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Prediction of NUPEC's Multi-Axis Loading Tests of Concrete Shear Walls

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ABSTRACT

The Nuclear Power Engineering Corporation (NUPEC) of Japan is performing multi-axis loading tests of reinforced concrete (RC) shear wall models. The project, which includes both static and dynamic cyclic tests, started in 1994 and is scheduled to be completed in 2004. The static tests are performed on single elements, box type and cylindrical type structures. Both unidirectional and multidirectional loads are placed on the models during the static test phase. The dynamic tests will be performed on a shaking table for both the box type and cylindrical type structures. As part of collaborative efforts between the United States and Japan, the U. S. Nuclear Regulatory Commission (NRC) and Brookhaven National Laboratory (BNL) are participating in the multi-axial cyclic static loading tests and the shaking table tests.

The multi-axis loading tests are unique and will provide significant insights into the effect of out-of-plane loads on the capacity of shear wall structures. Current analysis methods use simplified assumptions and do not specifically take this effect into account. Since the fragility levels of RC shear walls are key elements in a seismic PRA of a nuclear plant, it is important to verify the methodology for determining these levels. The NUPEC tests will provide valuable data for this purpose.

Pre-test predictions of the box type structure's response to the multi-axis static loading are discussed in this paper. The tests were performed by NUPEC between June and August 2000. Two models are used to make these predictions. The first is an engineering model typical of those used in current design analyses. The second is a finite element model of the structure utilizing the ANSYS computer code. In both cases cyclic load behavior into the inelastic range is considered.

INTRODUCTION

The Nuclear Power Engineering Corporation (NUPEC) has conducted static cyclic tests [1] on "box" type structures made up of four shear walls with stiff, massive roof and floor elements. The tests were performed on the structure by applying cycles of increasing shear displacements (relative displacement of the roof and floor) to the structure. The displacement cycles were applied in both horizontal directions as described below. Before the tests, NUPEC provided the test conditions and the model details and NRC/BNL performed pre-test analyses. The objective of this paper is to present the pre-test predictions made of the structure's response using both engineering models which are typical of those that might be used in the design of nuclear power station facilities and finite element models. In the next phase of the project NUPEC will provide the test results and NRC/BNL will perform post-test analyses.

The engineering model is based on the use of strength of materials approaches to calculate the response of the structure to a monotonically increasing load (a pushover analysis). The resulting load deflection curve is called a backbone curve. Relatively simple rules are then applied to the backbone curve to generate the cyclic response of the structure. A nonlinear concrete element, which is included in the ANSYS computer code, is used to develop the finite element solutions.

The structural characteristics of the test model and general configuration of the test are described first. The engineering and finite element models are then described.

DESCRIPTION OF NUPEC TESTS

The NUPEC test model and program are described in [1]. A sketch of the test model is shown in Fig. 1. The model has the same elevation from either view. There is a 900 mm diameter hole at the center of the top slab. The top and bottom slabs are assumed to be rigid so that the hole has no influence on the analyses discussed here. A vertical preload, resulting in a vertical stress in the walls equal to 1.47 MPa, is applied to the model for all tests. The reinforcement ratio in each of the walls is 0.012 in both the horizontal and vertical directions.

The model is loaded by imposing horizontal displacements to the top slab while restraining the base slab and rotations of the roof. Two types of load patterns were considered for the pre-test analyses: a cross loading pattern, and a rectangular load pattern. Loading is defined in the two principal horizontal directions, defined as X and Y. The cross load pattern consists of:

- Two cycles of $\Delta_x = 0$ to 0.5 mm, to –0.5 mm, to 0 with $\Delta_y = 0$
- Two cycles of $\Delta_x = 0$ to X_m to $-X_m$ to 0 with $\Delta_y = 0$ followed with $\Delta_y = 0$ to Y_m to $-Y_m$ to 0 with $\Delta_x=0$
- Perform previous cycles with (X_m,, Y_m) = (1 mm, 0.8 mm), (2 mm, 1.6 mm), (4 mm, 3.2 mm), (6 mm, 4.8 mm), and (8 mm, 6.4 mm)

The rectangular load pattern consists of:

- Two cycles of $\Delta_x = 0$ to 0.5 mm, to –0.5 mm, to 0 with $\Delta_y = 0$
- Load to $\Delta_y = Y_m$, $\Delta x = 0$; load to $\Delta_x = X_m$, $\Delta_y = Y_m$; load to $\Delta_y = -Y_m$, $\Delta_x = X_m$; load to $\Delta_x = -X_m$, $\Delta_y = -Y_m$; load to $\Delta_y = Y_m$, $\Delta_x = -X_m$; load to $\Delta_x = X_m$, $\Delta_y = Y_m$; load to $\Delta_y = -Y_m$, $\Delta_x = X_m$; load to $\Delta_x = -X_m$, $\Delta_y = -Y_m$; load to $\Delta_y = 0$, $\Delta_x = -X_m$; load to $\Delta_x = 0$, $\Delta_y = 0$
- Perform previous cycles with (X_m,, Y_m) = (1 mm, 0.8 mm), (2 mm, 1.6 mm), (4 mm, 3.2 mm), (6 mm, 4.8 mm), and (8 mm, 6.4 mm)

The concrete compressive strength, modulus of elasticity, and Poisson's ratio used for the pre-test analyses are 34.9 MPa, 26.3 GPa, and 0.21 respectively. The steel yield strength and modulus of elasticity are 375 MPa and 200 GPa, respectively.

ENGINEERING MODEL

A bilinear curve (backbone curve) describing the deformation of the structure for a monotonically increasing load is the basis of the model. Relatively simple rules as developed in [2] are then used to superimpose cyclic load effects on the backbone curve. The restraints against rotation of the roof introduce torsional moments on the structure. It is assumed that these effects are insignificant. These effects will be considered during the post-test analyses of the data.

Backbone Curve

The backbone curve represents the response of the structure to a monotonically increasing load. This curve is represented with a bilinear curve. The initial linear portion of the curve represents the elastic portion of the curve up to the yield load. The slope of the second post yield load portion is taken to be 10 % of the pre yield portion of the curve (this assumption is based on results obtained from ANSYS models of shear walls [3]). The yield load of the structure is equated to the shear strength since preliminary analyses have demonstrated that flexural strength of the wall is larger than the shear strength. Both the shear and flexural deformations are included in the calculation of the yield deflection.

Two of the shear walls resist the shear load in each of the principal directions so that the combined thickness of the walls is 150 mm (5.91 in). The capacity of a shear wall as given in ACI [4] using English units is:

$$V_u = V_c + V_s$$

Where,

$$V_c = 3.3\ [f'_c]^{1/2}\ h\ d + N_u\ d\ /\ (4\ l_w)$$

$$V_s = A_v\ f_y\ d\ /\ s_2$$

and, h = wall thickness = 5.91 inches, l_w = width of wall = 62 inches, d = 0.8 * l_w = 49.6 inches, N_u = axial load on wall = 0.213 * 5.91 * 62 = 78.0 k, A_v = area of horizontal steel in spacing of s_2 = 0.012 * 5.91 * s_2

Therefore the ACI shear capacity for the given wall parameters is:

$$V_c = 84.4\ \text{k},\quad V_s = 191.4\ \text{k},\quad V_u = 275.8\ \text{k} = 1{,}227\ \text{kN}$$

The ACI capacity is known to be conservative. An alternate analysis is given by Barda [5]) where the steel capacity remains the same as given in the ACI code (for equal horizontal and vertical reinforcement) and the concrete shear capacity is:

$$V_c = \{8.3\ - 3.4\ (h_w\ /\ l_w - 0.5)\}\ [f'_c]^{1/2}\ h\ d + N_u\ d\ /\ (4\ l_w)$$

Where, h_w = height of wall = 39.37 inches

Therefore the wall capacity is:

$$V_c = 168.1 \text{ k}, \quad V_s = 191.4 \text{ k}, \quad V_u = 359.5 \text{ k} = 1{,}600 \text{ kN}$$

The strength used to define the end of the elastic portion of the backbone curve is taken as the average between the ACI Code and Barda models (V = 317.7 k = 1414 kN).

The shear deflection of the structure is:

$$\Delta = 1.2\, V\, h_w / h\, l_w\, G = 1.2 * 317.7 * 39.37 / 5.91 * 62 * 1576 = 0.026 \text{ inches} = 0.66 \text{ mm}$$

This deflection is doubled to account for cracking in the wall so that the yield shear deflection is assumed to be 1.32 mm. The flexural deflection is computed using the effective moment of inertia of the structure as defined in [4]. The predicted flexural, shear and total deflections up to the predicted yield of the wall in shear at 1414 kN is shown in Fig. 2. As may be seen the shear deflections predominate over the flexural deflections. The backbone curve is represented with a linear portion from (0, 0) to (1414 kN, 1.98 mm) and a second portion beginning at (1414 kN, 1.98 mm) and continuing at a slope of (1414 / 1.98 * 10 = 71.4 kN / mm).

Cyclic Load Characteristics of Structure

The cyclic load characteristics of the model are developed from the work in [2]. The load cycles used in the test occur in pairs so that there are two complete cycles applied at each deflection level and each succeeding set of cycles is at increasing deflections. The assumed cyclic behavior for a double cycle is illustrated in Fig. 3. The backbone curve discussed in the previous section is used to describe the model. A double cycle to 8 mm is applied to the model. Each portion of the curve in Fig. 3 is described:

- A – B Point A corresponds to the beginning of the double cycle and will lie at the origin if the structure has not been loaded past yield before or at point O of the previous double cycle when the loading has exceeded yield. The location of point B depends on whether previous loads have exceeded yield. If the yield load has not been exceeded the curve is elastic up to the yield point on the backbone curve (1414 kN; 1.98 mm). If this cycle follows other inelastic cycles then point B for the new cycle is located at the point C load of the previous cycle and a deflection equal to the point C deflection of the previous cycle increased by ($1 / \gamma - 1$). Gama (γ) is taken to be 0.95.
- B – C Follow the plastic portion at a slope (0.1 * 1414 / 1.98 = 71.4 kN / mm) to the maximum displacement of 8 mm.
- C – D Unload to 0 load to point D. The displacement is equal to the elastic recovery displacement reduced by a factor of ($1 - \alpha$). Alpha (α) is taken to be 0.35.
- D – E Follow along the plastic slope to 0 deflection.
- E – F Load along the elastic slope degraded by the factor (γ).
- F – G Load along the plastic slope to -8 mm.
- G – H Unload to 0 load along the elastic slope degraded by the factor (α).
- H – I Follow along the plastic slope to 0 deflection.
- I – J Locate a point J' at the Point C load and the point C displacement increased by ($1 / \gamma - 1$). Load along the line I – J' and locate point J on this line at the maximum displacement equal to 8 mm.
- J – K Unload to 0 load to point K. The displacement is equal to the elastic recovery displacement reduced by a factor of ($1 - \alpha$).
- K – L Follow along the plastic slope to 0 deflection.
- L – M Locate a point M' at the point G load and the point G displacement increased by ($1 / \gamma - 1$). Load along the line L – M' and locate point M on this line at the minimum displacement equal to -8 mm.
- M – N Unload to 0 load along the elastic slope degraded by the factor (α).
- N – O Follow along the plastic slope to 0 deflection.

Prediction of Test Results

The model discussed in the previous section is used to predict the test results. The simple engineering model does not account for loading in two directions. Of course the loading in two directions places both axial and shear loads on the walls. The pre-test analysis assumed that this would not have a serious effect on the results.

Loading in the X direction consists of cycles of loading to 0.5 mm, 1 mm, 2 mm, 4 mm, 6 mm, and 8 mm. The structure would be expected to remain elastic for the first 3 sets of cycles with peak loads equal to 357 kN, 714 kN, and1424 kN. The results for the final 3 sets of cycles are shown in Fig. 4.

Loading in the Y direction consists of cycles of loading to 0.8 mm, 1.6 mm, 3.2 mm, 4.8 mm, and 6.4 mm. The structure would be expected to remain elastic for the first 2 sets of cycles with peak loads equal to 571 kN, and1143 kN. The results for the final 3 sets of cycles are shown in Fig. 5.

It is expected that the model will fail when the peak shear deflection results in a story drift of 0.5 %. This occurs when the deflection is about 6 mm. It is therefore concluded that the specimen is likely to fail when the first portion (between points A and B) of the 8 mm cycle is applied and the peak load reaches 1486 kN.

FINITE ELEMENT MODEL

A finite element model of the structure is developed and solutions obtained using the ANSYS (Version 5.6) computer code. Element SOLID65 with smeared reinforcing steel is used to model the walls of the model. The roof and base of the model are assumed to be rigid. The concrete in the element is capable of cracking in tension and crushing in compression. The user may specify the shear stiffness along cracks after they form and again along the cracks after they close. The element used in these calculations neglects crushing of the concrete and sets the shear stiffness across cracks equal to 0.5 times and one times the uncracked stiffness for open and closed cracks respectively.

Several finite element models of the structure are developed ranging from coarse (120 elements) to fine (1176 elements). Problems were also run with single and double elements placed through the thickness of the walls. The coarse model is found to give results which are very comparable to those obtained with the more refined models and this is used for the final results.

A backbone curve is first developed and this result is shown in Fig. 6 and compared with that obtained with the engineering model. As can be seen the bilinear representation of the backbone curve developed with the engineering model is a fair representation of the nonlinear curve generated from the ANSYS results.

The predicted response of the model to a single load cycle from 0 to 4mm to –4 mm to 0 is shown in Fig. 7 and compared with the same data generated with the engineering model. While the peak loads and average slope of the hysteresis loops compare quite well, the hysteresis loops generated from the engineering model are much wider than those generated with ANSYS. Preliminary data on the test program indicate that the measured hysteresis loops are closer to those predicted with the engineering model than predicted with the ANSYS finite element model.

Convergence problems are encountered with the ANSYS solutions when the two-directional load patterns are applied or when the loading approaches the failure load. It appears that the ANSYS program has difficulty treating the concrete nonlinear properties when cyclic loads are applied for load magnitudes that are approaching the structural strength. It has been decided to use another program for finite element solutions during the post-test analysis phase.

SUMMARY

An engineering model and finite element model are used to predict the response of the NUPEC shear wall structure. The engineering model is based on a backbone curve representing the load–deflection characteristics of the structure for a monotonically increasing load. The response of the structure to cyclic loading is then predicted by modifying the backbone curve by simple rules developed from experimental data. The ANSYS computer code is used for the finite element solutions.

It is shown that the backbone curve derived from the engineering model is close to that developed from the finite element solutions. The engineering and finite element models, however, result in somewhat different predicted behavior for cyclic loading. The peak loads reached during a load cycle to a given displacement and average slopes of the hysteresis loops are similar but the hysteresis loops predicted with the engineering model are wider than those predicted with the finite element model. Convergence problems are also encountered when extending the finite element solutions to multiple cycles with loads approaching the capacity of the structure. Another program will be used for studies with the finite element model during the post-test analysis phase.

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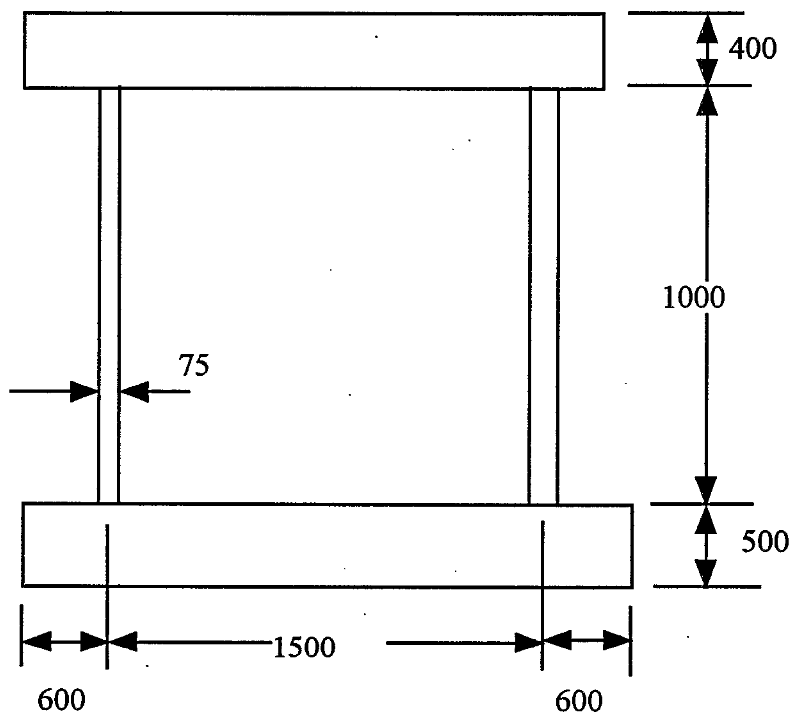

Elevation From Either Side

Fig. 1 NUPEC Test Model (All Dimensions in mm)

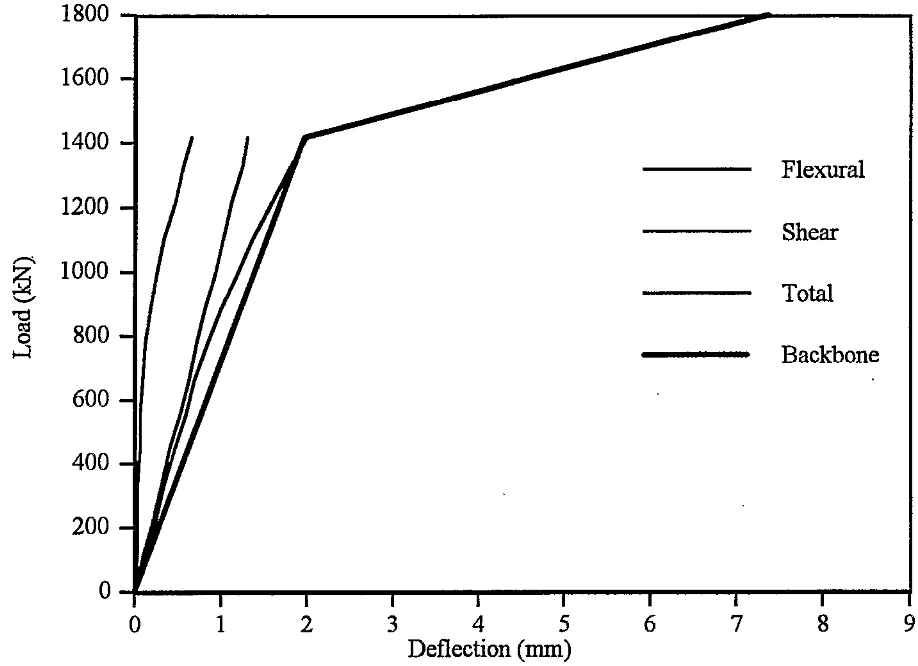

Fig. 2 Predicted Deflections

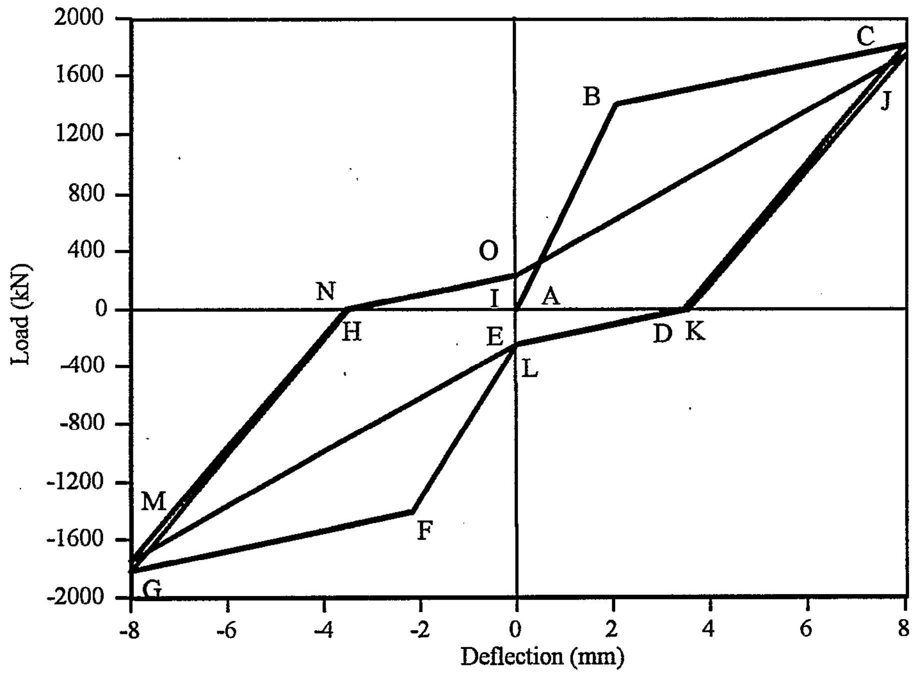

Fig. 3 Sample Problem to Demonstrate Cyclic Behavior Rules

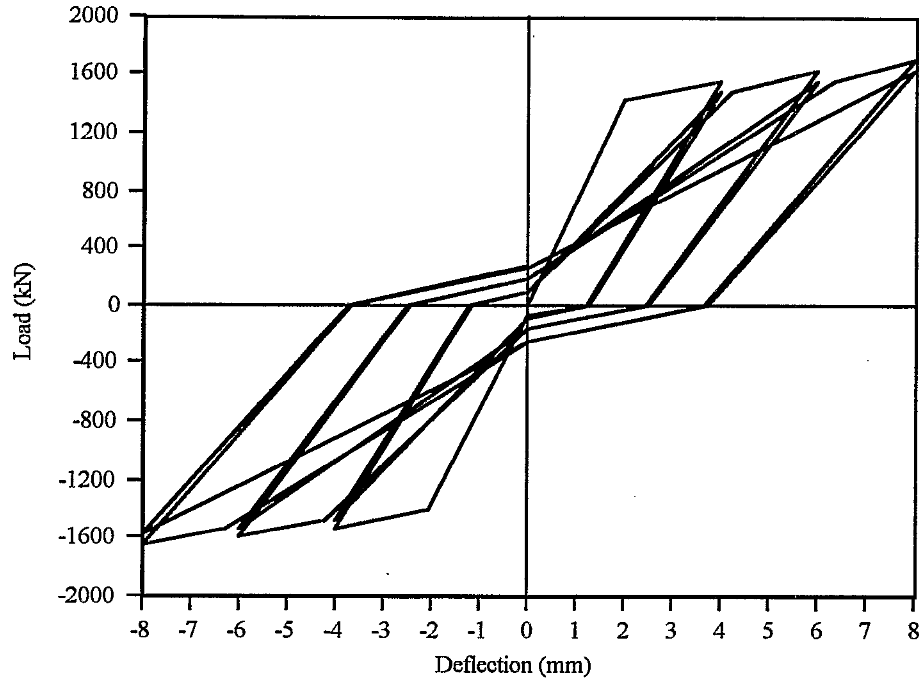

Fig. 4 Predicted Response in X Direction

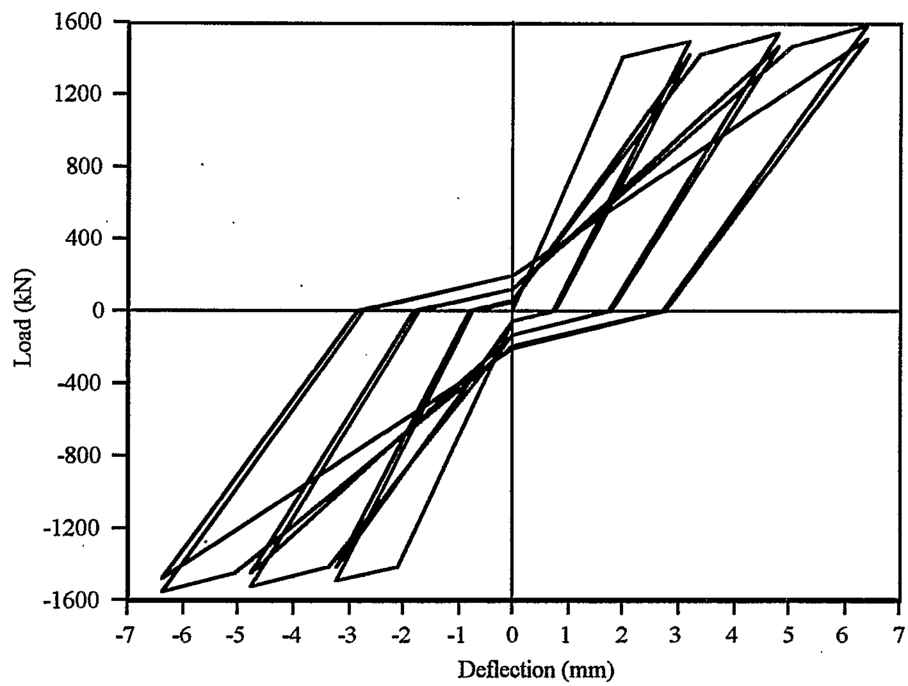

Fig. 5 Predicted Response in Y Direction

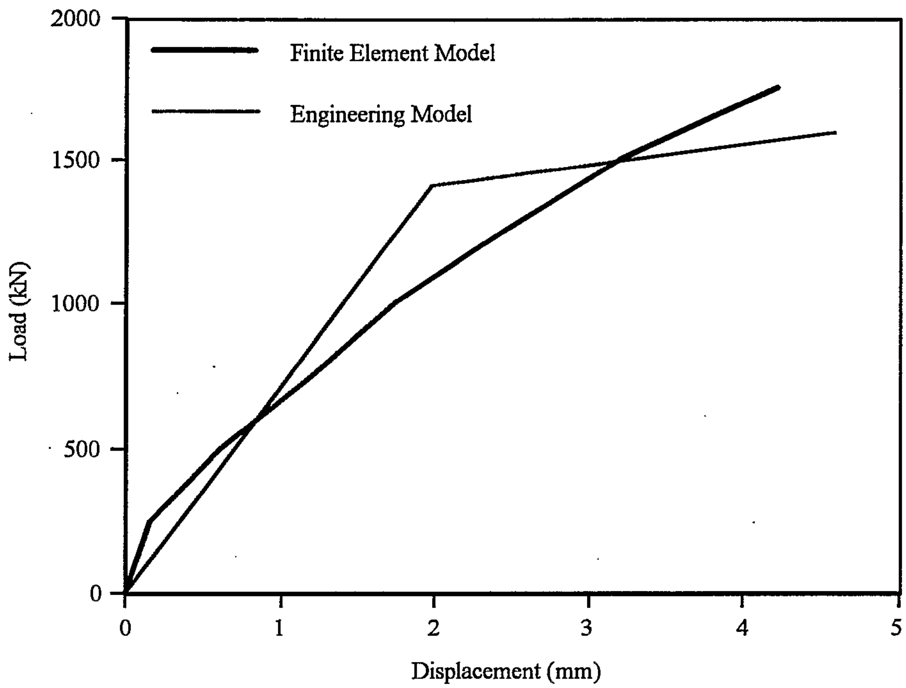

Fig. 6 Engineering and Finite Element Model Prediction of Backbone Curve

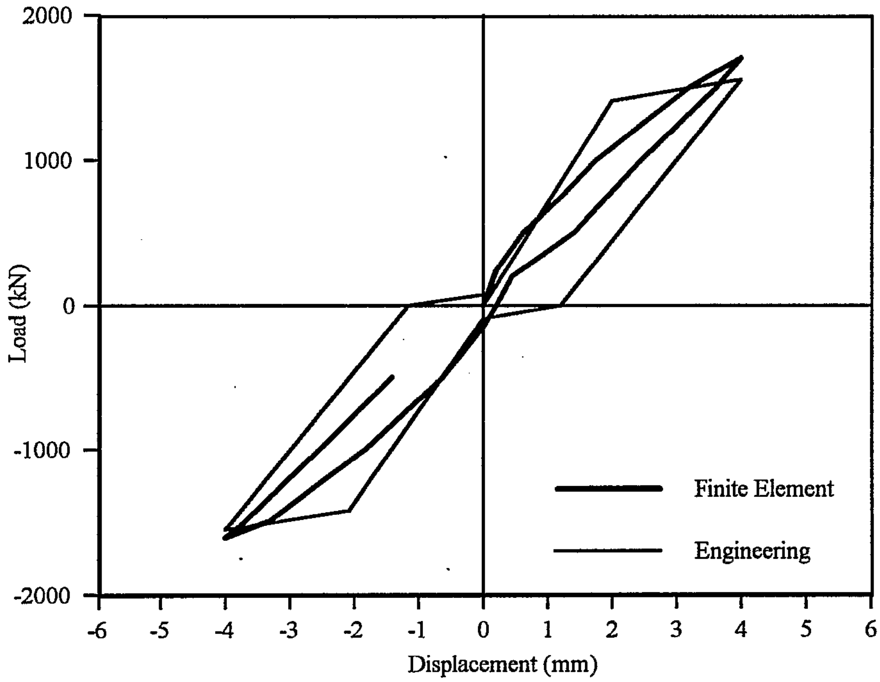

Fig. 7 Engineering and Finite Element Model Predictions for 4 mm Cycle