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HYSTERESIS LOOPS OBSERVED IN EARTHQUAKE RESPONSE TESTS ON STEEL FRAME MODELS

by

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1. INTRODUCTION

It is widely held as a design philosophy that buildings may undergo some inelastic deformations but they must avoid fatal damages during severe earthquakes. In design procedures, recent computer algorithms have potential to predict the inelastic behavior precisely. Experimental studies are still indispensable, not only because precise computer analyses require more accurate informations on actual behaviors of structural elements, but also because it must be verified whether the global response of the whole system can be predicted by assembling the mathematical models of each elements. From this point of view, the authors have conducted several earthquake response tests on scaled steel frame models to collect actual records of inelastic responses [2,3,4,5,6]. This paper summarizes nineteen cases of these test results to show typical hysteresis loops of braced and unbraced steel frames, and also this paper discusses 1) the properties of dynamic loading paths on 3-story frames, and 2) the correlation of inelastic test results and elastic response spectra.

2. SUMMARY OF EARTHQUAKE RESPONSE TESTS

The earthquake response tests reported herein consist of five cases of shaking table tests and fourteen cases of computer-actuator on-line pseudo-dynamic tests. In the latter test method, the restoring forces referred in the numerical integration of equation of motion are consecutively measured in a loading test, which is carried out in parallel with the computation [1,4].

Various types of scaled steel frame model were tested under unidirectional horizontal ground motions. The test setups are illustrated in Figs. 1(a) to 1(d). The profiles of the models are summarized on Table 1 with the following items: (a) Test code, (b) Number of stories, (c) Mass of each floor, (d) Braced or unbraced, (e) Weak-column or weak-girder, (f) Dimensions of sections used, and (g) Properties of material used.

Two kinds of excitations used were scaled both in time and in amplitude from the N-S component recorded at El Centro in 1940 and the E-W component recorded at Hachinohe Harbor in 1968. The parameters of excitations are compared to the model parameters, such as fundamental period and yield strength, on Table 2.

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3. HYSTERESIS LOOPS

Restoring forces fi or acceleration records were measured at each floor levels, and these data were transformed into story shear forces, Qi. Hysteresis loops of the 1st story shear Q_1 vs. 1st story drift δ_1 relationships are shown in Figs. 2(1) to 2(19). While all the 3-story models but No.17 are weak-column type and regarded as shear-type interaction system, No.17 model is weak-girder type, and its story hysteresis loop has an irregular shape as shown in Fig. 2(17). As for the test No.17, the modal displacement vector {d} and the modal restoring force vector {q} are calculated from the test data by the following formulas:

$$\{x\} = [U]\{d\}, \qquad [U]^T\{f\} = \{q\} \qquad (1)$$

where {x}: Relative displacement vector measured at each floor levels.
{f}: Restoring force vector measured at each floor levels.
[U]: Classical normal mode matrix of elastic vibration. The mode shapes were derived from resonance tests.
$[U]^T$: Transposed matrix of [U].

The hysteresis loop of the first mode, q_1-d_1 relationship, looked like an ordinary type of elastic-plastic hysteretic model, as demonstrated in Fig. 2(17)'. The reason why the yielding force in the first mode hysteresis is kept constant is that the failure mode of the weak-girder model was very close to the first vibrational mode, in other words, that the first mode shape was almost orthogonal to the yield surface of the frame.

4. DYNAMIC LOADING PATHS ON 3-STORY FRAME MODELS

A set of the three story shear forces, (Q_1, Q_2, Q_3), make a load point in the 3-dimensional load space. The trajectory of the point represents the dynamic loading path on the model during the response test. Three projections of the trajectory to the Qi-Qj plane are shown in Figs. 3(1) to 3(4). As for the test No.17, modal restoring forces are used instead of story shear forces. In the figures the sections of the yield surfaces of the frame models are also illustrated, and they are found to bound the existing range of the load point. The dashed lines show the projection of the direction in the first mode of the elastic vibration. It is noteworthy that even in the inelastic vibration the behaviors of the loading paths are strongly controlled by the first mode vibration.

5. CORRELATION OF INELASTIC TEST RESULTS AND ELASTIC RESPONSE SPECTRA

In the past, various types of methods were proposed to predict the inelastic earthquake responses from the elastic response spectra. In this paper, the following three methods[7,8,9] are verified by the test results:

$$(Q_Y/Q_e) = 1 / \sqrt{2\eta + 1} \qquad (2)$$

$$(Q_Y/Q_e) = 1 / \sqrt{2 \mu' + 1} \quad (3)$$

$$(Q_Y/Q_e) = 1 / (\mu' + 1) \quad (4)$$

Eq.(2) represents the assumption of "identical strain energy" after Housner[7], where η denotes the hysteretic energy consumption normalized by the product of the yield strength Q_Y and the yield deformation δ_Y, and Qe denotes the response shear force of elastic system. The values of η were estimated from the test hysteresis loops and plotted to the values of Q_Y/Q_e in Fig. 4(1). The relationship of eq.(2) was also plotted in the figure and proved to match with the test results.

Eqs.(3) and (4) represent the assumption of "identical apparent strain energy" after Newmark and Veletsos[8] and the assumption of "identical displacement" after Penzien[9], respectively, where μ' denotes the normalized excess of peak response displacement from the elastic limit. These two equations and the test results were plotted on the μ' - (Q_Y/Q_e) plane in Fig. 4(2). It is found that eq.(3) overestimates the test values of μ', and that eq.(4) matches with the test results so far as the values of (Q_Y/Q_e) are greater than 0.15.

6. CONCLUDING REMARKS

Nineteen cases of earthquake response tests were carried out to simulate inelastic responses of various types of steel frame models.

(1) All the 3-story frame models but No.17 were regarded as shear-type frame models, and their hysteresis loops were shown in story shear vs. story drift relationships. As for the No.17 weak-girder model, load and displacement vectors were transformed by classical normal modes in elastic vibration, and it was demonstrated that the transformed hysteresis loop of the first mode looked like an ordinary elastic-plastic hysteresis.

(2) Trajectories of story shear forces in 3-story frame models were presented. It was found, 1) the trajectories were bounded by the yield surfaces which indicated global yieldings or failure modes of the frames, and 2) the behaviors of the story shear vectors inside the yield surfaces were considerably controlled by the elastic vibrational modes. These results support that the modal properties in the elastic vibration of the frame should be well reflected on the vertical distribution of the design story shears as done in the current seismic provisions of Japan.

(3) Three kinds of methods to predict inelastic responses from elastic response spectra were applied to the test results. 1) The hysteretic energy consumption in the tests were well predicted by the assumption of "identical strain energy" after Housner. 2) The peak response displacements in the tests were overestimated by the assumption of "identical apparent strain energy" after Newmark and Veletsos. 3) The peak response displacements were approximately predicted by the assumption of "identical response displacement" after Penzien, so far as the yield strength of the frame was kept larger than some levels.

ACKNOWLEDGEMENTS

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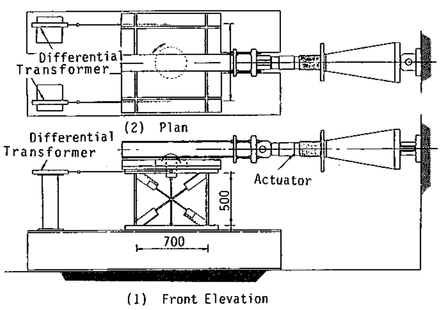
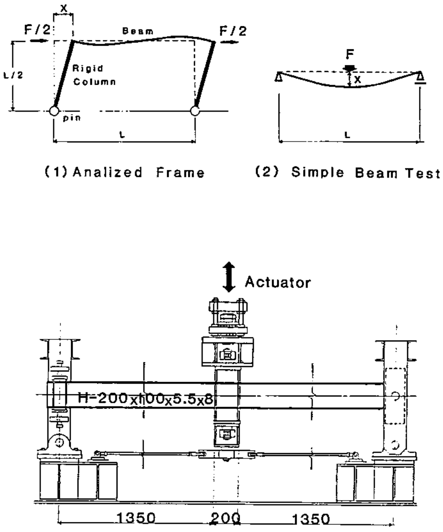
REFERENCES

[1] Takanashi,K., Udagawa,K., Seki,M., Okada,T., and Tanaka,H., "Non-linear Earthquake Response Analysis of Structures by a Computer-Actuator On-line System (Detail of System)," ERS Bulletin, No.8, Institute of Industrial Science, Univ. of Tokyo, 1975.
[2] Ohi,K., Takanashi,K., and Tanaka,H., "Shaking Table Tests on Inelastic Responses of Multi-story Steel Frame Models," Proceeding of the 6th Japan Earthquake Engineering Symposium, Dec. 1982.(in Japanese)
[3] Takanashi,K. and Ohi,K., "Shaking Table Tests on 3-story Braced and Unraced Steel Frames," the 8th World Conference on Earthquake Engineering, July 1984.
[4] Takanashi,K. and Ohi,K., "Earthquake Response Analysis of Steel Structures by Rapid Computer-Actuator On-line System (Trial System and Dynamic Response of Steel Beams)," ERS Bulletin, No.16, March 1983.
[5] Takanashi,K. and Ohi,K., "A Correlation Study in Pseudo-Dynamic On-line Tests vs. Shaking Table Tests," 1984 Annual Technical Session and Meeting of Structural Stability Research Council, April 1984.
[6] Takanashi,K. and Ohi,K., "Response and Failure Observation of Weakly Designed Steel Structure Models (Part I) A Progress Report- An Outline of the Project and the Preliminary Computer-Actuator On-line Analysis," ERS Bulletin, No.18, March 1985.
[7] Housner,G.W., "Limit Design of Structures to Resist Earthquakes," the 1st World Conference on Earthquake Engineering, 1956.
[8] Veletsos,A. and Newmark,N.M., "Effect of Inelastic Behavior on Response of Simple System to Earthquake Motions," the 2nd World Conference on Earthquake Engineering, 1960.
[9] Penzien,J., "Elasto-plastic Response of Idealized Multi-story Structures Subjected to a Strong Motion Earthquake," the 2nd World Conference of Earthquake Engineering, 1960.
[10] Ohi,K. and Takanashi,K., "Accuracies and Errors in Predicting Inelastic Responses of Steel Frames Subjected to Severe Earthquakes (Part 1)," Transactions of the Architectural Institute of Japan, No.373, March 1987.(in Japanese)

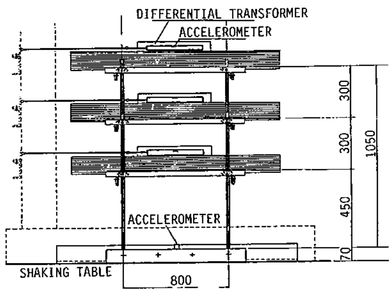


(a) Test Code: 05 to 12, and 01 (no bracing) - On-line Pseudo-dynamic Tests

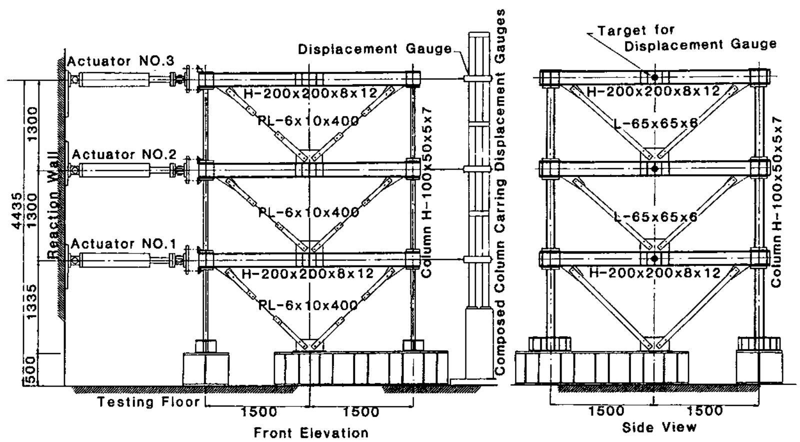


(3) Test Setup

(b) Test Code: 02 to 04 - On-line Pseudo-dynamic Tests



(c) Test Code: 13 to 17 - Shaking Table Tests



(d) Test Code: 18 and 19 - On-line Pseudo-dynamic Tests

Fig. 1 Test Setups for Simulation of Earthquake Responses

Table 1 Profiles of Test Frame Models

(a) Test Code	(b) Stories	(c) Mass Fl.	(c) Mass (ton cm⁻¹sec²)	(d) Braced or Unbraced	(e) Weak-Column or Weak-Girder	(f) Dimensions of sections used: Column (mm)	Girder (mm)	Brace (mm)	λ	(g) Properties of Material used: Column or Girder σ_Y (ton/cm²)	Column or Girder σ_Y/σ_B	Brace σ_Y (ton/cm²)	Brace σ_Y/σ_B
01	1	R	0.00197	U	WC	-26.5x15.9	—	—	—	2.81	0.61	—	—
02		R	0.0507		Wg	—	H-200x100x5.5x8 (strong-axis)	—	—	Flange : 3.12	0.70	—	—
03		R	0.0182							Web : 3.82	0.79		
04		R	0.0182										
05		R	0.167	B	WC	-40.1x24.8	—	□-12.3x5.6	130.	2.53	0.58	2.42	0.73
06		R	0.167										
07		R	0.172			—	—	□ -6.9x5.6	64.8				
08		R	0.172										
09		R	0.204			-20.0x24.8	—	□-18.3x5.6	130.				
10		R	0.204										
11		R	0.205			—	—	□-10.5x5.6	64.8				
12		R	0.205										
13	3	2	0.000602	U	WC	-30.x12.	—	—	—	2.77	0.61	—	—
		3	0.000595										
		R	0.000597										
14	3	2	0.000601	U	WC	-30.x12.(1st) -15.x12.(2nd) -11.x12.(3rd)	—	—	—				
		3	0.000594										
		R	0.000596										
15	3	2	0.000602	U	WC	-30.x12.	—	—	—				
		3	0.000595										
		R	0.000597										
16	3	2	0.000601	U	WC	-30.x12.(1st) -15.x12.(2nd) -11.x12.(3rd)	—	—	—				
		3	0.000594										
		R	0.000596										
17	3	2	0.000592	U	Wg	-13.5x19.	□-9.x19.	—	—	1.83	0.60	—	—
		3	0.000592										
		R	0.000592										
18	3	2	0.0153	B	WC	H-100x50x5x7 (weak-axis)	—	□-10.x6.	139.	Flange : 3.30	0.74	2.90	0.81
		3	0.0153										
		R	0.0153										
19	3	2	0.0153	B	WC					Web : 3.60	0.78		
		3	0.0153										
		R	0.0153										

U : unbraced, B : braced, WC : weak-column, W_g : weak-girder, □-bxd : rectangular section

σ_Y : yield stress, σ_B : tensile strength, derived from quasi-static tension tests

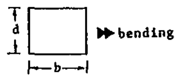


Table 2 Parameters of Earthquake Response Tests

(1) Test Code	(2) Shaking Table Test or On-line Test	(3) Input Excitation: Wave Shape	(4) Input Excitation: γ	(5) Input Excitation: Duration (sec)	(6) Input Excitation: $\lvert\ddot{y}\rvert_{max}$ (gal)	(7) Additional Observation of Free Vibration (sec)	(8) T_1/γ (sec)	(9) α_Y (gal)	(10) $\lvert\ddot{y}\rvert_{max}/\alpha_Y$	(11) Test Speed (*real speed)	(12) p-Δ effect
01	O	H	0.5	5.12	865.	+5.12	0.65	450.	1.9	0.02	-0.035t/cm
02	O	E	1.0	8.0	320.	+2.0	0.51	200.	1.6	0.04	ignored
03	O	E	1.0	8.0	640.	+2.0	0.31	560.	1.1	0.04	
04	O	E	1.0	8.0	960.	+2.0	0.31	560.	1.7	0.20	
05	O	E	1.0	8.0	40.	+2.24	0.37	22.	1.8	0.01	
06	O	E	1.0	8.0	100.	+2.24	0.37	20.	5.0		
07	O	E	1.0	8.0	32.	+2.24	0.36	14.	2.3		
08	O	E	1.0	8.0	80.	+2.24	0.36	14.	5.7		
09	O	E	1.0	8.0	40.	+2.24	0.41	24.	1.7		
10	O	E	1.0	8.0	100.	+2.24	0.41	23.	4.3		
11	O	E	1.0	8.0	36.8	+2.24	0.39	14.	2.6		
12	O	E	1.0	8.0	91.8	+2.24	0.39	14.	6.6		
13	S	E	0.5	5.12	576.	+5.12	0.77	370.	1.6	1	due to actual weights
14	S	E	0.5	5.12	530.	+5.12	0.84	370.	1.4		
15	S	H	0.5	5.12	453.	+5.12	0.77	370.	1.2		
16	S	H	0.5	5.12	572.	+5.12	0.84	370.	1.5		
17	S	H	0.5	5.12	751.	+5.12	1.05	360.	2.1		
18	O	E	1.0	10.0	160.	+10.0	0.48	57.	2.8	0.01	-0.45t/cm(1st st.) -0.30t/cm(2nd st.) -0.15t/cm(3rd st.)
19	O	E	1.0	10.0	130.	+10.0	0.48	57.	2.3		

O : computer-actuator on-line test, S : shaking table test, H : Hachinohe EW (Tokachioki earthquake in 1968)
E : El Centro NS (Imperial Valley earthquake in 1940), γ : scaling factor in time, T_1 : natural period (1st mode),
$\lvert\ddot{y}\rvert_{max}$: peak acceleration of simulated earthquakes, α_Y : yield acceleration of 1st story or 1st mode

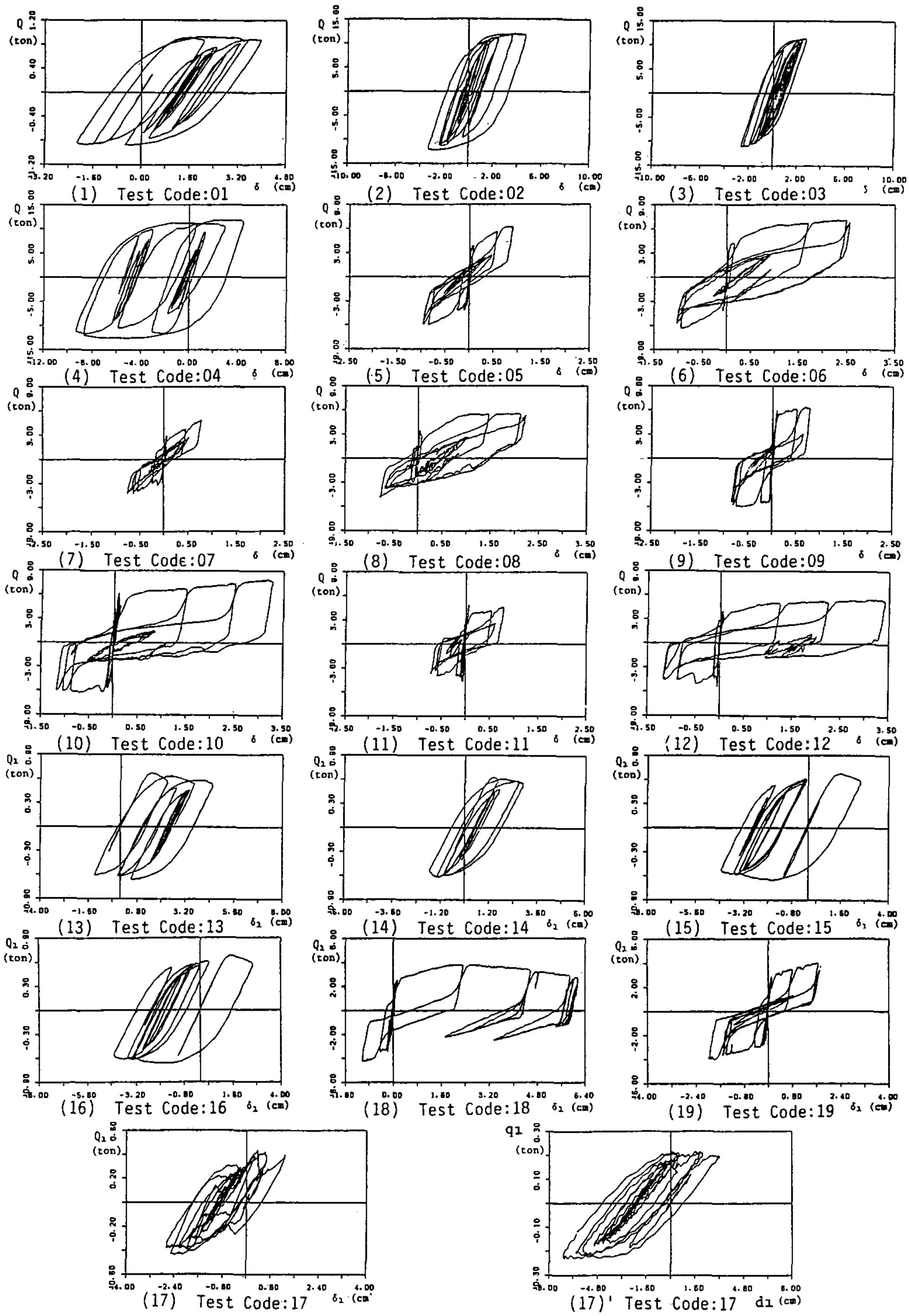
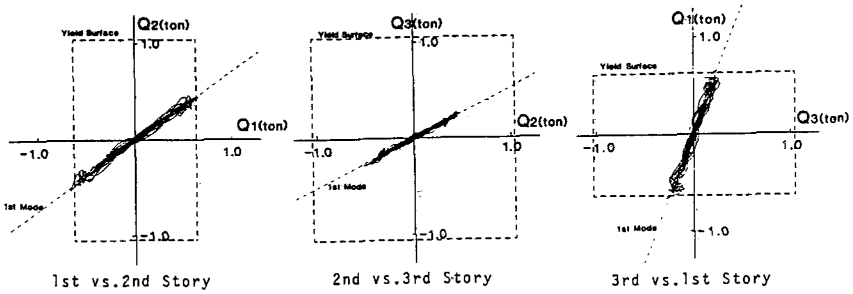
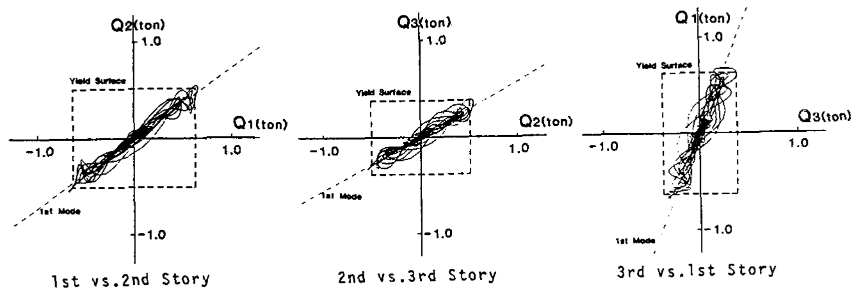


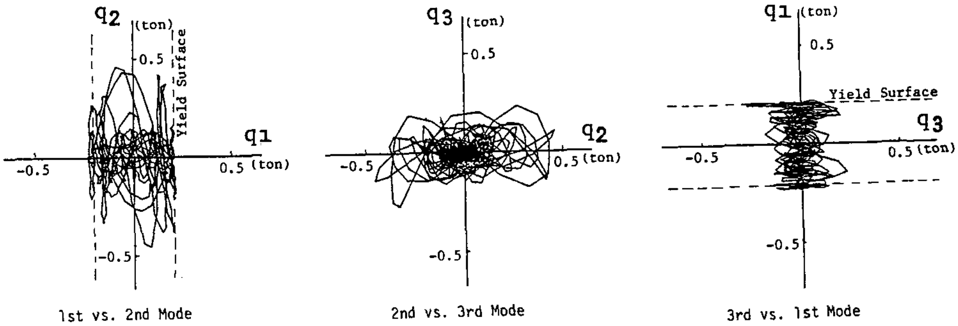
Fig. 2 Hysteresis Loops Observed



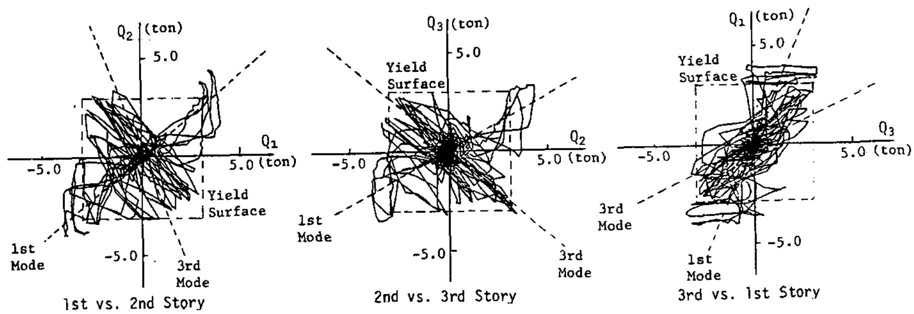
(1) Story Shear Forces (Test Code: 13)



(2) Story Shear Forces (Test Code: 14)

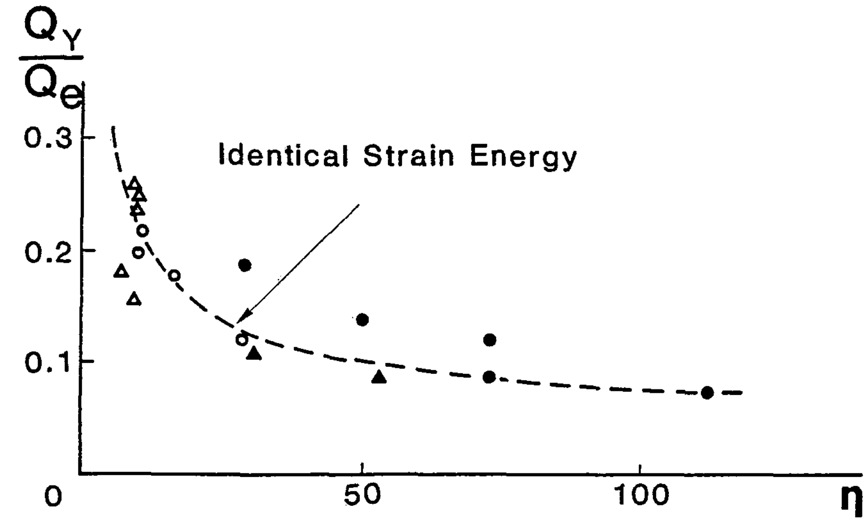


(3) Modal Restoring Forces (Test Code: 17, Weak-girder Type)

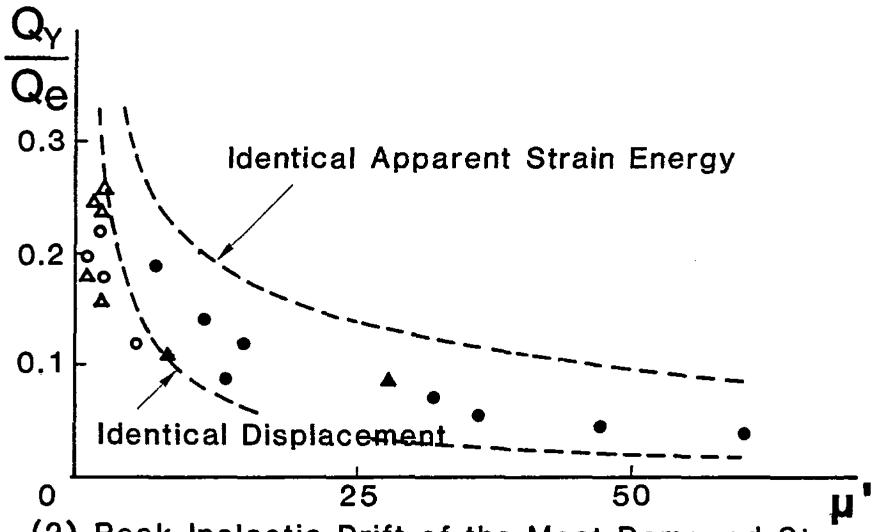


(4) Story Shear Forces (Test Code: 18)

Fig. 3 Trajectories of Dynamic Loading Paths for 3-story Models



(1) Energy Dissipation of the Most Damaged Story



(2) Peak Inelastic Drift of the Most Damaged Story

○ 1-story unbraced △ 3-story unbraced

● 1-story braced ▲ 3-story braced

Fig. 4 Correlation of Inelastic Test Results and Elastic Response Spectra