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Comprehensive evaluation of verification tests for seismic analysis codes. Part 6 : evaluation method of strength and stiffness of shear walls with openings

Ono H.(1), Murazumi Y.(1), Kitada Y.(2), Akino K.(2), Takiguchi K.(3)
(1) Taisei Corporation, Japan
(2) Nuclear Power Engineering Corporation, Japan
(3) Tokyo Institute of Technology, Japan

ABSTRACT : We discuss the evaluation method of the skeleton curve of the walls with many small openings in seismic design. The skeleton curves of the walls with openings are calculated in the way to multiply these values without openings used in seismic design by the reduction factor calculated from opening condition. It was verified that the skeleton curve of the walls with small openings could be expressed accurately as good as that of the walls with no openings obtained by current design formula.

1. INTRODUCTION

There are numerous small openings for pipes and ducts on seismic shear walls in reactor buildings.

It is important to evaluate the effect of openings on restoring force characteristics so as to improve the seismic design reliability. Model tests of seismic shear walls with small openings were carried out by Nuclear Power Engineering Corporation (NUPEC). In these tests, a total of 23 wall specimens were tested to discuss the effect of openings on strength and stiffness of shear walls. Parameters tested were shape,number and local arrangement of openings, and proposed the method to evaluate the shear strength reduction of wall caused by openings.The objective of our study is proposing the method to obtain skeleton curve for response analysis of the walls with many small openings in the range from elastic state to ultimate state. Considering the applicabilities to a reactor building structural design ,proposed method is simplified by engineering judgment.

2. METHOD OF EVALUATING THE REDUCTION FACTOR FOR OPENINGS

2.1 *Outline of past tests*[1)]

The wall thickness, wall length and shear span ratio of past test specimen were 15cm, 200cm, and 0.6 respectively, and sectional shape is H-shape. A reinforcing ratio was 0.95% in both horizontal and vertical directions. In some cases, additional bars were placed close to the openings. An arrangement of openings of representative specimen is shown in Fig.1. In almost test models, shear sliding failure or failure formed between openings were observed.

2.2 *Comparison of reduction factors by openings between test and various evaluation methods*

Using the shear force and shear displacement relations in the past experimental results, reduction factors of following items of the wall with openings to the wall without openings were calculated.

1) the forces at first and second turning point on the skeleton curve
2) maximum shear strength and the displacement at the strength

In the next step, following five evaluation methods were selected from design standards and literatures to express numerically the influence of the openings on the strength and stiffness of the walls, and the calculated values were compared with experimental values.

Method 1) loss ratio of horizontal cross section
Method 2) square root of the ratio of opening area to wall surface
Method 3) AIJ (Architectural Institute of Japan) Standard's method[2] (minimum value of 1) or 2))
Method 4) effective strut method (proposed by Tokuhiro and Ono)[3]
Method 5) effective strut method (modified by previous test)[1]

The concepts of these method are shown in Fig.2.
Though Method 1), 2) and 3) are derived for the wall with single opening, these method are used widely for walls with the numerous openings in this study as a trial.
Method 4) is the method for the walls with plural openings. In this method , the ratio of effective sectional area of the strut which declines 45° to total cross sectional area of the wall is evaluated taking account of stress flow in the wall. The effective strut is defined as shaded area in Fig.2 . By past studies, this method underestimates a little the wall strength.
Method 5) is improved method of 4), and assumes the effective strut even in narrow area between openings. Though the reduction factor of openings to wall strength shows good agreement with experimental results, the calculation procedure is complicated in case of the walls with many openings because of geometrical evaluation of the effective area. We suggested the method in which the width of the strut was constant regardless of openings position, and the strut didn't turn in a wall. This method is easy to calculate using computer.
Fig.3 shows the correlation between the reduction factor calculated by each method and observed reduction factor on maximum shear force and displacement at the strength. Observed reduction factor is defined as the ratio of the observed strength (or displacement) to the theoretical strength (or displacement) of the specimen without openings. The reduction factor by the effective strut method shows best correlation with observed value among each method. Shear forces at first and second turning point on the skeleton curves by the effective strut method are shown in Fig.4 comparing observed value. These forces doesn't show good correlation in any methods, so it is judged that the influence of the openings on the forces is small.

2.3 *Evaluation of the influence of the openings on the initial stiffness*
Elastic analysis was carried out using FEM model to investigate influence of the openings on the initial stiffness of the walls and reduction factor of the walls without openings. The configuration of the walls for the analysis is same as the wall in past studies. Parameters of the openings are size, position, shape and number. Additional 12 cases except tested opening types were calculated. The calculated results were compared with the values obtained by above-mentioned 5 methods.
An example of the analytical mode is shown in Fig.5. In these models, 8 -nodes shell elements were used. Fig.6 shows the comparison of stiffness reduction factor for an analytical series of which parameter is opening number. The total area of openings are same in each

cases. Analytical result by effective strut method shows best agreement with FEM analysis results.

3. EVALUATING METHOD OF SKELETON CURVE

Though influence of the openings on the first and second turning point force on skeleton curve is small as discussed in 2.2, turning point strength reduced by FEM nonlinear analysis comparing the strength of the wall without openings, and reducing values are agreed with the values obtained by effective strut method.
Taking account of a series of investigated results, we propose the following evaluation method of the skeleton curve of the wall with openings.

1) Skeleton curve is calculated using JEAG's formula[4] assuming that there are no openings. In this formula, flexural displacement and shear displacement is calculated separately.
2) The influence of the openings are taken into account only in shear force and shear displacement relations, and are not taken into account in bending moment and curvature relations, because experimental result showed less influence of the factors on the curvatures.
3) The influence of the openings on the shear force and shear displacement is expressed by multiplying the reduction factor obtained by the effective strut method to initial stiffness and each turning point force in the skeleton curve.

The procedure is shown in Fig.7.
When small openings are in close vicinity and the reduction factor is less than 0.85, shear fracture may happen between the openings, and the force for the fracture may be maximum strength of the wall. In this case, shear deflection angle will be less than 4/1000(deflection angle at maximum strength by design formula). Following two evaluation methods for deflection angles of these walls are suggested.

1) regard the angle as a function of the reduction factor

$$\gamma_3' = (5.3r - 3.5) \cdot 4/1000$$

where γ_3' : shear strain at maximum strength
r : reduction factor by effective strut method

2) calculate the reduction factor subtracting the strut area between the openings, and assume the angle to be 4/1000.
First method shows better agreement with experimental result, and second method is easy to apply in the design, and evaluate the absorbed energy conservatively.
The strut areas which were regarded effective in each method is shown in Fig.8, and the skeleton curves are shown in Fig.9.

4. COMPARISON WITH EXPERIMENTAL RESULTS

The skeleton curves by our proposed method and envelope curves obtained by the experiments are shown in Fig.10. In this case, the shear strain at maximum shear strength was calculated using the first method. The skeleton curve obtained by the calculation agreed well with the experimental results. The absorbed energy which is defined as the area contained by the skeleton curves and deformation axis, of the calculated and experimental results are shown in Fig.11.

5. CONCLUSION

Evaluation method of the skeleton curves of the shear walls with openings are proposed. This method was derived taking account of the applicability to structural design work. As a result of the comparison with past experimental results, it was verified that the skeleton curve of the walls with small openings could be expressed accurately as good as that of the walls with no openings obtained by JEAG's design formula.

ACKNOWLEDGMENT

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4) *Technical Guidelines for Aseismic Design of Nuclear Power Plants Translation of JEAG 4601-1987*, Electrical Technical Standard Survey Committee, Japan Electric Association

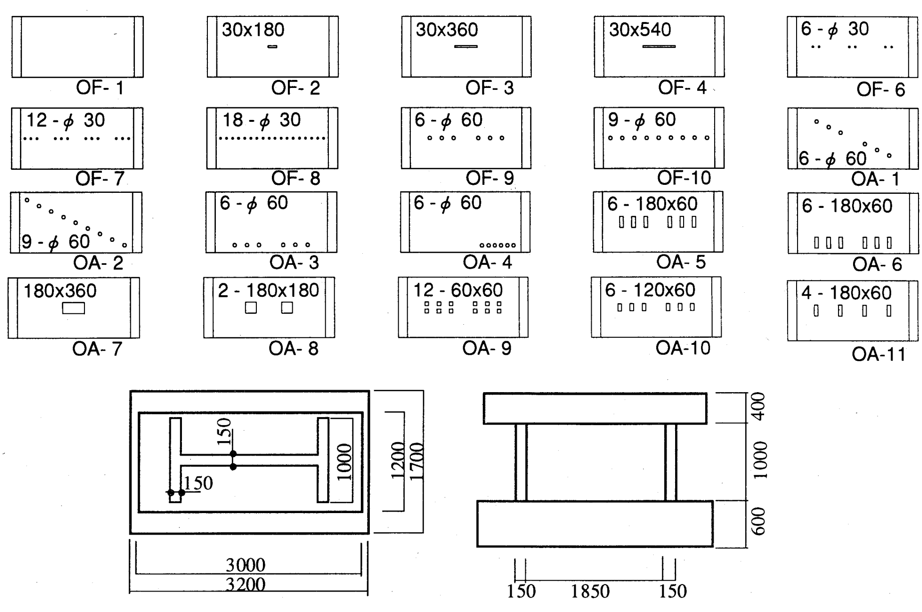

Fig.1 Size and Opening Arrangement of Previous Test

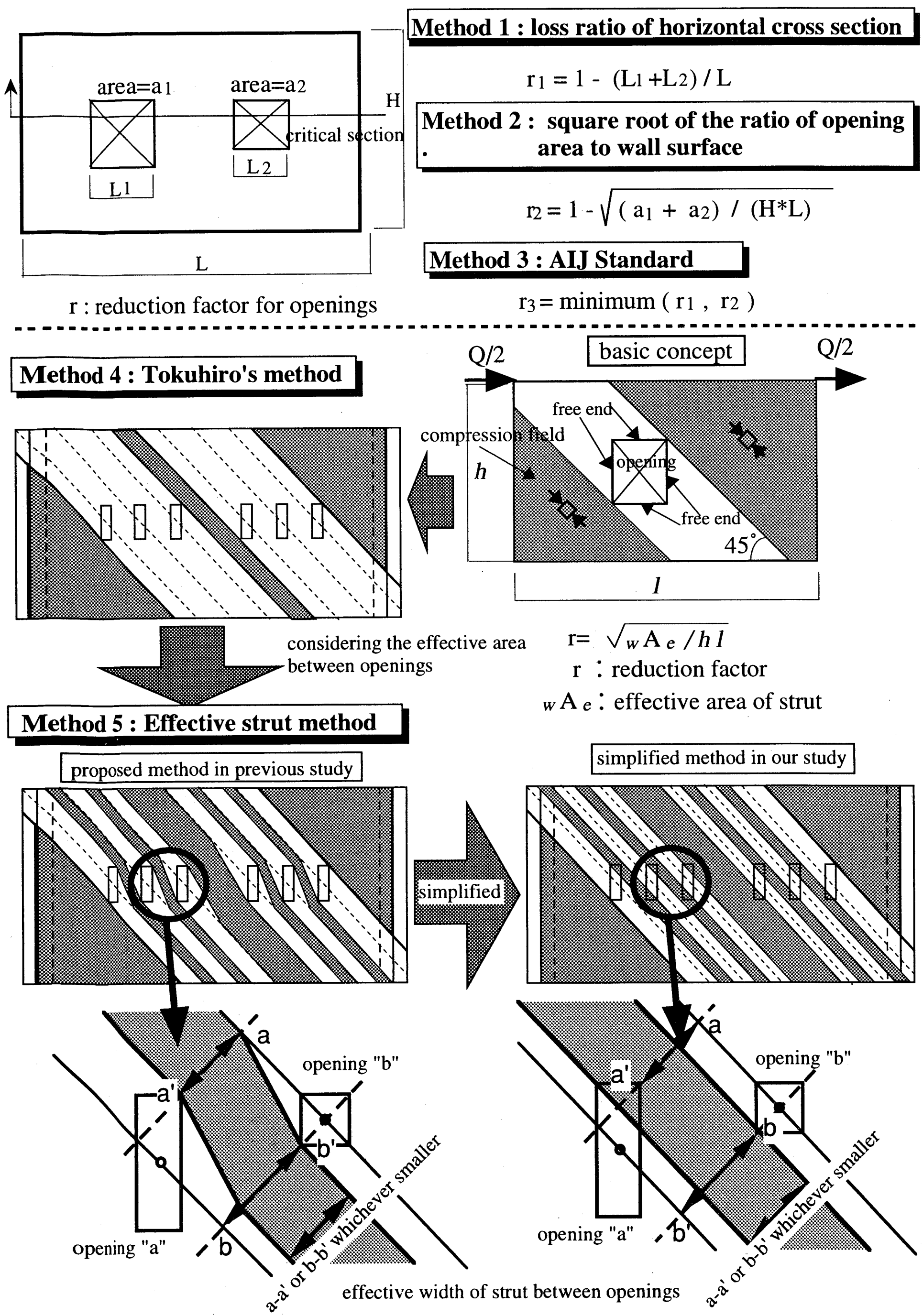

Fig.2 Evaluation Methods of the Effect of Openings

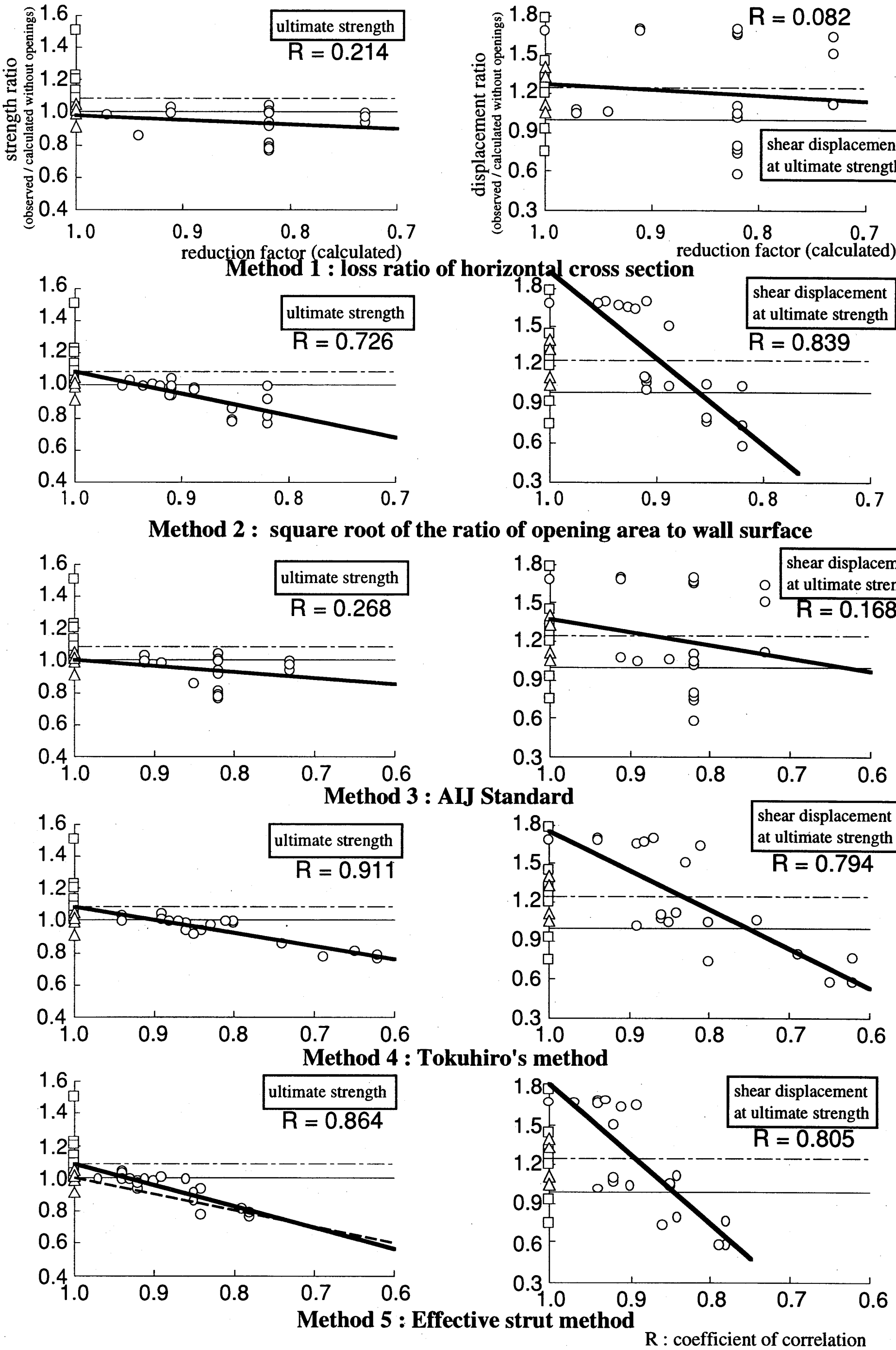

Fig.3 Comparison of Observed and calculated Reduction Factor in Each Method

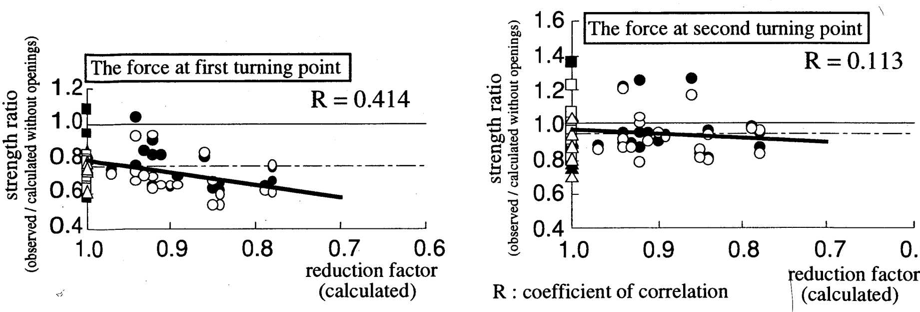

Fig.4 Comparison of Observed and Calculated Reduction Factor at the First and Second Turning Point in Effective Strut Method

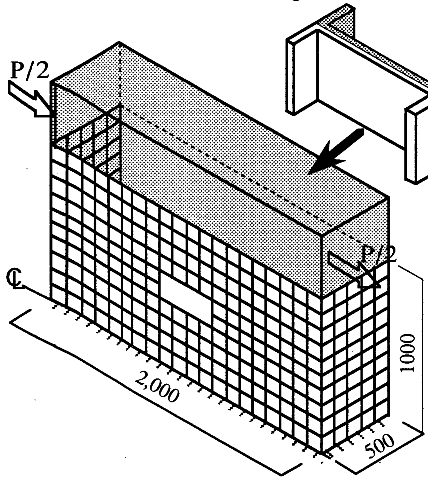

Fig.5 Analytical Model to Evaluate Initial Stiffness

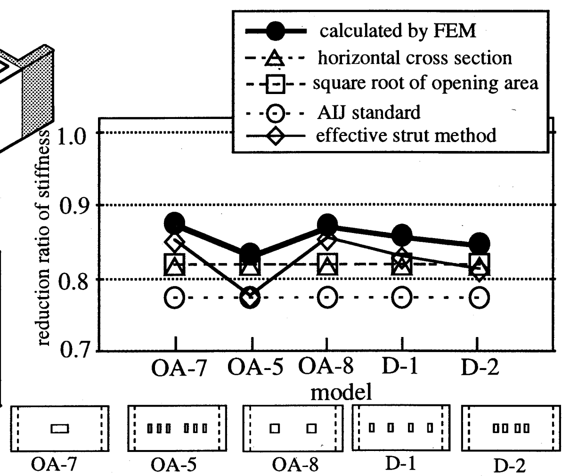

Fig.6 Comparison of Initial Stiffness by FEM and Each Method

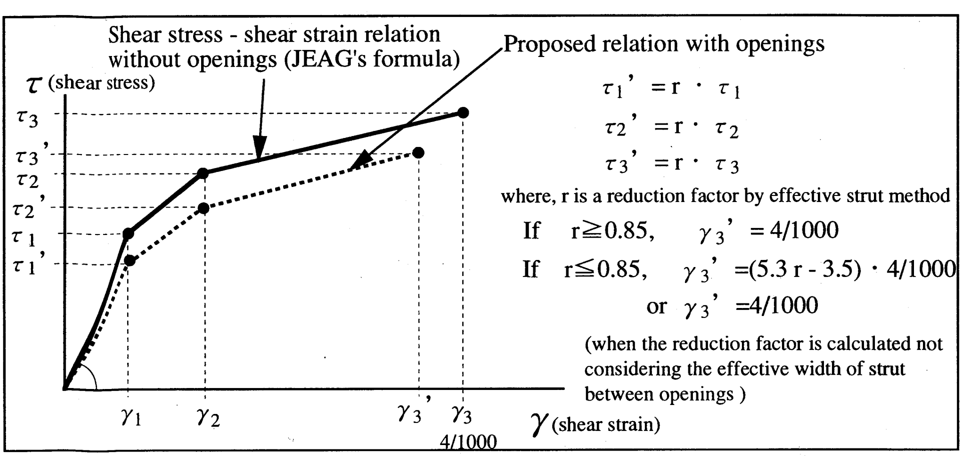

Fig.7 Proposed Shear Stress - Shear Strain Relation for Shear Wall with Openings

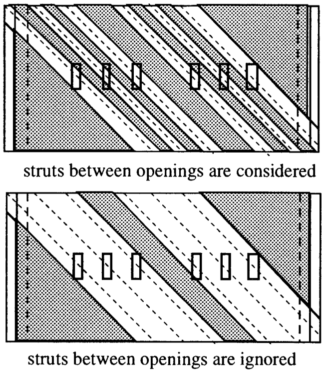

Fig.8 Effective area of struts between openings

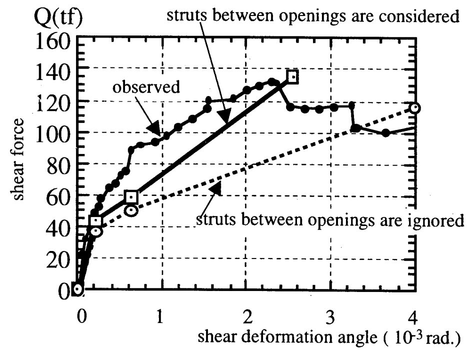

Fig.9 Comparison of Shear skeleton

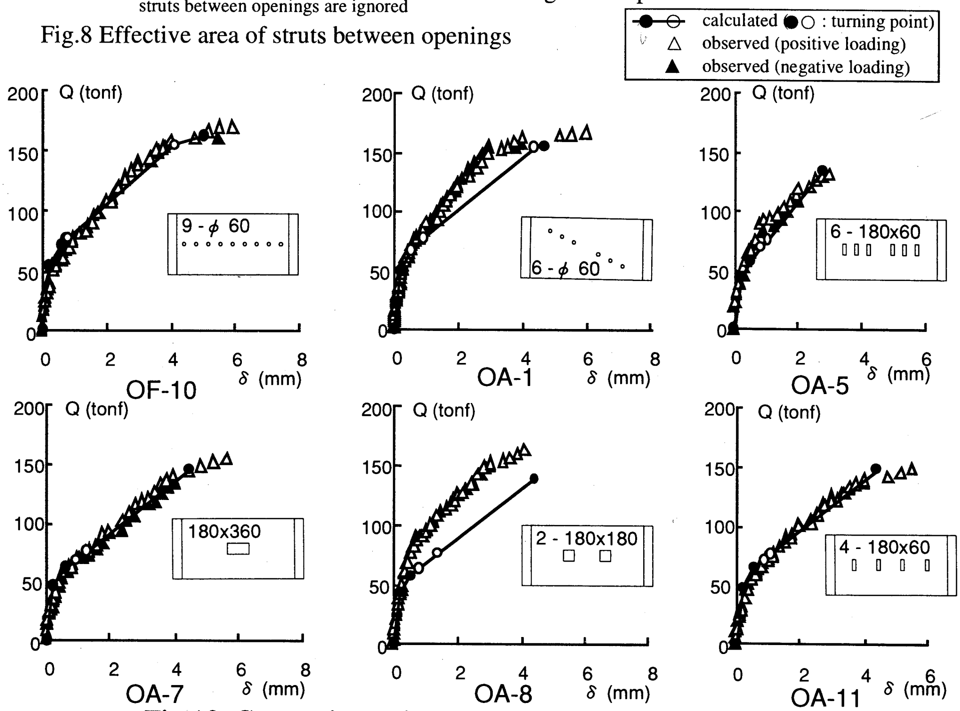

Fig.10 Comparison of Shear Force - Displacement Relation

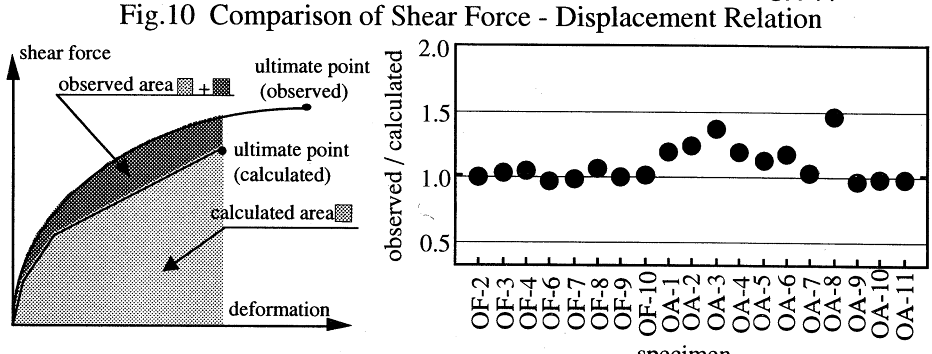

Fig.11 Comparison of Absorbed energy Calcurlated by the Skeleton Curves