ANALYTICAL AND EXPERIMENTAL INVESTIGATION ON SEISMIC BEHAVIOR OF FRAME-PANEL TYPE NONSTRUCTURAL WALLS

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SYNOPSIS

Nonstructural walls such as light weight concrete panels and walls with mortar finishes were severely damaged by recent earthquakes in Japan. Analytical investigation of the behavior of furring frame with overlayed panels was made when it is subjected to a horizontal racking force due to story drift. The effects of aspect ratio, number of division of panels and layout of joints were studied. Also comparison of an analytical solution and an experimental result was made on a certain construction type.

INTRODUCTION

Most nonstructural walls such as exterior curtain walls and partitions are made up with a furring frame and an overlayed panel. The furring frame might be a part of the structural frame or a furring attached to the frame. Examples of panels are light weight concrete panels in dry construction and mortar finishes in wet construction. Some of these nonstructural walls were severely damaged in recent earthquakes in Japan such as Izu-Ohshima Earthquake (Jan. 14, 1978 [1]) and Off-Miyagi Earthquake (June 12, 1978 [2]).

In analytical investigation to study the theoretical behavior of nonstructural walls which are subjected to a horizontal racking force due to story drift, the following assumptions were made; the furring frame deforms parallelogramatically and the overlayed panel does not deform in its plane but rotates on the furring frame. The effects of aspect ratio (height/width), number of division of panels and layout of joints were studied based on linear analysis.

Horizontal racking tests were carried out using an instrument which simulates the story drift during earthquakes. The experiments were made on several construction types of nonstructural walls [3]. The comparison of an experimental behavior and a theoretical non-linear one on the force-displacement diagram was made.

THEORETICAL LINEAR BEHAVIOR OF FRAME-PANEL TYPE WALLS

General

Among various construction types of nonstructural walls, a furring frame with an overlayed panel is popular. The theoretical behavior of this type (frame-panel type) when subjected to story drift was investigated according to the following assumptions.

i) The geometry of the furring frame as well as the overlayed panel and the layout of the joints between them are symmetrical around the center of the element.

ii) The furring frame (without overlayed panel) is flexible enough to deform parallelogramatically without any resistance.

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iii) The panel is rigid enough not to deform in its plane.

iv) The behavior of the joint between the furring frame and the overlayed panel is linear-elastic.

When a frame panel type of nonstructural wall is subjected to a horizontal racking force due to story drift, the furring frame tends to deform parallelogramatically, while the panel does not deform in its plane but rotates along the center as shown in Fig. 1. The difference of movements between the furring frame and the panel produces restoring forces due to the relative displacement at joints. This relative movement takes place in such a manner that the rotational moment given to the panel by the restoring force at the joints keeps equilibrium.

Based on this theory, the following parametric study in connection with geometrical characteristics was made:

i) Aspect ratio of panel : Height/Width

ii) Number of division of panel

Analysis

The frame and the panel change their positions according to story drift in different ways as illustrated in Fig. 1. However, because of the symmetry of the wall, the centers of the frame and the panel move in the same way — they both shift their positions horizontally. The distance between the original position O and the shifted position O_s is half of the story drift δ. Consequently, the coordinates in the following discussion are based on reference axes in which the shifted center O_s is regarded as the original point.

A point on the furring frame is considered to move horizontally, because, if story drift is small, the change of position along the vertical direction is also small and can be ignored. However, a point on the panel changes its position according to the rotation along the shifted center O_s. Each movement of the points on the frame and the panel is shown in Fig. 2. Story drift is indicated by the angle θ_f in radian, which is the ratio of story drift δ to the height of the element H. The movement of a point on the furring frame is shown by $\overline{P_sP_f}$ in Fig. 2, and its horizontal displacement, $\overline{P_sP_f}$, is $\theta_f y$. The rotational angle of the panel is indicated by θ_p. The movement of a point on the panel is shown by $\overline{P_sP_p}$ in Fig. 2, and its horizontal displacement, Δx, is $(\theta_f-\theta_p)y$ and the vertical displacement, Δy, is $\theta_p x$.

The resultant relative displacement, $\overline{P_pP_f}$, between the two points is expressed as follows:

$$\text{Relative Displacement} = \sqrt{(\theta_p x)^2 + \{(\theta_f - \theta_p)y\}^2}$$

$$= \theta_f \sqrt{r^2x^2 + (1-r)^2 y^2} \qquad (1)$$

$$\text{where} \quad r = \theta_p / \theta_f$$

The restoring force at this joint is expressed as follows:

$$\text{Restoring Force} = R\,\theta_f \sqrt{r^2x^2 + (1-r)^2y^2} \qquad (2)$$

$$\text{where} \quad R = \text{stiffness of the joint}$$

Accordingly, two components, x-direction and y-direction, of restoring forces are expressed as follows:

$$F_x = R\,\theta_f\sqrt{r^2x^2 + (1-r)^2y^2}\cdot\frac{(\theta_f - \theta_p)y}{\theta_f\sqrt{r^2x^2 + (1-r)^2y^2}}$$
$$= R\,\theta_f(1-r)y \qquad (3)$$
$$F_y = R\,\theta_f\sqrt{r^2x^2 + (1-r)^2y^2}\cdot\frac{\theta_p x}{\theta_f\sqrt{r^2x^2 + (1-r)^2y^2}}$$
$$= R\,\theta_f\,rx$$

Finally, the equilibrium of rotational moment as a whole around the shifted center, O_s, is expressed as follows:

$$M = \Sigma\,(F_x\cdot y - F_y\cdot x) = \Sigma\,\{R\,\theta_f\,(1-r)yy - R\,\theta_f\,rxx\}$$
$$= R\,\theta_f\,\{(1-r)y^2 - rx^2\} = 0 \qquad (4)$$

From this equation, the value of r is computed. For practical compution, the summation of the above equation has only to be carried out in the first quarter of the panel, because of the symmetry. When the value of r is obtained, the horizontal racking force which is carried by the frame-panel wall is expressed as follows (The summation should be carried out on the upper half of the wall.):

$$P = \Sigma\,F_x = \Sigma\,R\,\theta_f(1-r)y \qquad (5)$$

For further investigation, Aspect Ratio is defined as follows:

$$\alpha = H/B$$

where H = *Height of the element*

where B = *Width of the element*

If the panel is divided into two or more portions, the aspect ratio changes depending on the method of application, as shown in Table 1.

$$\alpha' = \frac{H}{B/n} = \frac{nH}{B} \quad : \quad \textit{vertical Application}$$

$$\alpha' = \frac{H/n}{B} = \frac{H}{nB} \quad : \quad \textit{horizontal Application}$$

where n = *number of division*

In the following examples, in connection with seven types of joint layout, the following values were computed:

r : *Rotation ratio* $(r = \theta_p/\theta_f)$

d_H : Horizontal relative displacement along horizontal boundary between panels (that is, between the panel of the element under consideration and the panel of the adjacent element, or between the divided panels in the element) as shown in Table 1.

d_V : Vertical relative displacement along vertical boundary between panels.

K : Initial stiffness of the element defined as

$$K = P / \delta$$

where P = *Horizontal Racking Force*

δ = *Story Drift*

Examples

Several Types of joint layout as shown in Table 1 were studied as follows:

A) Joint Layout Type A - If there are only two joints, one at the top and the other at the bottom of the panel, there is no discrepancy produced between the points at the joints on the frame and the panel. Then the results are very simple.

B) Joint Layout Type B - If there are only two joints, at the opposite sides of the panel, there is also no discrepancy produced. The results are as simple as in Type A.

C) Joint Layout Type C - If the joints are located at four corners, the above mentioned equation of equilibrium of rotational moment, Eq. 4, can be directly applied.

D) Joint Layout Type D - If the joints are uniformly and closely distributed along the top edge and the bottom edge, these joints could be assumed to form a continuous joint and Eq. 4 should be modified into integral form. In this and the following cases (D - F), stiffness of joints, R , represents the stiffness per unit length.

E) Joint Layout Type E - If the joints are uniformly and closely distributed along edges on both sides, the joint could be assumed to form a continuous joint and the same modification should be made for Eq. 4.

F) Joint Layout Type F - If the joints are uniformly and closely distributed along the edges on all sides, the joint could be assumed to form a continuous joint and the modification of Eq. 4 is almost similar to D and E.

G) Joint Layout Type G - If the joints are uniformly distributed all over the panel and they are very close to one another, these joints could be assumed to form a continuous joint and Eq. 4 should be modified into double integral form. The r in this type is the same as that in Type C and stiffness of joint, R, represents the stiffness per unit area.

Results

Figures 3 shows the examples of results (Joint Layout Type G) of the parametric study based on the formulation given by Table 1.

Graphs of $n=1$ show the fundamental solution for the single panel. Graphs of $n_H = 2$ or 3 indicate the effect of horizontal application with two and three divisions, respectively. Graphs of $n_V = 2$ or 3 show the effect of vertical application.

NON-LINEAR BEHAVIOR OF FRAME-PANEL TYPE WALLS

General

As an example of the extension of the above mentioned theory, non-linear behavior of a nonstructural wall was investigated based on experimental data.

The employed specimen of the experiment is a gypsum board wall with an wooden frame.

In the analysis, the same assumptions are made as in the previous chapter, except for the provision of linearity.

Analysis

The only difference between a linear system and a non-linear one is related to restoring forces at the joints between the frame and the gypsum board. The non-linearity was assumed to be the elasto-plastic type, as shown in Fig. 6. The horizontal (x) and the vertical (y) components of the restoring force at a joint are expressed as follows insted of Eq. 3.

$$F_x = \frac{\theta_f y - \theta_p y}{\sqrt{(\theta_p x)^2 + \{(\theta_f - \theta_p) y\}^2}} \cdot f = \frac{(1-r) y}{\sqrt{r^2 x^2 + (1-r)^2 y^2}} \cdot f$$

$$F_y = \frac{\theta_p x}{\sqrt{(\theta_p x)^2 + \{(\theta_f - \theta_p) y\}^2}} \cdot f = \frac{r x}{\sqrt{r^2 x^2 + (1-r)^2 y^2}} \cdot f \qquad (6)$$

$$\text{where} \quad f = \begin{cases} R \cdot \Delta : & \Delta \leqq \Delta_y \\ f_y : & \Delta_y < \Delta \leqq \Delta_f \\ 0 : & \Delta_f < \Delta \end{cases} \qquad (6)'$$

Δ = *Relative Displacement* = $\theta_f \sqrt{r^2 x^2 + (1-r)^2 y^2}$
Δ_y = *Displacement at Yielding*
Δ_f = *Displacement at Failure*
f_y = *Yielding Stress*

Consequently, the equilibrium of rotational moment around the shifted center O_s is expressed as follows:

$$M = \Sigma (F_x \cdot y - F_y \cdot x) = \Sigma \left\{ \frac{(1-r) yy}{\sqrt{r^2 x^2 + (1-r)^2 y^2}} \cdot f - \frac{r x x}{\sqrt{r^2 x^2 + (1-r)^2 y^2}} \cdot f \right\}$$

$$= \Sigma \frac{(1-r) y^2 - r x^2}{\sqrt{r^2 x^2 + (1-r)^2 y^2}} \cdot f = 0 \qquad (7)$$

In this equation, f is a function of r as expressed in Eq. 6'. Therefore, when a certain value of θ_f is given, this equation should satisfy both r and f. The iteration method can be used for practical compution. The value of r is assumed to yield the value of f, and then the value of M is computed. If M is too large, the value of r is modified and the same process is repeated until a small enough value of M is obtained. If a combination of r and f is obtained according to the above-mentioned process, then the horizontal racking force which is carried by the frame-panel wall is expressed as follows (The summation should be carried out on the upper half part of the wall.):

$$P = \Sigma F_x = \Sigma \frac{(1-r) y}{\sqrt{r^2 x^2 + (1-r)^2 y^2}} \cdot f \qquad (8)$$

Experiment and Comparison

An actual specimen of a gypsum board with a wooden furring frame is shown in Fig. 4. The horizontal racking test was carried out. The simulated story drift was given to the top member and the bottom one of the wooden frame and both sides were kept free in the racking test. The gypsum board could rotate without any restriction at boundaries(top, bottom, both sides). The force-displacement diagram was obtained as shown in Fig. 7.

The real non-linear characteristics of each joint in this specimen were not known. Therefore, in the simulation by the model, trial-and-error method was employed using the assumed non-linear characteristics of joints as shown in Fig. 6. Theoretical results based on the following assumptions gave fairly good agreement with experimental results on the force-displacement diagram, as shown in Fig. 7.

$$\Delta_y = 0.35\ cm$$
$$\Delta_f = 1.40\ cm$$
$$f_y = 15.2\ kg$$

CONCLUSION

In the linear analysis the effects of the aspect ratio of a panel, method of application and the number of division on the rotation ratio, relative displacements and initial stiffness were formulated as shown in Table 1. Some examples were illustrated in Fig. 3. The values of relative displacements might be useful information about the amount of story drift which a nonstructural wall could accommodate. Also the values of initial stiffness could give the extent of secondary structural effect on the primary structure.

The successful comparison of theoretical and experimental non-linear behaviors shows the possibility of prediction of actual behavior by theory for nonstructural walls with similar construction method.

Acknowledgement

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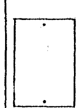
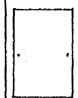
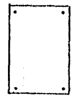
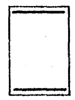
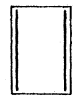
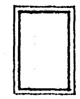
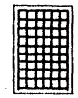
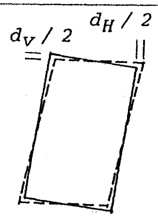
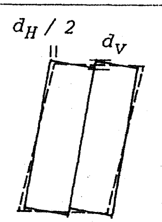
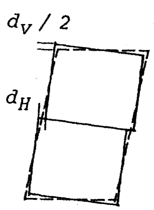
References

[1] "Report on the Building Damage in Izu-Ohshima Earthquake, Jan. 14, 1978", Architectural Institute of Japan (to be published, in Japanese).

[2] "Report on the Building Damage in Off-Miyagi Earthquake, June 12, 1978", Architectural Institute of Japan (to be published, in Japanese).

[3] Sakamoto, I., Itoh, H., and Yamashita, T., (1977) "Experimental Investigation of nonstructural walls in reference to accommodativeness to story drift", Proceedings of Annual Meeting, Kanto Branch, Architectural Institute of Japan (in Japanese).

TABLE 1 FORMULATION OF ROTATION RATIO, HORIZONTAL RELATIVE DISPLACEMENT, VERTICAL RELATIVE DISPLACEMENT AND INITIAL STIFFNESS

METHOD OF APPLICATION OF PANEL		SPECIFIC FACTOR \ JOINT LAYOUT TYPE	A	B	C	D	E	F	G
									
SINGLE PANEL $n = 1$		ROTATION RATIO r	1	0	$\frac{\alpha^2}{\alpha^2+1}$	$\frac{3\alpha^2}{3\alpha^2+1}$	$\frac{\alpha^2}{\alpha^2+3}$	$\frac{\alpha^2(\alpha+3)}{(\alpha+1)^3}$	$\frac{\alpha^2}{\alpha^2+1}$
		HORIZ. REL. DISP. $d_H = (1-r)\theta H$	0	$1\theta H$	$\frac{1}{\alpha^2+1}\theta H$	$\frac{1}{3\alpha^2+1}\theta H$	$\frac{3}{\alpha^2+3}\theta H$	$\frac{3\alpha+1}{(\alpha+1)^3}\theta H$	$\frac{1}{\alpha^2+1}\theta H$
		VERT. REL. DISP. $d_V = r / \alpha \cdot \theta H$	$\frac{1}{\alpha}\theta H$	0	$\frac{\alpha}{\alpha^2+1}\theta H$	$\frac{3\alpha}{3\alpha^2+1}\theta H$	$\frac{\alpha}{\alpha^2+3}\theta H$	$\frac{\alpha(\alpha+3)}{(\alpha+1)^3}\theta H$	$\frac{\alpha}{\alpha^2+1}\theta H$
		INITIAL STIFFNESS K	0	0	$\frac{1}{\alpha^2+1}R$	$\frac{1}{\alpha(3\alpha^2+1)}\frac{RH}{2}$	$\frac{\alpha}{\alpha^2+3}\frac{RH}{2}$	$\frac{(\alpha+3)(3\alpha+1)}{\alpha(\alpha+1)^3}\frac{RH}{6}$	$\frac{1}{\alpha(\alpha^2+1)}\frac{RH^2}{36}$
VERT. APPLICATION $n_V \geqq 2$		ROTATION RATIO r	1	0	$\frac{n^2\alpha^2}{n^2\alpha^2+1}$	$\frac{3n^2\alpha^2}{3n^2\alpha^2+1}$	$\frac{n^2\alpha^2}{n^2\alpha^2+3}$	$\frac{n^2\alpha^2(n\alpha+3)}{(n\alpha+1)^3}$	$\frac{n^2\alpha^2}{n^2\alpha^2+1}$
		HORIZ. REL. DISP. $d_H = (1-r)\theta H$	0	$1\theta H$	$\frac{1}{n^2\alpha^2+1}\theta H$	$\frac{1}{3n^2\alpha^2+1}\theta H$	$\frac{3}{n^2\alpha^2+3}\theta H$	$\frac{3n\alpha+1}{(n\alpha+1)^3}\theta H$	$\frac{1}{n^2\alpha^2+1}\theta H$
		VERT. REL. DISP. $d_V = r / n\alpha \cdot \theta H$	$\frac{1}{n\alpha}\theta H$	0	$\frac{n\alpha}{n^2\alpha^2+1}\theta H$	$\frac{3n\alpha}{3n^2\alpha^2+1}\theta H$	$\frac{n\alpha}{n^2\alpha^2+3}\theta H$	$\frac{n\alpha(n\alpha+3)}{(n\alpha+1)^3}\theta H$	$\frac{n\alpha}{n^2\alpha^2+1}\theta H$
		INITIAL STIFFNESS K	0	0	$\frac{n}{n^2\alpha^2+1}R$	$\frac{1}{\alpha(3n^2\alpha^2+1)}\frac{RH}{2}$	$\frac{n}{n^2\alpha^2+3}\frac{RH}{2}$	$\frac{(n\alpha+3)(3n\alpha+1)}{\alpha(n\alpha+1)^3}\frac{RH}{6}$	$\frac{1}{\alpha(n^2\alpha^2+1)}\frac{RH^2}{36}$
HORZ. APPLICATION $n_H \geqq 2$		ROTATION RATIO r	1	0	$\frac{\alpha^2}{n^2+\alpha^2}$	$\frac{3\alpha^2}{n^2+3\alpha^2}$	$\frac{\alpha^2}{3n^2+\alpha^2}$	$\frac{\alpha^2(3n+\alpha)}{(n+\alpha)^3}$	$\frac{\alpha^2}{n^2+\alpha^2}$
		HOFIZ. REL. DISP. $d_H = (1-r) / n \cdot \theta H$	0	$\frac{1}{n}\theta H$	$\frac{n}{n^2+\alpha^2}\theta H$	$\frac{n}{n^2+3\alpha^2}\theta H$	$\frac{3n}{3n^2+\alpha^2}\theta H$	$\frac{n(n+3\alpha)}{(n+\alpha)^3}\theta H$	$\frac{n}{n^2+\alpha^2}\theta H$
		VERT. REL. DISP. $d_V = r / \alpha \cdot \theta H$	$\frac{1}{\alpha}\theta H$	0	$\frac{\alpha}{n^2+\alpha^2}\theta H$	$\frac{3\alpha}{n^2+3\alpha^2}\theta H$	$\frac{\alpha}{3n^2+\alpha^2}\theta H$	$\frac{\alpha(3n+\alpha)}{(n+\alpha)^3}\theta H$	$\frac{\alpha}{n^2+\alpha^2}\theta H$
		INITIAL STIFFNESS K	0	0	$\frac{n}{n^2+\alpha^2}R$	$\frac{n}{\alpha(n^2+3\alpha^2)}\frac{RH}{2}$	$\frac{1}{3n^2+\alpha^2}\frac{RH}{2}$	$\frac{(3n+\alpha)(n+3\alpha)}{\alpha(n+\alpha)^3}\frac{RH}{6}$	$\frac{1}{\alpha(n^2+\alpha^2)}\frac{RH^2}{36}$

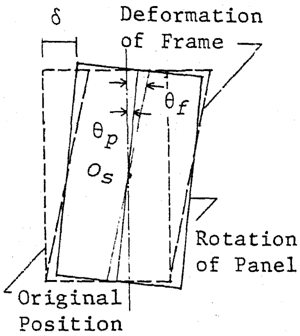


FIG. 1 MOVEMENT OF FRAME AND PANEL

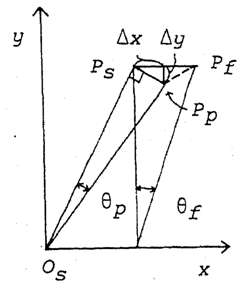


FIG. 2 DISPLACEMENT AT JOINT

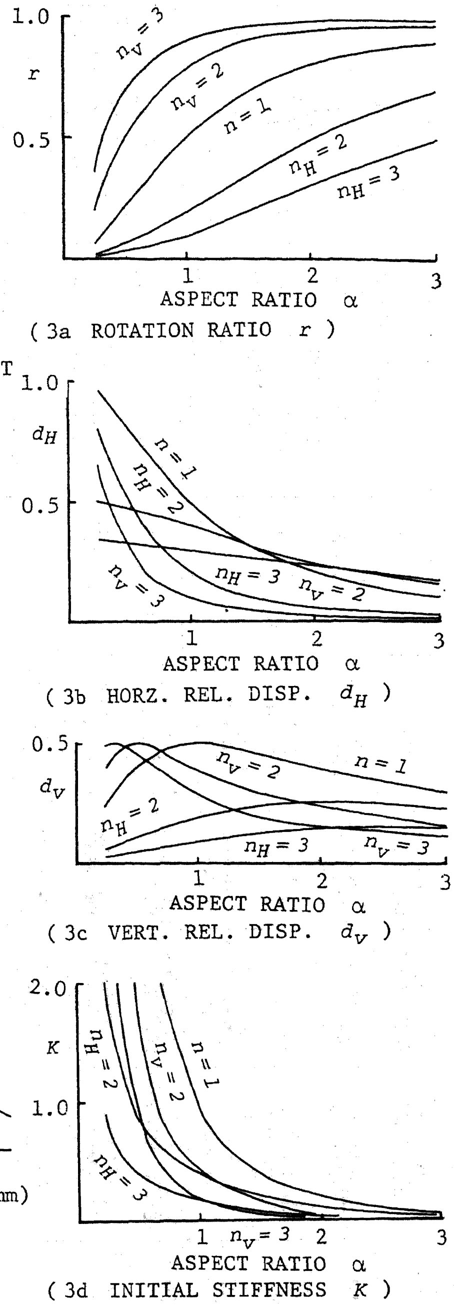


FIG. 3 EXAMPLE FOR TYPE G

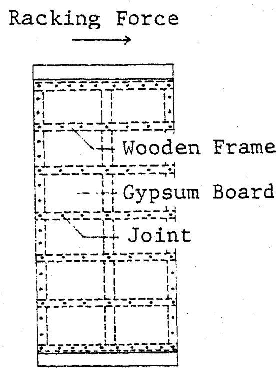


FIG. 4 SPECIMEN OF EXPERIMENT

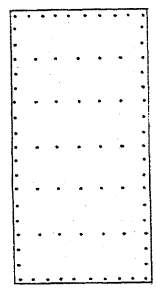


FIG. 5 MODEL FOR SIMULATION

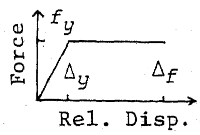


FIG. 6 ASSUMED P- δ OF JOINT

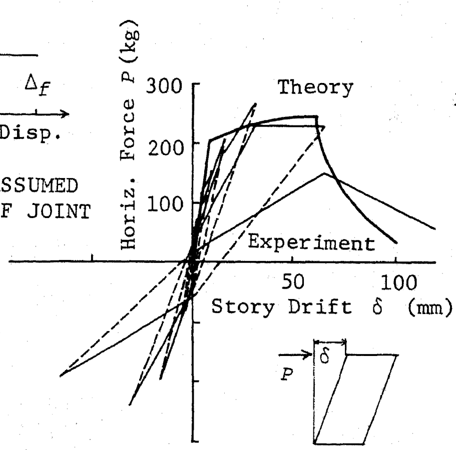


FIG. 7 COMPARISON OF THEORY AND EXPERIMENT