Study on steel plate reinforced concrete bearing wall for nuclear power plants Part.2 ; Analytical method to evaluate response of SC walls

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ABSTRACT

In this paper, an evaluation method of earthquake resistance characteristic of a steel plate reinforced concrete wall (it is called SC) will be reported. An evaluation formula was studied to be simple and easy same as a rebar reinforced concrete wall (it is called RC) in order to develop a practical design method of SC structure building. And experimental results presented a paper in Part 1 were compared with calculated results, and the effectiveness of this evaluation method was confirmed.

1. Introduction

A few studies on SC structure were performed by the authors, and some evaluation methods to obtain a bending and a shear strength of SC walls have been suggested. These evaluation methods give good agreement with the experimental results, but it is too complicated to use for the design. In this paper, a practical design formula for the SC structures will be presented, just the same as RC structure's design method in common use[3]. And calculated results were compared with experimental results to confirm the effectiveness of those.

2. Evaluation method of shear strength and deformation characteristic

(1) Evaluation method

A relationships between shear force Q and shear strain γ of a SC wall is defined by tri-linear skeleton curve shown in Fig.1 same as reinforced concrete walls[3]. Each turning point of tri-linear curve show a cracking strength, yield point and maximum point of a SC wall given in Eq.(1) to (6).

① Cracking point (first turning point)

$$Q1 = (Ac + (Gs / Gc)\cdot As)\cdot \tau cr \quad (1)$$

$$\gamma 1 = \tau cr / Gc \quad (2)$$

$$\tau cr = \sqrt{0.31\sqrt{\sigma_B}\cdot\left(0.31\sqrt{\sigma_B}+\sigma_V\right)}$$

② Yielding point (second turning point)

$$Q2 = \left(K_\alpha + K_\beta\right)\Big/\sqrt{\left(3K\alpha^2 + K\beta^2\right)}\cdot As\cdot\sigma_y \quad (3)$$

$$\gamma 2 = Q2 / \left(K_\alpha + K_\beta\right) \quad (4)$$

③ Maximum strength point (ultimate point)

$$Q3 = Ac\sqrt{(As/Ac)\cdot\sigma_y\cdot\nu\cdot\sigma_B} \quad (5)$$

$$\gamma 3 = 6.0\times 10^{-3} \quad \text{(rad)} \quad (6)$$

Where,

As : Shear effective cross-section area of the surface steel plate (mm^2)
Ac : Shear effective cross-section area of concrete (mm^2)

Gs : Shear modulus of a steel plate (N/mm^2)
Gc : Shear modulus of concrete (N/mm^2)
Es : Young's modulus of the surface steel plate (N/mm^2)
Ec' : Young's modulus of cracking concrete (N/mm^2)
ν s : Poisson's ratio of the surface steel plate
σ v : Axis stress of a wall (+ compression ,N/mm^2)
K_α :Shear stiffness of the surface steel plate (= As · Gs)
K_β :Effective shear stiffness of cracking concrete
(= 1 / { 4 / (Ac·Ec') + 2·(1- ν s) / (As·Es) })
σ_y : Yield strength of the surface steel plate (N/mm^2)
σ_B : Compresive strength of concrete (N/mm^2)
ν : An effective coefficient of concrete compression strength in shear destruction
(=0.7- σ_B /2000)

(2) Evaluation of a cracking point of concrete

A shear cracking strength of RC walls was evaluated with $\sqrt{\sigma_B}$ generally. As results of experiments, a cracking strength of concrete inside SC wall could be evaluated in the same way as RC walls. Therefore, the first point (cracking point) of tri-liner skeleton curve is given in the sum of cracking strength of concrete and stress of steel plate that obtained from deformation at the time of concrete cracking as the Eq.(1). The comparison of caluculated results by the Eq.(1) and experimental results are shown in Fig.2. The calculated values show the average of experimental values.

(3) Evaluation of yielding point of the surface steel plate

A stiffness of SC walls was observed to reduce after yielding of the surface steel plate from the results of experiments. Based on some basic assumptions (Fig.3), yield strength of the surface steel plates of SC walls can be evaluated as follwos,

(assumption 1) concrete and a steel plate completely deform as equal shape for a shear force.
(assumption 2) cracking concrete resists only compression force of diagonal 45° .
(assumption 3) young's modulus of cracking concrete reduce in 0.7 times.
(assumption 4) a steel plate does not buckle by the effect of a lot of studs.
(assumption 5) beams and columns of circumference of a SC wall resist only axis course as effective reinforced materials.
(assumption 6) yield of steel plate is judged by Von-Mises yield criterion.

Based on assumptions mentioned above, stress - strain relationship of a SC wall is pursued in the following.

(stress - strain relationship of concrete)

$$\begin{Bmatrix} {}_c\sigma_x \\ {}_c\sigma_y \\ {}_c\tau \end{Bmatrix} = \frac{Ec'}{4} \cdot \begin{bmatrix} 1 & 1 & -1 \\ 1 & 1 & -1 \\ -1 & -1 & 1 \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_x \\ \gamma \end{Bmatrix} \quad (7)$$

(stress - strain relationship of the surface steel plate)

$$\begin{Bmatrix} {}_s\sigma_x \\ {}_s\sigma_y \\ {}_s\tau \end{Bmatrix} = \frac{Ec'}{1-\nu_s{}^2} \cdot \begin{bmatrix} 1 & \nu_s & 0 \\ \nu_s & 1 & 0 \\ 0 & 0 & (1-\nu_s)/2 \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_x \\ \gamma \end{Bmatrix} \quad (8)$$

(stress - strain relationship of a column / a beam of circumference)

$$\begin{Bmatrix} {}_f\sigma_x \\ {}_f\sigma_y \\ {}_f\tau \end{Bmatrix} = Es \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_x \\ \gamma \end{Bmatrix} \quad (9)$$

(balance with external force)

$$[Ac]\cdot\begin{Bmatrix} {}_c\sigma_x \\ {}_c\sigma_y \\ {}_c\tau \end{Bmatrix} + [As]\cdot\begin{Bmatrix} {}_s\sigma_x \\ {}_s\sigma_y \\ {}_s\tau \end{Bmatrix} + [Af]\cdot\begin{Bmatrix} {}_f\sigma_x \\ {}_f\sigma_y \\ {}_f\tau \end{Bmatrix} = \begin{Bmatrix} 0 \\ N_y \\ Q \end{Bmatrix} \qquad (10)$$

Where,

[Af]: Steel materials cross-section area of a column/a beam of circumference
Ny : External force of axis direction
Q : External force of horizontal direction

When the shear force which a steel plate resists is expressed with Qs ($=As\cdot{}_s\tau$) and the shear force which concrete resists is expressed with Qc ($=Ac\cdot{}_c\tau$), the relationship between Qs and Qc is shown with the Eq.(11).

$$Qs : Qc = As\cdot{}_s\tau : Ac\cdot{}_c\tau = K_\alpha : K_\beta \qquad (11)$$

Where,

K_α : Shear stiffness of a steel plate ($=As\cdot Gs$)

K_β : Shear effective stiffness of concrete after a cracking

The reinforced effect of a column and a beam of circumference is ignored ([Af]=[0]), and effect of external force of axis direction is also ignored ($N_y=0$). K_β can be expressed by the Eq.(12) simple equation that is to be shown.

$$K_\beta = 1 / \{ 4 / (Ac\cdot Ec') + 2\cdot(1-\nu s) / (As\cdot Es) \} \qquad (12)$$

Using above equations, external shear force Q2 when a steel plate yields by von-Mises yield criterion can be obtained, and the Eq.(3) is provided. The shear strain γ is given in the Eq.(4). The yield strength and deformation of experiments and calculated result are shown in Fig.4 and Fig.5. The calculated values show the average of experimental values same as cracking strength.

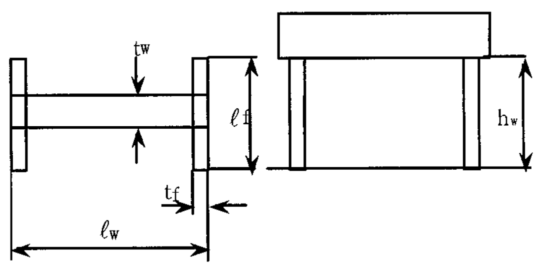
(4) Evaluation of a maximum strength

In late years maximum strength of RC wall is evaluated by the sum of a resistance by truss mechanism of rebar - concrete and a resistance by Arch mechanism of concrete. The resistance mechanism of SC walls is the same as resistance mechanism of RC walls generally. And tension Arch mechanism of steel plates is added so that a steel plate can resist a diagonal with resistance mechanism of a SC wall. Therefore maximum strength of a SC wall can be evaluated with the Eq.(13).

$$V= =t_w l_w p_{ws}\,\sigma_w \cot\phi + \tan\theta\,(1-\beta c) t_w l_w\,\nu\,\sigma_B/2 + \tan\theta\,(1-\beta s) t_w l_w p_{ws}\,\sigma_{wy}/2 \qquad (13)$$

Where,

p_{ws} : The cross-section area ratio of steel plates (tw・lw/tws・lw)
Tws : The sum of thickness of two pieces of steel plates
σw : Steel plate stress to contribute to Truss mechanism
σwy : Yielding strength of steel plates
$\nu\,\sigma B$: Effective compressive strength coefficient of concrete of diagonal course in collapse
ϕ, θ : An effective angle of Truss mechanism
βc : A ratio of concrete stress to contribute to compression Arch mechanism
βs : A ratio of steel plate stress to contribute to pulling Arch mechanism



Based on the lower bound theory, a value of Pws* σ_w and cot ϕ can be obtained by following three cases of equations according to steel plate strength and concrete strength.

(case 1) In case of $\sqrt{P_{ws} \cdot \sigma_{wy} / \nu \cdot \sigma_B} \leqq \tan\theta$,

$$Pws \cdot \sigma_w = Pws \cdot \sigma_{wy}, \quad \cot\phi = 1/\tan\theta .$$

(case 2) In case of $\tan\theta < \sqrt{P_{ws} \cdot \sigma_{wy} / \nu \cdot \sigma_B} \leqq 1/\tan\theta$

$$Pws \cdot \sigma_w = Pws \cdot \sigma_{wy}, \quad \cot\phi = \sqrt{\nu \cdot \sigma B / P_{ws} \cdot \sigma_{wy}}$$

(case 3) In case of $1/\tan\theta \leqq \sqrt{P_{ws} \cdot \sigma_{wy} / \nu \cdot \sigma_B}$

$$Pws \cdot \sigma_w = \nu \cdot \sigma_B / (\tan\theta)^2, \quad \cot\phi = \sqrt{\nu \cdot \sigma B / P_{ws} \cdot \sigma_{wy}} .$$

As for designing the bearing wall of nuclear power plant building, the ratio of wall thickness and steel plate thickness (T/t) can be designed by range of 30-200 and the shear span ratio is small comparatively. Such SC walls can be evaluated with case 2 that is resistance mechanism only of truss mechanism. In other words βc and βs are 1, and the maximum strength is given by V= tw·lw·Pws* σ wy·cot ϕ. The cross-section area of concrete (tw·lw) is expressed with Ac, and the cross-section area of steel plate (tws·lw) is expressed with As, and an Eq.(13) is rewritten, an Eq.(5) is provided. The maximum strength of experiments and calculated result are shown in Fig.6. The equation gives approximation to the experimental result, and the calculated result is bottom of experiment values is shown.

On a deformation, specimen of SC walls reaches maximum strength with bigger shear deformation angle 5000-8000 μ for RC wall being 4000 μ. And a SC wall maintains high resistance ability against the load after having reached maximum strength, and has a better ductility compared with RC wall. Therefore, specification of maximum deformation of a SC wall is regarded as uselessness, but a maximum deformation value is established for comparison with RC wall. This tendency is considered for the effect that brittleness destruction of concrete is restrained by surface steel plate. A good ductility is confirmed from compression test of the SC wall which the authors performed. Compressive fracture of concrete materials occurs usually when compression strain reached about 2000 μ. However, a SC wall is not fractured it till compression strain reaches 3000 μ. Deformation ability improves in about 1.5 times. So shear deformation angle 6000 μ (equivalent to concrete diagonal compressive strain 3000 μ) was defined as maximum volume of deformation as had shown in an Eq.(6). Maximum deformations of experiments and evaluation value are shown in Fig.7.

(5) General comparison with experimental results

The comparison of load-deformation relationships given by evaluation method with some experimental result is shown in Fig.8. The curve given by the suggested equations almost agree with experimental results.

3. Evaluation method of bending strength and deformation characteristic

(1) Evaluation method

The relationship between bending moment M and curvature ϕ of a SC wall is also defined by tri-linear curve shown Fig.1 same as RC walls. Each turning point of tri-linear curve show a cracking point, yield point and maximum point of a SC wall. Bending characteristic of a SC wall were reported in Part 1 to be similar with RC wall's one. Therefore, the equations of each turning point are defined by rewriting the equation of RC wall's to replace the rebar factor to the steel plate factor as follows.

① Cracking point

$$M1 = Ze \cdot (0.38 \sqrt{\sigma_B} + \sigma_V) \quad (14)$$

$$\phi 1 = M1 / (Ec \cdot Ie) \quad (15)$$

② Yielding point

$$M2 = My \quad (16)$$

$$\phi 2 = \phi y \quad (17)$$

③ Maximum strength point

$$M3 = Mu \quad (18)$$

$\phi 3 = 0.004 / Xnu$ (19)

Where,

Ie : Second moment of inertia (mm^4)

Ze : Section modulus (mm^3)

$0.38\sqrt{\sigma_B}$: Bending pulling strength of concrete (N/mm^2)

σ_V : Axis stress of a wall (+ compression ,N/mm^2)

My : Bending moment of steel plate yielding on the basis of an assumption of strain remaining in-plane (N·mm)

ϕ_y : Curvature at reaching bending moment (1/ mm)

Mu : Bending strength on the basis of full-plastic cross-section assumption (N·mm)

Xnu : Distance from compression edge to a neutral axis in full-plastic cross-section (mm)

(2) General comparison with experimental result s

Experimental curve of relationship with horizontal load and shear and bending deformation angle regarding the experiment that bending yield appeared in and calculated curves by evaluation equations are shown in Fig.9. That calculated values are similar by experimental results generally can be realized. Up to shear and bending yielding point, that calculation curves and experiment curves are similar smartly can be realized. And maximum load of experiment agrees with either small value of calculated shear strength and bending strength. Differences are found in deformations of neither in maximum load, but, about the whole deformation which added bending deformation to shear deformation, experiment value and calculation value are almost equal. In evaluation method of shear strength and bending strength of statement above, those destruction is treated as independence phenomenon. Interaction by those destruction needs to be considered, but, from comparison result shown by Fig.9, the influence may think that it can be ignored usually.

4.Summary

A practical evaluation method of shear and bending strength and deformation characteristic of SC walls was presented. Through simulation analyses of the experimental result, and availability of this evaluation formula was confirmed.

Acknowledgments

This report is based on the result of joint research for SC structure, organized by 10 power companies, 3 plant makers and 5 building contractors. The authors wish to express their gratitude to Dr. Hiroyuki Aoyama, Dr. Hikaru Saito, Dr. Shio Morita and Dr. Hiroshi Akiyama, for their helpful suggestions.

REFERENCES

[1] Takeuchi, M., Matsuo, I., et al,. 1995. Study on a concrete filled steel structure for nuclear power plants (Part 1-4), Proc. 13th SMiRT Conf. H: 15-38

[2] Takeuchi, M., Matsuo, I., et al., Study on a concrete filled structure for nuclear power plants, Nuclear Engineering and Design 179 (1998) 209-223

[3] JEAG4601, 1991. Technical guidelines for aseismic design of nuclear power plants (Suppl.), pp. 79-92

[4] Funakoshi, A., Akita., et al., 1997. Experimental Study on A Concrete Filled Steel Structure (Part 8 Bending Shear Tests - Study on Load-Deformation Relationships), Proceedings Annual meeting of Arch. Inst. Japan, Sep. :1065-1066

[5] Fujita, T., Funakoshi, A., et al, 1998. Experimental Study on A Concrete Filled Steel Structure (Part 16 Bending Shear Tests - Effect of bending strength), Proceedings Annual meeting of Arch. Inst. Japan, Sep. :1125-1126

[6] Niwa, N., Takeuchi, M., et al., 1995. Study on Concrete Filled Steel Structure for Nuclear Power Plants (Part 3 Evaluation of Bending Shear Tests), Proceedings Annual meeting of Arch. Inst. Japan, Aug. :987-998

[7] Usami, S., Kokubo, W., et al., 1995. Study on Concrete Filled Steel Structure for Nuclear Power Plants (Part 4 Evaluation of Bending Shear Tests), Proceedings Annual meeting of Arch. Inst. Japan, Aug. :989-990

[8] Usami, S., Sekimoto, H., et al., 1991. Compression and shear loading test of concrete filled steel bearing wall, Proc. 11th SMiRT Conf. H12/2: 323-328

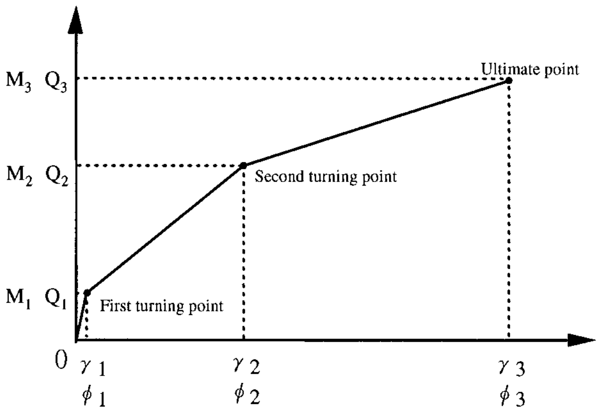


Fig.1 Trilinear skeleton curve

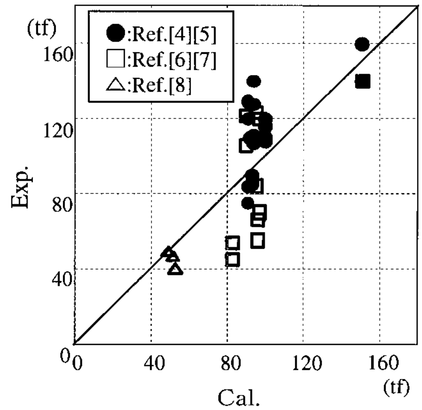


Fig.2 Shear Strength Q_1 at Cracking point

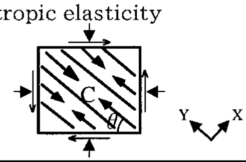
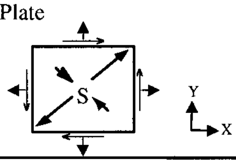
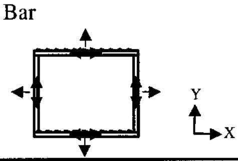
	Model	Stress-Strain Relationship
Concrete	Anisotropic elasticity 	$Ec' \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Steel plate	Elastic Plate 	$\frac{Es}{1-\nu s^2} \cdot \begin{pmatrix} 1 & \nu s & 0 \\ \nu s & 1 & 0 \\ 0 & 0 & (1-\nu s)/2 \end{pmatrix}$
Frame	Elastic Bar 	$Es \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Fig.3 Assumption of concrete and steel condition after shear cracking

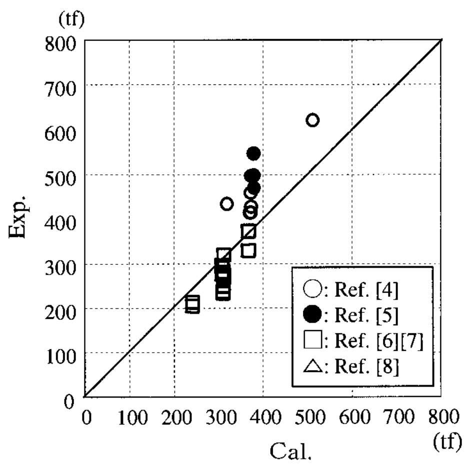


Fig.4 Shear Yield Strength Q_2

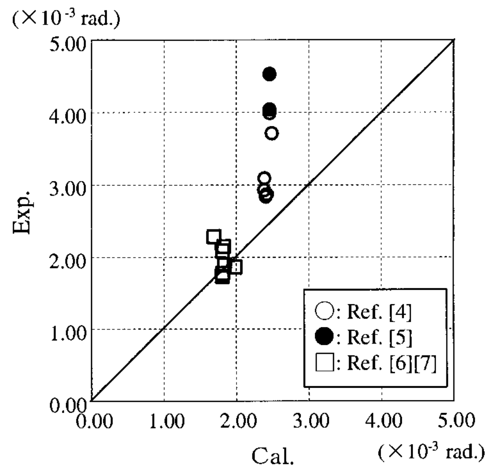


Fig.5 Shear Deformation Angle γ_2 of Yield Point

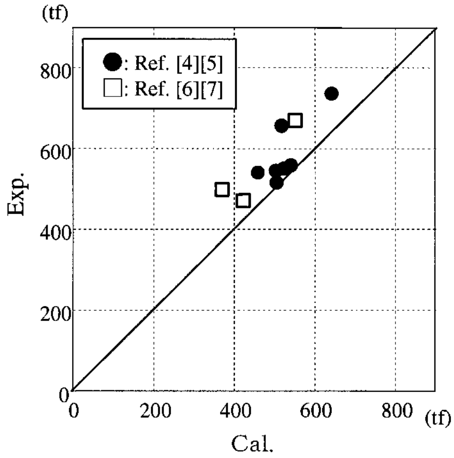


Fig.6 Maximum Shear Strength Q_3

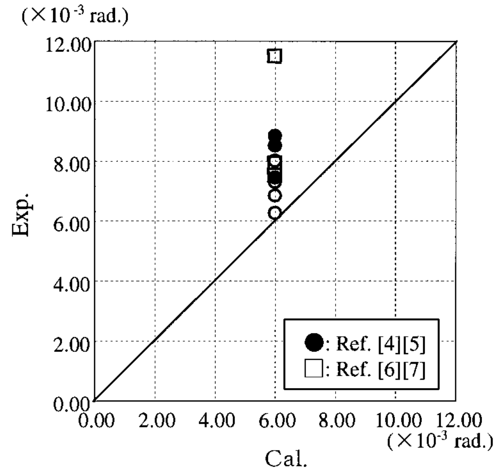


Fig.7 Shear Deformation Angle γ_3 at Max. Point

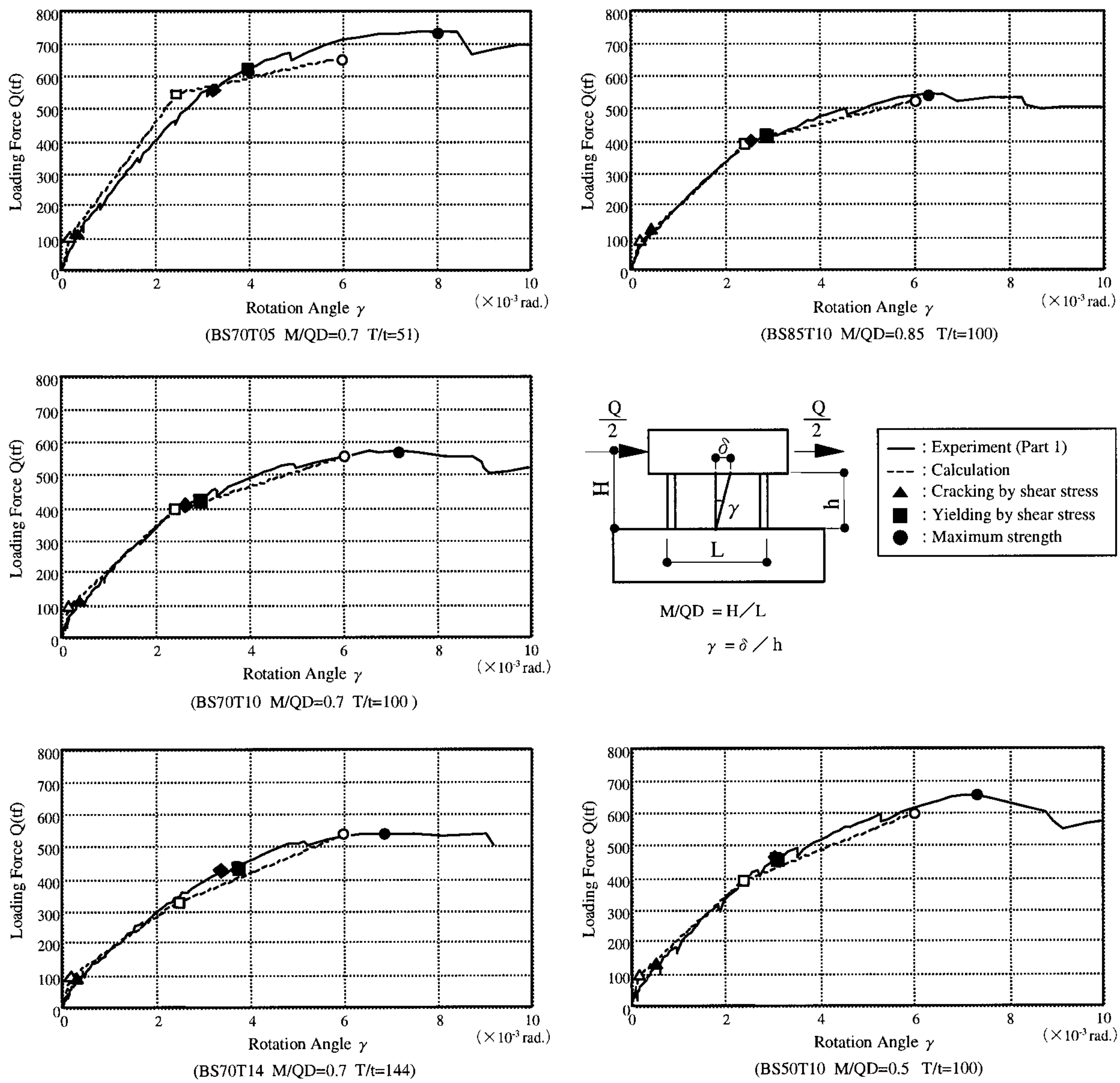


Fig.8 Calculated Shear Skeleton Curve and Experimental Curve

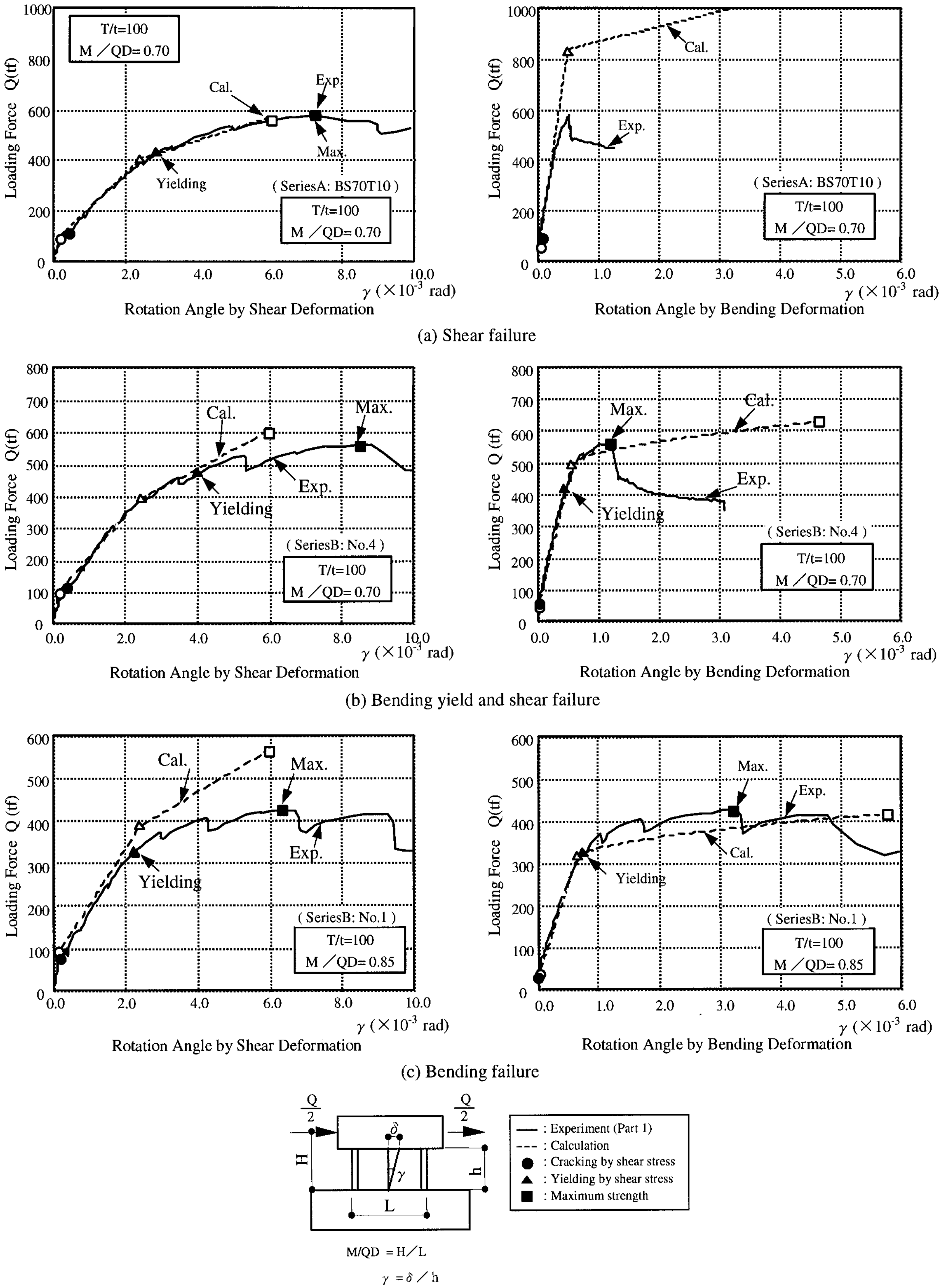


Fig.9 Calculated Shear/Bending Skeleton Curve and Experimental Curve