STUDY ON HORIZONTAL STRENGTH OF TRADITIONAL WOODEN HOUSES BY TESTS IN SITES

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SUMMARY

I have studied by diagrams and experiments on static and dynamic horizontal strengths of traditional wooden houses, with 4 rooms separated only doors, made of papers and wood in Shiga prefecture in Japan since 1990. Followings have been clear;

1) On their drawings, their walls are often short of lengths, regulated at the article 46th of the Cabinet Orders on Japanese Architectural Standard. But they are satisfied by adding a few walls at suitable positions.

2) From static horizontal tests on their houses, it was been estimated that they would endure the tremor of the 6th degree of Japanese seismic scale.

3) From dynamic horizontal tests on their frames, it has been clear that the shear wall ratios are from 4.4 to 5, only by columns and girders, and that strengths of composite frames, composed of 3 frames, connected by perpendicular girders are equal to the sum of the strengths of each frame within 1/120~1/60 radian.

INTRODUCTION

The earthquake-proof of wooden houses is checked by wall lengths in Japan, since 1950. Many wooden houses built before then, are lack of horizontal walls lengths. It is the same as for wooden cathedrals of shrines or Buddhist temples. In consequence, they need to be added some lengths of walls or re-built. I think that horizontal resistances of these wooden buildings can be expected by bending and shear resistances of columns and girders as same as in reinforced concrete or steel buildings. In order to examine this, I have statically and dynamically tested on traditional wooden houses, built about 150 years ago. In the followings, I show their outlines.

PROGRESS OF MY STUDIES AND THEIR RESULTS

1. Study on Wall Lengths on Drawings
The only rule to earthquake-proof of wooden houses was wall lengths at the article 46th of the cabinet orders on Architectural Standard in Japan. This provides wall lengths to fill according to floor areas of each house, in two cases of roofs, heavy or light. If this order is applied to traditional wooden buildings, wall lengths are often short. Followings are 16 results which I examined on drawings. They are wooden

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houses with two stories. I examined their walllengths in longitudinal and latitudinal direction at each story in the houses from the north district to the south district in Shiga prefecture. Photo 1. is a representative house under construction. Fig.1. is its plan of the 1st story.

![Photo 1. An example of wooden house with 2 stories, conventionally constructed of columns and girders](image)

![Fig.1. Plan of the 1st story](image)

![Fig.2. Wall ratio and eccentricity ratio](image)

At the 2nd story, walls are set evenly in 4 surroundings, so there are little problems in their lengths and arrangements. At the 1st story, from 4 to 6 rooms are orderly arranged, and their partitions are only sliding doors, made of wood and paper. Walls are set only at the back of two innermost rooms. So wall lengths and their arrangements are against the order at many houses. G in Fig.1 is the center of gravity, D is the center of horizontal resistances by walls. D' is that after a few walls added.

In Fig.2, the results are plotted 16 similar wooden houses in Shiga prefecture. Horizontal axis is wall ratio, that is wall lengths divided by floor area, in longitudinal and latitudinal directions. Wall ratios are regulated larger than 0.33m/m² at the 1st floor, 0.21m/m² at the 2nd floor in case of heavy tiled roof. Vertical axis is eccentricity, the distance between G and D (or D'), divided by elastic radius. This is needed to be lower than or equal to 0.15. The followings are known from Fig.2:

1. At the 1st floor, 60% houses satisfy wall ratio, 50% satisfy eccentricity, but only 20% houses satisfy both regulations.
At the 2nd floor, more than 90% houses satisfy wall ratio, a little more than 60% satisfy eccentricity, and 60% houses both regulations.

2. Static Horizontal Tests on Traditional Wooden Houses Built about 150 years ago

2.1 Horizontal Forces Supported by Columns

In August 1999, we had a chance of pull tests on a traditional wooden house of thatched roof, built about 150 years ago at Minakuchi Town (photo 2.). Its plan Fig. 3. is almost the same as Fig. 1. Strain gauges and displacement gauges were set on 10 columns surrounding 4 rooms.

We pulled by 2 winches in 2 latitudinal directions until 110kN, about 50% of weight 216kN of this house. At the max. horizontal load, tops of columns displaced about 10cm, and cracks ran in soil pasted walls and parts of them fell, but the house did not sign collapse.

Horizontal force supported by each column is shown in Fig.4, using strains and Young’s modulus, got by bending tests on 2 columns. From this, it is clear that the biggest column “Daikoku basira” supported max. about 2 kN and 10 columns surrounding 4 rooms supported 8.5% of horizontal load. Eight houses of this sort were in the same village, and other 130 houses had 2 stories and tiled roofs.
2.2 Horizontal Forces Supported by Columns and Girders
In August 2002, we again pulled another traditional wooden house with thatched roof, built about 150 years ago at Kouka Town. We set about 400 strain gauges on columns and girders, pulled their 3 frames in latitudinal direction, and 2 frames in longitudinal direction by winches and examined the magnitudes and flows of forces supported by each frame in Fig.5, 6.

Fig. 7. shows that a pulled frame X3 supports 66% of pull forces, and other adjacent frames supports 33% of pull force. The frames crossing against load direction transport these forces by bending and shear stress.

![Fig. 5. Perspective of tested house, in Kouka town.](image1)

![Fig. 6. Plan of tested house](image2)

![Fig. 7. Flow of forces, transported by girders and columns](image3)

![Fig. 8. Forces supported by columns](image4)

Mean horizontal strengths per unit horizontal length of wall were 4.55kN/m at 1/120 rad. of column inclination. This inclination is called “limit of no damage”. The standard strength at this inclination is 1.27 kN, so this measured strength is 3.59 times larger than it.

Mean total horizontal strength of this house at 1/120 rad. can be 86.3, 99.5kN in latitudinal, longitudinal direction respectively. As the total weight of this house is 245kN, the ratio of horizontal strength to total weight is 0.352, 0.406 in each direction at 1/120 rad. of column inclination.

3. Dynamic Vibration Test on Structural Frames of a Traditional Wooden House
On the horizontal vibration stage of steel members, we rebuilt the structural frames of the traditional wooden house of 2.2 and made them shake by a high-power oil jack, using oil pump for a construction machine. Each frame was constructed of columns, upper and middle girders only.
At the first, two frames Y2 and Y5 in longitudinal direction were re-built separately on the stage, and shaken. Afterward, each frame was combined by crossing frames, and shaken. Accelerations, displacements and strains gauges were set on the top, middle height and bottom of columns.

3.1 Cases of test: Fig. 9.
a) Y2, Y5 frame in longitudinal direction, composed of columns, an upper girder and middle girders respectively.
b) Total structure, combined by crossing frames in latitudinal direction, using columns, upper girders and middle girders.

3.2 Measured data
Accelerations, displacements and strains were measured at the tops, middle girders and bottom of columns. The bottom of each column was set on steel channel, surrounded by steel members and only restricted horizontally. So the acceleration and displacement of the stage, made of steel members were represented by them at the bottom of the column of each frame.

3.3 Test results
In each case, we tested 2 series, composed of 10 steps in a series, dividing rotation number (2020~500rpm) of oil pump into 10 sections. The brief outlines of the results are shown in 3.4.
a) Relations between column inclinations and accelerations of top and bottom of columns: Inclination was calculated, dividing displacements difference between top and bottom of each column by their heights difference.
b) Distributions in vertical direction of accelerations and displacements of columns: Main columns’ distributions are shown.
c) Relations between horizontal forces and column inclinations at the top of columns: The mass of each member had been measured, so the force of the part, measured acceleration was calculated by them..

Fig. 9. Tested frames
3.4 Consideration on test results

In Table 1, the accelerations and distributions of the tops of columns are listed. From this and Fig. 10, 11, the followings are made clear.

**a) On accelerations**

In case of Y2 and Y5 frame alone, the max. acceleration of the top of the column is respectively 1510, 904 gal. They are 7.6, 2.2 times larger than each acceleration 176, 281 gal. at the bottom of column at the time of push. At the time of pull, the max. acceleration is 1189, 1154 gal. They are 5.6, 16 times larger than each acceleration 179, 68 gal. at the bottom of column.

On the contrary, in X3 frame connected by crossing frames of upper and middle girders, the max. accelerations at the top of columns are from 5.4 to 327 gal in push, very much smaller than those of separate frames. The acceleration of the bottom of columns is −343 gal. (in pull side), so the ratios of top to bottom acceleration are from 1.95 to 1.02. The restrain effects of 3 dimensions are big. In pull, the accelerations at the top of columns are from 260 to 0 gal. They are from 6 to 1 times larger than 36 gal. of common acceleration at the bottom of columns. An example is shown in Fig. 10 (b), (c).

**b) On the max. displacements and column inclinations**

In case of Y2, Y5 frame alone, the max. displacement is 190, 140 mm, and column inclination is 1/19, 1/26 rad. This is near to “safety limit” of 1/15 rad. to failure, “re-usable limit” of 1/30 rad., respectively. On the contrary, in X3 frame connected by crossing frames of upper and middle girders, the displacement of Y2 frame diminished to 30%. Y5 was as same as Y5 alone and Y8 frame was as same as Y2 alone in pull. Y8 frame is lack of 40% of upper girder, so torsion happened in the total structure. At push, max. displacements diminished to from 1/1.5 to 1/1.3.
Table 1. Max. accelerations and displacements of the tops of columns, their amplification ratios and column inclinations

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c) Relations between horizontal forces and column inclinations at 3 limits angles

Let's consider the relations between the horizontal forces and column inclinations of the top of columns (X2, Y2), (X5, Y5) in frames Y2, Y5 and X3. Three limits of column inclination are defined as follows:

1/120 rad.: “Limit of no damage”, is a little damages and needn’t be repaired.
1/60 rad.: Limit, can be re-used after a little repairs.
1/30 rad.: Limit, can be re-used after several repairs.

It is clear that the horizontal forces supported by X3 frame, connected with 3frames Y2, Y5 and Y8 by crossing frames are 3.15 times larger than each Y2, Y5 frame at 1/120 rad. and 2.95 times larger at 1/60 rad. This implies that the strength of total frames is calculated by adding each strength of frames. This is equal to “Design method of limit strength”. At 1/30rad. the magnitude is only 1.45 times larger than each frame alone. It seems that at this stage, restrain effect of crossing frames became weak. Wall ratios of frames Y2 and Y5 were calculated 3.99, 5.49 from horizontal strengths at 1/120.

CONCLUSION

We have studied static and dynamic horizontal strengths of traditional wooden houses with 4 rooms, which are many in the west Japan, as same as Shiga prefecture. Main results are followings:

a) On drawings, if wall lengths are calculated, they are sometimes short of the order 46th. But they are satisfied by adding a few walls at several parts.
b) From static horizontal tests, it was speculated that these sort of houses can bear to seismic intensity 6, at column inclination 1/120.
c) From dynamic horizontal test, followings have been clear;

① Strength of the three dimensional structures, composed of frames, crossing each other is equal to the sum of the strengths of each frame at 1/120 and 1/60 rad. of column inclination. This imply the validity of “Design method of limit strength”.
② The wall ratio of frame only, composed of upper, middle girders and columns, is from 4.0 to 5.5.

REFERENCES

Fig. 11. Relations between accelerations and column inclinations