EFFECT OF SMALL OPENINGS ON STRENGTH AND STIFFNESS OF SHEAR WALLS IN REACTOR BUILDINGS

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ABSTRACT

A series of tests called "Model Tests for Evaluation of Seismic Behavior of Reactor Buildings" has been carried out by the Nuclear Power Engineering Corporation (NUPEC), under the sponsorship of the Ministry of International Trade and Industry (MITI) of Japan. As a part of the tests, a total of 23 wall specimens were tested to discuss the effect of small openings on strength and stiffness of shear walls in reactor buildings. Parameters tested were shape, number and local arrangement of openings. Reversed cyclic loads were applied to the specimens and their strength and restoring force characteristics were compared with each other to understand the effects of those parameters.

Based on the test results, two methods for predicting the shear strength of walls with numerous small openings are examined in this paper. One is a direct method to calculate the strength along assumed failure lines, and the other is a method to estimate design factors used in practice. Both methods are found to be useful to roughly estimate the strength of shear walls with openings. It is also shown that the stiffness of such walls may be evaluated by a combined multi spring model.

1 INTRODUCTION

Shear walls in reactor buildings inevitably have many openings for penetrations of pipings. When a large number of openings exist in a wall, even if the sizes of openings are relatively small compared to the wall thickness, those openings are supposed to affect the structural performances of shear walls and cause reduction in strength, stiffness and deformation capacity, depending on their sizes, numbers and shapes. In the AIJ (Architectural Institute of Japan) Standard¹⁾, strength reduction of a shear wall with a single opening is given by the larger value of the loss ratio in horizontal cross section or the square root of the ratio of opening area to wall surface. And one minus the value is defined as a strength reduction factor for design practice. But this reduction factor can not be applied to the case that a large number of small openings exist in a wall.

To establish a method for estimating the strength reduction of shear walls due to small and grouped openings in the walls, 23 specimens were tested.

2 OUTLINE OF TESTS

The wall thickness, wall length and shear span ratio of all the specimens are 15 cm, 200cm and 0.6 respectively, as shown in Fig.-1. As for wall reinforcements, a pair of D10 bars was provided at a spacing of 10cm in both

horizontal and vertical directions, and a reinforcing ratio was 0.95% for all the specimens. In cases that some of the reinforcing bars were interrupted at the openings, the same amount of additional bars were placed close to the openings.

The yield strength of reinforcing bars was 397 - 417 MPa, and the compressive strength of the concrete ranged from 27.3 MPa to 43.5 MPa with the mean value and standard deviation of 34.1 and 4.25 MPa. As for the elastic modulus of the concrete, the mean value and standard deviation were 23.9×10^3 and 2.06×10^3 MPa, respectively.

The specimens are divided into three categories, that is, OF-, OA- and OR-series. Opening arrangements of all the specimens are compared in Fig.-1. In the OF-series, openings are located at the middle height of the specimens and arranged in a line or replaced with a slit so that the fundamental effect of loss ratio in horizontal cross section can be studied. In this study, the loss ratio is defined as the maximum of the ratios of the open areas in any horizontal section to the total wall section area. The second series OA basically have a fixed loss ratio of 20%, and is planned to investigate the effect of shapes, locations and numbers of openings. Although the openings in most of these specimens do not coincide with actual scale of those in reactor buildings, they are chosen to represent cases that a group of small openings are closely located with each other. As for the OR-series, the shapes and arrangement of openings are decided so as to simulate actual shear walls in reactor buildings and the effect of grouped small openings is examined.

Reversed cyclic loads, corresponding to drift angles of 0.0005 - 0.01, were applied to the specimens, and their strength and restoring force were compared with each other.

Fig.-1 Specimen (Size and Arrangements of Openings, unit:mm)

3 TEST RESULTS

3.1 Strength Reduction

Before comparing the strength reduction of each specimen, the value should be converted, taking account of the difference in material strength of each specimen. In this study, a strength reduction factor defined as the ratio of the observed strength to the theoretical strength of the specimen but without openings, is introduced as an index for strength reduction due to openings.²⁾ In calculation of theoretical strength, a method proposed in a former study²⁾ is employed. And the ratios are normalized so that the value of the specimen OF-1, which had no opening, become 1.0, and are listed in Table-1 as "Observed Strength Reduction Factor."

Table-1 Test Results and Material Properties

Specimen	Material Properties		Loss Ratio in Cross Section (%)	Observed Strength (MN)	Failure Mode	Observed Strength Reduction Factor	Predicted Strength (MN)	Proposed Design Factor
	Concrete σ_B (MPa)	Rebar σ_y (MPa)						
OF- 1	32.7	417	0	1.80	A	1.00	1.72	1.00
OF- 2	34.8	417	10	1.80	A	0.98	1.76	0.94
OF- 3	35.5	417	20	1.75	U	0.95	1.58	0.89
OF- 4	33.8	417	30	1.63	B	0.90	1.38	0.84
OF- 5	36.2	417	100	0.44	U	-	-	-
OF- 6	43.5	404	10	1.83	A	0.94	1.77	0.97
OF- 7	42.6	404	20	1.82	A	0.94	1.63	0.94
OF- 8	41.7	404	30	1.80	A	0.94	1.48	0.91
OF- 9	39.9	404	20	1.78	A	0.94	1.43	0.93
OF-10	38.4	404	30	1.72	U	0.92	1.23	0.92
OA- 1	31.4	402	-	1.65	A	0.94	1.41	0.92
OA- 2	32.1	402	-	1.65	A	0.93	1.12	0.90
OA- 3	27.3	400	20	1.67	U	0.99	1.32	0.94
OA- 4	36.7	400	20	1.56	B	0.90	1.48	0.92
OA- 5	33.4	400	20	1.29	B	0.72	1.21	0.78
OA- 6	33.4	400	20	1.36	B	0.76	1.25	0.79
OA- 7	31.5	400	20	1.52	B	0.87	1.46	0.80
OA- 8	27.3	400	20	1.59	B	0.94	1.31	0.86
OA- 9	34.7	397	20	1.34	B	0.75	1.22	0.78
OA-10	33.5	397	20	1.30	B	0.73	1.27	0.84
OA-11	34.6	397	13	1.46	B	0.82	1.45	0.85
OR- 1	28.4	400	-	1.72	A	1.01	-	0.93
OR- 2	31.3	400	-	1.58	A	0.90	1.58	0.82

Failure Mode A : Shear Sliding Failure, as observed in OF-9
 B : Failure Formed between Openings, as observed in OA-5
 U : Unspecified or Intermediate Failure

Example of Type-A (OF-9)

Example of Type-B (OA-5)

The test results are summarized in Table-1, along with material properties and loss ratios in horizontal cross section. In Table-1, "Predicted Strength" and "Proposed Design Factors" are also shown. These two values will be mentioned in later discussion. From the test results, it is found that the strength reduction due to scattered small openings is smaller than the value expected from the loss ratio.

Also found is that the shape and location of openings affect the magnitude of reduction, even if the loss ratio in horizontal cross section and/or the total area of openings in the wall surface are the same. For example, although most of the OA-series specimens had the same loss ratio of 20%, observed strength reduction factors varied from 0.72 (OA-5) to 0.99 (OA-3), and clear reductions more than 10% were observed only in cases of OA-5, 6, 7, 9 and 10. Although the loss ratio was smaller than 20%, OA-11 indicated a considerable strength reduction as these five specimens. OA-5, 6, 7 and 8 had the same loss ratio and total open area, but the degree of strength reduction was different from each other. This suggests that the strength reduction does not simply depend on the loss ratio and/or the total open area.

Comparison between OF-9 and OA-3 suggests another interesting fact. Their reduction factors are different from each other simply depending on the location of openings.

3.2 Failure Modes

As shown in Table-1, two different types of failure modes appeared through the tests. One is very close to shear sliding failures which are common in heavily reinforced shear walls. For example, the specimen OF-1 and OF-9 had this type of failure mode and scattered many diagonal cracks were seen all over the wall surfaces. The other type of failure mode was typically observed in OA-5 and OA-7. A failure line connecting the openings was clearly formed as if the specimen consisted of multiple wall elements, and the total number of shear cracks was not so large as in OF-1 or OF-9. In general, the strength reduction was small in case of the former type of failure mode compared to the latter type.

4 DISCUSSION

4.1 Strength

Two methods for predicting the shear strength of walls with numerous small openings are studied. One is a direct method to calculate the strength along predicted failure lines, and the other is a method to estimate strength reduction factors useful for design practice.

In the first method²⁾, the wall is divided into several wall elements along a predicted failure line as shown in Fig.-2. The strength of each element is calculated and the total of all the elements' strengths gives a theoretical shear strength of the specimen. The results are listed in Table-1 as "Predicted Strength", and are compared with the tested values in Fig.-2. In Fig.-2, hollow squares represent the values of specimens which had strength reduction larger than 10% and solid squares represent the specimens which had smaller strength reduction. It can be said that this method is applicable to the specimens which were considerably affected by the openings but will underestimate the strengths of specimens which were slightly affected by the openings.

In the second method, a design factor is proposed, taking account of the global stress flow in walls. A similar method has been already introduced by Tokuhito et al.³⁾, but the method is modified and examined in this study.

As shear stress in a wall is thought to be carried by diagonal struts, the strength of the wall is considered to be dependent on the capacity of the struts. However, the openings in the wall disturb the smooth stress flow and

decrease the area of effective struts. In Tokuhiro's method, only the struts formed in 45° direction are assumed to be effective and, as a result, the method underestimates the strength.

In this proposed method, possible effective struts formed in directions other than 45° are taken into account. First, the wall is divided into the struts separated by boundaries passing through the center of each opening in 45° direction. And then, the width of each strut is defined according to the minimum width throughout its length. Thus, the effective struts shown in Fig.-3 are assumed in this study. As a result, the effective area given by this proposed method becomes a little larger than the Tokuhiro's method. Estimated design factors obtained by this method are compared with observed values and plotted in Fig.-3 and also listed in Table-1 as "Proposed Design Factor." The ratios of calculated values to observed values fall in a range from 0.90 to 1.10 for most of the specimens. Thus, this method seems to provide a practical design factor.

4.2 Stiffness

To discuss the stiffness, a multi-spring model is examined. In this method, the wall is divided into multiple spring elements similar to the direct strength evaluation method. Restoring force characteristics of each element

Fig.-2 Comparison of Observed and Predicted Strength

Fig.-3 Comparison of Observed and Proposed Reduction Factor

is decided according to the former study⁴⁾. The total of restoring force of each spring element, then, gives the restoring force of the specimen at given displacement. Some of the results are shown in Fig.-4. It can be said that the stiffness of such walls could be roughly evaluated by this multi spring model.

5 CONCLUSION

The strength and the stiffness of shear walls with numerous small openings are discussed based on the test results of 23 specimens.

As a result, the following conclusions are obtained.

- 1) Strength reduction due to small openings in shear walls can not be simply evaluated by the loss ratio in horizontal cross section.
- 2) Scattered small openings scarcely affect wall strength, but do affect if they are closely located with each other.
- 3) Predicted strengths obtained from assumed failure lines in walls agree with the test results, provided that those failure lines are clearly formed as they are expected.
- 4) The design factor proposed here is useful to roughly estimate the strength reduction of shear walls with scattered numerous small openings.
- 5) Possibility of estimating the stiffness of walls with openings is shown by applying a simple multi spring model.

ACKNOWLEDGEMENTS: This work is conducted by "Committee of Seismic Verification Tests" and "Subcommittee of Seismic Behavior of Reactor Building" in NUPEC. The authors wish to express their gratitude to the committee members for their cooperation and valuable suggestions.

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