Hysteretic model for reinforced concrete containment

J.Tohma & H.Hwang
Department of Nuclear Energy, Brookhaven National Laboratory, Upton, N.Y., USA

1 INTRODUCTION

The responses of a reinforced concrete containment to severe earthquakes excitations may be in the nonlinear range. Thus, it is desirable to establish a structural analysis method which will take the nonlinear structural characteristics into consideration. For this prupose, the hysteretic shear force-displacement relationship needs to be established if the structure is represented by a stick model.

This paper presents an analytical model for the hysteretic behavior of reinforced concrete containment under cyclic loadings such as earthquakes. The values of the parameters which difine the hysteretic model are determined from the comparison of the simulated and experimental results of a 1/25-scale model structure of a cylindrical containment.

2 HYSTERETIC MODEL FOR TIME HISTORY ANALYSIS

In this study, a reinforced concrete containment is represented by a multi-degree-of-freedom(MDF) stick model as shown in Fig.1. Each mass has only one degree of freedom, i.e., the horizontal displacement in the direction of earthquakes. The restoring shear force is related to the displacement between the two masses. This displacement is denoted as the inter-node displacement.

2.1 Skeleton curve

Under static monotonic increasing loads, the relationship of the restoring shear force Q and the inter-node displacement U is described by a bi-linear curve as shown in Fig.2. In this study, the yielding shear strength Qy and the yielding inter-node displacement Uy are determined from an experimental test result. Details are given in Section 3. ke and kp in Fig.2 represent the initial and post-yielding stiffness, respectively. ke is Qy/Uy and kp is usually experessed as

$$kp = \alpha s \, ke \qquad \cdots\cdots\cdots (1)$$

and αs is the post-yielding slope parameter. This bi-linear shear force displacement curve is called the skeleton curve.

2.2 Hysteretic rules

In recent years, reinforced concrete panels, which represent sections of containments, were tested in the United States (Conley,et al 1981) (Oesterle, et al 1981). In addition, experiments of scale-model structures of the reinforced concrete containments were carried out in Japan (Uchida, et al 1979). From these experimental results, it has been obseved that the hysteretic diagrams exhibit pinching phenomenon. This is caused by the opening and closing of the shear cracks during the cyclic loadings. Is seems important to take the pinching effect as well as the degrading of stiffness into account when nonlinear analysis of the containments is performed.

In this paper, a modified Takeda model,as shown in Fig.3,is utilized to describe hysteretic shear force-displacement relationship of reinforced concrete containments. This model is originally proposed (Roufaiel, et al 1983)to describe the moment-curvature relationship for frame members under cyclic loads. This modified Takeda model has a bilinear skeleton curve and it takes stiffness degrading and pinching effects into consideration. The model is essentially governed by five different types of rules :

1) Elastic loading and unloading with the initial stiffness.
2) Inelastic loading with the post-yielding stiffness.
3) Inelastic unloading with the degrading stiffness.
4) Inelastic pinched reloading.
5) Peak oriented inelastic reloading.

These five rules result in five possible paths in the hysteretic diagram as identified in Fig.3 by corresponding numbers in circles.

The corresponding tangential stiffnesses are named as k_1 ,k_2 ,k_3 ,k_4 and k_5 .k_1 is equal to ke, and k_2 is equal to kp.k_3 ,k_4 and k_5 are determined by using the following points as shown in Fig.4.

(Umc, Qmc) : the maximum point reached in the positive (or negative) direction during the current loading cycle.

(Uo, Qo) : an auxiliary point determined as the intersection of two straight lines ; one line passing through (Umc, Qmc) with the slope of ke and the other line passing through the origin with the slope of kp.

(Um, Qm) : the maximum point reached during any of the previous loading cycles in the negative (or positive) direction.

(Ur, o) : the residual inter-node displacement at the zero shear force ; this point is determined as the intersection of the U-axis and an auxiliary straight line passing through (Uo, Qo) and (Um, Qm).

(Un, Qn) : a point with no pinching effect ; this point is defined as the intersection of the skeleton curve and the auxiliary line mentioned above.

(Up, Qp) : the pinching point ; this point is defined as

$$(Up, Qp) = (\alpha p Un, \alpha p Qn) \qquad \cdots\cdots\cdots (2)$$

where αp is a pinching factor and it represents the effect of shear cracks on hysteretic behavior.

The value of αp is between 0 and 1. For this study, αp is determined from the simulation of the experimental results as detailed in Section3.

3 DETERMINATION OF THE PARAMETERS IN HYSTERETIC MODEL

The hysteretic model described in Section 2 is characterized by four parameters :

(1) the pinching factor αp
(2) the yielding shear factor Qy,
(3) the yielding displacement Uy, and
(4) the post-yielding slope parameter αs

It is noted that the last three parameters determine the skeleton curve. The initial stiffness ke can be calculated from Qy and Uy. Furthermore, the post-yielding stiffness kp is determined by ke and αs. In this study, the appropriate values of these parameters are determined by simulating the results of an experimental work conducted by Uchida et al.

3.1 Description of the experimental work

Since no experimental work under earthquake excitation was available, the experimental result of a cylindrical specimen subjected to quasi-static horizontal cyclic loading is used as the target for the simulation. The cylindrical specimen, as shown in Fig. 5, is a 1/25-scale model of a containment cylinder. The dimensions are : 160cm in height, 154cm in inside diameter, and 6cm in wall thickness. First, the specimen was tested with the internal water pressure alone, then it was tested under the combined action of the internal pressure and the static cyclic lateral load. The lateral displacement is measured at the top stub. Figure. 6 shows the shear force-displacement diagram.

3.2 Simulation of the experimental work

The cylindrical specimen is modeled as one-degree-of-freedom system. The effects of mass and damping are disregarded because the experiment was performed under quasi-static cyclic lateral load. The displacement at the top stub can be calculated for a given load time history and a set of parameter values for the hysteretic model.

In the process of simulation, four different skeleton curves are selected from the inspection of the experimental hysteretic curve and leveled as Cases A, B, C and D as shown in Table 1. For each case, 10 different values of the pinching factor varying from 0.1 to 1.0 with interval of 0.1 are assigned. Therefore, a total of 40 simulation runs is carried out. Given various values of the pinching factor, the hysteretic curves for the four cases are carefully examined. From the comparison of the maximum positive/negative point and the area of the hysteretic curve, it is concluded that the hysteretic curve from Case A with $\alpha p = 0.3$ is most representative of the actual experimental results. Fig. 7 shows the comparison of the experimental and the simulated hysteretic curves (10th cycle). Based on the selected parameter values, i.e. case A with $\alpha p = 0.3$, the diaplacement history at the top stub of the specimen is shown in Fig. 8. It can be seen that the simulated result (a dash line) compares very well with the actual experimental result (a solid line).

The initial stiffness ke is less than the so-called uncracked shear stiffness ko due to the existence of the shear cracks. The uncracked shear stiffness is computed as

$$k_o = \frac{G_o A_s}{h} \qquad \cdots\cdots (3)$$

where

Go is the shear modulus of the uncracked concrete.
As is the shear area of the structure.
h is the height of the structure.
Go is determined by the Young's modulus of concrete, Ec, and the Poisson's ratio ν, as follows,

$$G_o = \frac{E_c}{2(1+\nu)} \qquad \cdots\cdots\cdots (4)$$

Given Ec = 2.65 $\times 10^5$ kg/cm^2 (Uchida et al)and ν=0.2 (assumed), Go is calculated as 1.10$\times 10^5$ kg/cm^2 . For a circular cross-section, the shear area As is one half of the total cross-sectional area. The cross-sectional area of the specimen is 3000cm^2 , thus, the shear area is 1500 cm^2 . Given the value of Go and As as well as h = 160cm, the shear stiffness of the uncracked concrete, ko, as computed from Eq. (3), is equal to 1.0 $\times 10^6$ kg/cm (100 ton/mm). In this study, the initial stiffness ke is determined to be 7.0 ton/mm (Case A in Table 1) Thus, the shear modulus is reduced to about 7 percent of the uncracked value. It should be noted that this large amount of reduction was caused by the cracks due to internal pressure which was applied during experiment.

4 CONCLUDING REMARKS

This paper presents a hysteretic model for reinforced concrete containments. The containment is idealized as a stick model with shear beam elements. A modified Takeda model is utilized to describe the hysteretic shear force and inter-node displacement relationship. The model is taken the pinching effect and the degrading into consideration.

The proposed hysteretic model is defined by the following four parameters : (1) the pinching factor αp, (2) the yielding shear force Qy, (3) the yielding shear displacement Uy and (4) the post-yielding slope factor αs. These parameters are determined from the simulation of an experimantal work. In order to verify the parameter values obtained in this study, the simulation of other experimental works is recommended.

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Table 1 Parameter Values of the Assumed Skeleton Curves

Case	Yielding Strength Q_y (ton)	Yielding Displacement U_y (mm)	Initial Stiffness k_e(ton/mm)	Post-Yielding Slope α_s
A	70	10	7	0.2
B	70	10	7	0.3
C	90	15	6	0.2
D	90	15	6	0.1

Note: 1 ton = 1,000 kg.

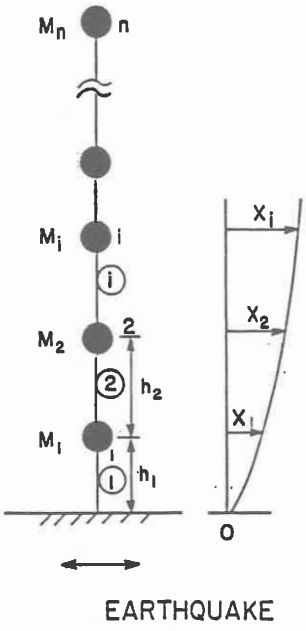

Fig. 1 Stick Model of Containment

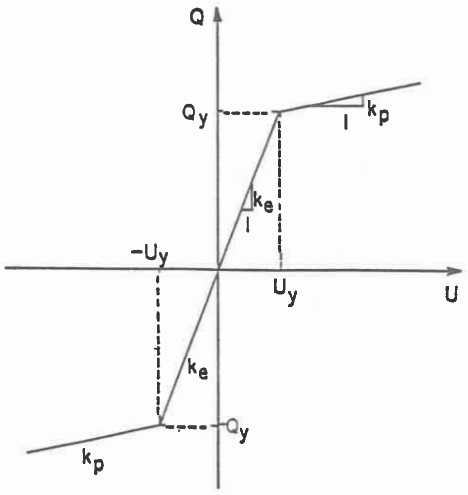

Fig. 2 Skeleton Curve

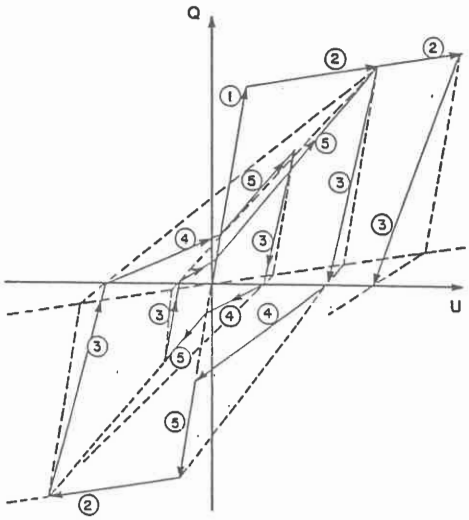

Fig. 3 Hysteretic Shear Force and Inter-Node Displacement Relationship

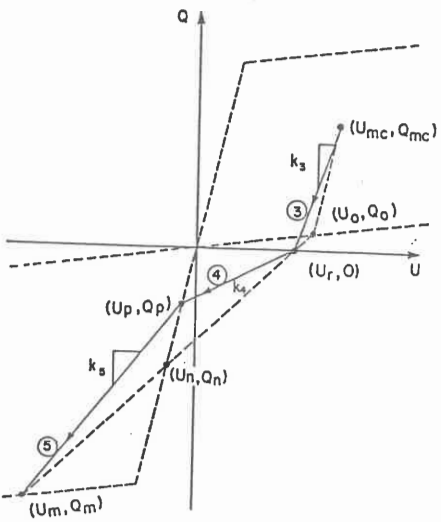

Fig. 4 Unloading and Reloading Stiffness

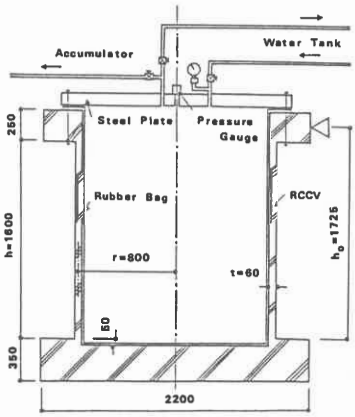

Fig. 5 Cylindrical Model of Concrete Containment

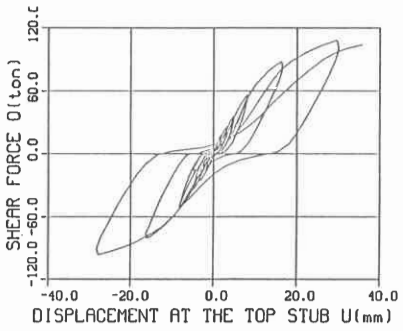

Fig. 6 Experimental Hysteretic Curve

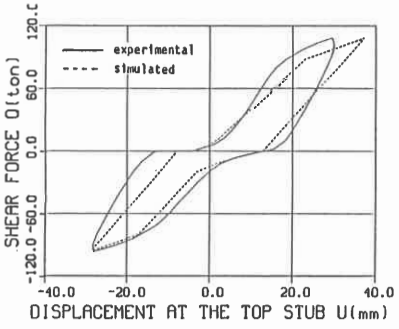

Fig. 7 Experimental and Simulated Hysteretic Curve at 10th Cycle

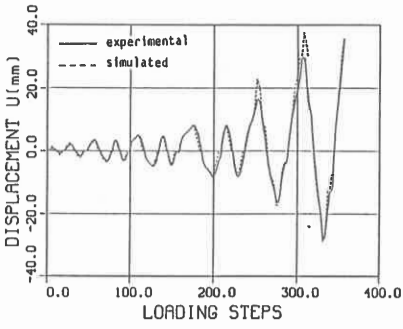

Fig. 8 Experimental and Simulated Displacement History