouses. Also, they employ clay tile roofing with mud paving and mud external walls.

Gojo:
There are 7 target study houses investigated in 2013. Houses have “Kirizuma-zukuri Hira-iri*” and widths of frontage of houses are wide. Also, they employ clay tile roofing with mud paving and mud external walls.

Yuasa:
There are 7 target study houses investigated in 2011. Houses have “Kirizuma-zukuri Hira-iri*” and are long, narrow townhouses. Also, they employ clay tile roofing with mud paving and mud external walls.

Kiragawa:
There are 8 target study houses investigated in 2008. Houses have “Kirizuma-zukuri Hira-iri*” and are long, narrow townhouses. They employ clay tile roofing with mud paving. Many of the houses employ thick mud external walls made of mud covered with numerous layers of Tosa plaster. Some houses also combine these with brick walls.

* The house have its main entrance on the side which runs parallel to the roof's ridge
** The house have its main entrance on the side which is orthogonal to the roof's ridge

3. Analysis of structural characteristics values

3.1 Structural characteristics values

This section describes structural characteristic values (a)-(f) such as yield base shear force Q_y and wall length L_1.

(a) Floor area A_1 and A_2 on each floor is the area of the portion surrounded by the center line of the walls or columns on each floor. Total floor area $A = A_1 + A_2$. Also, 1st floor area A_1 includes dirt floor.

(b) Weight W is the weight from the half of the height of the 1st story to the top. Under ordinary circumstances, weight is calculated using fixed load and live load per unit area of Article 84, Section 2 of Enforcement Order of the Building Standards Law of Japan and is calculated from density and materials of Chapter 3 of AIJ Recommendations for Loads on Buildings where not indicated.

(c) Natural frequency f is the primary natural frequency obtained by ambient vibration measurements.

(d) Yield base shear force Q_y is calculated based on limit strength calculation [9] and is that when 1st story drift is 1/30 rad. Also, yield base shear coefficient C_y is the value of yield base shear force Q_y divided by weight W.

(e) L_1 is defined as total wall length on the 1st story. N_1 is the number of hanging walls on the 1st story. Here only hanging walls that are more than at least 900 mm height are counted.

(f) Of the 2 directions (ridge direction, span direction), the direction in which yield base shear coefficient C_y is larger is called the “strong axis” and the one in which it is smaller is called the “weak axis”. f, Q_y, L_1, N_1 and C_y are each analyzed for respective direction.

Also, in regard to Narai, we only confirmed average of W/A_1, Q_y/A_1 and values of f and C_y in respective house. In addition, as for Kuroshima, it should be noted that method of calculation of the breakdown of yield base shear force for resistant elements is different from other regions. In regions other than Kuroshima, basically the proof stress of frame is included in the proof stress of resistant elements such as full wall and hanging wall.

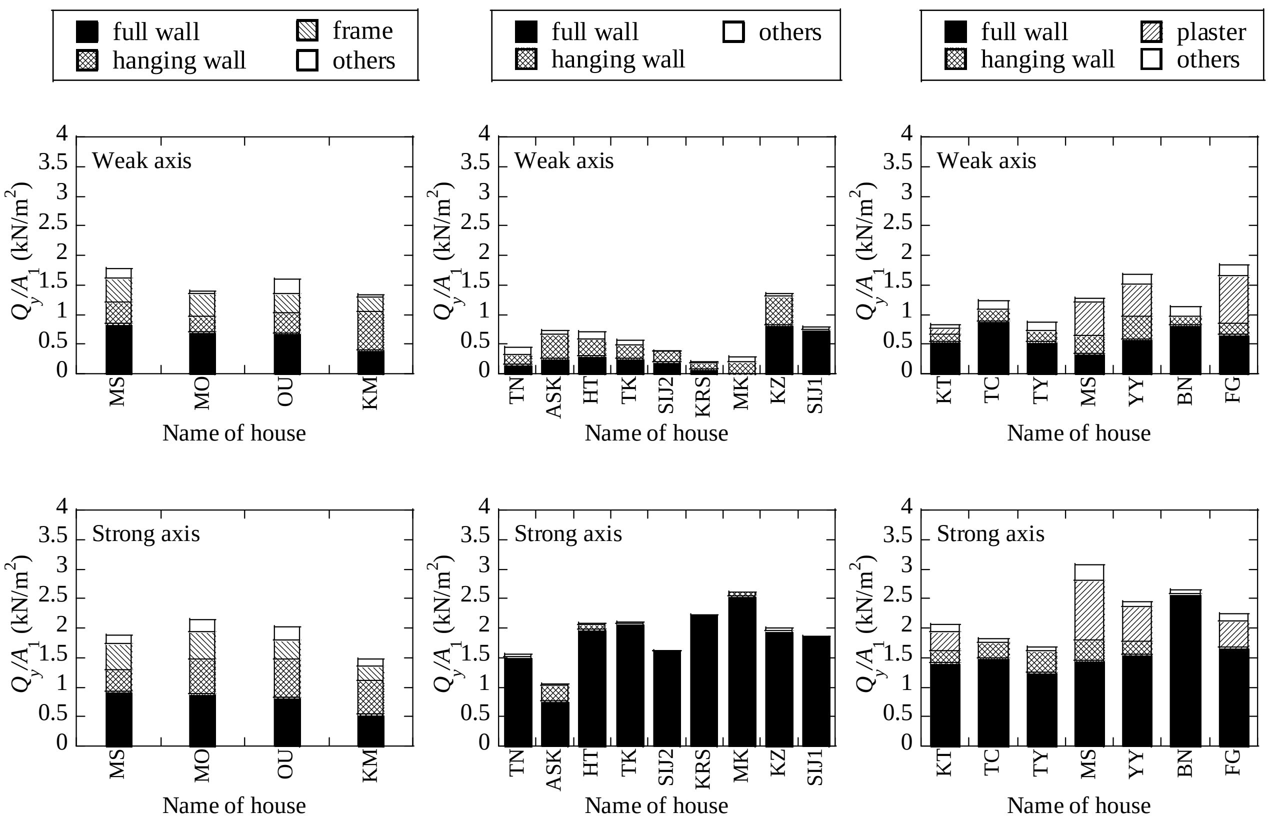
3.2 Yield base shear force per unit 1st floor area Q_y/A_1

Figure 2 shows yield base shear force per unit 1st floor area Q_y/A_1 for each house in Kuroshima, Kyoto and Yuasa so that the breakdown for each resistant elements (full walls, hanging walls, plaster boards, etc.) of house and direction can be seen. Figure 3 gives the average of Q_y/A_1 for each region and Figure 4 gives the breakdown of resistant elements of Q_y/A_1. It should be noted that the breakdown of yield base shear force for resistant elements is unknown in only Narai.

Figures 2 and 3 also show a difference according to region for Q_y/A_1, its direction and breakdown of resistant elements. For example, there is a significant difference in (i) the weak axis (street parallel direction) and the strong axis (street orthogonal direction) for townhouses in regions other than Kuroshima, and (ii) full walls account for a high percentage in the strong axis direction. In Kuroshima, on the other hand, (i) no clear difference is observed in proof stress or breakdown of resistant elements between both axis directions.

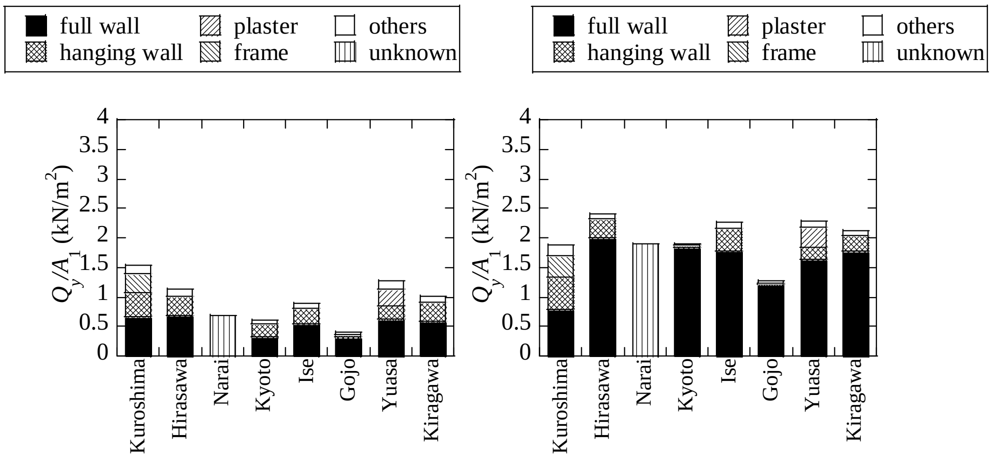
Next, Figure 4 confirms that the percentage of full walls accounted for by Q_y/A_1 is about 50 percent for all regions in the weak axis direction, and at least 70 to 80 percent in the strong axis direction for all regions except Kuroshima. It also shows it is about 20 percent in the weak axis direction and about 10 percent in the strong axis direction for hanging walls in almost all of regions. This tells us the percentage of full walls accounted for by Q_y/A_1 is large regardless of the region.

Finally, as shown in Figures 2 - 4, because plaster board is used for renovations to 4 of 7 of the target houses in Yuasa, higher proof stress is observed.



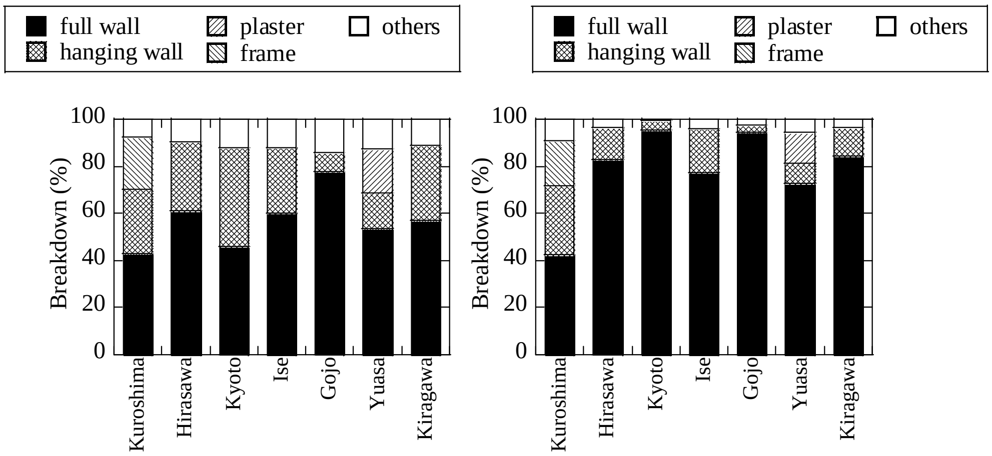
(a) Kuroshima (b) Kyoto (c) Yuasa

Figure 2 – Yield base shear force per unit 1st floor area Q_y/A_1 for each house in Kuroshima, Kyoto and Yuasa (Above row shows the results in weak axis. Below row shows the results in strong axis.)



(a) Weak axis (b) Strong axis

Figure 3 – Average of Q_y/A_1 for each region



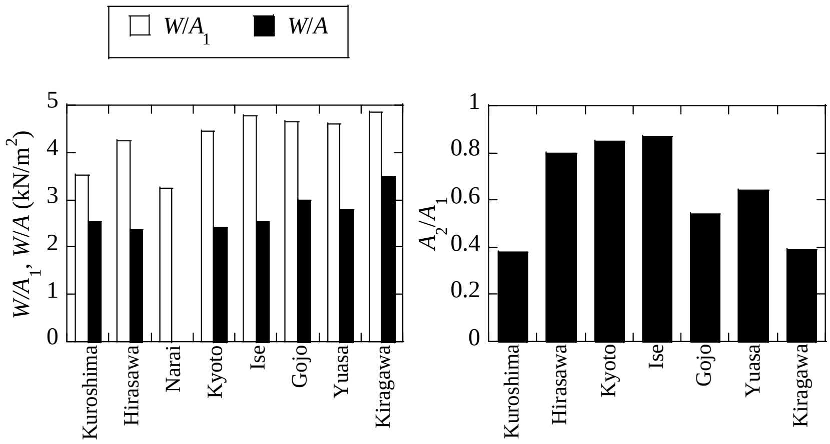
(a) Weak axis (b)Strong axis

Figure 4 – Breakdown of resistant elements of Q_y/A_1

3.3 Weight per unit 1st floor area

Figure 5 (a) shows average by region of weight per unit 1st floor area W/A_1 and weight per unit total floor area W/A. Figure 5 (b) shows comparison of A_2/A_1.

The figure also shows that, in Kiragawa, weight per unit total floor area W/A is 3.5 kN/m^2 and approximately 1 kN/m^2 larger with its thick mud walls than in other regions. In addition, in Narai, weight per unit 1st floor area W/A_1 is 3.2 kN/m^2 and approximately 1.5 kN/m^2 smaller with metal roofing and board of external walls. In Kuroshima and Kiragawa, A_2/A_1 is around 0.4 and markedly smaller, and in Kuroshima, W/A_1 is somewhat smaller. On the other hand, except Narai and Kuroshima where the specification of roof and walls in the houses are different from other regions as shown in Table 1, there was no different from W/A_1 at approximately 4.5 kN/m^2. Therefore, regionality is observed for weight per unit total floor area W/A and weight per unit 1st floor area W/A_1 with specification of roof and walls.



(a) $W/A_1, W/A$ (b) A_2/A_1

Figure 5 – Average by region of weight per unit 1st floor area W/A_1 and weight per unit total floor area W/A and comparison A_2/A_1 of 2nd story floor area and 1st story floor area

3.4 Relationship of yield base shear coefficient C_y and natural frequency f

Figure 6 shows the relationship of yield base shear coefficient C_y and natural frequency f obtained for houses in the 7 regions without distinction for weak and strong axes. Also, the houses of Kuroshima are distinguished from those of other areas by a block dot in the figure. The figure also shows a close correlation for the two in respect to townhouses in regions other than Kuroshima; the formula [10] in the figure shows the fact that the two are correlated. With the exception of some of the houses in Kiragawa which have brick walls, Kuroshima appears to deviate from the relational expression in the figure. Because the same tendency was observed for traditional wooden houses that were exposed to 2000 Tottori earthquake and the northern Miyagi earthquake in 2003 [10], it may be one of the causes that ambient vibration measurements have been conducted immediately following the earthquakes.

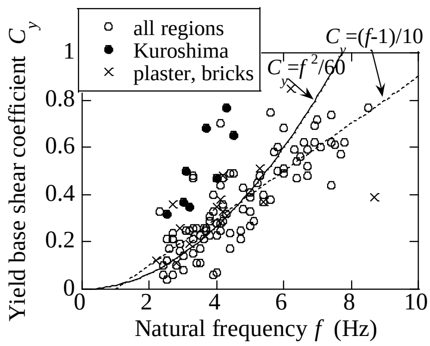


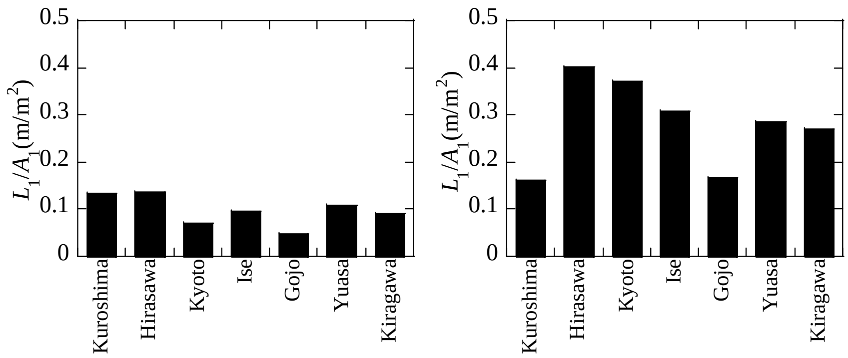
Figure 6 – Relationship of yield base shear coefficient C_y and natural frequency f obtained for houses in the 8 regions without distinction for weak and strong axes

3.5 Total length of full wall and the number of hanging walls per unit 1st floor area

Because the percentage of full walls and hanging walls accounted for by Q_y/A_1 was significant regardless of the region, Figures 7 and 8 show the full wall length per unit 1st floor area L_1/A_1 and number of hanging walls per unit 1st floor area N_1/A_1. It should be noted that 2 out of 9 houses are unknown of total wall length on 1st story L_1 and the number of hanging walls N_1 in Kyoto. The figures show a significant difference in L_1/A_1 of strong and weak axes in all regions other than Kuroshima. There is also a significant difference in the number of hanging walls N_1/A_1 according to region, suggesting the possibility that danger of collapse of columns on the lower side of hanging walls may vary significantly according to region.

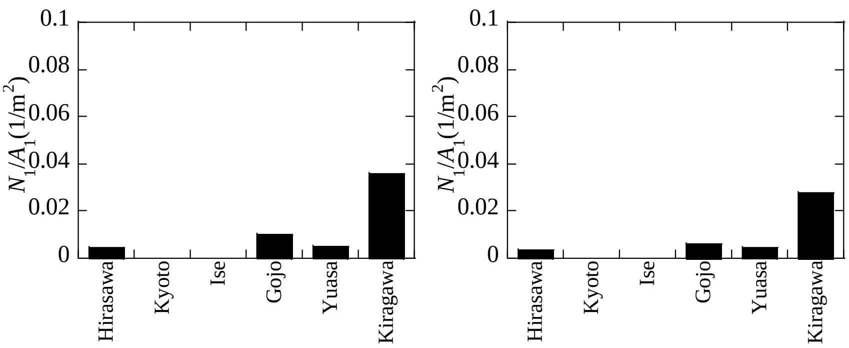
Figures 9 and 10 show the relationship of natural frequency f and L_1/W, and that of L_1/A_1 and Q_y/A_1, respectively. Figure 9 shows a generally close correlation between natural frequency f and L_1/W for all regions, including Kuroshima, which tended to differ from the other regions as for the relationship of yield base shear coefficient C_y and natural frequency f.

Figure 10 shows a generally close correlation between L_1/A_1 and Q_y/A_1 ; without considering hanging walls and other resistant elements, yield base shear force Q_y could roughly be estimated from L_1 and A_1.



(a) Weak axis (b)Strong axis

Figure 7 – Average of full wall length per unit 1st floor area L_1/A_1



(a) Weak axis (b)Strong axis

Figure 8 – Average of number of hanging walls per unit 1st floor area N_1/A_1

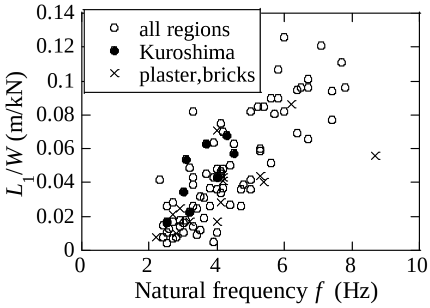


Figure 9 – Relationship of natural frequency f and L_1/W

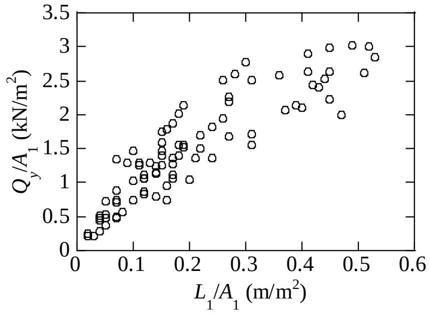


Figure 10 – Relationship of L_1/A_1 and Q_y/A_1,

4. Conclusions

The findings obtained from this paper are as follows:

1) Regionality is observed for yield base shear force per unit 1st floor area Q_y/A_1 and in breakdown by resistant elements.
2) The weight per unit 1st floor area W/A_1 vary from regions to compare, depending on specifications of the roofs and walls in houses.
3) There is a strong correlation in both weak and strong direction between the total length of the full walls in 1st floor per weight L_1/W and the natural frequency f and between the total length of full walls in 1st floor per unit 1st floor area L_1/A_1 and the yield base shear force per unit 1st floor area Q_y/A_1.
4) There is also a strong correlation between the natural frequency f and the yield base shear coefficients C_y except for the houses in a region where ambient vibration measurements was conducted immediately after the earthquake occurred.

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