SHAKING-TABLE STUDY OF A FOUR-STOREYED MASONRY BUILDING MODEL

M. Tomaževič (I)
R. Žarnić (II)
Presenting Author: M. Tomaževič

SUMMARY

The behaviour of a four-storeyed masonry building model subjected to simulated earthquake loading has been studied. Apart from shaking-table tests, mechanical properties of selected model masonry have been determined on three types of wall specimens. The response of model to ground motion has also been calculated. Four DOF lumped mass system with storey characteristics, evaluated on the basis of experimentally obtained mechanical properties of model masonry, has been used for calculation. Sufficiently good correlation between the measured and calculated response has been obtained, although simple bilinear elasto-plastic and trilinear stiffness-degrading, origin oriented hysteretic rules were used for modeling the nonlinear behaviour of model as first approximation.

INTRODUCTION

In this paper, the experimental study of a four-storeyed masonry building model subjected to simulated earthquake loading, recently carried out at the Institute for Testing and Research in Materials and Structures (ZRMK), will be discussed. By means of this study, an attempt has been made to verify the already proposed numerical method for calculation of earthquake resistance of masonry buildings (Ref.1) as well as to define a suitable mathematical model for prediction of earthquake effects on masonry buildings.

DESCRIPTION OF TESTS

Model Materials

According to the limited capacity of the earthquake simulator at disposition at ZRMK, the 1:7 modeling scale was selected as the most suitable. Special model bricks, as shown in Fig.1, made of fuel ash, perlite, clay and corundum dust, burned at 815°C (compressive strength 1.4 MPa, specific mass 1100 kg/m^3) and model mortar, composed of quartz sand and clay (compressive strength 1.6 MPa), were used for model construction. Aluminum wire of 1.0 mm diameter was used as horizontal reinforcement, placed in each second horizontal joint for improving the ductility of model masonry.

(I) Senior Research Enginer, (II) Research Engineer, Institute for Testing and Research in Materials and Structures, Ljubljana, Yugoslavia .

Wall Specimens and Test Set-Up

In order to determine the mechanical properties of model masonry, the following types of wall specimens have been tested:
- type V (five specimens 142 x 318 x 42 mm - see Fig.2) for determination of compressive strength f_c and elastic modulus E - compression tests;
- type S (four specimens 142 x 173 x 42 mm - see Fig.3) for determination of tensile strength f_t and shear modulus G - shear resistance tests at constant vertical and cyclic horizontal loading;
- type F (three specimens 142 x 318 x 42 mm - see Fig.2) - flexural resistance tests at constant vertical and cyclic horizontal loading.

For type S and F tests a special test set-up has been designed which keeps constant vertical load and parrallel support planes during testing. Horizontal displacements have been programmed and corresponding horizontal forces measured by means of load cells. Uplifting of the upper support has been measured for correction of horizontal displacements of walls.

Four-Storeyed Masonry Building Model

The model was composed of two wall panels in the direction of motion, pierced by window and door openings and stiffened by transverse walls at the corners. The dimensions of model in plan were 712 x 427 mm, the height of the model was 1392 mm. Four 30 mm thick reinforced concrete slabs were prefabricated. They were placed on the walls during construction process at each 348 mm storey height level. Four lead bricks (total mass 40 kg) were fixed to each floor slab as additional mass.

In order to prevent overturning of model during testing, the model was vertically prestressed into foundation slab by means of steel knitted ropes of 1.5 mm diameter, symmetrically placed on both sides of walls. Alltogether 20 ropes were prestressed in pairs. Soft springs on the top floor slab were used for controlling the prestressing forces, equal to 1 kN per pair of prestressing ropes.

The dimensions of model and the position of prestressing ropes are shown in Fig.4.

Earthquake Simulator, Measurements and Testing Procedure

The earthquake simulator was composed of a two-way acting programmable actuator Schenck Type 250 DL, connected with the steel rail-guided platform, onto which the foundation slab of the model was fixed.

Earthquake motion was programmed in the shape of El-Centro 1940 N-S component ground displacements, with the increased intensity of motion in each successive test run. However, because of the limited capacity of the actuator, the ground accelerations, recorded during testing, are not in correlation with the El-Centro ground accelerations. Moreover, the shapes of their time-hystories are considerably different in each successive test run.

Displacements of model, relative to the foundation slab, and accelerations of model at each story level have been measured. Simultaneously, displacements and accelerations of the shaking platform have been recorded,too.

Before shaking tests, as well as after each successive test run, first natural frequency and damping were evaluated by hiting the model with a wooden hammer at the top floor level. First natural mode shape in the elastic range has been determined by shaking the model at resonant frequency with a very small amplitude of motion.

The model was subjected to the increased intensity of earthquake motion in 11 testing phases. However, the collapse occurred when the model was subjected to sinusoidal ground motion, tracing the decaying natural frequency.

The general view of shaking test is presented in Fig.5.

ANALYSIS OF TEST RESULTS

Mechanical Properties of Model Masonry

The results of vertical compression tests(walls type V) are given in Table 1. Elastic moduli were evaluated at 20% and 30% of the compressive strength.

Table 1 Vertical Compression Tests

Wall	Cross-sectional area A (mm^2)	Ultimate load V_u (N)	Compressive strength f_c (MPa)	Elastic modulus - E	
				at 20% f_c (MPa)	at 30% f_c (MPa)
V_1	5964	7880	1.32	315	280
V_2	5964	8720	1.46	530	462
V_3	5964	8790	1.47	702	580
V_4	5964	7460	1.25	905	456
V_5	5964	7990	1.34	638	420

The results of shear resistance tests (walls type S) are given in Table 2. Shear moduli were evaluated at 30% of ultimate horizontal load and at displacement level, obtained during first natural mode shape determination test. Typical hysteresis loops obtained during shear resistance tests as well as the corrected hysteresis envelopes are shown in Figs. 6 and 7. Typical failure mode is shown in Fig.7b.

Table 2 Shear Resistance Tests

Wall	Cross-sectional area A (mm^2)	Vertical load V (N)	Ultimate hor.load H_u (N)	Tensile strength f_t (MPa)	Shear modulus - G	
					at 30% f_t (MPa)	at 0.12% R (MPa)
S_2	5964	1120	752	0.117	74	-
S_3	5964	1120	743	0.115	141	78
S_4	5964	1120	801	0.128	143	90
S_5	5964	1120	720	0.110	107	87

Table 3 Flexural Resistance Tests

Wall	Cross-sectional area A (mm^2)	Vertical load V (N)	Ultimate hor.load H_u (N)
F_2	5964	1420	450
F_3	5964	1420	523
F_4	5964	1420	516

The results of flexural resistance tests (walls type F) are given in Table 3. Typical hysteresis loops as well as the corrected hysteresis envelopes are shown in Figs.8 and 9. Typical failure mode is shown in Fig.9b.

Figs.6c and 8c show changes of the equivalent viscous damping ratio with the increased displacements for walls type S in F, respectively.

Dynamic Characteristics of Masonry Building Model

Taking into account the experimentally obtained mechanical properties of model masonry, storey horizontal force-deformation relationships have been calculated (Ref.1). The idealized hysteresis envelope for the first storey of model is presented in Fig.10. Taking into account the calculated elastic stiffnesses, the natural frequencies and mode shapes have been determined, assuming the model to be four DOF lumped mass system. First mode values are compared to the measured ones in Table 4.

The changes of dynamic characteristics of model, such as fundamental frequency and equivalent viscous damping of the tested structure, are given in Table 5. In Table 5, the values of peak ground accelerations and maximum first storey drifts, recorded during the subsequent testing phases, are also presented.

During Test No.6, vertical cracks occurred at vertical joints of corner walls and at corners of window openings. During Test No.8, shear cracks became visible in window pier, and subsequently, a combination of shear and flexural cracks occurred in neighboring walls. The model collapsed after the middle window pier disintegrated at very large amplitudes of vibrations at resonant frequency.

In order to calculate the response of model to ground motion, the model was idealized as a four DOF lumped mass system. Linear acceleration method was used for integration of differential equations of motions at time intervals of 0.002s. Two simple story hysteresis models were compared in the calculation: clasical bilinear elasto-plastic and trilinear stiffness-degrading, origin-oriented model. Hysteresis envelopes, as presented in Fig.10, have been taken into account. Typical response is presented in Fig. 11 for Test No.8.

CONCLUSIONS

The following general conclusions can be drawn when analyzing the test results:

- accurate values of storey force-deformation relationship (stiffness, resistance, ductility) have been obtained by calculation, what confirms the assumptions of the already proposed numerical method for calculation of earthquake resistance of masonry buildings.
- sufficiently good correlation between the measured and calculated response has been obtained, although simple bilinear elasto-plastic and trilinear stiffness-degrading, origin-oriented hysteretic rules were used for modeling the nonlinear behaviour of model.

However, the formulation of more accurate hysteretic rules is under way, and the results of this study will be reported in the near future.

ACKNOWLEDGEMENT

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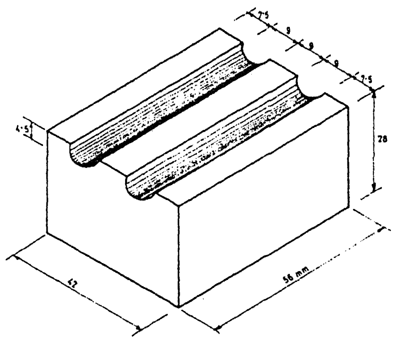


Fig.1 Model Brick

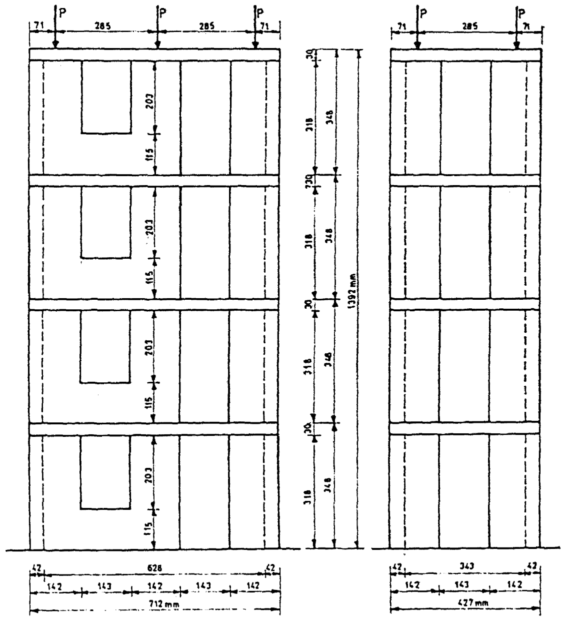


Fig.4 Dimensions of Four-Storeyed Masonry Building Model

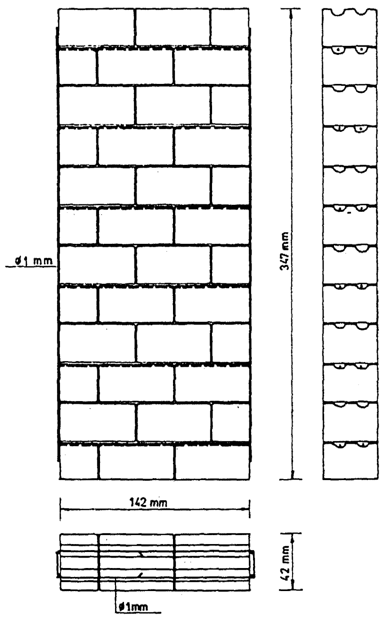


Fig.2 Wall Specimens Type V and F

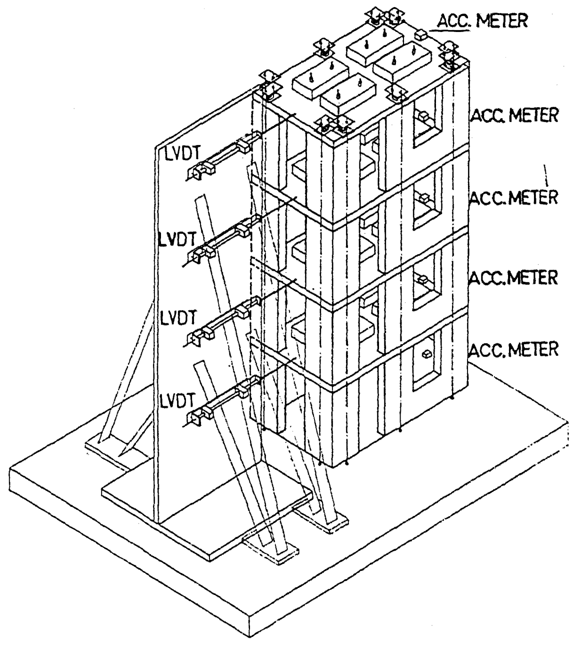


Fig.5 Set-up of Shaking Table Test

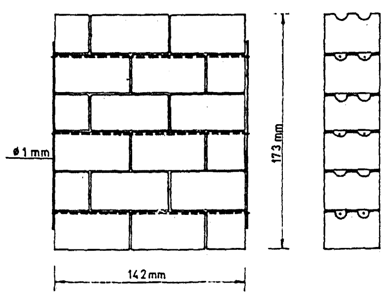


Fig.3 Wall Specimens Type S

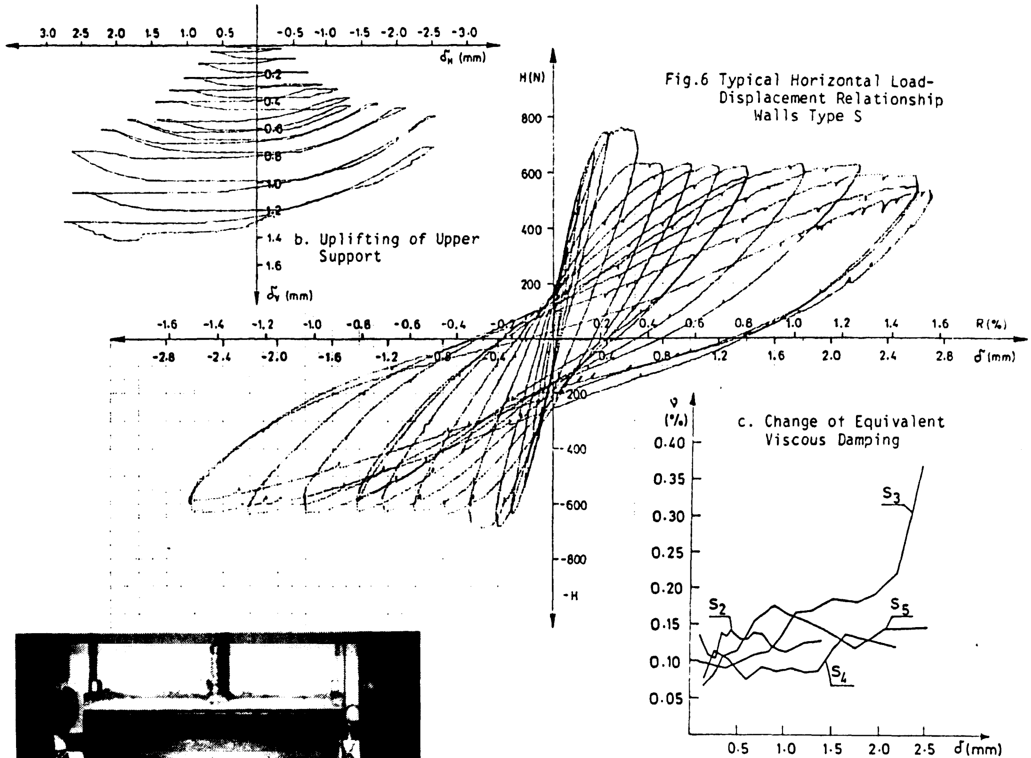
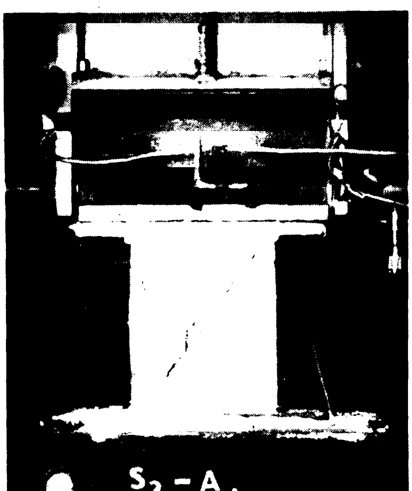


Fig.6 Typical Horizontal Load-Displacement Relationship Walls Type S



b. Typical Failure Mode - Walls Type S

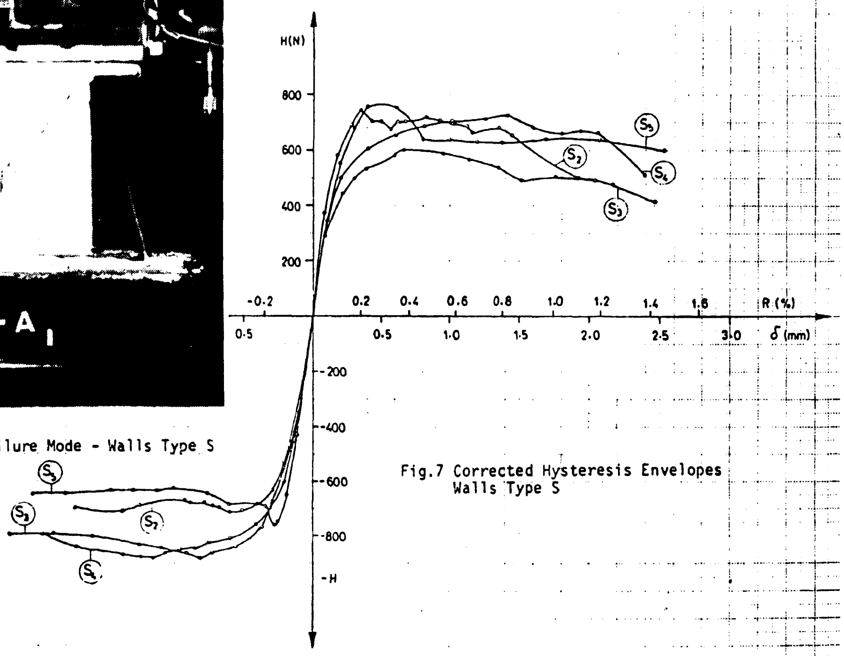


Fig.7 Corrected Hysteresis Envelopes Walls Type S

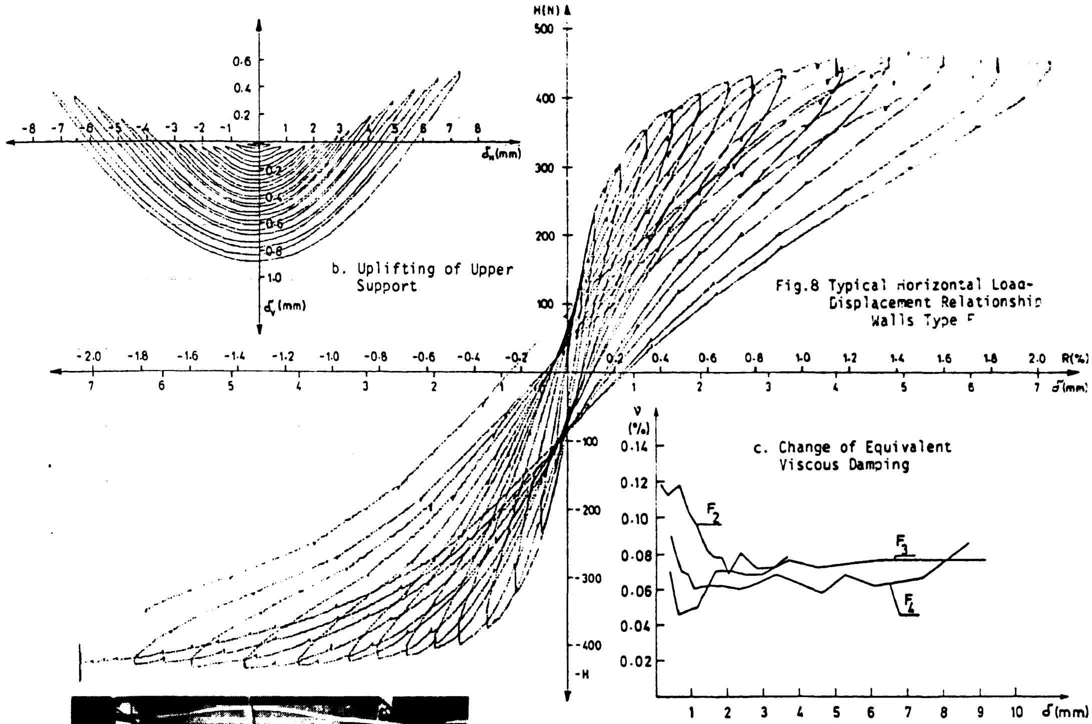


Fig.8 Typical Horizontal Load-Displacement Relationship Walls Type F

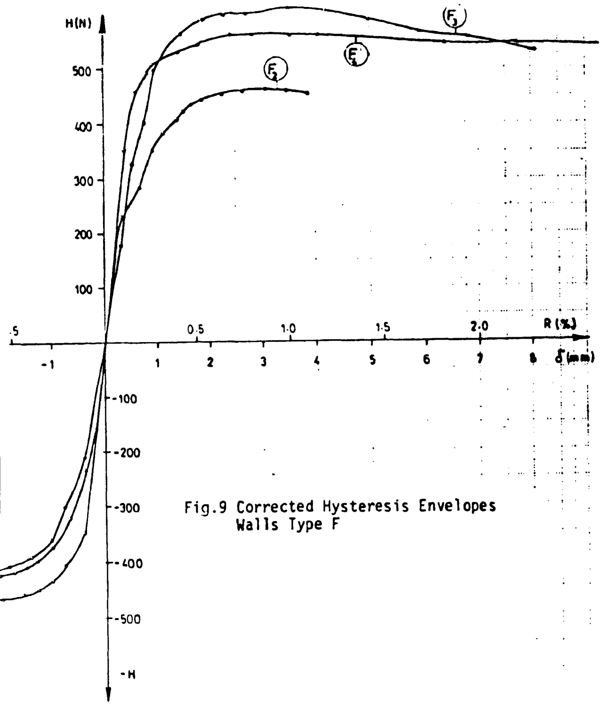


Fig.9 Corrected Hysteresis Envelopes Walls Type F

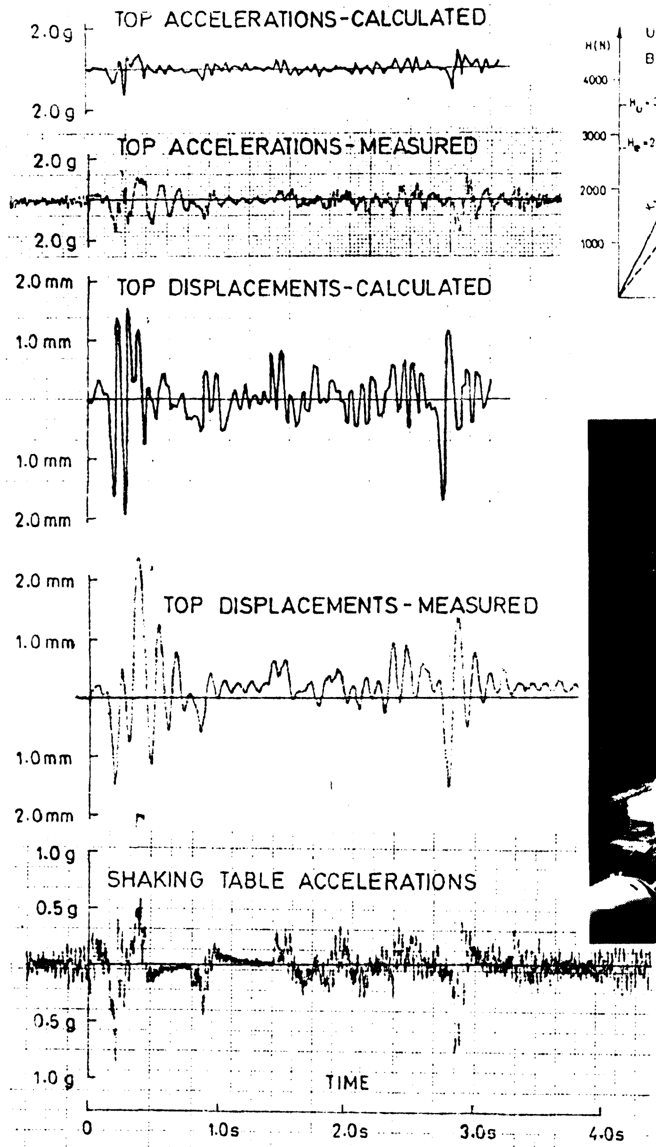
Table 4 First Mode Characteristics

		Measured	Calculated	Ratio
Frequency		12.82	14.01	0.92
Mode shape	4	1.000	1.000	1.00
	3	0.837	0.889	0.94
	2	0.596	0.664	0.90
	1	0.319	0.355	0.90

Table 5 Characteristics of Shaking Tests

Test No.	Duration (s)	Peak GA (g)	1-st Storey Drift (mm)	Frequency After Testing (s^{-1})	Eq. Viscous Damping (%)
1	6.18	0.122	0.063	12.73	0.038
2	6.18	0.167	0.094	-	-
3	6.18	0.339	0.238	11.13	0.042
5	6.18	0.250	0.156	-	-
6	6.18	0.679	0.894	-	-
7	3.24	0.493	0.313	-	-
8	3.24	0.864	1.063	10.22	0.059
9	3.24	1.071	4.740	8.96	0.079

Fig.11 Response of Model During Test No.8



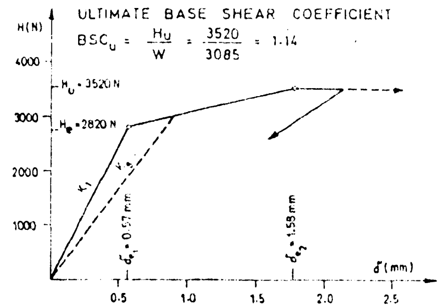


Fig.10 Idealized Calculated Storey Hysteresis Envelope

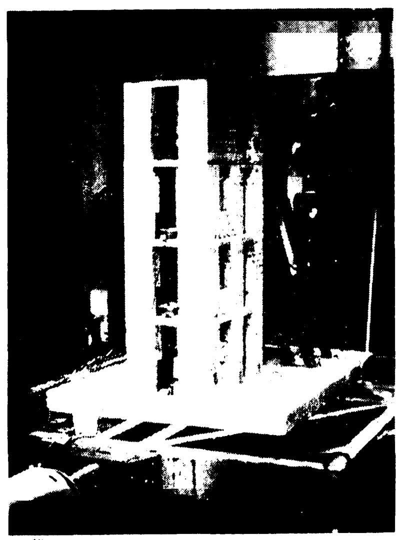


Fig.12 Model During Shaking Tests