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NONLINEAR SEISMIC ANALYSIS METHOD FOR REINFORCED CONCRETE CONTAINMENTS

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SUMMARY

For the probabilistic structural analysis, it is desirable to establish a structural analysis method which utilizes a simplified structural model with nonlinear behavior taken into consideration. This paper presents such a nonlinear seismic analysis method for reinforced concrete containments. The containments 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 has a bilinear skeleton curve and includes the pinching effect and the degrading stiffness. The parameters describing the hysteretic model are determined from the simulation of an experimental work. The proposed nonlinear seismic analysis method is applied to an actual reinforced concrete containment in the United States.

NONLINEAR SEISMIC ANALYSIS

The responses of reinforced concrete containments to severe earthquake excitations may be in the nonlinear range. For the probabilistic structural analysis, it is desirable to establish a structural analysis method which utilizes a simplified structural model with nonlinear behavior taken into consideration. Under this condition, 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 equations of motion for such an MDF system subject to a horizontal earthquake ground acceleration is

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + \{F_s\} = -[M]\{I\}\, a_g \qquad (1)$$

where, $[M]$ is the mass matrix; $[C]$ is the damping matrix; $\{I\}$ is the identity vector; $\{X\}$ is the nodal displacement vector relative to the fixed base; $\{F_s\}$ is the restoring force vector and a_g is earthquake ground acceleration.

The mass of the building is discretized at the mid-height of each story and lumped at the floor level. Thus, the mass matrix $[M]$ is a diagonal matrix. The damping matrix $[C]$ is taken as the Rayleigh damping matrix, which is the combination of the mass matrix $[M]$ and the initial stiffness $[K_e]$ of the structure.

HYSTERETIC MODEL

The restoring shear force acting on a shear beam element is related to the inter-node displacement between the two masses. In this study, the hysteretic relationship of the restoring shear force and inter-node displacement is modeled by the modified Takeda model [1] as shown in Fig. 2. This modified Takeda model has a bilinear skeleton curve and includes stiffness degrading and pinching effect. The modified Takeda model is essentially governed by the following five 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 and (5) peak oriented inelastic reloading. These five rules result in five possible paths in the hysteretic diagram as identified in Fig. 2 by corresponding numbers in circles. The hysteretic model described above is characterized by four parameters: (1) the pinching factor α_p, (2) the initial stiffness k_e, (3) the yielding displacement U_y and (4) the post-yielding slope factor α_s. These parameters are determined from the simulation of an experimental results from the test of a 1/25-scale model of a containment cylinder [2].

In the process of simulation, four different skeleton curves are selected from the inspection of the experimental hysteretic curve and labeled 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 has been carried out. First, we examine the effect of α_p. For each specific skeleton curve, the 10th cycle of the hysteretic curves corresponding to various α_p values are carefully examined. It is observed that a pinching factor of 0.3 results in the most appropriate pinching phenomenon as compared to the experimental result. Given the pinching factor α_p of 0.3, the 10the cycle of the hysteretic curves for the four cases are compared. 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 [1]. In this study, the initial stiffness k_e is determined to be 7.0 ton/mm. This is 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 [2]. Based on the selected parameter values, i.e., Case A with $\alpha_p = 0.3$, the displacement history at the top stub of the specimen is shown in Fig. 3. It can be seen that the simulated result (a dash line) compares very well with the actual experimental result (a solid line). Furthermore, Fig. 4 shows the comparison of the entire simulated hysteretic curve with the expermental curve.

NONLINEAR SEISMIC ANALYSIS OF AN ACTUAL CONTAINMENT

The nonlinear seismic analysis method is applied to an actual reinforced concrete containment structure in the United States. As sketched in Fig. 5, the containment consists of a circular cylinder with a hemispherical dome on the top. The dimensions of the containment are also shown in Fig. 5. The containment is reinforced with three different types of reinforcing steel: hoop, meridional and diagonal rebars. The details of the rebar arrangement are described in Ref. 3.

The containment is represented by a stick model with a fixed base. The mass of the containment is discretized into 13 movable nodes. To establish the hysteretic model, the skeleton curves for all elements are specified according to the rules established in this study. In addition to the skeleton curve, the pinching factor α_p is required to describe the hysteretic behavior, the pinching factor α_p is set to be 0.3 for all elements.

In this study, four artificial earthquake acceleration time histories denoted as EQ1, EQ2, EQ3 and EQ4 are utilized and applied horizontally at the base of the containment model. These earthquake time histories are generated from the horizontal response spectrum specified in the Regulatory Guide 1.60 with 5 percent damping [4]. In this study, the peak ground acceleration (PGA) is chosen to be 1.0g and the total duration is specified as 15 seconds.

The nonlinear seismic analysis method is utilized to evaluate the nonlinear responses of the reinforced concrete containment under four earthquakes, i.e., EQ1 through EQ4. To obtain these responses, the Newmark's Beta scheme with $\beta = 1/4$ is utilized for time integration. The time increment is chosen to be 0.005 second. The maximum values of the top displacement, the top acceleration, and the base shear due to these four earthquakes are tabulated in Table 2. The ratio of the smallest value (Min) over the largest value (Max) is also shown in the table. The variation due to different earthquake inputs is not negligible.

Under these four earthquakes, the reinforced concrete containment exhibits nonlinear behavior in the lower portion. The upper portion of the containment remains elastic. The nonlinearity is most apparent due to EQ1. The hysteretic shear force and inter-node displacement diagram of element 1, i.e., the element adjacent to the fixed base, is shown in Fig. 6. It can be seen that the yielding point is only exceeded once in the entire time history and the hysteretic loop is stable. The maximum ductility ratio μ is determined as 1.5 under EQ1. Thus, the norlinearity is very moderate. This containment is located in the eastern United States (EUS). The chance of an earthquake with PGA of 1.0 g occurring in the EUS is extremely small. Under smaller earthquakes, the entire containment probably will remain elastic. Thus, this containment is quite safe under realistic sesimic hazards.

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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 Factor 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.

Table 2 Variations of the Nonlinear Responses

	EQ1	EQ2	EQ3	EQ4	$\frac{\text{Min.}}{\text{Max.}}$
Displacement at the top (in)	13.3	9.9	11.4	11.4	0.74
Base Shear Force (kips)	59606	55587	57871	56366	0.93
Acceleration at the top (in/sec^2)	1441	1438	1190	1258	0.83

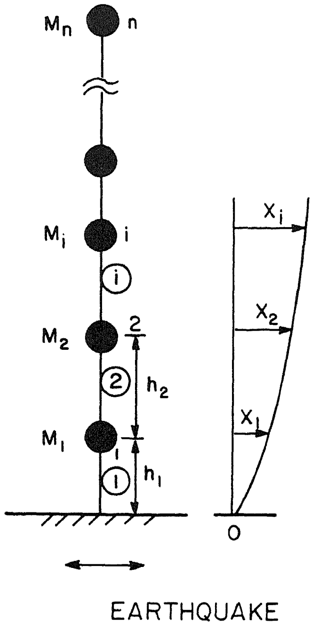

Fig. 1 Stick Model of Containment.

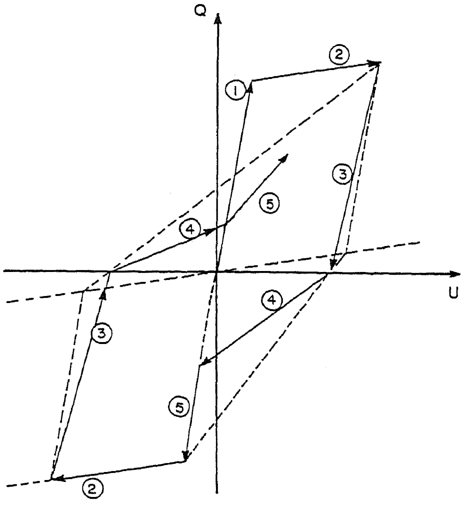

Fig. 2 Hysteretic Diagram.

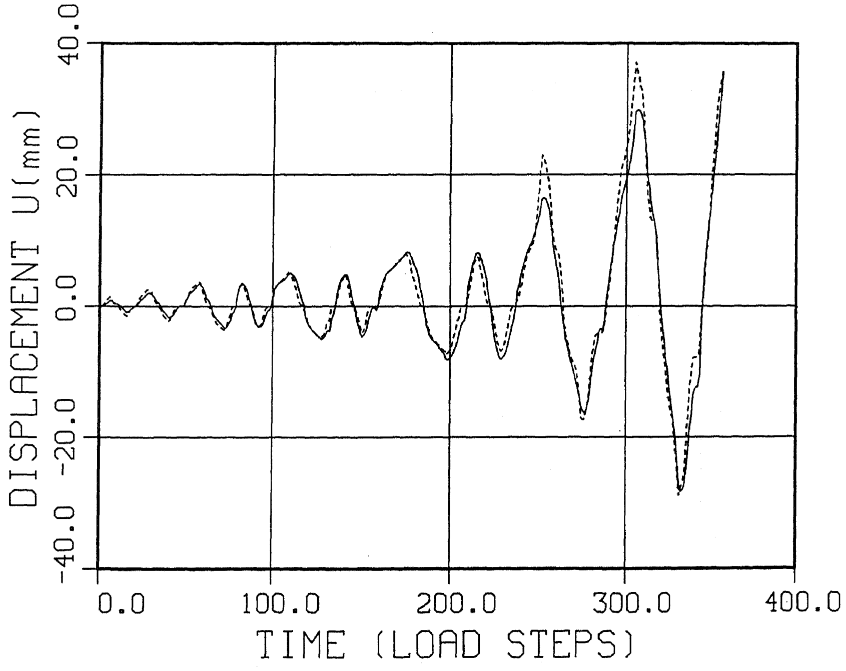

Fig. 3 Experimental and Simulated Displacement Histories.

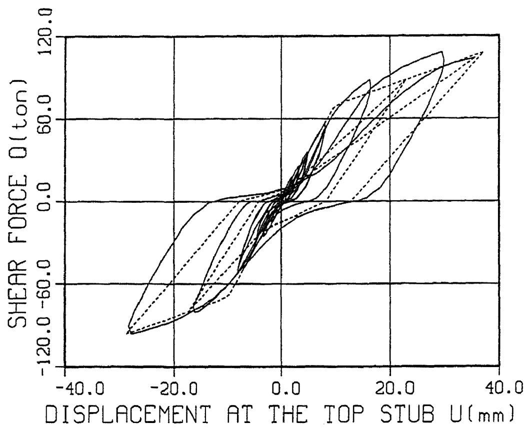

Fig. 4 Experimental and Simulated Hysteretic Diagrams.

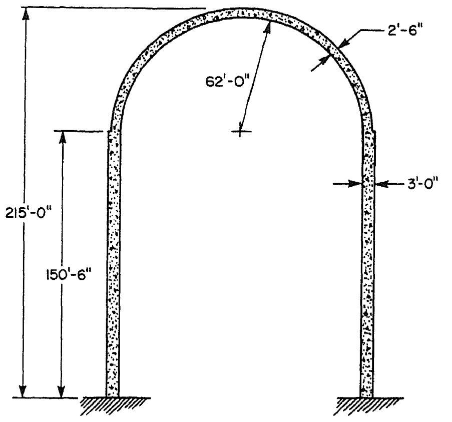

Fig. 5 Sketch of Containment.

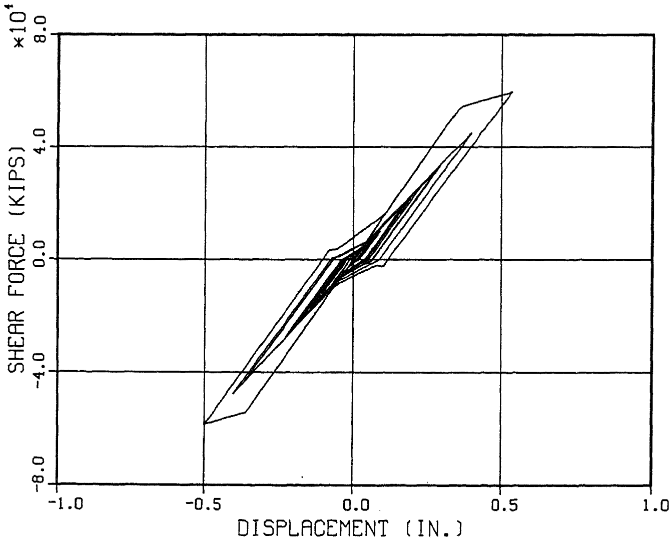

Fig. 6 Hysteretic Diagram (Element 1, EQ1).