A Membrane Element Analysis of Concrete Containment Vessels Subject to Lateral Force

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Summary

In this paper we deal with a membrane element analysis which is one of the simple analytical methods applied to concrete containment vessels subject to lateral force and the mechanical behaviors are analyzed. Further, test results of concrete containment vessels examined by the authors and the analytical results are compared. And the proposed analytical method is referred to in the validity. As a method to analyze concrete containment vessels, the finite element method is typical, but it requires considerable time for computation.

N.B. Duchon has proposed a mathematical model to analyze a reinforced concrete membrane subject to tention and shear. The present membrane element analysis is based on Duchon's mathematical model. The present method is as follows:

The relationships of stress and strain in reinforcing steel and concrete are modelized nonlinearly based on the test results of the materials. The stresses at any point in a concrete containment vessel subject to lateral force are assumed to be only in-plane stresses consisting of the two normal stresses and shear.

Under these membrane stresses, the two principal strains and the directions of these strains in the membrane element are computed from the conditions of equilibrium and strain compatibility. In the analytical procedure, the elastic model for the uncracked membrane element and Duchon's model for the cracked membrane element are adopted. According to the membrane element analysis, the strains in the reinforcing steel and concrete, and the shear deflection of the membrane element are produced at any loading stage of increasing lateral force.

Due to the above-mentioned method, the relationships of the flexural and shear deflection to the lateral force acting on the concrete containment vessel can be produced. The total deflection is obtained by the sum of the flexural and shear deflections at any loading stage.

A computer program is developed to implement the analytical method. In order to demonstrate the validity of the present method, the mechanical behaviors of six test specimens with about a one-thirtieth scale of the prototype of the concrete containment vessel are analyzed by the present method.

The proposed method of membrane element analysis can be analyzed and the mechanical behavior of concrete containment vessels can be obtained in the very short time of 60 seconds in CPU time. It will be shown that the analytical results are nearly in agreement with the test results.

1. Introduction

In recent years, experimental studies[1],[2] have been carried out on cylindrical concrete shear walls, in terms of RCCV and PCCV, for nuclear power plants, particularly for light water-cooled reactor buildings.

The purpose of these studies has been to grasp the mechanical behavior of the walls directly from experiments. On the other hand, various numerical methods, such as the finite element method, are used to grasp the mechanical behavior indirectly, but they involve problems with the considerable time needed for their computation[3].

In this regard, this study is to apply a simpler method, or membrane element method (M.E.M.) to cylindrical shear walls (containment vessels), so that the effectiveness of this method can be shown by comparison with the experiment results obtained.

In this method of membrane element analysis, the stress applied to the membrane element (cylindrical shear wall element) is assumed to be a membrane stress, and the elastic model has been used until cracks occur in the membrane element, and thereafter the mathematical model proposed by N.B.Duchon[4] has been used.

2. Preparation for Membrane Element Analysis

2.1 Model for constitutive materials

From the test results of materials, such as reinforcing steel and concrete, the stress-strain curves are expressed in the models as shown in Figs.1 and 2.

2.2 Membrane stress determination

The stress at arbitrary point P when a lateral load applies to a cylindrical shear wall, as shown in Fig.3, is assumed to be membrane stress, and the following membrane stress will be obtained:

(1) Circumferential membrane stress: σ_x

This computation assumes a uniform external pressure P_0 that is correspondingly equivalent to the design prestress of the test specimen immediately before applying the experimental load, and σ_x is calculated from the rigid condition at the edge of the cylinder and the elastic theory to a semi-infinite cylinder. Then, the displacement in the radial direction at distance h cm from the rigid edge is given by:

$$W(h)=W_0\left\{1-\sqrt{2}\,e^{-\beta h}\cdot \sin(\beta h+\pi/4)\right\} \quad (2.1)$$

where $W_0=P_0 r^2(2-\nu_c)/2E_{ex}t$, $\beta=\sqrt[4]{3(1-\nu_c^2)/r^2t^2}$

P_0 = Equivalent external pressure (kg/cm^2), r = Radius of cylinder (cm)

t = Wall thickness (cm), ν_c = Poisson's ratio of concrete

E_{ex} = Effective Young's modulus in circumferential (x) direction (kg/cm^2)

Therefore, the circumferential membrane stress at distance h is given by eq.2.2.

$$\sigma_x(h)=(W(h)/W_0)P_0 r(2-\nu_c)/2t \quad (2.2)$$

where σ_x is assumed to be constant after the plastic stage of cylindrical shear wall.

(2) Longitudinal membrane stress: σ_y

When the initial design prestress due to unbonded prestressing steel has been introduced longitudinally in the cylindrical wall, plastic deflection of the wall due to lateral load causes changes in the resulting longitudinal force and its point of action. These changes, however, are ignored here in calculation of σ_y.

The procedure for calculation is as follows:

(a) Assuming a linear strain distribution in the cylindrical section, the analysis of the relationship between moment (M) and curvature (φ) are carried out.

(b) Because the moment by an arbitrary load Q at level h' away from the point where a force is applied is given as M(h'), or $Q \cdot h'$, the relationship between M and φ of (a) will provide curvature, or strain distribution, corresponding to this M(h').

(c) By assuming fiber strains at the tension and compression sides caused by load Q to be ε_t and ε_c (including the initial longitudinal strain), the longitudinal strain ε_θ at an arbitrary point P in the section is given by:

$$\varepsilon_\theta = (\varepsilon_t + \varepsilon_c)/2 + (\varepsilon_t - \varepsilon_c)\, Cos\theta/2 \qquad (2.3)$$

(d) Thus, the longitudinal membrane stress is expressed through the stress-strain characteristics of reinforcing steel and concrete by the following equation:

$$\sigma_y = P_y \cdot \sigma_s(\varepsilon_\theta) + (1 - P_y) \cdot \sigma_c(\varepsilon_\theta) \qquad (2.4)$$

where P_y = Ratio of reinforcement in longitudinal direction

$\sigma_s(\varepsilon_\theta)$ = Stress determined by stress-strain characteristics of reinforcement

$\sigma_c(\varepsilon_\theta)$ = Stress determined by stress-strain characteristics of concrete

(3) Shear membrane stress: τ_{xy}

For simplicity, the shear membrane stress is assumed to exist in the form of elastic distribution throughout the cylindrical section even after plastic deflection of the cylindrical walls. As a result, the shear membrane stress at an arbitrary point P is given by:

$$\tau_{xy} = Q \cdot Sin\,\theta / \pi r t \qquad (2.5)$$

3. Membrane Element Analysis

Analyses up to the present permit the mambrane stresses (σ_x, σ_y and τ_{xy}) caused by load Q to be given at an arbitrary point P on the cylindrical wall. Now, the method of calculation is shown for the strains of reinforcement and concrete under these stresses.

The analysis is carried out by assuming the reinforced concrete membrane element to be as an elastic model until cracks occur in the element, and thereafter by using the equilibrium conditions of forces involving the strain compatibility as proposed by N.B.Duchon.

3.1 Before cracking

As shown in Fig.4, by assuming that $\{\varepsilon\} = \{\varepsilon_x, \varepsilon_y, \gamma_{xy}\}^T$ expresses the strain of the reinforced concrete membrane element whose reinforcement ratios in x and y directions being P_x and P_y respectively when this element has received membrane stress $\{\sigma\} = \{\sigma_x, \sigma_y, \tau_{xy}\}^T$, the following equation holds between $\{\sigma\}$ and $\{\varepsilon\}$.

$$\{\sigma\} = [D]\{\varepsilon\}, \text{ or } \{\varepsilon\} = [D]^{-1}\{\sigma\} \qquad (3.1)$$

where [D] = elastic stress - strain matrix of reinforced concrete.
To obtain $[D]^{-1}$, consider a stress-strain state where reinforcing steel and concrete are separated as shown in Fig.4. This will provide the following relationships:
(1) Equilibrium conditions

$$\sigma_x = (1 - P_x) \cdot \sigma_{cx} + P_x \cdot \sigma_{sx} \qquad (3.2)$$

$$\sigma_y = (1 - P_y) \cdot \sigma_{cy} + P_y \cdot \sigma_{sy} \qquad (3.3)$$

$$\tau_{xy} = \tau_{cxy} \qquad (3.4)$$

(2) Constitutive equations of strains

Concrete

$$\left\{\begin{aligned} \varepsilon_x &= \sigma_{cx}/E_c - \nu_c \cdot \sigma_{cy}/E_c && (3.5)\\ \varepsilon_y &= -\nu_c \sigma_{cx}/E_c + \sigma_{cy}/E_c && (3.6)\\ \gamma_{xy} &= \tau_{cxy}/G_c = 2\tau_{cxy}/E_c(1+\nu_c) && (3.7) \end{aligned}\right.$$

Reinforcing steel

$$\left\{\begin{aligned} \varepsilon_x &= \sigma_{sx}/E_s = \sigma_{sx}/nE_c && (3.8)\\ \varepsilon_y &= \sigma_{sy}/E_s = \sigma_{sy}/nE_c && (3.9) \end{aligned}\right.$$

Solving equations (3.5) to (3.9) for each stress, substituting the solutions in equations (3.2) to (3.4), and arranging the results will provide the following equations:

$$\sigma_x = \left\{ \frac{1-P_x}{1-\nu_c^2} + n \cdot P_x \right\} E_c \cdot \varepsilon_x + \frac{(1-P_x)\nu_c E_c \cdot \varepsilon_y}{1-\nu_c^2} \quad (3.10)$$

$$\sigma_y = \frac{(1-P_y)\nu_c \cdot E_c \cdot \varepsilon_x}{1-\nu_c^2} + \left\{ \frac{1-P_y}{1-\nu_c^2} + nP_y \right\} E_c \cdot \varepsilon_y \quad (3.11)$$

$$\tau_{xy} = \frac{E_c(1+\nu_c) \cdot \gamma_{xy}}{2} \quad (3.12)$$

Here, solving equations (3.10) to (3.12) for $\{\varepsilon\}$ will give the following equation:

$$\{\varepsilon\} = [D]^{-1} \cdot \{\sigma\} \quad (3.13)$$

Where,

$$[D]^{-1} = \frac{1}{K \cdot E_c} \begin{bmatrix} 1+(n-1)P_y - nP_y\nu_c^2 & -(1-P_x)\nu_c & 0 \\ -(1-P_y)\nu_c & 1+(n-1)P_x - nP_x\nu_c^2 & 0 \\ 0 & 0 & 2K/(1+\nu_c) \end{bmatrix} \quad (3.14)$$

$$K = \{1+(n-1)P_x\}\{1+(n-1)P_y\} - n^2 P_x P_y \cdot \nu_c^2 \quad (3.15)$$

Since $[D]^{-1}$ is given, the element strain for the membrane stress under load Q can be obtained from equation (3.13).

3.2 After cracking

Fig.5 shows the analysis model after cracks have occurred ($\varepsilon_1 \geqq \varepsilon_{ct2}$) in the reinforced concrete element. The mechanism of resitance against the membrane force will be described below.

(1) Concrete cracks are at right angles to the direction of principal strain (ε_1) in tension.

(2) The aggregate interlock resistance on the cracked surface is ignored.

(3) Reinforcing steel in x and y directions resists only in those directions, and the dowel action is ignored.

Now assume that the membrane stress action against the x-y coordinate system shown in Fig.5 is positive, and that counterclockwise direction of the directional angle (ϕ) from the x-axis (positive side) of the principal strain is positive.

The meaning of symbol i (j, k) that will appear in the succeeding equations is that the stress-strain state of x-reinforcement (y-reinforcement, concrete) existing in divisional linear sections (i, i + 1) {(j, j + 1), (k, k + 1)} , as shown in Fig.6.

The equations for the analytical model are shown below:

(1) Equilibrium conditions

$$\sigma_x = P_x \sigma_{sx} + \sigma_2 \cdot \sin^2\phi, \quad \sigma_y = P_y \cdot \sigma_{sy} + \sigma_2 \cdot \cos^2\phi, \quad \tau_{xy} = -\sigma_2 \cdot \sin\phi \cdot \cos\phi \quad (3.16)$$

(2) Stress-strain relationships

$$\sigma_{sx} = A_{si} + E_{si} \cdot \varepsilon_{sx} \;,\quad \sigma_{sy} = A_{sj} + E_{sj} \cdot \varepsilon_{sy} \;,\quad \sigma_2 = B_{ck} + E_{ck} \cdot \varepsilon_2 \tag{3.17}$$

Where, $A_{si} = \sigma_{si} - E_{si} \cdot \varepsilon_{si}$, $A_{sj} = \sigma_{sj} - E_{sj} \cdot \varepsilon_{sj}$, $B_{ck} = \sigma_{ck} - E_{ck} \cdot \varepsilon_{ck}$ (3.18)

(3) Strain compatibilities

$$\varepsilon_{sx} = \varepsilon_1 \cdot Cos^2\phi + \varepsilon_2 \cdot Sin^2\phi \;,\quad \varepsilon_{sy} = \varepsilon_1 \cdot Sin^2\phi + \varepsilon_2 \cdot Cos^2\phi \tag{3.19}$$

Arranging equations (3.16) to (3.19) for ε_1 and ε_2 will provide:

$$f = a \cdot \varepsilon_1 + b \cdot \varepsilon_2 \tag{3.20}$$

$$g = c \cdot \varepsilon_1 + d \cdot \varepsilon_2 \tag{3.21}$$

$$h = e \cdot \varepsilon_1 \tag{3.22}$$

where,

$$\left.\begin{aligned}
&a = P_x \cdot E_{si} \cdot Cos^2\phi \;,\quad b = (P_x \cdot E_{si} + E_{ck}) Sin^2\phi \\
&c = P_y \cdot E_{sj} \cdot Sin^2\phi \;,\quad d = (P_y E_{sj} + E_{ck}) Cos^2\phi \\
&e = -E_{ck} \cdot Sin\phi \cdot Cos\phi \;,\quad f = \sigma_x - P_x \cdot A_{si} - B_{ck} \cdot Sin^2\phi \\
&g = \sigma_y - P_y \cdot A_{sj} - B_{ck} \cdot Cos^2\phi \;,\quad h = \tau_{xy} + B_{ck} \cdot Sin\phi \cdot Cos\phi
\end{aligned}\right\} \tag{3.23}$$

Solving equations (3.20) and (3.21) for the principal strain ε_1 and ε_2 will give:

$$\varepsilon_1 = (f \cdot d - g \cdot b)/\xi \;,\quad \varepsilon_2 = (g \cdot a - f \cdot c)/\xi \tag{3.24}$$

Where,

$$\xi = P_x E_{si} (P_y \cdot E_{sj} + E_{ck}) \cdot Cos^4\phi - P_y \cdot E_{sj} (P_x \cdot E_{si} + E_{ck}) \cdot Sin^4\phi \tag{3.25}$$

By substituting equation (3.24) in (3.22) and using (3.23) and (3.25), the following equation is provided.

$$\left.\begin{aligned}
&(\tau_{xy} + B_{ck} \cdot Sin\phi \cdot Cos\phi)\{P_x E_{si} (P_y E_{sj} + E_{ck}) \cdot Cos^4\phi - P_y E_{sj} (P_x E_{si} + E_{ck}) Sin^4\phi\} \\
&+ E_{ck} \cdot Sin\phi \cdot Cos\phi \{(\sigma_y - P_y \cdot A_{sj}) P_x E_{si} \cdot Cos^2\phi - B_{ck} \cdot P_x \cdot E_{si} \cdot Cos^4\phi \\
&- (\sigma_x - P_x A_{si}) \cdot P_y E_{sj} \cdot Sin^2\phi + B_{ck} \cdot P_y \cdot E_{sj} \cdot Sin^4\phi\} = 0
\end{aligned}\right\} \tag{3.26}$$

Arranging the above equation with $\tan\phi$ provides:

$$\sum_{n=1}^{6} q_n (\tan\phi)^n + q_0 = 0 \tag{3.27}$$

Where,

$$\left.\begin{aligned}
&q_6 = \tau_{xy} \cdot P_y \cdot E_{sj} (P_x E_{si} + E_{ck}) \;,\quad q_5 = P_y \cdot E_{sj} \{B_{ck} \cdot P_x E_{si} + E_{ck} (\sigma_x - P_x \cdot A_{si})\} \\
&q_4 = q_6 \;,\quad q_3 = E_{ck} (\sigma_x - P_x A_{si}) P_y E_{sj} - E_{ck} (\sigma_y - P_y \cdot A_{sj}) P_x E_{si} \\
&q_2 = -\tau_{xy} \cdot P_x E_{si} (P_y E_{sj} + E_{ck}) \;,\quad q_1 = -B_{ck} P_x E_{si} P_y \cdot E_{sj} - E_{ck} (\sigma_y - P_y A_{sj}) P_x E_{si} \;,\quad q_0 = q_2
\end{aligned}\right\} \tag{3.28}$$

The above discussion results in that equation (3.27) express the equilibrium condition of force involving the condition of strain compatability, with only ϕ remaining as unknown. By solving this equation for ϕ , the principal strains ε_1 and ε_2 are given from equation (3.24) and the strain of reinforcement in x or y direction is from equation (3.19).

The shear distortion of the membrane element is given by:

$$\gamma_{xy} = (\varepsilon_1 - \varepsilon_2) Sin\, 2\phi \tag{3.29}$$

Now, the relationship between the load and strain for each portion of the cylindrical shear wall subject to lateral force is given by application of this membrane element analysis.

4. Load-Deflection Analyses

4.1 Load-flexural deflection analysis

Since the use of moment-curvature relationship provides the angle of rotation at each layer under load Q, that is, flexural deflection, the flexural deflection δ_B of the cylindrical section is obtained by integrating over all layers. In actual calculation, 10 layers (n = 10) are used.

4.2 Load-shear deflection analysis

The load-shear deflection analysis is based on the computation from shear strain of the membrane element provided by the membrane element analysis in the cylindrical shear wall. As shown in Fig.7, the shear deflection of cylindrical shear walls is assumedly controlled by the black area of the figure, and the average shear deflection for i-layer ($\bar{\delta}_{si} = \bar{\gamma}_i \cdot \Delta h$) is obtained by assuming that the work done by the average shear stress acting on i-layer is the sum of the work done by shear stress acting on each element of i-layer. This is expressed by the following equation:

$$\left(\frac{Q}{A_w} \cdot A_w\right) \cdot (\bar{\gamma}_i \cdot \Delta h) = 2 \sum_{j=1}^{m} \left(\tau_{ij} \cdot \frac{A_w}{2m}\right) \cdot (\gamma_{ij} \cdot \Delta h) \tag{4.1}$$

From equation (2.5), the shear stress at angle θ_j from the direction of applied load is as follows.

$$\tau_{ij} = Q \cdot S_{in}\,\theta_j / A_w \tag{4.2}$$

So, the average shear deflection $\bar{\delta}_{si}$ for i-layer is given by:

$$\bar{\delta}_{si} = \bar{\gamma}_i \cdot \Delta h = \Delta h / m \cdot \sum_{j=1}^{m} (\gamma_{ij} \cdot S_{in}\,\theta_j) \tag{4.3}$$

Therefore, the total shear deflection of cylindrical shear wall is regarded as the sum of the average shear deflection of each layer, and expressed as follows:

$$\delta_s = \sum_{i=1}^{n} (\bar{\delta}_{si}) = \sum_{i=1}^{n} \left(\Delta h / m \cdot \sum_{j=1}^{m} (\gamma_{ij} \cdot S_{in}\,\theta_j)\right) \tag{4.4}$$

4.3 Load-total deflection relationship

Since 4.1 and 4.2 have provided flexural deflection and shear deflection respectively, the total deflection of the cylindrical shear wall under laod Q is given by:

$$\delta_T = \delta_B + \delta_S \tag{4.5}$$

5. Experimental Program

Six specimens shown in Table I are about a one-thirtieth scale model of the prototype of the concrete containment vessel. Dimensions of all test specimens were 126cm outside diameter, 6cm wall thickness and 107.5cm in cylindrical height. Parameter in these specimens are at the level of initial design prestress, percentage of reinforcing steel and internal pressure.

The overall dimensions of the test specimen are shown in Fig.8. The cylindrical shear wall of each specimen is reinforced orthogonally with two layers of 6mm deformed bars. To introduce longitudinal prestress, 24 unbonded prestressing steel rods (9.2mm) are uniformly arranged, tensioned with a hydraulic jack to the initial design prestress and then secured. To introduce circumferential prestress, steel butresses are arranged vertically at 4 positions (at 90° intervals) outside the shear wall, around which prestressing steel rods (12mm) are positioned at 10cm intervals to provide tension and then secured to the butresses.

6. Comparison of Test and Analytical Results

6.1 Load-strain curves

Fig.9 shows the load-strain curves of x and y reinforcement at the web zone (cylindrical section nearly parallel to the applied force). The difference in the test and analytical results for the load at which cracks occur is observed in each test specimen. The reason seems to be that, in the computation, the tensile strength of concrete uses the values provided by the splitting test of the control cylinder (10cm dia. x 20cm) while the tensile strength of concrete in the actual test specimen is reduced by the restraining effect of the reinforcement on drying and shrinking processes.

On the other hand, in the behaviors after cracking, the test and analytical results quite agree each other for specimen No.1 without the initial design prestress. Although the test and analytical results agree approximately for specimens with the initial design prestress, the difference in behaviors is greater than that for specimen No.1.

6.2 Load-deflection curves

Fig.10 shows the load-deflection curves of test specimens. As described in 4.3, the envelope curve of the calculated values is the addition of the flexural and shear deflections of the test specimen. The calculated value seems to follow the test results.

Fig.11 shows an example of the load-deflection curves where the flexural and shear deflections of specimen are separated. As the plastic stage of the specimen develops, the shear deflection seems to dominate. In this example, the calculated values are smaller than the test values in both flexural and shear deflections.

7. Conclusion

Assuming membrane stress as the stress acting on each part of a cylindrical concrete shear wall subject to a lateral force, the mechanical behaviors are studied on the moment-curvature analysis of cylindrical section and the elasto-plastic analysis of membrane element, and compared with the test results.

This confirms the effectiveness of the proposed analytical method, such that the experimental behaviors can approximately be followed in a very short time of about 60 seconds in CPU time.

Further detailed studies should be done on remaining problems, such that the liner strain distribution in the cylindrical section is assumed for concrete cylindrical shear wall håving the ratio of shear span to effective depth being 1, and the shear transfer of a cracked surface in the membrane element analysis.

8. Acknowledgement

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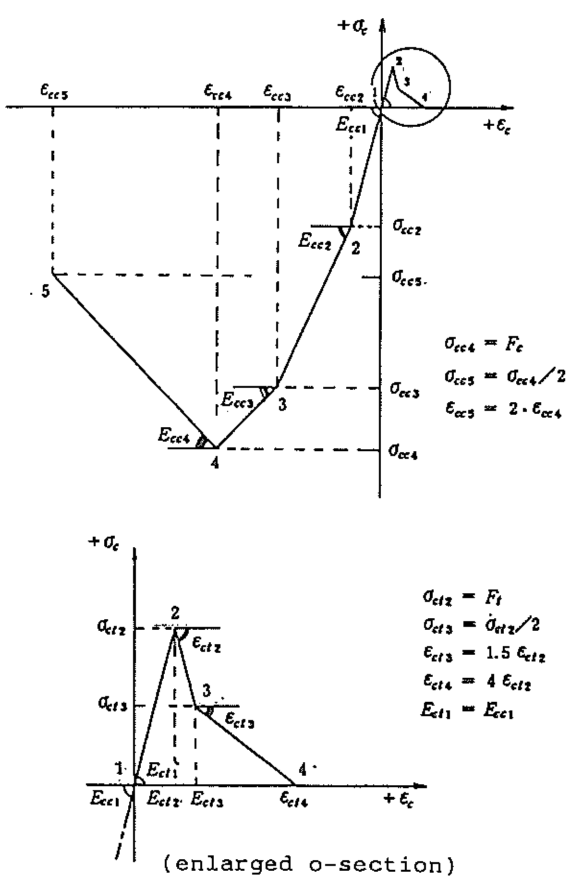


Fig.2 Assumed stress-strain diagram for concrete

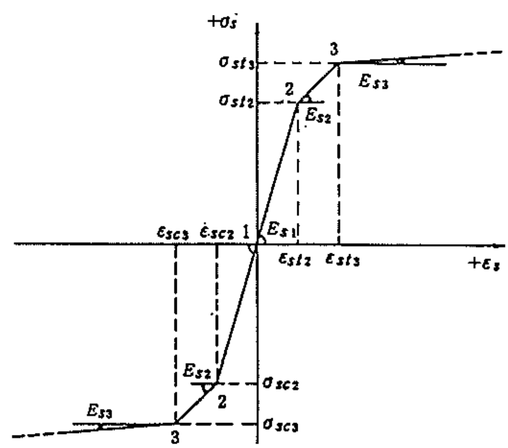


Fig.1 Assumed stress-strain diagram for reinforcing steel

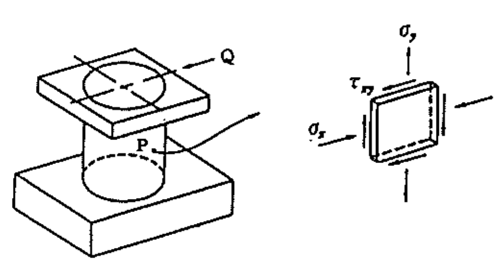


Fig.3 Assumption of membrane stress

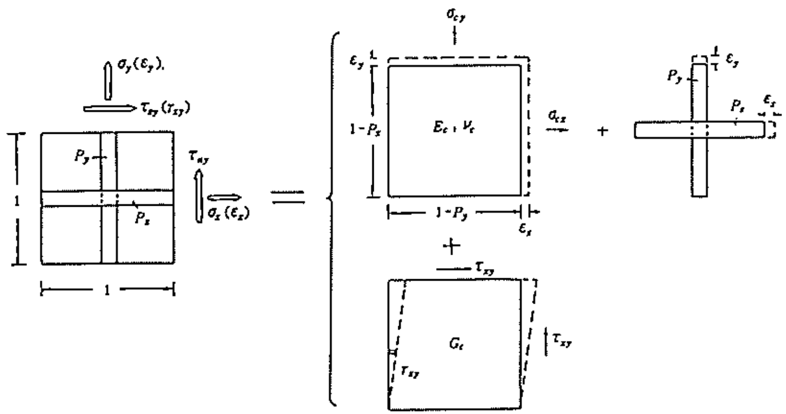


Fig.4 Separation of stress-strain relationship for concrete and reinforcement

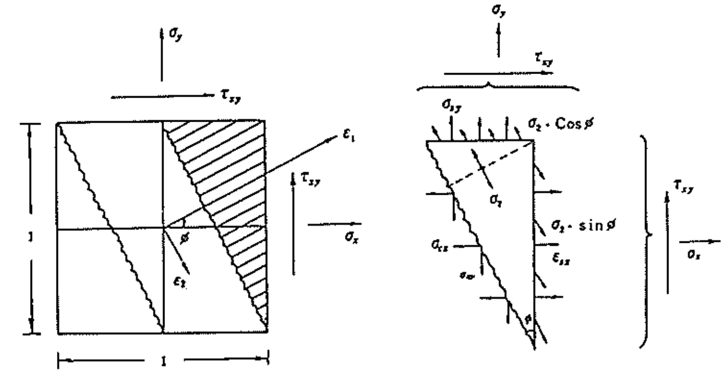


Fig.5 Analytical model for cracked membrane element

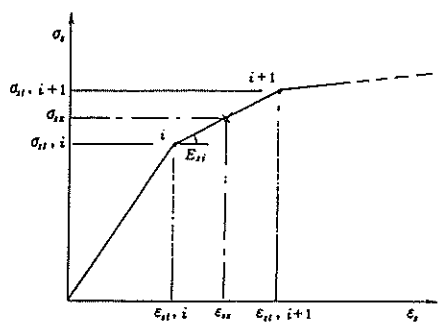


Fig.6 Divisional linear indication of stress -strain relationship

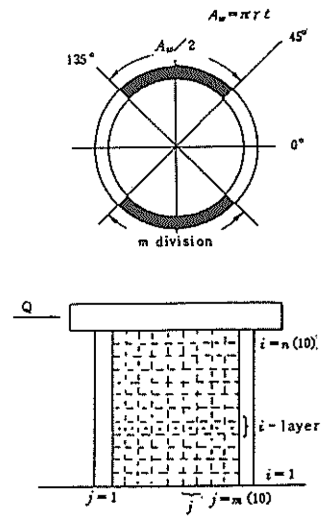


Fig.7 Assumption of area that controls shear deflection

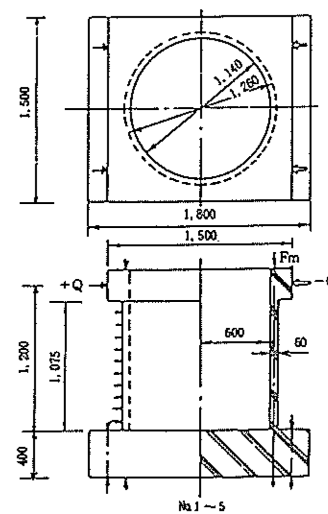
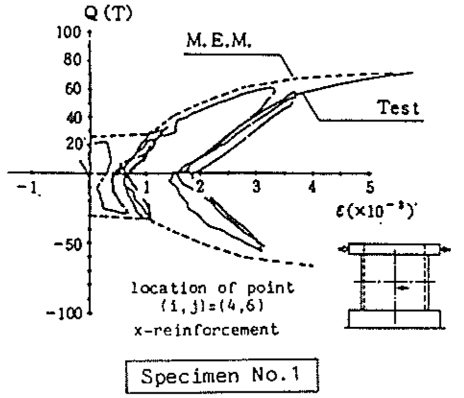


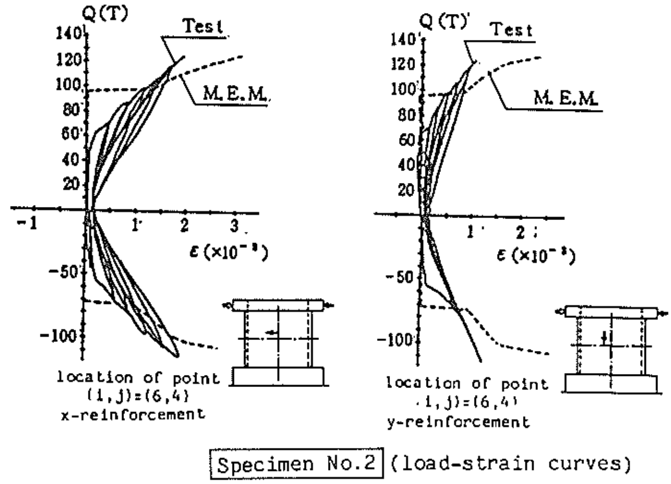
Fig.8 Overall dimensions of test specimens

Table I Program of test specimens

No. of Specimen		1	2	3	4	5	6
Reinforcement Ratio	Px (%)	1.0	1.0	1.0	2.0	3.0	1.0
	Py (%)	3.0					
Prestress (KG/CM²)	X-Direction	0	50	100	50		
	Y-Direction	0	25	50	25		
Load		Holizontal (Q)					$Pi^* + Q$

• Pi : Internal Pressure (5.0 KG/CM²)





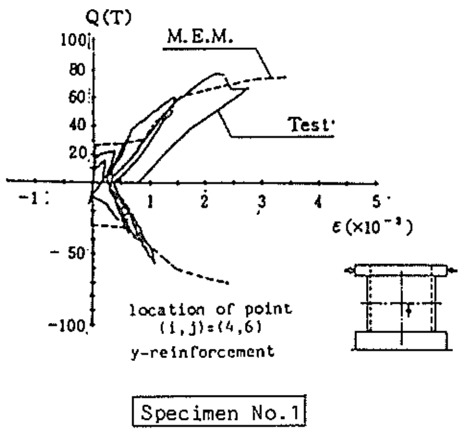
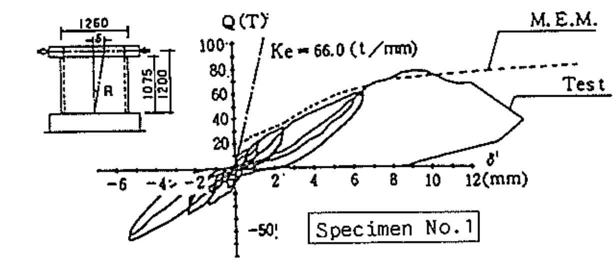
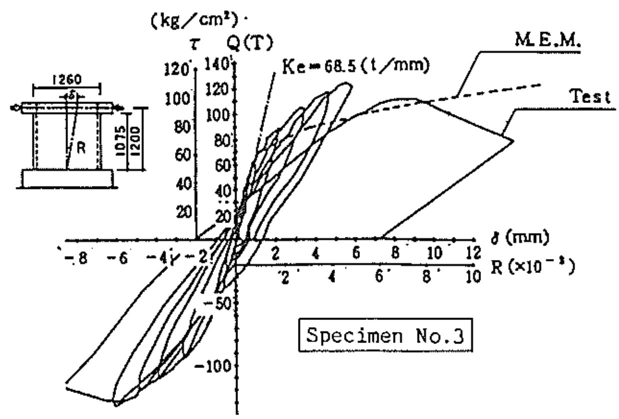


Fig.9 Examples of load-strain curves





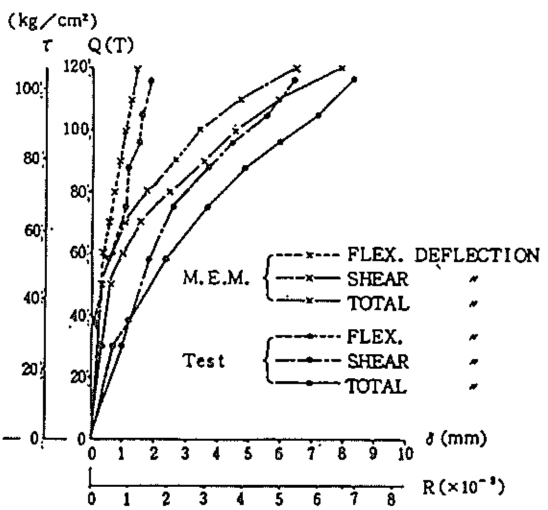


Fig.11 An example of load-deflection curves separated to the flexural and shear (specimen No.5)

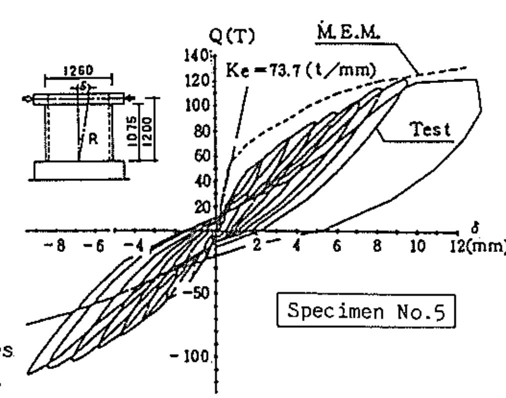


Fig.10 Examples of load-deflection curves