AN ESTIMATION METHOD FOR SEISMIC EFFECTS OF REINFORCED CONCRETE NON-STRUCTURAL WALLS TO STRUCTURAL FRAME MEMBERS

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SUMMARY

To resolve the undesirable effects of reinforced concrete non-structural walls to the earthquake behaviour of structural members, weak points (called "Structural Slits") are intentionally provided at the connection between structural members and non-structural walls. This paper presents an estimation method for the stress developed in the "Structural Slits" which are applied to the non-structural walls of reinforced concrete high-rise residential buildings.

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INTRODUCTION

Recently in Japan, many high-rise buildings have been constructed for redevelopment in cities to use sites effectively and to deal effectively with the problems of land cost skyrocketing. Reinforced concrete frame type structures are very often adopted as the structural system for high-rise residential buildings, because of the low construction cost and the inherent high-stiffness for lateral forces.

In seismic design for high-rise buildings, two basic principles are required: 1) to clear the resisting mechanism to earthquake forces and (2) to provide sufficient strength

and ductility to the resisting mechanism planned. To respond to such principles, a beam-yield type's frame structure which has strong columns and ductile beams is planned. However, as various shapes of reinforced concrete non-structural walls are constructed with structural members using the same concrete materials, the clear resisting-mechanism often is not realized by the effects of such non-structural walls. Each small exterior wall shown in Figure 1, which represents part of a typical elevation of high-rise residential buildings developing in Japan, is also one of the non-structural walls. Such non-structural walls generate secondary stress into the frames subjecting them to lateral deformation. Figure 2

FIGURE 1: ILLUSTRATION OF NON-STRUCTURAL WALLS IN HIGH-RISE RESIDENTIAL BUILDINGS

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FIGURE 2 : MOMENT DIAGRAMS OF BEAMS WITH OR WITHOUT NON-STRUCTURAL WALLS

illustrates the state of moment distribution on the beam with or without non-structural walls. In the beam with non-structural walls, because of secondary stress, the slope of moment diagram becomes more steep than the case without non-structural walls. Consequently, the frame may become a different mechanism from the original one planned. The beam becomes more susceptible to brittle shear-failure. If it is possible to remove such non-structural walls from the frame, the problem may be cleaned up. However, they are provided for such reasons as fire protection, sound insulation, construction cost, design of facade, etc., so it is not so easy to remove them for only a structural assertion.

To resolve comprehensively such problems as earthquake related problems and other requirements, weak points (called "Structural Slits") to break intentionally in times of severe earthquake have been thought out and provided at the connections between structural members and non-structural walls. Figure 3 shows typical shapes of "Structural Slits".

FIGURE 3 : TYPICAL STRUCTURAL SLITS

As "Structural Slits" are planned to break themselves, it is necessary to know the possible maximum failure-capacity for their use. This paper presents an estimation method for the stress and capacity developed in "Structural Slits". The equations for the estimates were based on the results from twelve tests in which the parts surrounded by broken lines in Figure 1 were modelled.

TEST PROGRAMS

The Objectives of the Tests

Two typical reinforced concrete non-structural walls which form the exterior walls of high-rise residential buildings were modelled to test : Model-A combines a mullion type wall with a half-height spandrel; the other is the mullion type wall, Model-B.

The objective of the tests for Model-A is to determine a reasonable location for setting "Structural Slits". The objective of the tests for Model-B is to obtain data for stress developed in "Structural Slits".

Test Specimens

The shapes and sizes of specimens are shown

FIGURE 4 : SHAPE AND SIZE OF TEST-SPECIMENS

in Figure 4. Two same non-structural walls are opposite in a specimen. The adoption of the opposite-walls-system reflects consideration for stability of the specimen during tests.

In general, a reinforced concrete member shows the characteristics of longitudinal elongation which occurs by the development of cracks. The non-structural walls in a frame also must have such elongation, if there is little restriction for it. However, in the non-structural walls as shown in Figure 1, the development of longitudinal elongation due to lateral deformation may be restricted by the surrounding frame with strong columns. The arrangement of non-structural walls with the multi-storied condition may also restrict each elongation by itself. The thin flexible steel plates in either side of the specimen and the steel rod at the center of the specimen as shown in Figure 4 are set to restrict the longitudinal elongation in consideration of the condition mentioned above.

Two types of "Structural Slits" are provided : the concave type (called Rectangular Slits) and the single shear type (called "Single Shear Slits") shown in Figure 3. Normal stress is transmitted through the "Structural Slits" in the case of "Rectangular Slits". Shearing stress is trans-

TABLE 1 : THE LIST OF SPECIMENS

Specimen	Spandrel	Mullion		Structural Slits		Strength of Concrete (kgf/cm ²)
		Width	Height	Type	Location	
No. 1	with	50 cm	60 cm	without	without	234
No. 2	with	50 cm	60 cm	RS, 30%	Top of Wall	197
No. 3	with	50 cm	60 cm	RS, 60%	Top of Wall	197
No. 4	with	50 cm	60 cm	SS	Side of Wall	197
No. 5	with	50 cm	60 cm	RS, 30%	Side & Bottom	197
No. 6	with	50 cm	60 cm	SS	Side & Bottom	197
No. 7	without	50 cm	100 cm	without	without	197
No. 8	without	50 cm	100 cm	RS, 30%	Bottom	270
No. 9	without	50 cm	100 cm	RS, 60%	Bottom	197
No.10	without	50 cm	100 cm	SS	Bottom	238
No.11	without	30 cm	100 cm	RS, 30%	Bottom	180
No. 12	without	90 cm	100 cm	RS, 30%	Bottom	270

RS : Rectangular Slits, SS : Single Shear Slits

TABLE 2 : PROPERTIES OF REINFORCING BARS

Size of Bar	Yield Strength	Strain at Yield	Tensile Strength
D6 (for wall)	3650 kg/cm ²	0.22%	5280 kg/cm ²
D22(for beam)	3840 kg/cm ²	0.24%	5800 kg/cm ²

D6 : Deformed bars with nominal diameter, 6 mm

D22 : Deformed bars with nominal diameter, 22 mm.

mitted in the case of "Single Shear Slits". In the "Rectangular Slits", two kinds of "Structural Slits" (in which the net wall thickness at the part of "Structural Slits" was reduced to 30% of the entire wall thickness [called 30% offset] and to 60% [called 60% offset] are provided for the tests. The non-structural walls without "Structural Slits" (Specimens No. 1 and No. 7) are also provided as companion specimens. The thickness of the wall is 7.5 cm, about one half of the actual thickness. The features of each specimen are summarized in Table 1. The properties of the materials used are shown in Table 2.

Loading and Measuring

Both supports of the bottom beam, assuming the inflection points of the frame, were provided for the condition of simple-support. Lateral load-reversals for positive and negative loading were applied alternately from one side of the top beam. The loads and the displacement during tests was controlled on the basis of the horizontal displacement at the top beam corresponding to a story-drift.

The data concerned with lateral loads, displacements, strains of side-plates, forces of the steel rod for longitudinal restriction to the non-structural wall, strains of reinforcing bars and the surface concrete, etc., were measured at each load-step.

TEST RESULTS

The Forces Developed in Non-Structural Walls

The relation between the lateral loads (Q) and the drift angles (R) of each specimen are shown in Figure 5 by the enveloped curves for cyclic loading. The failure modes after the test in each specimen are shown in Figure 6. The failure mode of the opposite wall not presented here was similar to Figure 6 in each specimen, respectively.

No. 1 specimen, in which the "Structural Slits" were not provided, failed by brittle behaviour due to diagonal tension. The diagonal tension cracks occurred at about 0.004 radian of drift-angles. In No. 2 specimen with "Rectangular Slits of 30% offset" at the top of the wall, the "Structural Slits" crushed in overall width by diagonal compression and simultaneously slipped horizontally. In No. 3 specimen with "Rectangular Slits of 60% offset", the "Structural Slits" crushed partially only near the corner. Diagonal tension cracks occurred, and covered concrete of the top beam failed by splitting.

In the specimens Nos. 4 - No. 6, in which "Structural Slits" were provided vertically or with U-shape in the spandrels, diagonal tension cracks did not occur. In No. 6 specimen with the "Single-Shear Slits", the damage was concentrated at the slit-zone. The force developed in non-structural walls

a) Specimen No. 1 - No. 6

b) Specimen No. 7 - No. 12

FIGURE 5 : ENVELOPED CURVES OF RELATION BETWEEN LATERAL LOAD (Q) AND DRIFT-ANGLE (R)

FIGURE 6 : FAILURE MODES OF EACH SPECIMEN AFTER TEST

FIGURE 7 : EQUILIBRIUM OF VERTICAL FORCES IN THE SPECIMEN

FIGURE 8 : COMPRESSION FORCES IN NON-STRUCTURAL WALLS.

was remarkably small compared to the No.4 and No. 5 specimens. Although the "Single-Shear Slits" has difficulties for construction and for rainproofing, it offers excellent performance for mitigation of forces developed in non-structural walls and also for control of damage in non-structural walls.

The Forces Exerted on Beams From Non-Structural Walls

Figure 7 illustrates the vertical forces exerted on the upper half of the specimen. The force (C) of compression zone at the corner is expressed by Eq. (1).

$$C = T_p + T'_p + T_s + N_r \quad (1)$$

where, T_p and T'_p are the restrictive force in each side of the steel plates, T_s is the tensile force of reinforcing bars in the wall, and N_r is the external restriction force by steel rod without prestress.

Figure 8 shows the compressive force (C) obtained by Eq. (1) using measured T_p , T'_p , T_s and N_r . The horizontal axis presents drift-angles (R).

In the specimens with "Structural Slits", the compressive forces are mitigated by the effects of "Structural Slits". If the compressive forces are estimated originally, they could be projected to the seismic design of beams with non-structural walls.

FIGURE 9 : STRAIN DISTRIBUTION AT THE TOP OF NON-STRUCTURAL WALL

The Behaviour of Non-structural Walls During Tests

Figure 9 shows the distribution of longitudinal strains along the connection between the wall and the beam. As shown in the figure, the strain distribution is approximately linear in each range of drift-angle. Figure 10 shows the relation between the drift-angle (R) and the rotation angle (θ_j) which is measured at the end of the wall with "Structural Slits". It is observed that θ_j is approximately the same as R in the range before the failure of "Structural Slits". This seems to indicate that the non-structural wall between the top and the bottom almost behaves as a rigid body.

ESTIMATION OF COMPRESSION FORCE DEVELOPED IN "STRUCTURAL SLITS"

Assumptions to Express the Equation of Compression Force

The following is assumed to precede the equation for estimation of the compression force (C) in "Structural Slits". (See Figure 11).

- 1) The distance between top and bottom beam, h_0 is kept constant during loading.
- 2) The non-structural wall behaves as a rigid body. The drift angle (R) is the same as the rotation angle (θ_j) at the end of the wall with "Structural Slits".
- 3) The triangular compressive strain-zones are formed at the top and the bottom end of the wall.
- 4) The ratios of the strains at both compression fibres ($\alpha = \epsilon_w / \epsilon_j$) are proportional to the offset ratios of wall thickness. (See Figure 12).
- 5) The nominal deformations sunk into beams is $0.1h_0$ times the fibre strain in each compression zone.

FIGURE 10 : RELATION BETWEEN θ_j AND R

FIGURE 11 : MODEL ASSUMED FOR ESTIMATION OF COMPRESSION FORCE

The Length of Compression Zone in "Structural Slits"

The relation between the drift-angle (R) and the compression fibre strain (ϵ_j) in the "Structural Slits" is expressed in Eq. (2) from the geometric deformation on the above assumptions.

$$R = \sin^{-1} \left(\frac{h_o}{\sqrt{l_w^2 + h_o^2 (1 - 0.1(1 + \alpha) \cdot \epsilon_j)^2}} \right) - \tan^{-1} \left(\frac{h_o (1 - 0.1(1 + \alpha) \cdot \epsilon_j)}{l_w} \right) \quad (2)$$

where, l_w and h_o are the width and the height of the non-structural wall, respectively. The length of compression zone in the "Structural Slits", (x_n) is expressed by Eq. (3), see Figure 11.

$$x_n = 0.1 h_o \cdot \epsilon_j / \tan R \quad (3)$$

Comparison of Estimated Values with Test Results

Applying the "e-function expression" proposed by Dr. H. Umemura [1] for the stress-strain relationships of concrete in compression, the maximum compressive resultants (C_{max}) developed in the zone (x_n) were calculated for each specimen. The results calculated are presented in Table 3 compared with the test results. The estimated values for the specimens in which concrete-crushing occurred in "Structural Slits" are comparatively close to the measured values. In No. 1 specimen, in which the shear failure occurred prior to the concrete-crushing, and in No. 12 specimen, in which the failure of covered concrete occurred without any crushing in "Structural Slits", the measured values are lower than the estimation.

FIGURE 12 : RELATION BETWEEN α AND (t'/t)

INTRODUCTION OF EFFECTS BY NON-STRUCTURAL TO STRUCTURAL DESIGN

The effects of compression forces developed in non-structural walls which were arranged with the multi-storied condition could be dealt as a coupled moment, as shown in Figure 13, and could be expressed by Eq. (4). The secondary moments and shear forces due to Figure 13 should be added to the original frame-stresses analysed for the frame without non-structural walls.

$$M = C \times J_w \quad (4)$$

where, C is the resultant compression-force, and J_w is the distance between the coupling forces (C).

Additional stress by non-structural walls

FIGURE 13 : COUPLING FORCE EXERTED ON BEAMS FROM NON-STRUCTURAL WALLS

TABLE 3 : COMPRESSION FORCES (C:tonf) AND FAILURE MODES

Specimen No.	1	2	3	4	7	8	9	11	12
C(measured)	20.71	15.00	20.54	23.48	25.20	16.06	19.43	10.92	16.52
C(estimated)	35.66	13.86	22.52	30.02	30.02	18.99	22.52	8.01	34.19
Failure mode	D.T.	Fj	Fj-Fb	Fb	Fb	Fj-Fb	Fj-FW	Fj	Fb

D.T. : Diagonal tension, Fj : Crushing in slits, Fb : Splitting failure of covered concrete of beam bottom, Fw : Splitting failure of wall.

TABLE 4 : DISTANCE OF COUPLING FORCES (J_w/ℓ_w)

Specimen No.	1	2	3	4	5	7	8	9	11	12
Method-1	0.80	-	-	-	-	-	0.68	0.74	0.72	0.72
Method-2	0.62	0.64	0.64	0.66	0.66	0.58	0.82	0.73	0.71	0.82
Method-3	0.70	0.76	0.68	0.79	0.68	0.59	0.87	0.65	0.59	0.84

Method-1 : obtained from principal strain at the centre of wall,

Method-2 : obtained from the equilibrium of moment (See Figure 7),

Method-3 : obtained from the direction of diagonal compression strut combined lateral force (Q) with compression force (C).

Eq. (5) is the compression force normalized by the width and the thickness of the non-structural wall and concrete strength. It was the equation in which the compression forces estimated using Eq. (3) and "e-function stress-strain relationships" for concrete were approximated by the least Square method. Figure 14 shows Eq. (5) compared with the test results.

$$\begin{aligned}\beta &= C/(t\ell_w \cdot F_c) \\ &= (t'/t)(0.7 - 0.3(t'/t))\end{aligned}\quad (5)$$

FIGURE 14 : RELATION BETWEEN NORMALIZED COMPRESSION FORCE (β) AND OFFSET RATIO (t'/t)

For J_w in Eq. (4), the following Eq. (6) could be recommended. It was obtained considering that the average of J_w analysed by some methods was approximately $0.7\ell_w$ as shown in Table 4.

$$J_w = 0.7\ell_w \quad (6)$$

FAILURE MODES IN THE PART OF "STRUCTURAL SLITS"

Three failure modes were observed in the specimens with the "Rectangular Slits" as mentioned above : 1) concrete-crushing in "Structural Slits", 2) splitting failure of covered concrete of the beam adjacent to "Structural Slits" and 3) splitting failure of the wall adjacent to "Structural Slits".

Figure 15 illustrates the possible failure modes in the part of "Structural Slits". The mode of concrete-crushing (F_j) depends on the strength of the offset-concrete in "Structural Slits". The mode of splitting failure in the covered concrete of the beam (F_b) depends on the bearing strength of beam-concrete subjected to compression force from "Structural Slits". The mode of splitting failure in the wall (F_w) also depends on the bearing strength of wall-concrete subjected to the same compression from "Structural Slits".

Eqs. (7), (8) and (9) show each strength corresponding to the above three failure modes. The strength-increase due to size-effect is considered in Eq. (7) for the concrete-crushing strength of "Structural Slits", using the proposal by Dr. Baushinger [2]. The proposal by Prof. H. Muguruma is adopted for the bearing strengths of concrete in beams and walls shown in Eqs.(8) and (9), respectively [3].

FIGURE 15 : POSSIBLE FAILURE-MODES

$$P_{uj} = (0.95 + 0.2(t'/w)^2)t'F_c \quad \text{[for mode } F_j] \quad (7)$$

$$P_{ub} = 1.02(t'/t)^{0.55} \cdot t \cdot F_c \quad \text{[for mode } F_b] \quad (8)$$

$$P_{uw} = 0.95(t'/t)^{0.54} \cdot t \cdot F_c \quad \text{[for mode } F_w] \quad (9)$$

where, F_c is the cylindrical strength of concrete, and see Figure 15 for the notations of t' , t and w .

Figure 16 shows the relationship among the three strengths. The strength P_{ub} is larger than P_{uw} in every case. The possible failure of concrete-crushing in "Structural Slits" is observed in the range less than about $0.5(t'/t)$.

CONCLUSIONS

In the seismic design of buildings, not only the design for structural frames but also the discussion for non-structural elements should be required. Especially, in the case where the mechanism of ductile moment-resistance is expected, the effects of secondary stress exerted from non-structural elements should be considered to prevent the occurrence of yield-hinges on the unexpected points in frames. The equations shown in this paper are appropriate for estimation of secondary stress by mullion-shaped reinforced concrete non-structural walls.

FIGURE 16: RELATION BETWEEN FAILURE CAPACITY ON THE PART OF STRUCTURAL SLITS (P_u) AND OFFSET RATIO (t'/t)

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