AN ENERGY METHOD FOR THE ANALYSIS OF STRUCTURES SUBJECTED TO EARTHQUAKES

by

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M.Sc. (Wales)

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

Department of Civil Engineering

We accept this thesis as conforming to the required standard:

The University of British Columbia

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Date 23rd APRIL 1980.

DE-6 BP 75-511E

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ABSTRACT

Work toward developing a simple method for the aseismic design of structures considering energy dissipation as the prime design parameter is reported. Viscous damping is used to represent the non-structural energy dissipating elements in the system, and hysteretic energy dissipation is considered explicitly.

A detailed parametric study of the energy dissipation characteristics of single degree of freedom systems is reported first. Here the amount of energy dissipated by both hysteretic and viscous damping mechanisms in each system is determined for various ground motions, viscous damping values, system strengths etc. The results of this study are presented in the form of spectra, relating total energy dissipated, and energy distribution between mechanisms to known system properties.

The results and insights gained from the parametric study are incorporated into a design method which accounts explicitly for energy dissipation. The inclusion of a system strength parameter in the input of the proposed method is found to be most useful in terms of the limit state philosophy employed in the most recent editions of building codes. Also if special damping devices are to be built into the structure, this method will facilitate such design.

Finally a preliminary study of the energy dissipation characteristics of multi-degree of freedom systems is reported. Here the distribution of energy

dissipated by viscous damping and hysteresis, together with the location of the effective dissipating mechanisms within the structure, is studied. In particular the possibility of extrapolation from single degree of freedom spectra to the multi-degree of freedom systems is investigated and shown to give encouraging results.

TABLE OF CONTENTS

		PAGE
Abstract		ii
List of Tables		vii
List of Figures		x
Dedication		xvi
Acknowledgement		xvii
CHAPTER		
1	REVIEW OF CURRENT ANALYTIC METHODS IN EARTHQUAKE ENGINEERING.	1
	1.1 Development of the Principal Methods.	1
	1.2 The Ductility Method.	2
	1.3 Energy Methods.	4
	1.4 Limit State Philosophy.	5
	1.5 Multi-Degree of Freedom Energy Studies	6
2	THEORY AND PROGRAMMING CONSIDERATIONS FOR SINGLE DEGREE OF FREEDOM SYSTEMS	7
	2.1 Single Degree of Freedom Model	7
	2.2 Incremental Equations of Motion	10
	2.3 Accuracy of the Time Stepping Scheme	11
	2.4 Energy Calculations	12
	2.5 Non-Dimensionalising the Earthquake	14
	2.6 An Estimate for the Permanent Set	15

CHAPTER			PAGE
3	RESULTS OF SINGLE DEGREE OF FREEDOM STUDY		18
	3.1	Scope of Single Degree of Freedom Study.	18
	3.2	Total Energy Dissipated in System.	23
	3.3	Distribution of Energy Within System.	46
	3.4	Spectral Displacements.	64
	3.5	Displacement Ductilities.	75
	3.6	Permanent Sets.	87
	3.7	Classification of Structures by Yield Strength Ratio.	98
	3.8	Approximations for Total Energy Dissipated.	103
	3.9	Approximations for Distribution of Energy Within System.	117
4	DEVELOPMENT AND VERIFICATION OF DESIGN METHOD FOR SINGLE DEGREE OF FREEDOM SYSTEMS		120
	4.1	Introduction.	120
	4.2	Requirements for an Earthquake Design Method.	121
	4.3	Yield Strength Ratio and Damage Control.	122
	4.4	Some notes on Energy Dissipation Versus Time.	123
	4.5	Outline of the Design Method and Examples.	130
5	THEORY AND PROGRAMMING CONSIDERATIONS FOR MULTI-DEGREE OF FREEDOM SYSTEMS		137
	5.1	Mathematical Model for Multi-Degree of Freedom Systems.	137
	5.2	Equations of Motion for Multi-Degree of Freedom Systems.	139
	5.3	Energy Calculations.	141
6	TOTAL ENERGY DISSIPATED IN MULTI-DEGREE OF FREEDOM SYSTEMS		142
	6.1	Introduction	142

CHAPTER			PAGE
	6.2	Structures Used in this Study.	143
	6.3	Total Energy Dissipated in Elasto-Plastic Multi-Degree of Freedom Systems.	146
	6.4	Total Energy Dissipated in Stiffness Degrading Multi-Degree of Freedom Systems.	148
7		DISTRIBUTION OF ENERGY WITHIN M.D.F. SYSTEMS	151
	7.1	Introduction.	151
	7.2	Distribution of Energy between Hysteretic and Viscous Damping Mechanisms.	151
	7.3	Distribution of Energy in Elasto-Plastic M.D.F. Systems.	155
	7.4	Distribution of Energy in Stiffness Degrading M.D.F. Systems	166
8		CONCLUSION	174
	8.1	Energy Dissipated in Single Degree of Freedom Systems.	174
	8.2	The Proposed Design Method.	175
	8.3	Total Energy Dissipated by Multi-Degree of Freedom Systems.	176
	8.4	The Distribution of Dissipated Energy Within Multi-Degree of Freedom Systems.	177
	8.5	Future Work.	178
BIBLIOGRAPHY			179
APPENDIX A		RESULTS OF SINGLE DEGREE OF FREEDOM STUDY IN ORIGINAL FORM	181
APPENDIX B		LISTING OF SUBROUTINES ENERGY AND SPDIS	218
APPENDIX C		RESULTS OF MULTI-DEGREE OF FREEDOM STUDY IN ORIGINAL FORM	221

LIST OF TABLES

TABLE	TITLE	PAGE
3.1	Input Combinations used in Single Degree of Freedom Study	22
4.1	Energy Dissipation Versus Time For Single Degree of Freedom Systems	125
4.2	Displacements and Permanent Sets for Systems Analyzed by the Method Given in Chapter 4	136
6.1	Total Energy Dissipated by Elasto-Plastic M.D.F. Systems	147
6.2	Total Energy Dissipated by Degrading Stiffness M.D.F. Systems	149
7.1	Energy Dissipated in Hysteresis for Elasto-Plastic M.D.F. Systems	153
7.2	Energy Dissipated in Hysteresis for Stiffness Degrading M.D.F. Systems	154
7.3	Effect of Various Forms of Viscous Damping on Energy Distribution Within Elasto-Plastic M.D.F. Systems	156
7.4	Distribution of Energy in Structure 1 Elasto-Plastic Model 1% Viscous Damping	158
7.5	Distribution of Energy in Structure 1 Elasto-Plastic Model 10% Viscous Damping	159
7.6	Distribution of Energy in Structure 2 Elasto-Plastic Model !% Viscous Damping	161
7.7	Energy Distribution in Structures 1,2,3,4 & 5 Elasto-Plastic Model, 1% Viscous Damping Subjected to El Centro N.S.	163

TABLE	TITLE	PAGE
7.8	Distribution of Energy in Structure 6 Elasto-Plastic Model, 3% Viscous Damping	165
7.9	Distribution of Energy in Structure 1 Stiffness Degrading Model 1% Viscous Damping	167
7.10	Distribution of Energy in Structure 2 Stiffness Degrading Model 1% Viscous Damping	169
7.11	Energy Distribution in Structures 1,2,3,4 & 5 Stiffness Degrading Model 1% Viscous Damping Subjected to El Centro N.S.	171
7.12	Distribution of Energy in Structure 6 Stiffness Degrading Model 3% Viscous Damping	173
C 1	M.D.F. Results Set 1	221
C 2	M.D.F. Results Set 2	222
C 3	M.D.F. Results Set 3	222
C 4	M.D.F. Results Set 4	223
C 5	M.D.F. Results Set 5	223
C 6	M.D.F. Results Set 6	224
C 7	M.D.F. Results Set 7	224
C 8	M.D.F. Results Set 8	225
C 9	M.D.F. Results Set 9	225
C 10	M.D.F. Results Set 10	226
C 11	M.D.F. Results Set 11	226
C 12	M.D.F. Results Set 12	227
C 13	M.D.F. Results Set 13	227
C 14	M.D.F. Results Set 14	228
C 15	M.D.F. Results Set 15	228
C 16	M.D.F. Results Set 16	229
C 17	M.D.F. Results Set 17	229

TABLE	TITLE	PAGE
C 18	M.D.F. Results Set 18	230
C 19	M.D.F. Results Set 19	230
C 20	M.D.F. Results Set 20	231
C 21	M.D.F. Results Set 21	232
C 22	M.D.F. Results Set 22	233
C 23	M.D.F. Results Set 23	233
C 24	M.D.F. Results Set 24	234
C 25	M.D.F. Results Set 25	234
C 26	M.D.F. Results Set 26	235
C 27	M.D.F. Results Set 27	235
C 28	M.D.F. Results Set 28	236
C 29	M.D.F. Results Set 29	236
C 30	M.D.F. Results Set 30	237
C 31	M.D.F. Results Set 31	238
C 32	M.D.F. Results Set 32	239

LIST OF FIGURES

FIGURE		PAGE
2.1	Single Degree of Freedom Model	9
2.2	Permanent Set for Tri-Linear System Subjected to Pacoima S16E 1% Viscous Damping YSR = 0.085 Period = 0.8 Sec.	16
2.3	Permanent Set for Elasto-Plastic System Subjected to Taft N69W 1% Visc. Damping YSR = 0.638 Period = 0.8 Sec.	17
3.1	Hysteresis Loops	20
3.2	Effect of YSR on Total Energy Dissipated Some Typical Results	25
3.3	Effect of YSR on Total Energy Dissipated Means for 18 Combinations	26
3.4	Effect of YSR on Total Energy Dissipated Means for Each Earthquake Record	27
3.5	Means and Deviations in Total Energy Dissipated For all Systems Subjected to Taft N69W	29
3.6	Means and Deviations in Total Energy Dissipated For all Systems Subjected to El Centro N.S.	30
3.7	Means and Deviations in Total Energy Dissipated For all Systems Subjected to Parkfield N65E	31
3.8	Means and Deviations in Total Energy Dissipated For all Systems Subjected to Pacoima S16E	32
3.9	Effect of Earthquake Record on Total Energy Dissipated Elasto-Plastic Systems with 1.0% Viscous Damping	34

FIGURES	TITLE	PAGE
3.10	Effect of Earthquake Record on Total Energy Dissipated Tri-Linear Systems with 1.0% Viscous Damping	35
3.11	Effect of Material Hysteresis on Total Energy Dissipated Systems Subjected to Taft N69W with 1% Viscous Damping	37
3.12	Effect of Material Hysteresis on Total Energy Dissipated Systems Subjected to El Centro N.S. with 1% Viscous Damping	38
3.13	Effect of Material Hysteresis on Total Energy Dissipated Systems Subjected to Parkfield N65E with 1% Visc. Damping	39
3.14	Effect of Material Hysteresis on Total Energy Dissipated Systems Subjected to Parkfield N65E with 1% Visc. Damping	40
3.15	Effect of Visc. Damping on Total Energy Dissipated For all Systems Subjected to Taft N69W	42
3.16	Effect of Visc. Damping on Total Energy Dissipated For all Systems Subjected to El Centro N.S.	43
3.17	Effect of Viscous Damping on Total Energy Dissipated For all Systems Subjected to Parkfield N65E	44
3.18	Effect of Visc. Damping on Total Energy Dissipated For all Systems Subjected to Pacoima S16E	45
3.19	Effect of Yield Strength Ratio on Distribution of Energy within Systems. Some typical Results	47
3.20	Effect of YSR on Distribution of Energy Within Systems Means for all Elasto-Plastic Systems with 1% Damping	48
3.21	Effect of YSR on Distribution of Energy Within Systems Means for all Tri-Linear Systems with 1% Damping	48
3.22	Effect of Earthquake Record on Distribution of Energy Within Elasto-Plastic Systems with 1% Visc. Damping	50
3.23	Effect of Earthquake Record on Distribution of Energy Within Tri-Linear Systems with 1% Visc. Damping	51

FIGURES	TITLE	PAGE
3.24	Effect of Material Hysteretic Properties on Distribution of Energy Within Systems for all Systems Subjected to Taft N69W with 1% Damping	53
3.25	Effect of Material Hysteretic Properties on Distribution of Energy within Systems for all Systems Subjected to El Centro N.S. with 1% Damping	54
3.26	Effect of Material Properties on Distribution of Energy Within Systems for all Systems Subjected to Parkfield N65E with 1% Damping	55
3.27	Effect of Material Hysteretic Properties on Distribution of Energy Within Systems for all Systems Subjected to Pacoima S16E with 1% Damping	56
3.28	Effect of Viscous Damping on Distribution of Energy Within Systems Subjected to Taft N69E	58
3.29	Effect of Viscous Damping on Distribution of Energy Within Systems Subjected to El Centro N.S.	59
3.30	Effect of Visc. Damping on Distribution of Energy Within Systems Subjected to Parkfield N65E	60
3.31	Effect of Visc. Damping on Distribution of Energy Within Systems Subjected to Pacoima S16E	61
3.32	Schematic of Twin Parallel Resisting Element Model	62
3.33	Spectral Displacements for Systems Subjected to Taft N69W	67
3.34	Spectral Displacements for Systems Subjected to El Centro N.S.	69
3.35	Spectral Displacements for Systems Subjected to Parkfield N65E	71
3.36	Spectral Displacements for Systems Subjected to Pacoima S16E	73
3.37	Displacement Ductilities for Systems Subjected to Taft N69W	79

FIGURES	TITLE	PAGE
3.38	Displacement Ductilities for Systems Subjected to El Centro N.S.	81
3.39	Displacement Ductilities for Systems Subjected to Parkfield N65E	83
3.40	Displacement Ductilities for Systems Subjected to Pacoima S16E	85
3.41	Permanent Sets for Systems Subjected to Taft N69W	90
3.42	Permanent Sets for Systems Subjected to El Centro N.S.	92
3.43	Permanent Sets for Systems Subjected to Parkfield N65E	94
3.44	Permanent Sets for Systems Subjected to Pacoima S16E	96
3.45	Approximations for Total Energy Dissipated by Strong Systems	106
3.46	Approximations for Means of Total Energy Dissipated by all Strong Systems	108
3.47	Approximations for Total Energy Dissipated by Moderate Systems	112
3.48	Approximations for Total Energy Dissipated by Weak Systems	116
3.49	Approximations for Distribution of Energy Within Systems for Elasto-Plastic Systems	118
3.50	Approximations for Distribution of Energy Within Systems for Tri-Linear Systems	119
4.1	Time History of Energy Dissipated for a Tri-Linear System. YSR = 1.0, Period = 1.4 sec, 1% Visc. Dmpg. Subjected to Pacoima S16E	126
4.2	Time History of Energy Dissipation for a Tri-Linear System. YSR = 0.5, Period = 1.4 sec, 1% Visc. Dmpg. Subjected to Taft N69W	127

FIGURES	TITLE	PAGE
4.3	Time History of Energy Dissipation for an Elasto-Plastic System. YSR = 0.5, Period = 1.4 sec, 1% Visc. Dmpg. Subjected to Pacoima S16E	128
4.4	Time History of Energy Dissipation for an Elasto-Plastic System. YSR = 0.5, Period = 0.8 sec, 1% Visc. Dmpg. Subjected to Taft N69W	129
5.1	Multi-Degree of Freedom Model	138
6.1	Structures Used in M.D.F. Study	145
6.2	Comparison of Total Energy Dissipated by Multi-Degree of Freedom Systems with Single Degree of Freedom Results	150
A.1	Results for Combination 1. TAFEP.01	182
A.2	Results for Combination 2. PACEP.01	184
A.3	Results for Combination 3. ELCEP.01	186
A.4	Results for Combination 4. TAFTL.01	188
A.5	Results for Combination 5. PACTL.01	190
A.6	Results for Combination 6. PKFEP.01	192
A.7	Results for Combination 7. PKFTL.01	194
A.8	Results for Combination 8. ELCTL.01	196
A.9	Results for Combination 9. TAFEP.05	198
A.10	Results for Combination 10. PACTL.05	200
A.11	Results for Combination 11. ELCTL.05	202
A.12	Results for Combination 12. PKFEP.05	204
A.13	Results for Combination 13. TAFTL.00	206
A.14	Results for Combination 14. PACEP.00	208
A.15	Results for Combination 15. ELCEP.00	210

FIGURES	TITLE	PAGE
A.16	Results for Combination 16. PKFTL.00	212
A.17	Results for Combination 17. TAFRO.01	214
A.18	Results for Combination 18. ELCRO.01	216

DEDICATED TO MY WIFE MAUREEN,

MY PARENTS, AND MY CHILDREN,

ELAINE
GARETH
MARK
ANDREW
BETHAN

WHO HAVE SACRIFICED MUCH

AND LOVED ME MORE

TO MAKE THIS POSSIBLE.

If I have the gift of prophecy and can
fathom all mysteries and all knowledge . . . .
. . . but have not love, I am nothing.

I Cor. 13:2.

ACKNOWLEDGEMENT

I would like to express my sincere appreciation and gratitude to Profs. N.D. Nathan, D.L. Anderson and S. Cherry for their encouragement, guidance and constant availability for discussion during all stages of the work presented in this thesis.

Special thanks go to Mrs. Sheila Johnston for her care and patient typing of this thesis.

The research was financed by the National Research Council of Canada.

CHAPTER 1

REVIEW OF CURRENT ANALYTIC METHODS IN EARTHQUAKE ENGINEERING

1.1 Development of the Principal Methods

1.1.1 Elastic Response Spectra:

In 1940 Biot[1,2] introduced the concept of an elastic response spectrum, and outlined a method for applying his spectrum to the seismic analysis of structures. It was immediately apparent that the design forces the method produced were disproportionately large compared to the forces known to have existed in structures which had survived actual earthquakes. Similarly Biot's elastic spectral analysis results were considerably higher than the force levels specified by design codes. The provisions embodied in the codes had been based on studies of structures surviving previous earthquakes. In a first attempt to reconcile the difference between the analytic and observed force magnitudes Biot pointed out the importance of hysteretic damping in reducing the response.

Since 1945 architectural styles and construction methods have changed appreciably from the traditional forms employed previously. These changes reflect the economic pressures on land and construction costs. The trend toward lighter, taller structures using a minimum of non-structural materials, made it imperative that the means by which structures resist

earthquake excitation be better understood.

Biot's work found ready application from the start in earthquake engineering research. By 1953 Housner, Matel & Alford[3] had studied numerous response spectra and were able to confirm that the difference between the elastic spectral analysis results, and observations made after real earthquakes, could be accounted for by considering the non-linear effects in the structural response.

1.1.2 Time Step Integration Methods

The next major development in earthquake engineering came with the introduction of time step integration procedures for integrating the governing equations of motion. Newmark[4] and Clough & Wilson[5] produced time step procedures which enabled researchers to carry out time history investigations of structural response, both in the linear and non-linear range.

1.1.3 Ductility and Energy Methods

The second world conference on earthquake engineering took place in Tokyo in 1960. By this time two main streams of thought had emerged to account for the non-linear effects on the structural response. Firstly, Veletsos and Newmark[6] pioneered the ductility concept, and Housner[7], Berg and Thomaides[8] and Tanabashi[9], produced methods which considered energy dissipation as a basis for analysis.

1.2 The Ductility Method

The ductility concept contains a number of important assumptions which constrain the range of application of the method. The limitations inherent in the method must be clearly understood in order to avoid

inappropriate application.

The first of these assumptions is that an inelastic or yielding structure will have a peak displacement equal to the peak displacement of an elastic structure of equal period, when both structures have been subjected to the same earthquake record. This assumption is based on studies of Elasto-Plastic systems subjected to far field earthquake records.

The second assumption employs the fact that spectra obtained for elastic structures, have in general, the same shape as spectra obtained for structures with varying degrees of non-linearity. Further, the spectral values of the non-linear response vary in direct proportion to the ductility factor of the non-linear structure. This permits a design method based on an elastic analysis and the non-linear effects can be taken into account by simply dividing the elastic results by the ductility factor.

The third assumption which is inherent in the ductility method, but never defined explicitly, is that the ductility is assumed to be distributed uniformly throughout the system. In practice this is very difficult to achieve, and often impossible due to serviceability considerations. Experience in a number of recent earthquakes has shown that when this is not appreciated the structural response is quite different from that predicted by a ductility analysis. This is because the elastic vibrational mode shape used in the design is significantly different from the shape of the failure mode.

Furthermore, there is always difficulty in calculating the system ductility from the assemblage of members even when the individual member

ductilities may be well defined.

In review it can be pointed out that the major weakness of the ductility method lies in two main areas.

(1) The latitude of the assumptions on which the method is based must be fully understood in order that this deceptively simple method can be applied correctly.

(2) The method is not sufficiently flexible to take into account major concentrations of stiffness or flexibility within the structure.

1.3 Energy Methods

The alternative methods of accounting for the non-linear effects in the structural response considered energy dissipation within the system. There are two groups of energy methods considered.

Firstly, Housner[7] and Tanabashi[9] presented methods which essentially equated the maximum peak kinetic energy of a linear system, to the energy to be dissipated by the inelastic system during the earthquake. A value for the elastic peak kinetic energy is obtained by using the elastic spectral velocity. Correlation studies supporting the assumption that the elastic peak kinetic energy is proportional to the total energy dissipated by an inelastic structure during the earthquake excitation could not be found in the literature.

An alternative energy method, produced at the same time, was

presented by Berg & Thomaides[8]. This method considers the total energy dissipated by the structure for the duration of the earthquake excitation. By considering the response of single degree of freedom systems having elastic -- perfectly plastic stiffness properties, a series of total energy spectra for various yield levels can be produced. This is carried out by performing a time step analysis, evaluating the total energy at every step, and accumulating the total energy dissipated during the earthquake record. A similar study was carried out by Jennings[10] using a more general Ramberg-Osgood hysteresis loop to model the non-linear response.

The energy to be dissipated by the structure, obtained by the above methods, becomes the main analysis parameter, and the structure is designed to ensure that this energy can be dissipated safely.

The Reserve Energy Technique[11] is similar to the energy methods which equate the peak spectral kinetic energy to the energy dissipated in plastic work. Unfortunately, in presenting this method numerous unsubstantiated assumptions were employed which draw attention away from the energy balance kernel of the method. Consequently this method has never received widespread acceptance.

1.4 Limit State Philosophy

The main developments of identifying the problems and producing methods of solution in earthquake engineering had taken place by 1960. Since, the introduction, in 1962, of modal analysis for multi-degree of freedom systems by Merchant and Hudson[12], and Clough[13] all the techniques currently employed in analysis have been available.

From that time methods have received wide application in a proliferation of earthquake engineering research. The simultaneous growth of large capacity digital computers permitted studies of increasingly complex models to be made. The knowledge gained from these endeavours has resulted in a far more detailed understanding of the way in which structures resist earthquakes.

However, since 1940 the most important unanswered question in earthquake engineering has been how to produce a simple method of analysis which adequately accounts for the non-linear effects in the structural response. The need for such a method of analysis is now greater than ever due to the necessity of bringing the earthquake design of structures within the framework of the limit state design philosophy.[17,18,19] In terms of earthquake engineering this requires a two level analysis procedure. Such a method would provide for an elastic analysis, representing nominal damage levels, for an earthquake of moderate intensity, corresponding to a return period of say 10 - 20 years, and an ultimate plastic analysis avoiding total collapse in a severe earthquake with expected return periods of say 50 - 100 years.

1.5 Multi-Degree of Freedom Energy Studies

The only other energy dissipation studies available in the literature concern the way in which the energy is distributed throughout multi-degree of freedom systems. There seems to be remarkably little work done on this aspect of the problem to date, the only references found were by Spencer[14], Arya[15], Gluck[16], and Ruiz & Penzien[20].

CHAPTER 2

THEORY AND PROGRAMMING CONSIDERATIONS FOR SINGLE DEGREE OF FREEDOM SYSTEMS

2.1 Single Degree of Freedom Model.

The model for the single degree of freedom systems investigated in this study is shown in fig. 2.1.

The well known general equation of motion for such a system having non-linear stiffness elements and subjected to base excitation is given as:

$$M\ddot{x} + C\dot{x} + F(x) = -M\ddot{x}_g \qquad \ldots\ldots\ldots (2.1)$$

where dots denote differentiation w.r.t. time.

and $F(x)$ represents the force in the stiffness elements which are a function of the displacement (x).

The characteristics of non-linear single degree of freedom systems used in this study are defined by the following three parameters.

(i) Strength Parameter.

(Yield Level)

$$\text{Yield Level} = f_y = \frac{F_y}{M} \qquad \ldots\ldots\ldots (2.2)$$

where F_y = horizontal force, applied at the centre of gravity of the mass, which causes yielding in the non-linear stiffness elements.

M = Mass of the system.

Note: the parameter f_y is expressed in units of acceleration. It is used to reduce real system parameters to terms of unit mass.

(ii) Stiffness Parameter.

or Frequency of small amplitude vibrations = ω_o

first define $K_y = F_y / X_y$ ..... (2.3)

where K_y = elastic stiffness of system.
F_y = horizontal yield force.
X_y = relative deflection of the system at yield point.

hence $\omega_o = \sqrt{\frac{K_y}{M}} = \sqrt{\frac{F_y}{M X_y}}$ .....(2.4)

(iii) Damping Parameter.

or Percentage of critical viscous damping.

For this study it was assumed that the percentage of viscous damping is related to the elastic properties of the system at all times.

therefore η = percentage of critical damping = $\frac{C}{2\sqrt{K_y M}}$ .....(2.5)

Dividing equation (2.1) by M and substituting equations (2.4) and (2.5) gives: -

$$\ddot{x} + 2\eta\omega_o \dot{x} + \frac{\omega_o^2 F(x)}{K_y} = -\ddot{x}_g \qquad \text{..... (2.6)}$$

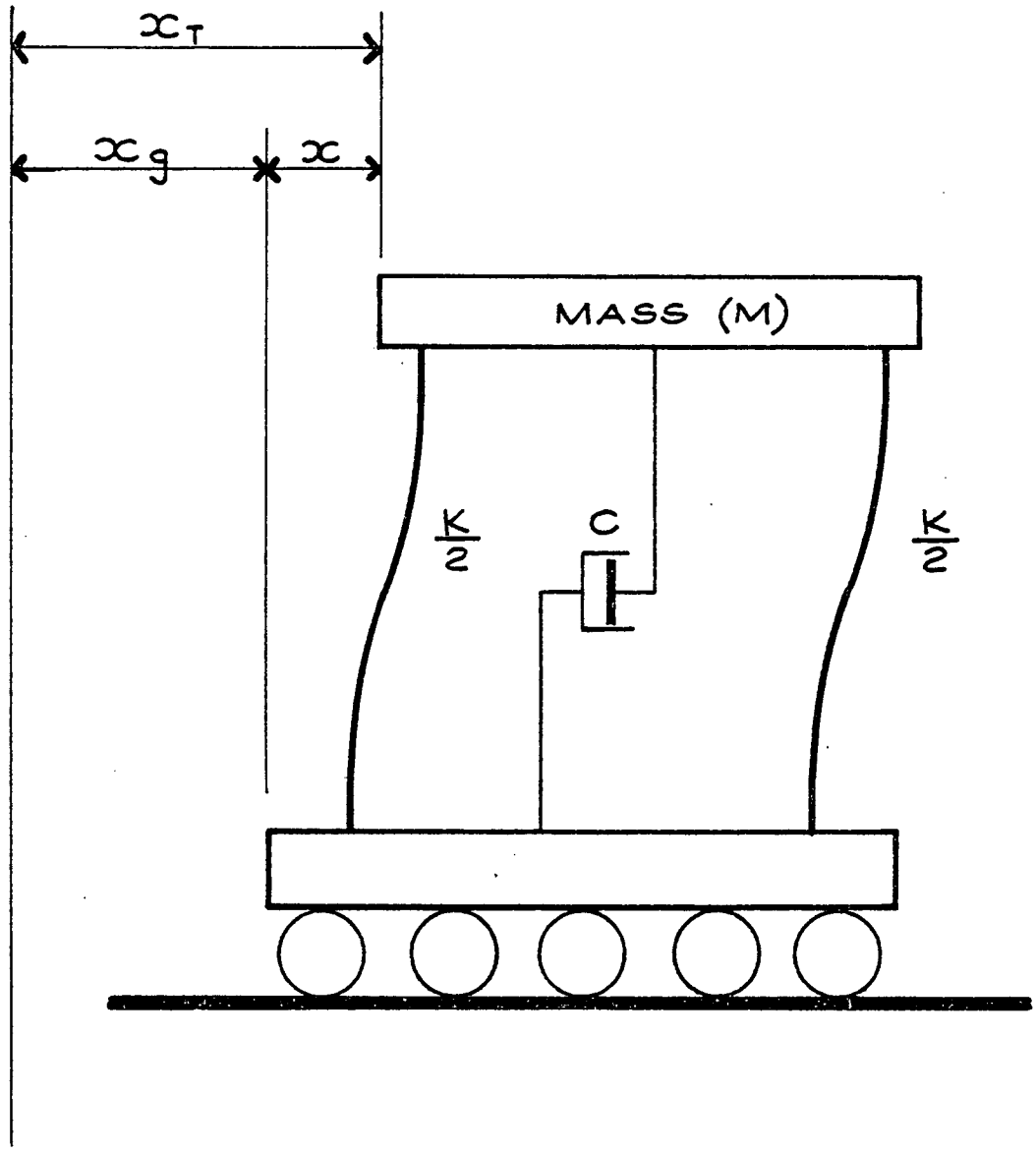


FIG. 2.1 SINGLE DEGREE OF FREEDOM MODEL

2.2 Incremental Equations of Motion.

In incremental form equation (2.6) becomes:

$$\Delta\ddot{x} + 2\eta\omega_o\Delta\dot{x} + \frac{\omega_o^2 \quad \Delta F(x)}{K_y} = -\Delta\ddot{x}_g \qquad \ldots\ldots\ldots (2.7)$$

In the constant average time step scheme the incremental acceleration and velocity are expressed in terms of the incremental displacement and the conditions existing at the start of the time increment by:

$$\left.\begin{aligned} \Delta\ddot{x} &= \frac{4\,\Delta x}{\Delta t^2} - \frac{4\,\dot{x}_o}{\Delta t} - 2\ddot{x}_o \\ \Delta\dot{x} &= \frac{2\,\Delta x}{\Delta t} - 2\dot{x}_o \end{aligned}\right\} \qquad \ldots\ldots\ldots (2.8)$$

where Δt = time increment length

$\dot{x}_o$ & $\ddot{x}_o$ = velocity and acceleration at the start of the increment respectively.

Substituting (2.8) into equations (2.7), noting that $\Delta F(x) = K_T \Delta x$, gives after some manipulation:

$$\left[\frac{4}{\Delta t^2} + \frac{4\eta\omega_o}{\Delta t} + \frac{K_T}{M}\right]\Delta x = -\Delta\ddot{x}_g + \dot{x}_o\left[\frac{4}{\Delta t} + 4\eta\omega_o\right] + 2\ddot{x}_o$$

$\ldots\ldots\ldots (2.9)$

where K_T = Tangent to the stiffness at the start of each increment.

For computational efficiency this equation was programmed as:

$$(FAC1 + K_T * FAC2) \Delta x = -\Delta\ddot{x}g + \dot{x}_o (FAC3) + 2 \ddot{x}_o \quad \ldots\ldots\ldots (2.10)$$

where $$FAC1 = \frac{4}{\Delta t^2} + \frac{4\eta\omega_o}{\Delta t}$$

$$FAC2 = \frac{1}{M}$$

$$FAC3 = \frac{4}{\Delta t} + 4\eta\omega_o$$

FAC1, FAC2 and FAC3 were calculated once only before the start of the time step loop.

2.3 Accuracy of the Time Stepping Scheme.

The constant average time stepping scheme was used for this study because it has the advantage of not introducing numerical damping into the calculations.[21] This was considered important because the effects of small percentages of viscous damping were to be studied.

The calculations were carried out using time steps of 0.01 sec., for systems with periods greater than 0.5 sec., and using time steps of 0.005 sec. for shorter period systems.

At the end of each time step an equilibrium balance check was made. Any error in equilibrium at the end of the time step was corrected for during the following time step. Close study of the equilibrium balance showed that this error was extremely small except at points of discontinuity of slope in the hysteresis relationship. At such points of discontinuity the error was reduced to extremely small amounts after the correction was applied for one time step. The following errors remained insignificant until the next hysteretic slope discontinuity was encountered. The successive application of these corrective error forces maintained dynamic equilibrium and prevented errors due to the non-linear hysteresis relationships from accumulating.

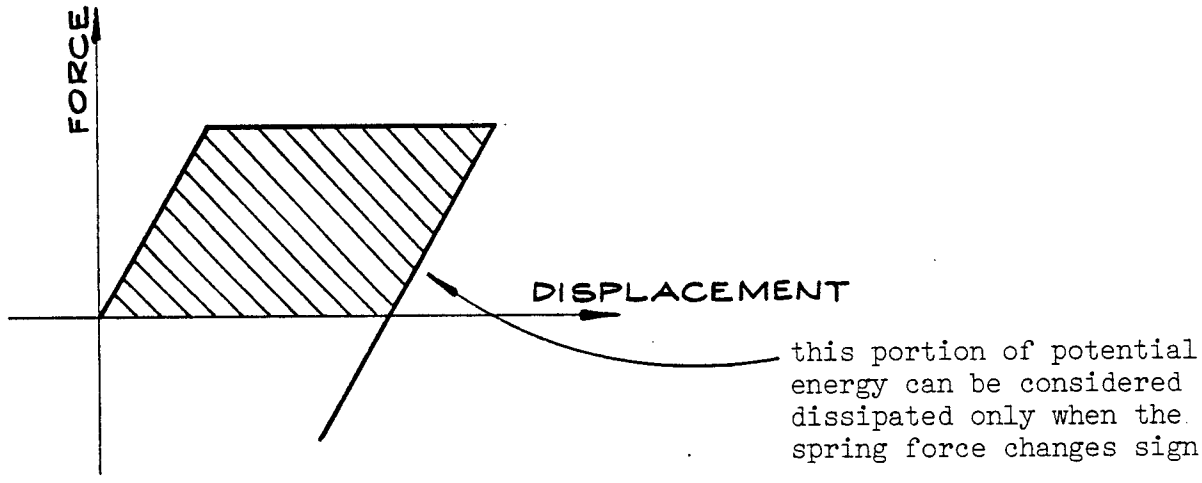
An alternative method of correcting for the equilibrium imbalance would be to subdivide the integration time step length whenever a point of non-linearity on the hysteresis curve is reached. However, such a method is more difficult to implement in a general computer program and would probably take more computer time to perform the calculations.

2.4 Energy Calculations

Energy calculations were made at the end of each time step with the following energies being calculated individually.

(1) Energy Dissipated by Hysteretic Springs

Energy was considered dissipated by the springs when it became clear that no portion of the potential energy in the spring could be recovered.



(2) Potential Energy in Springs

Energy stored in the springs is assumed to be recoverable unless there is a change of sign in the force.

(3) Kinetic Energy in System

Calculated at the instant of the end of each time step.

(4) Energy Dissipated in Viscous Damping

Calculated as a step function for each time step being continuously increased for the duration of motion.

These energies are summed to produce the total energy stored within the system at the end of each time step.

The input energy for the system is calculated for each time step using Newtons second law.

Energy IN = Mass * total acceleration * Ground Displacement.

In the situation where the inertia forces and ground displacement are of opposite sign energy is being radiated from the structure back into the ground. Hence at the end of calculations, the total energy input to the system represents the net energy stored or dissipated within the system.

Comparison of the sum of the energies within the system and the energy input to the system provides a useful check on the accuracy of calculations. A practical tolerable limit of 5% error for this check was placed. However at no point was this reached.

Listings of the computer subroutines which carry out these calculations are given in appendix B.

2.5 Non-Dimensionalising the Earthquake.

In this study it was necessary to compare the results of the response of systems subjected to four very different ground motion records. Because of this it is important to non-dimensionalise the records to one common baseline strength in order that comparative studies could be made.

The maximum peak ground acceleration was used as a measure of the earthquake strength for the following reasons.

(1) The peak ground acceleration has been used as a standard parameter for specifying earthquake ground motion records for some time, and its significance is well understood.

(2) Estimates of peak ground acceleration are available in empirical data which can be used to predict future ground motions at a given site.

(3) Alternative methods of nondimensionalising the earthquake record, R.M.S., spectral averages etc., were tried. However, no significant improvement in the correlation of the response data was observed. Because of this and in view of the well known difficulty in defining an average value, these normalizing methods were not used.

2.6 An Estimate for the Permanent Set

The response calculations were stopped at the end of the ground acceleration after 30 seconds of excitation. At this point the structures are still vibrating and a method of estimating the permanent set was required in order to avoid the computational expense of waiting for the residual vibrational energy to dissipate.

In all the ground acceleration records used, the most energetic portions of the records had occurred some time before calculations ceased. The permanent set is a result of excursions into the non-linear range of the hysteresis relationship, which had taken place before the calculations stopped. Hence the residual vibrations are taking place in a predominantly linear fashion centred about the true permanent set position.

An estimate of the permanent set was made by taking the average value of the displacement during the last three seconds of the earthquake record. A number of test runs were made to investigate the validity of this approximation and the results show good agreement with permanent set values obtained 10 seconds after the excitations had stopped. Some typical results are shown in figs. 2.2 and 2.3.

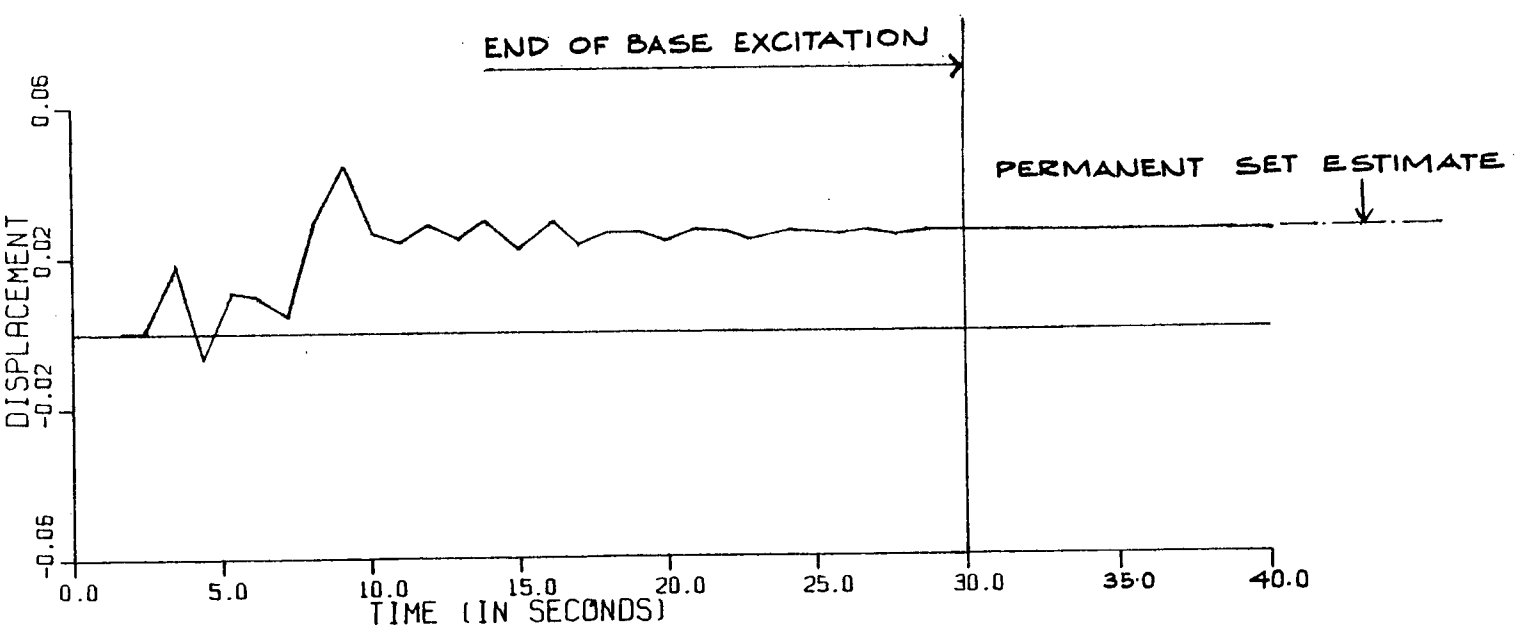


FIG. 2.2 PERMANENT SET FOR TRI-LINEAR SYSTEM SUBJECTED TO PACOIMA S16E
1% VISCOUS DAMPING YSR = 0.085 PERIOD = 0.8 SEC.

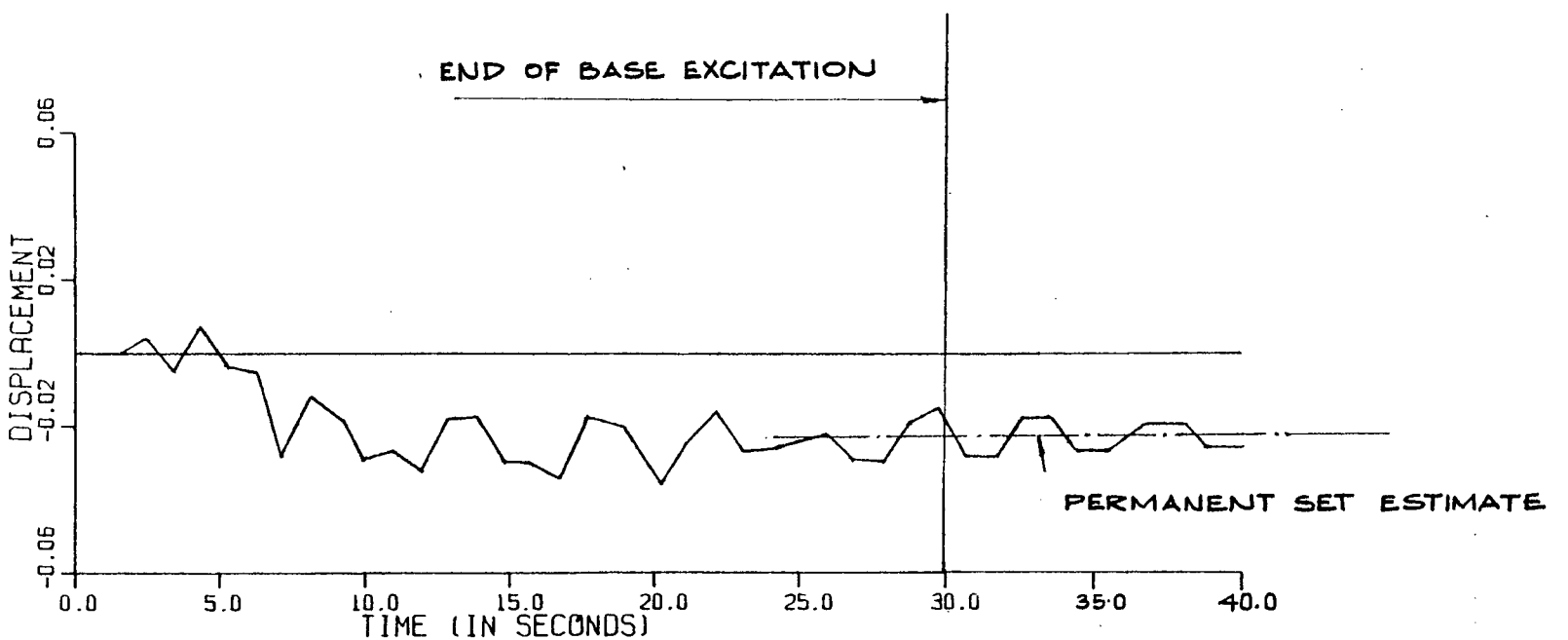


FIG. 2.3 PERMANENT SET FOR ELASTO-PLASTIC SYSTEM SUBJECTED TO TAFT N69W
1% VISCOUS DAMPING YSR = 0.638 PERIOD = 0.8 SEC.

CHAPTER 3

RESULTS OF SINGLE DEGREE OF FREEDOM STUDY

3.1 Scope of Single Degree of Freedom Study

This study employs the theory given in chapter 2. It takes the form of a broad investigation to identify the principal parameters affecting the energy dissipation characteristics and response of systems subjected to earthquake ground motions. Correspondingly as wide a range of input variables as possible was employed in order to expose general trends and effects.

The following input variables were used.

Base excitations: Taft N69W 1952, El Centro N.S. 1940, Pacoima Dam S16E 1971, Parkfield N65E 1956. i.e. two far field and two near source impulsive earthquakes. The earthquake records were non-dimensionalised by dividing by the maximum peak acceleration.

Hysteresis Properties (Fig. 3.1)

Elasto-Plastic.

Ramberg-Osgood[10] with parameters A = 0.1 R = 7; A = 0.1 R= 9 in various runs.

Both these hysteresis loops are representative of the experimentally produced hysteretic properties for steel frame systems.

Tri-Linear stiffness degrading models.[23]

with $\frac{P_{BY}}{P_{BC}} = 3$ and $\frac{K_2}{K_1} = 0.5$

This model represents typical hysteretic behaviour of reinforced concrete frames.

Viscous Damping

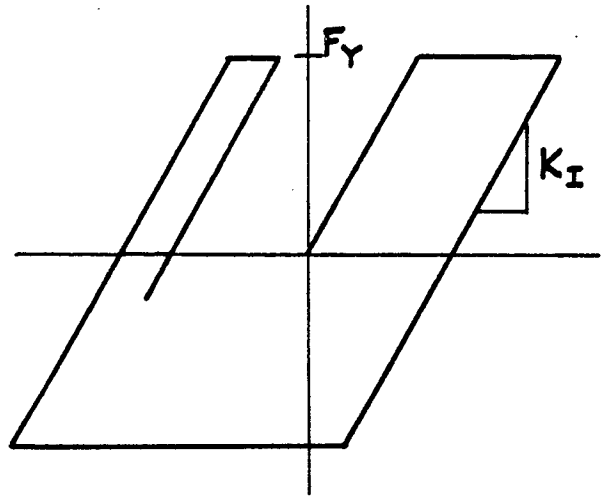
Three values were used in calculations:0%, 1% and 5% of critical damping. The viscous damping represents the non-structural damping in the structure.

Yield Strength Ratio

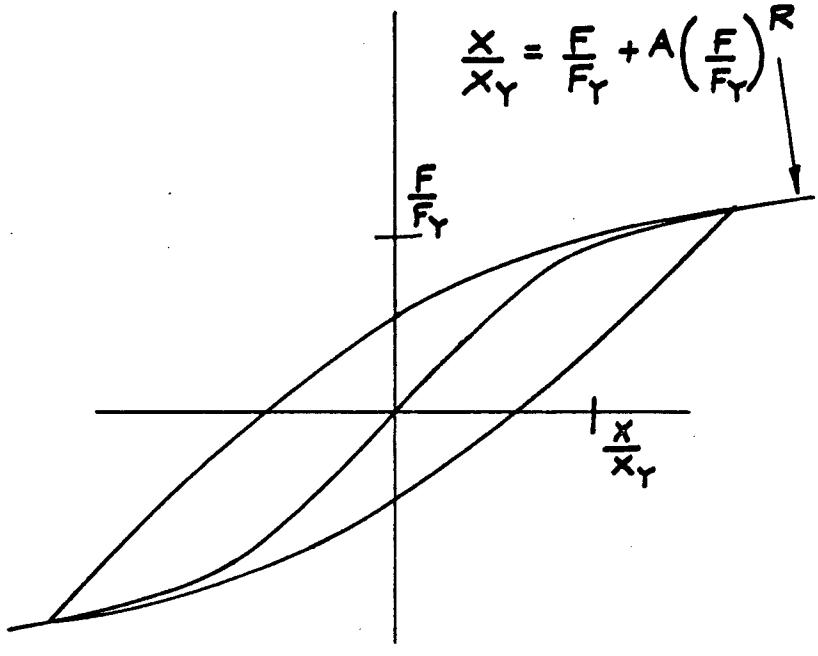
At an early stage it was clear that the "Yield Strength Ratio" defined as:

$$YSR = \frac{\text{Horiz Accel}^n \text{ req}^d \text{ to produce Yielding Inertia force}}{\text{Max Peak Ground Accel}^n}$$

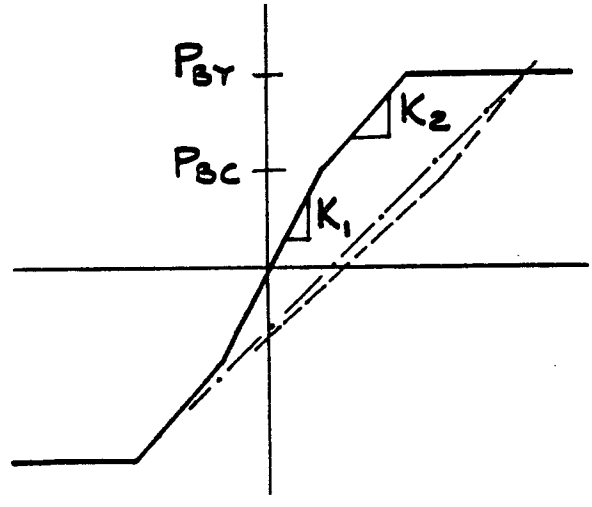
has a marked effect on the nature and magnitude of the response of all systems studied. The significance of this parameter will become clear in the discussion of the results which follow. A range of values from 0.1 to 10.0 is used.



ELASTO - PLASTIC



RAMBERG - OSGOOD[10]



TRI - LINEAR[23]
STIFFNESS DEGRADING

FIG. 3.1 HYSTERSIS LOOPS.

Initial Elastic Period

Ten values of initial elastic period for small vibrations, in seconds, are used:

0.1, 0.3, 0.5, 0.8, 1.0, 1.2, 1.8, 2.0, 2.5.

The input parameters of viscous damping, hysteretic properties and earthquake record were combined to produce eighteen data sets of results. In keeping with the overview philosophy of this study the sets cover as wide a range of combinations as possible in a limited study such as this. However, it is anticipated that the wide range of input variables and combinations employed will produce results that form a bounding set into which results of more detailed studies will fall. Details of the eighteen combinations considered are given in table 3.1.

The results of the eighteen combinations studied are presented in the form of response spectra covering the range of periods and yield strength ratios considered.

The following response parameters are studied in detail in the remainder of this chapter.

(a) Total Energy Dissipated in System,

(b) Distribution of Energy Within System,

(c) Spectral Displacements,

(d) Displacement Ductilities,

(e) Permanent Sets.

The complete results of this study are presented in original form in Appendix A.

Combination Number	Earthquake Record	Hysteretic Properties See Fig. 3.1	Percentage of Critical Viscous Damping	Abbreviation For System
1	Taft N69W	Elasto-Plastic	1.0%	TAFEP.01
2	Pacoima S16E	Elasto-Plastic	1.0%	PACEP.01
3	El Centro N.S.	Elasto-Plastic	1.0%	ELCEP.01
4	Taft N69W	Tri-Linear	1.0%	TAFTL.01
5	Pacoima S16E	Tri-Linear	1.0%	PACTL.01
6	Parkfield N65E	Elasto-Plastic	1.0%	PKFEP.01
7	Parkfield N65E	Tri-Linear	1.0%	PKFTL.01
8	El Centro N.S.	Tri-Linear	1.0%	ELCTL.01
9	Taft N69W	Elasto-Plastic	5.0%	TAFEP.05
10	Pacoima S16E	Tri-Linear	5.0%	PACTL.05
11	El Centro N.S.	Tri-Linear	5.0%	ELCTL.05
12	Parkfield N65E	Elasto-Plastic	5.0%	PKFEP.05
13	Taft N69W	Tri-Linear	0.0%	TAFTL.00
14	Pacoima S16E	Elasto-Plastic	0.0%	PACEP.00
15	El Centro N.S.	Elasto-Plastic	0.0%	ELCEP.00
16	Parkfield N65E	Tri-Linear	0.0%	PKFTL.00
17	Taft N69W	Ramberg-Osgood	1.0%	TAFRO.01
18	El Centro N.S.	Ramberg-Osgood	1.0%	ELCRO.01

TABLE 3.1 INPUT COMBINATIONS USED IN SINGLE DEGREE OF FREEDOM STUDY

3.2 Total Energy Dissipated in System

The total energy to be dissipated by a structure during an earthquake excitation is the basic design parameter for a method based on energy dissipation considerations. In this section the effect of varying the prime input parameters of yield strength ratio, earthquake record, material hysteresis and viscous damping, are collectively considered below.

3.2.1 Effect of Yield Strength Ratio on Total Energy Dissipated

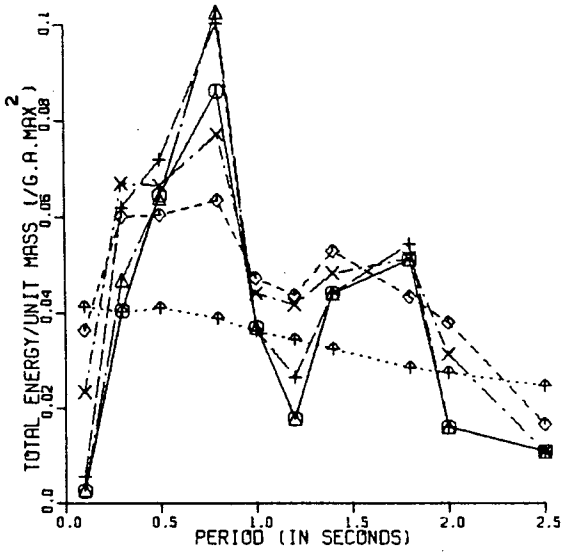
The most important effect of reducing the YSR is to lessen the frequency dependence of systems on the energy content of the ground motion. See fig. (3.2) and Appendix A. In all cases the maximum energy dissipated occurs in systems with YSR values of 1.0 or greater at frequencies which coincide with the peak energy frequencies of the earthquake record used. Similarly those stronger systems dissipate minimum energies at minimum frequencies of the record. The variation in energy dissipated for different periods is great for these stronger systems. However in all spectra produced it is seen that the strongest systems, which remained elastic throughout the response, do not form an upper bound on the total energy dissipated for all values of period. This point is of great practical significance because it invalidates attempts to extrapolate from the linear to the non-linear case.

As the value of YSR is reduced below 1.0, it is seen that in general the total energy to be dissipated is reduced, and also, the variation in total energy dissipated by systems with different frequencies is reduced. This variation becomes approximately bi-linear for systems with YSR = 0.5 and 0.3 and linear for systems with YSR = 0.1. These observations are also true when considering mean values of total energy dissipated for various combinations of results. Fig. 3.3 shows mean values of total energy dissipated for all

eighteen data sets in this study.

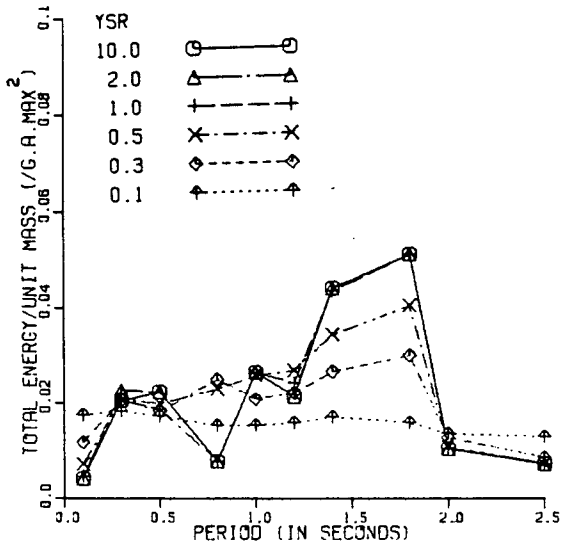
In fig. 3.4, means are plotted for systems subjected to each individual earthquake used in the study.

Another important factor affected by the value of YSR is the deviation from the mean in results obtained for any given combinations of variables. In fig. 3.5, 3.6, 3.7 and 3.8 it can be seen that this deviation reduces with YSR. Thus it is concluded that the effects of varying material type or damping diminishes as YSR is reduced.



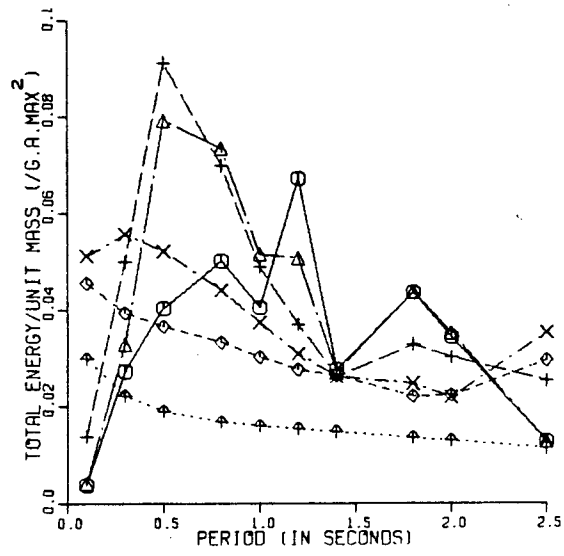
TAFT N69W ELASTO-PLASTIC SYSTEMS ETA=0.01

G.A. MAX = 5.0493 FT/SEC/SEC



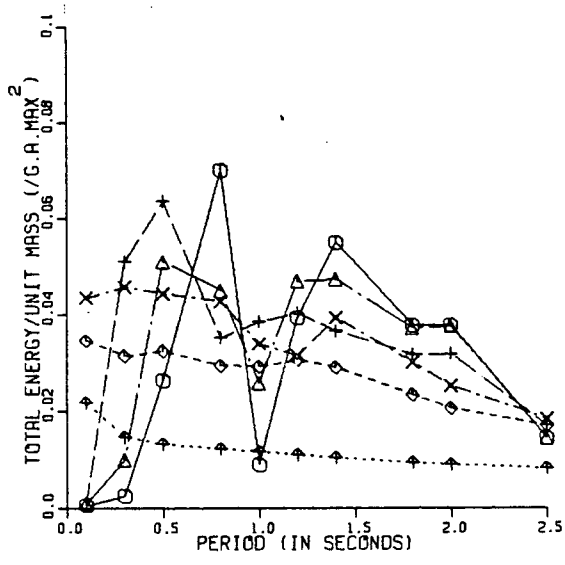
PACOIMA S16E ELASTO-PLASTIC SYSTEMS ETA=0.01

G.A. MAX = 37.698 FT/SEC/SEC



EL CENTRO N.S. TRI-LINEAR SYSTEMS ETA=0.01

G.A. MAX = 11.561 FT/SEC/SEC



PARKFIELD N65E TRI-LINEAR SYSTEMS ETA=0.01

G.A. MAX = 15.735 FT/SEC/SEC

FIG. 3.2 EFFECT OF YSR ON TOTAL ENERGY DISSIPATED. SOME TYPICAL RESULTS.

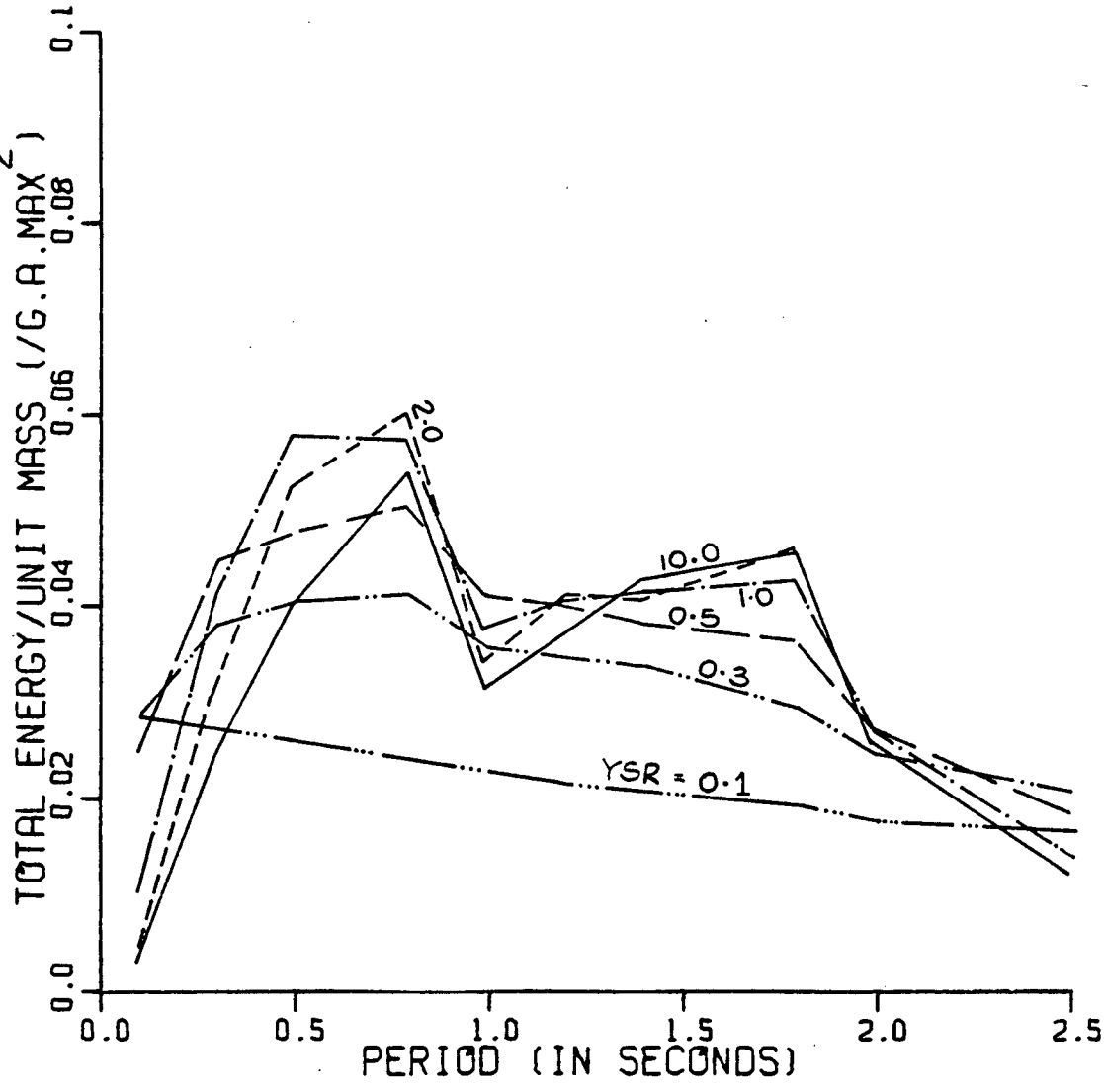
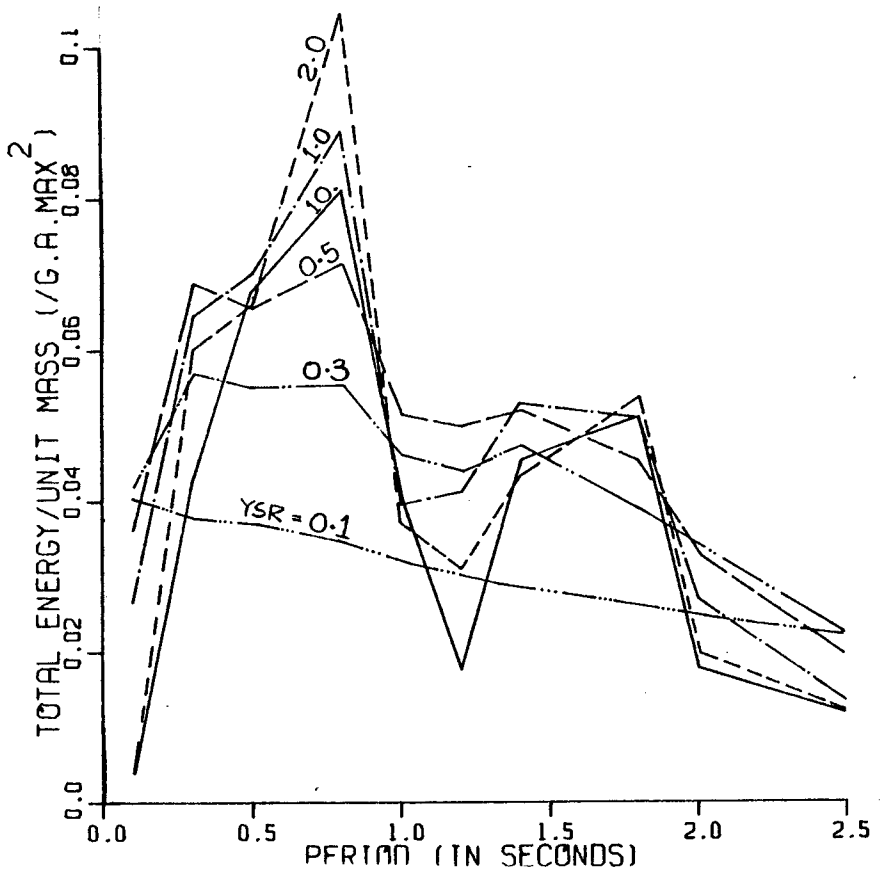
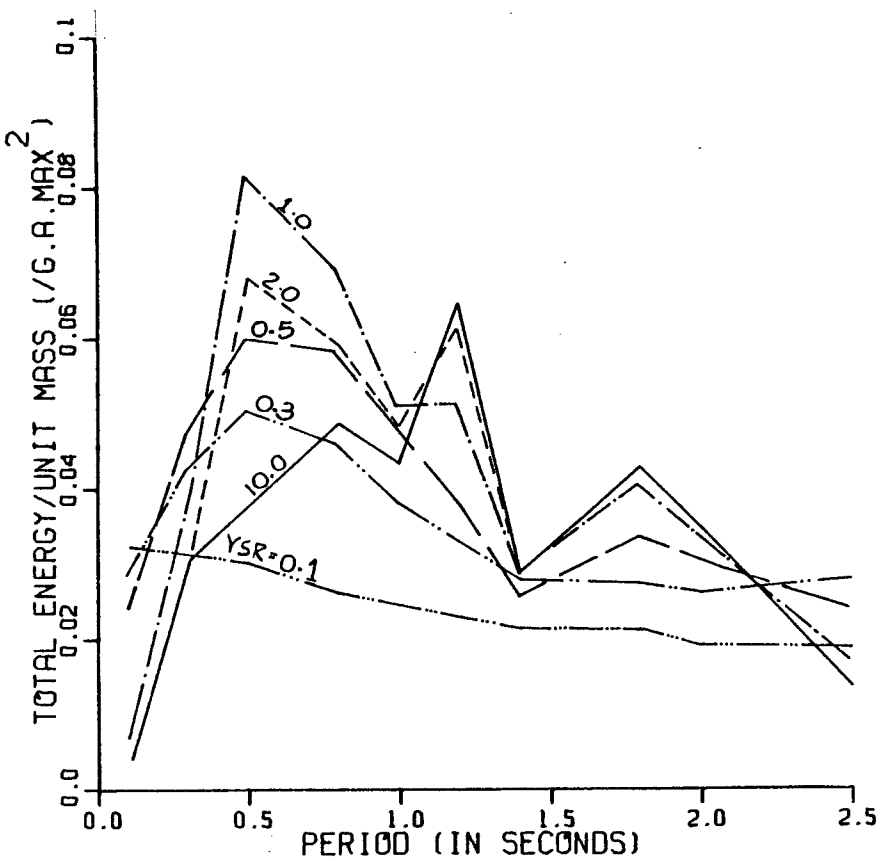


FIG. 3.3 EFFECT OF YSR ON TOTAL ENERGY DISSIPATED, MEANS FOR 18 COMBINATIONS.

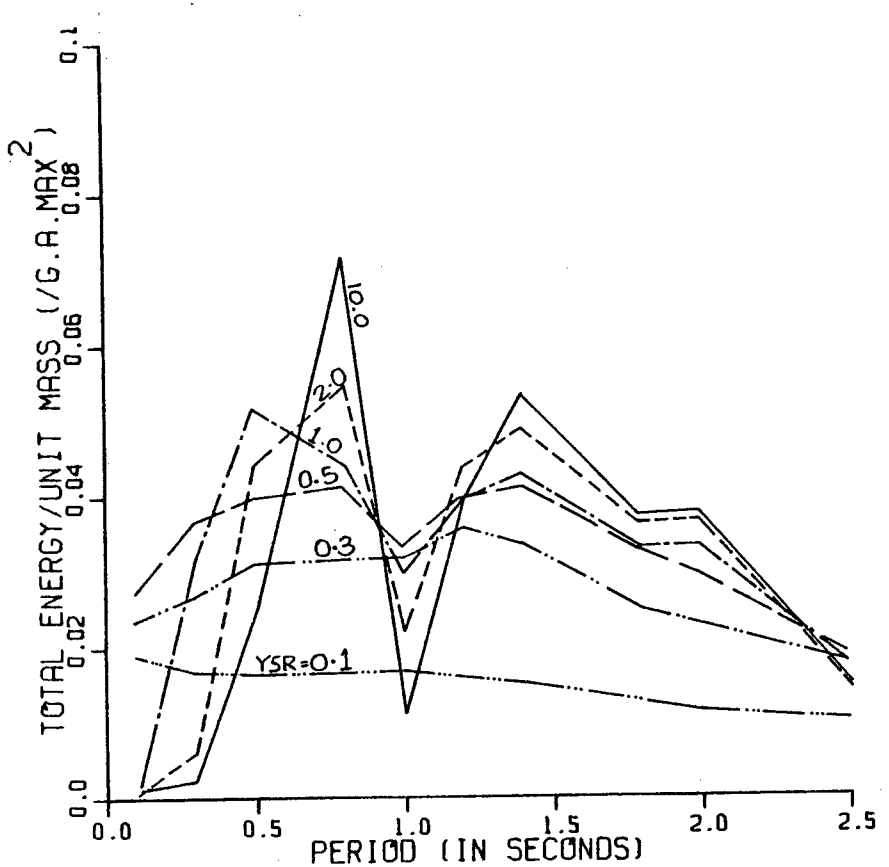


3·4 (a) TAFT N69W.

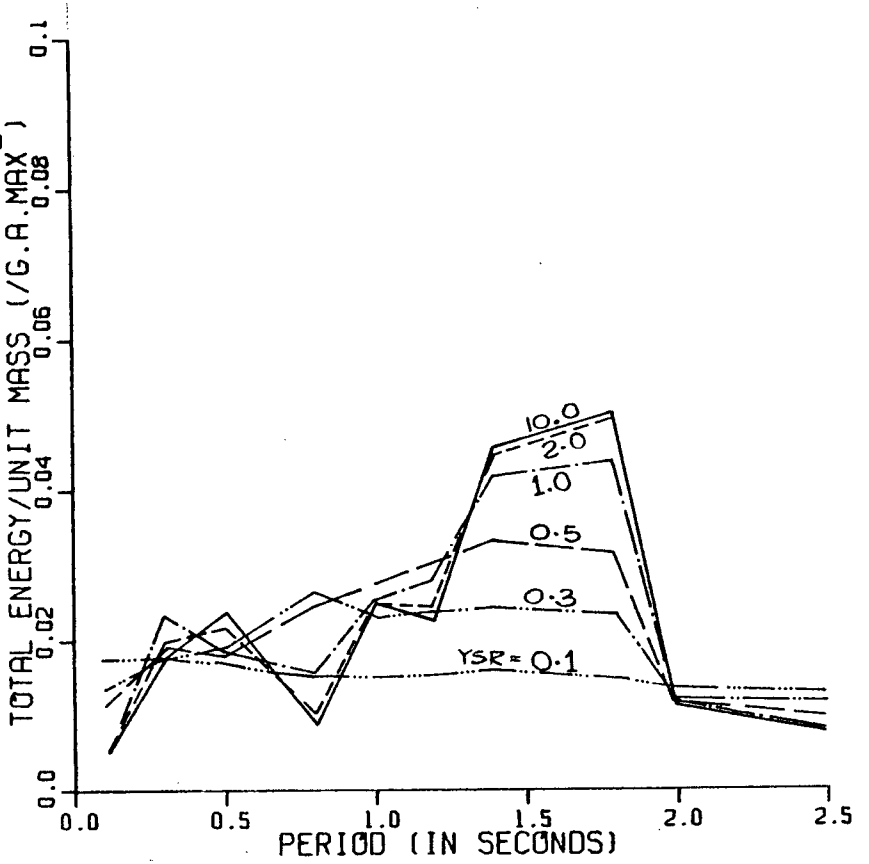


3·4 (b) EL CENTRO N.S.

FIG. 3.4 EFFECT OF YSR ON TOTAL ENERGY DISSIPATED. MEANS FOR EACH EARTHQUAKE RECORD.



3.4(c) PARKFIELD N65E.



3.4(d) PACOIMA S16E.

FIG. 3.4 CONTINUED

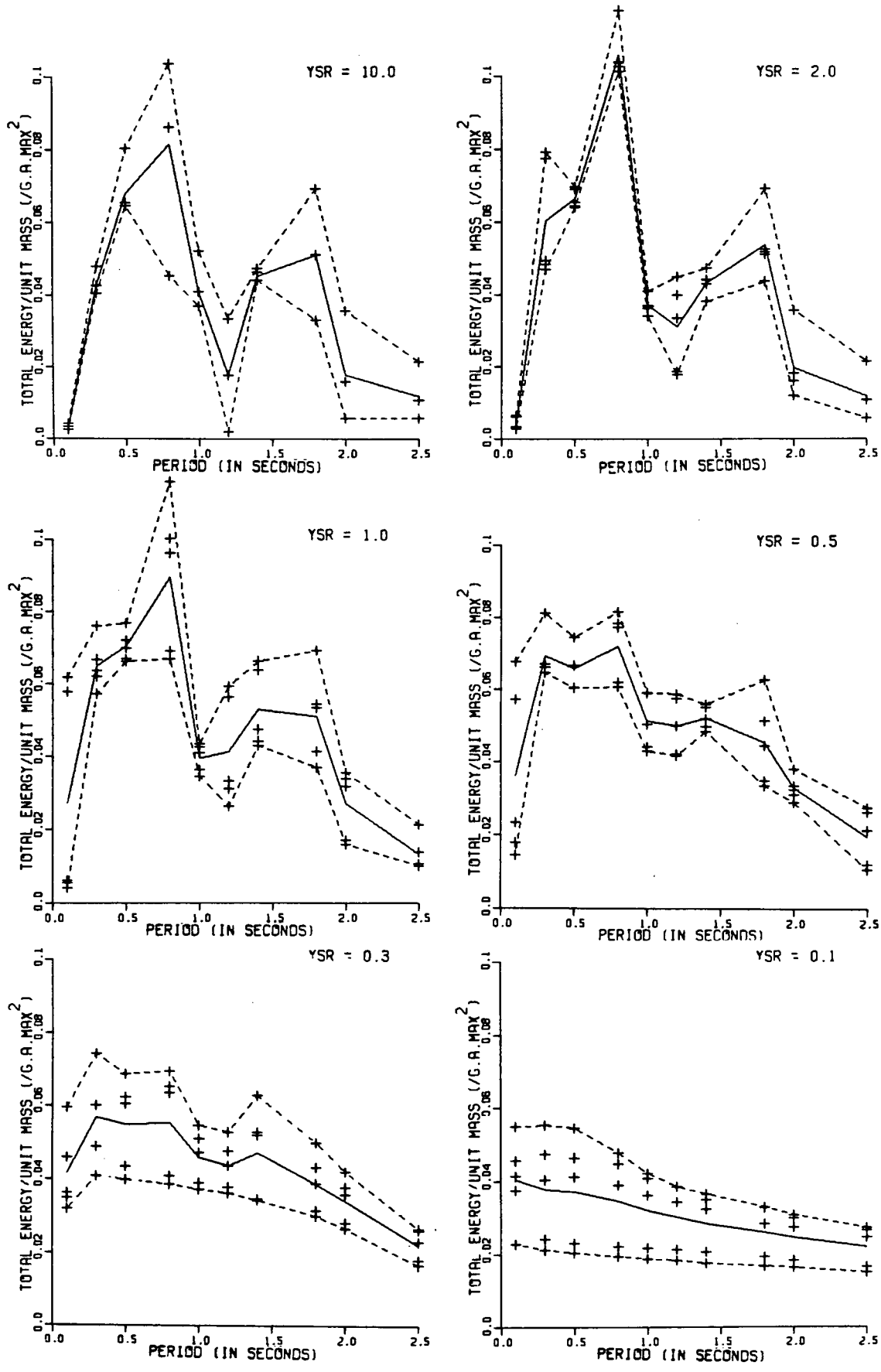


FIG. 3.5 MEANS AND DEVIATIONS IN TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO TAFT N69W.

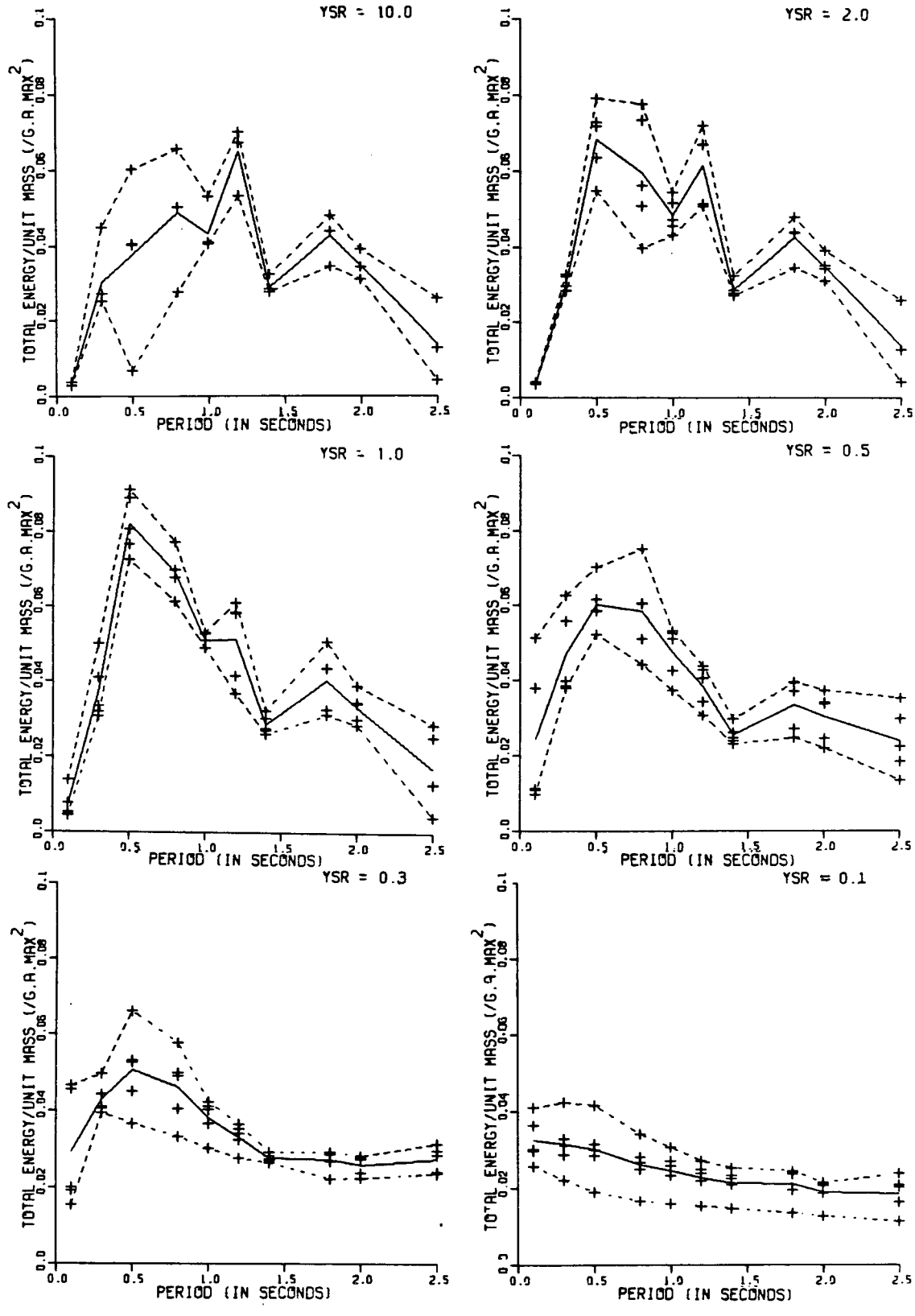


FIG. 3.6 MEANS AND DEVIATIONS IN TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO EL CENTRO N.S.

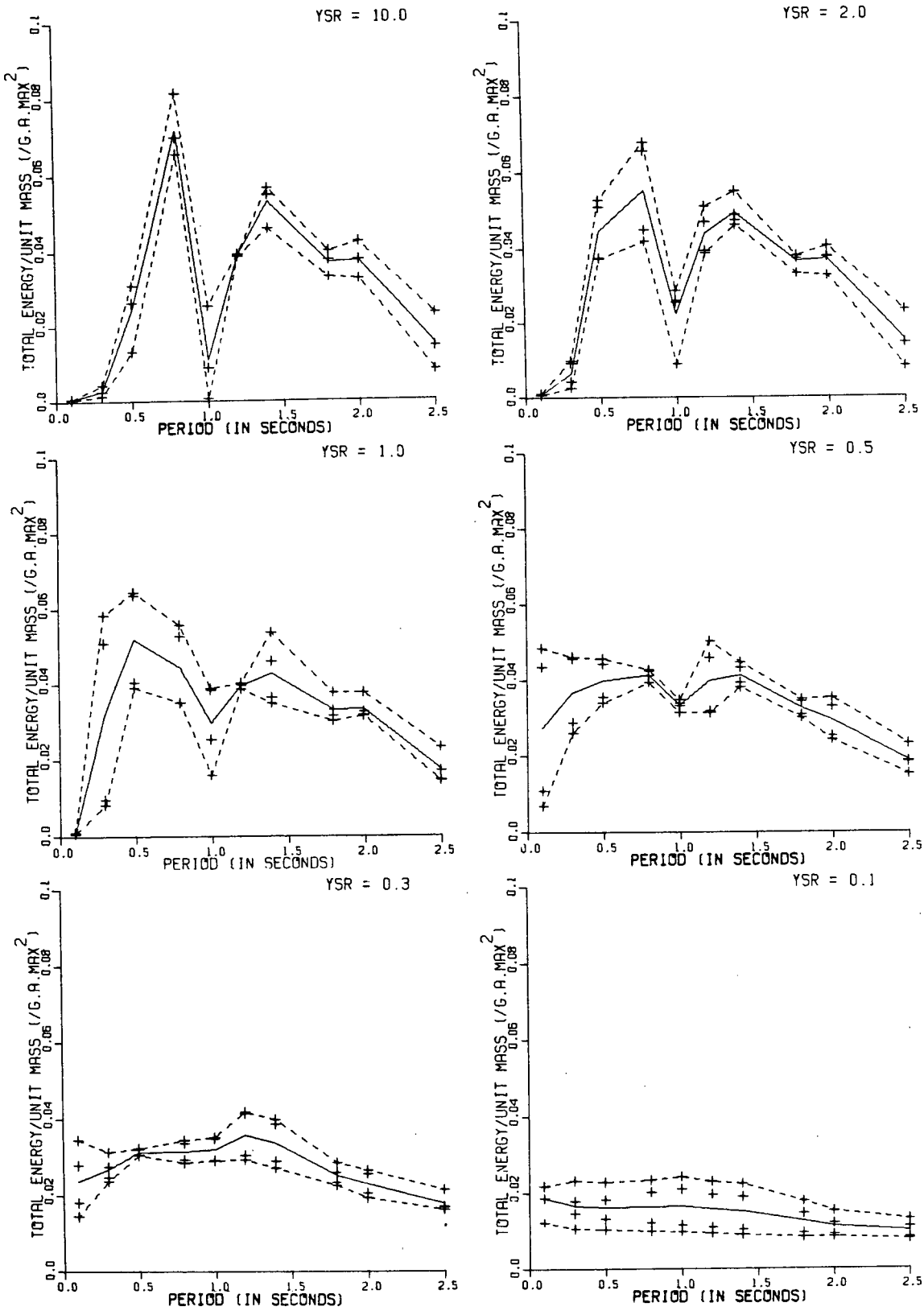


FIG. 3.7 MEANS AND DEVIATIONS IN TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO PARKFIELD N65E.

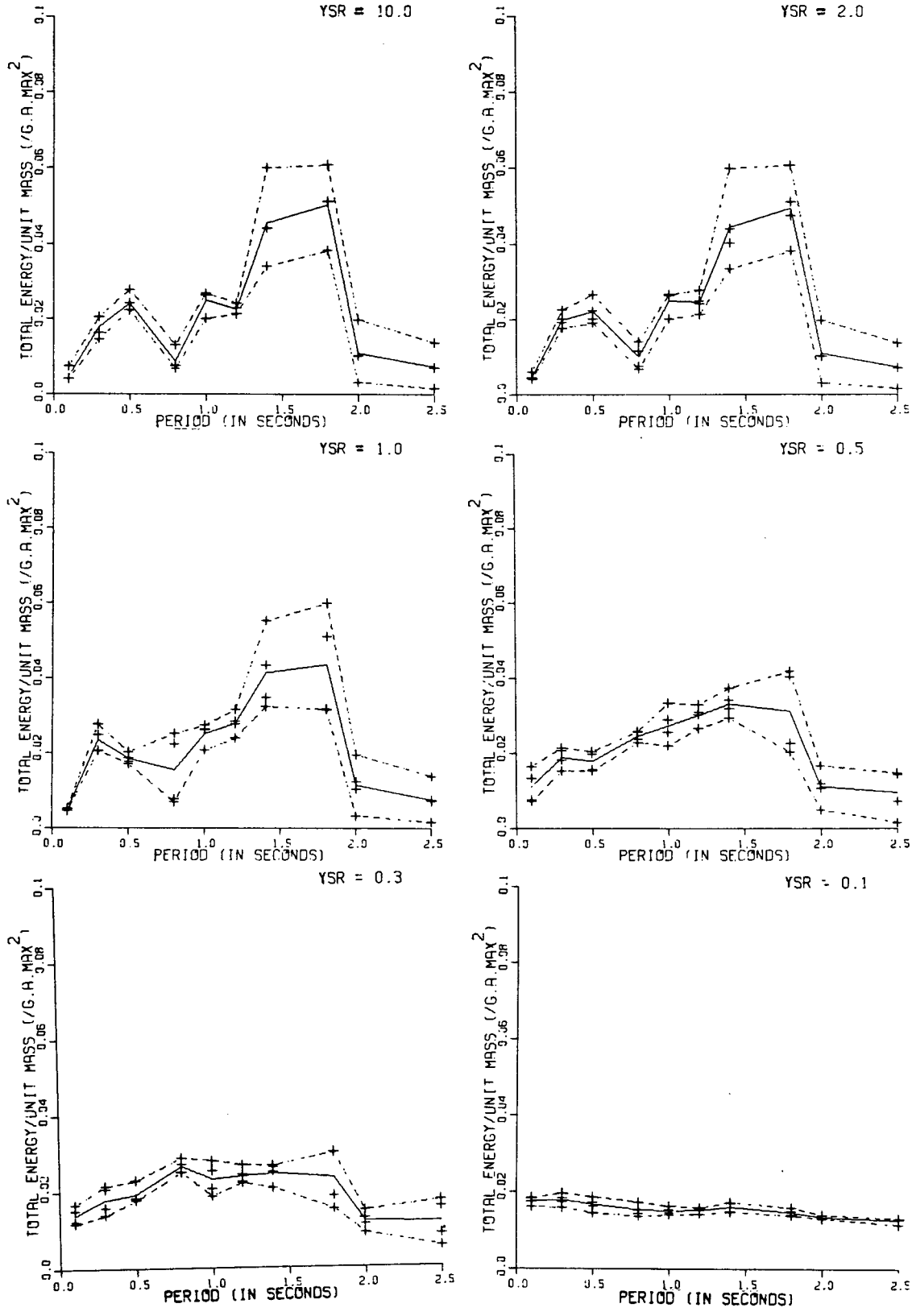


FIG. 3.8 MEANS AND DEVIATIONS IN TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO PACOIMA S16E.

3.2.2 Effect of Earthquake Record on Total Energy Dissipated

The quantity of total energy dissipated by the systems studied is found to be effected by two factors associated with the ground motion. These factors are the strength and frequency content of the ground motion.

In this study the earthquake strength is assumed proportional to the square of the maximum peak ground acceleration.*

The periods at which maximum and minimum values of total energy dissipated occur depends on the energy/frequency content of the earthquake record used. For the Taft, El Centro and Parkfield records the maxima occur at periods between 0.5 and 1.0 Sec. However, in the Pacoima S16E record the maxima occur at periods between 1.5 and 2.0 Secs. Also this record contains remarkably little energy for periods less than 1.0 Sec. Because of this the Pacoima S16E spectra do not fit into the general pattern for spectra shape exhibited by the three other ground motion records.

These effects are shown in figs. 3.9 and 3.10.

* The square of a maximum peak ground acceleration enters, since in normalizing the earthquake record, by dividing by the peak ground acceleration prior to calculating the response of the systems, all response parameters are scaled by this factor. The energy, being a product of force and displacement, or velocity squared, thus becomes reduced by the peak ground acceleration squared.

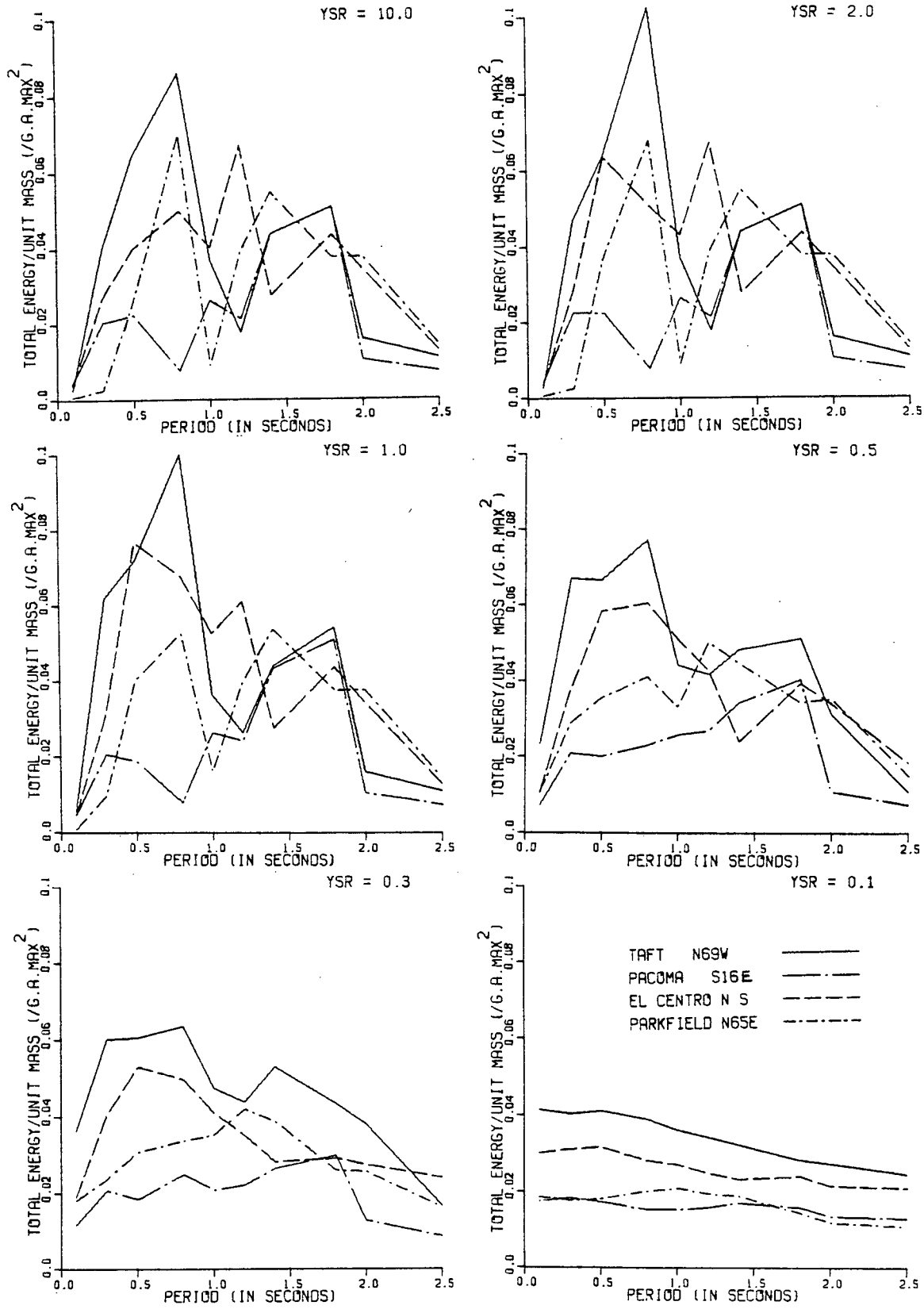


FIG. 3.9 EFFECT OF EARTHQUAKE RECORD ON TOTAL ENERGY DISSIPATED, ELASTO-PLASTIC SYSTEMS WITH 1.0% VISCOUS DAMPING.

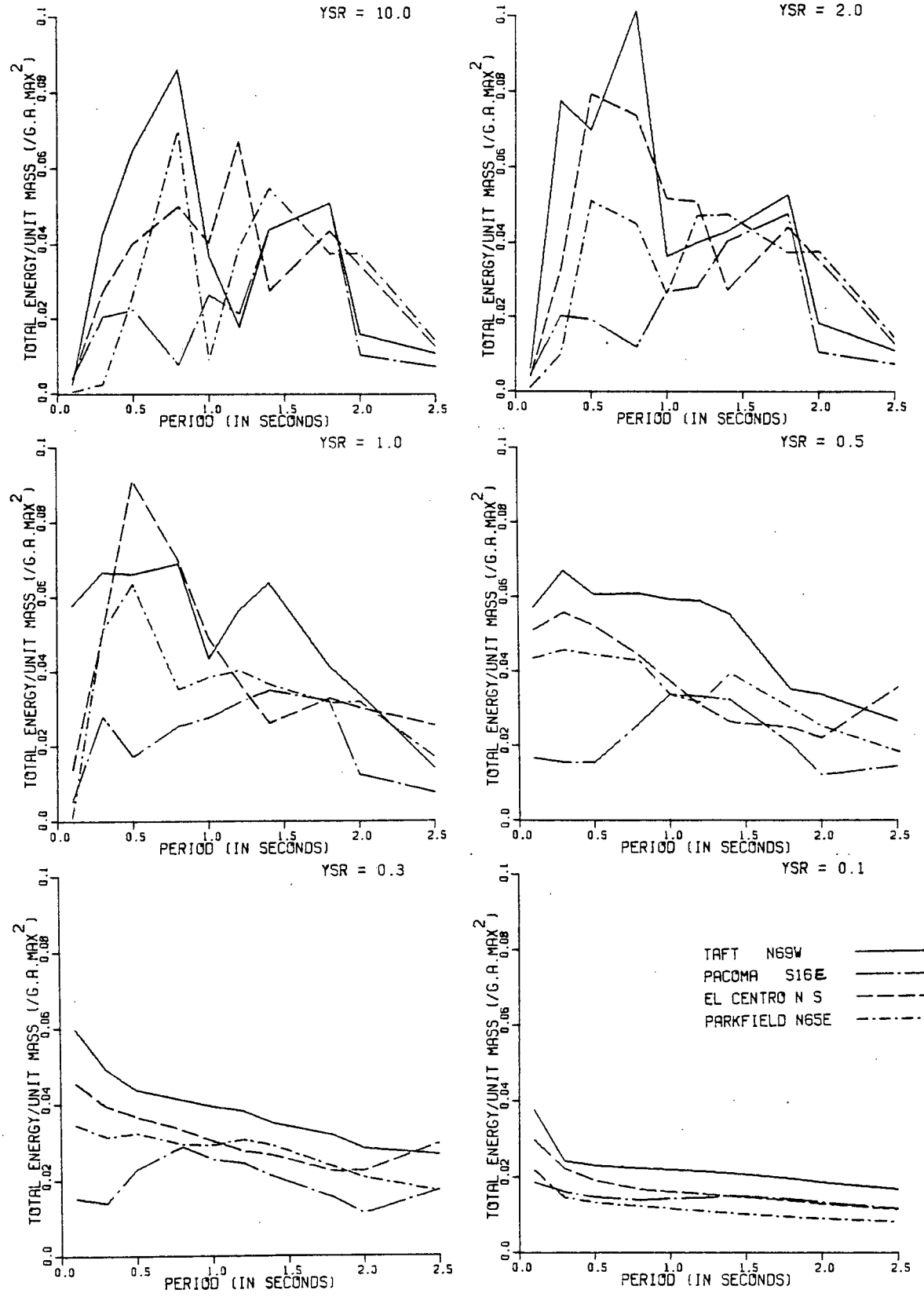


FIG. 3.10 EFFECT OF EARTHQUAKE RECORD ON TOTAL ENERGY DISSIPATED. TRI-LINEAR SYSTEMS WITH 1.0% VISCOUS DAMPING.

3.2.3 Effect of Material Hysteretic Properties on Total Energy Dissipated

The effect of varying material Hysteretic properties on total energy dissipated by systems can be seen in figs. 3.11, 3.12, 3.13 and 3.14.

For the strongest systems considered (YSR = 10.0) the total energy dissipated is identical for all material types. This is because all these systems remained within the elastic range and no non-linear effects influenced the response.

In the response of the weaker systems the effect of the differences in hysteretic behaviour is noticeable. The total energy dissipated can vary by up to 50% for some individual systems. For the weakest systems, YSR = 0.1, the Tri-linear systems form the lower bound. Tri-linear systems generally seem to be less influenced by the energy frequency content of the earthquake record.

The variations caused by different hysteretic behaviour do not effect the general pattern and shape of the spectra.

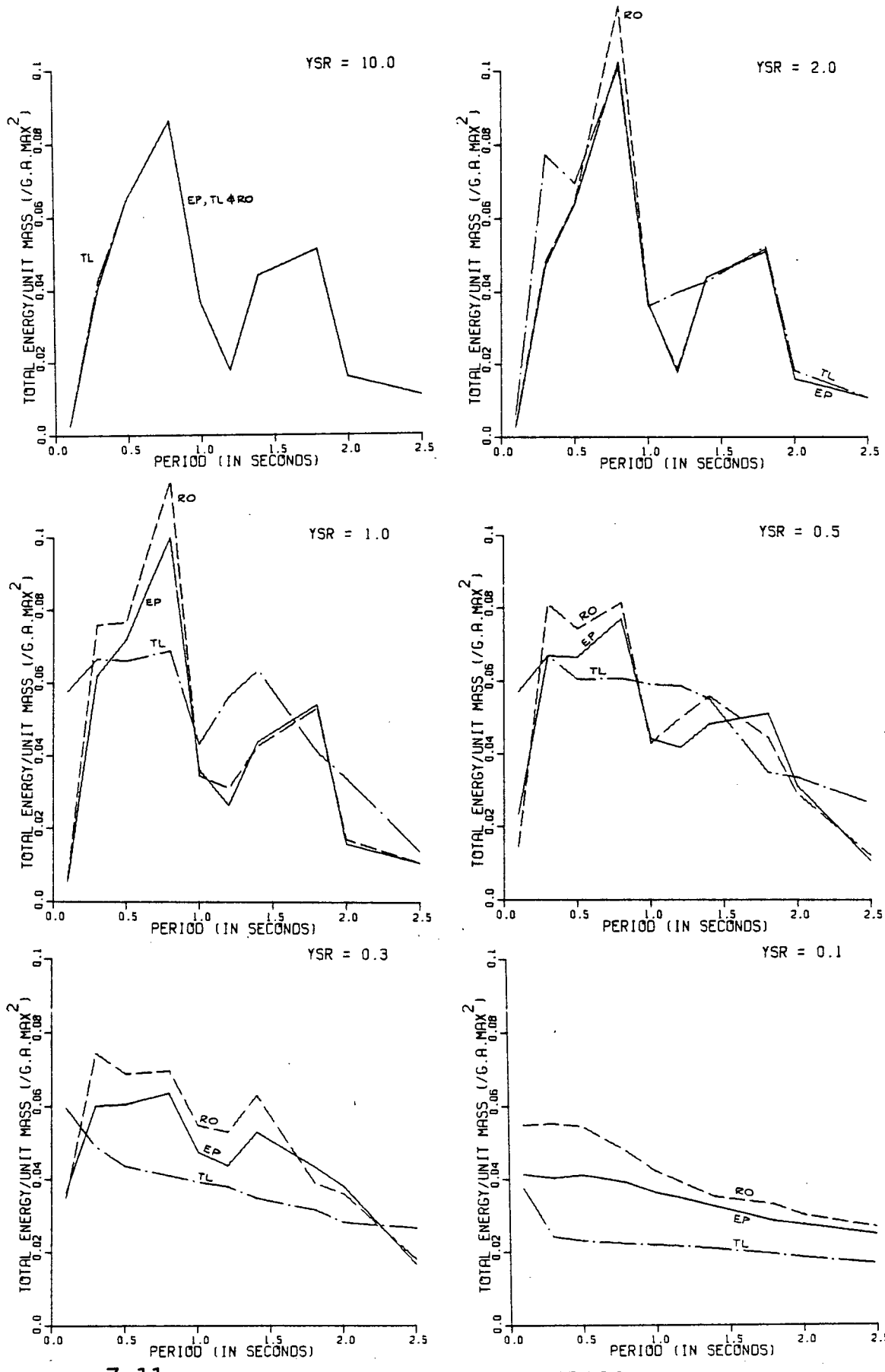


FIG. 3.11 EFFECT OF MATERIAL HYSTERSIS ON TOTAL ENERGY DISSIPATED. SYSTEMS SUBJECTED TO TAFT N69W WITH 1% VISCOUS DAMPING.

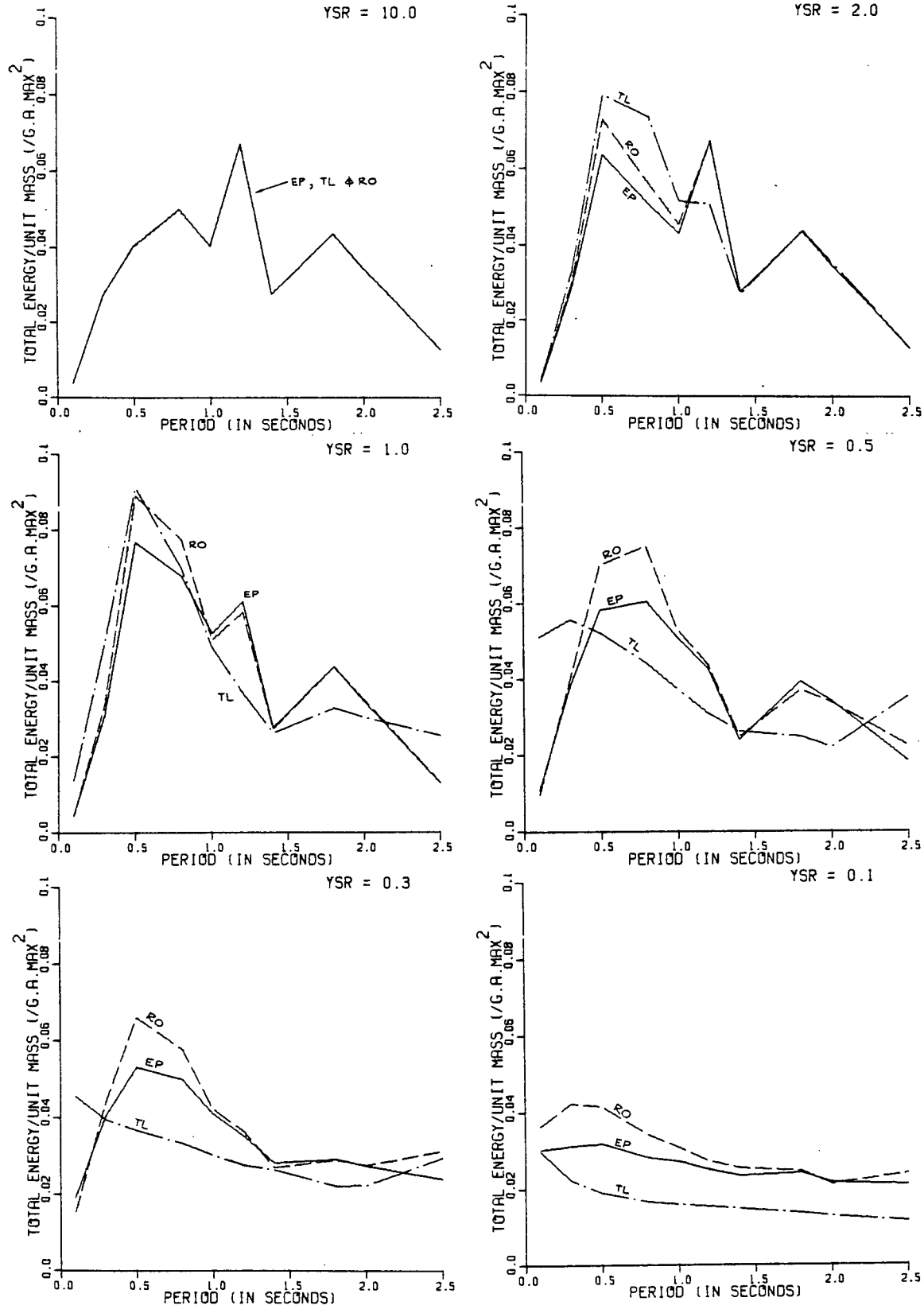


FIG. 3.12 EFFECT OF MATERIAL HYSTERSIS ON TOTAL ENERGY DISSIPATED. SYSTEMS SUBJECTED TO EL CENTRO N.S. WITH 1% VISCOUS DAMPING.

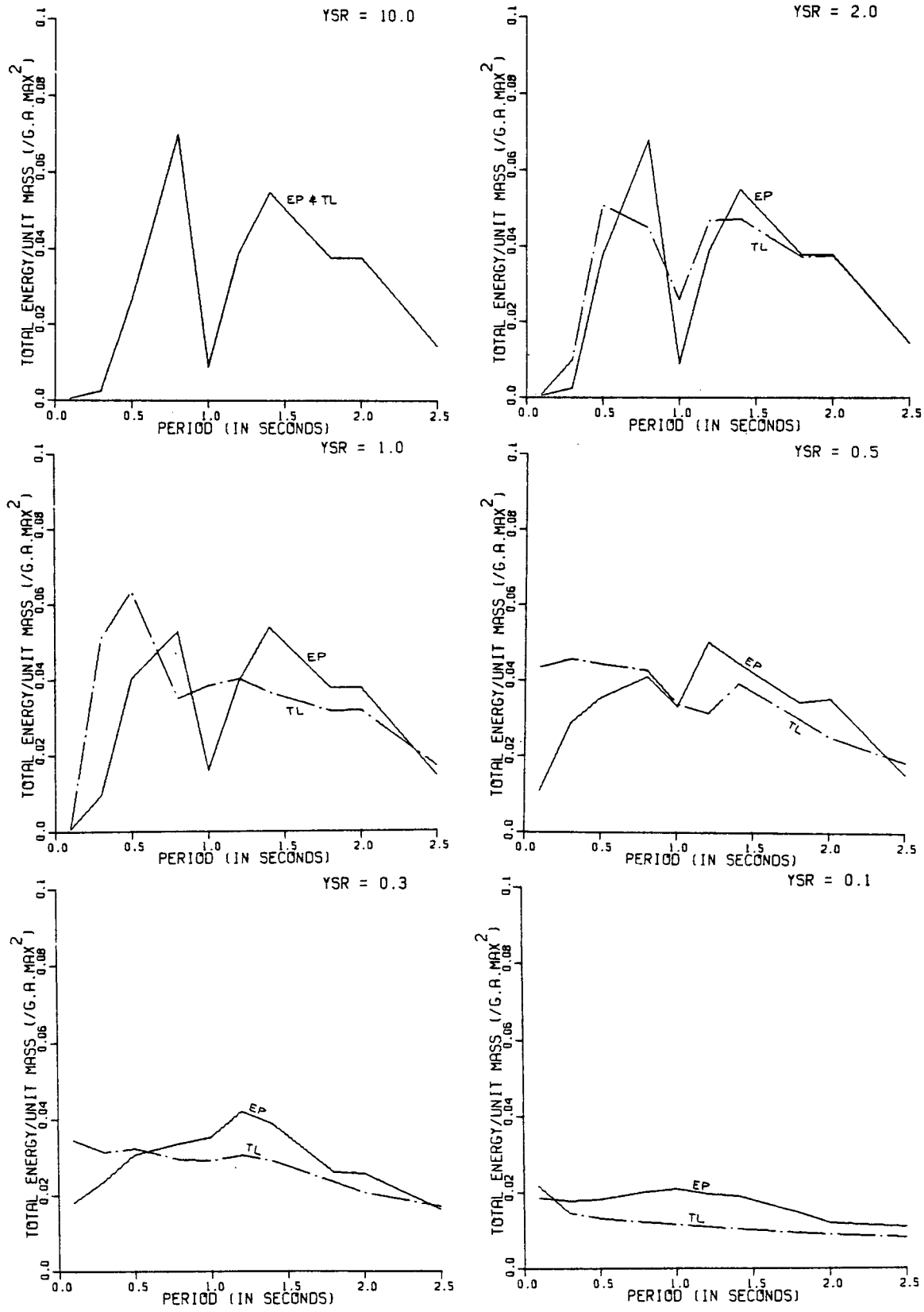


FIG. 3.13 EFFECT OF MATERIAL HYSTERSIS ON TOTAL ENERGY DISSIPATED. SYSTEMS SUBJECTED TO PARKFIELD N65E WITH 1% VISCOUS DAMPING.

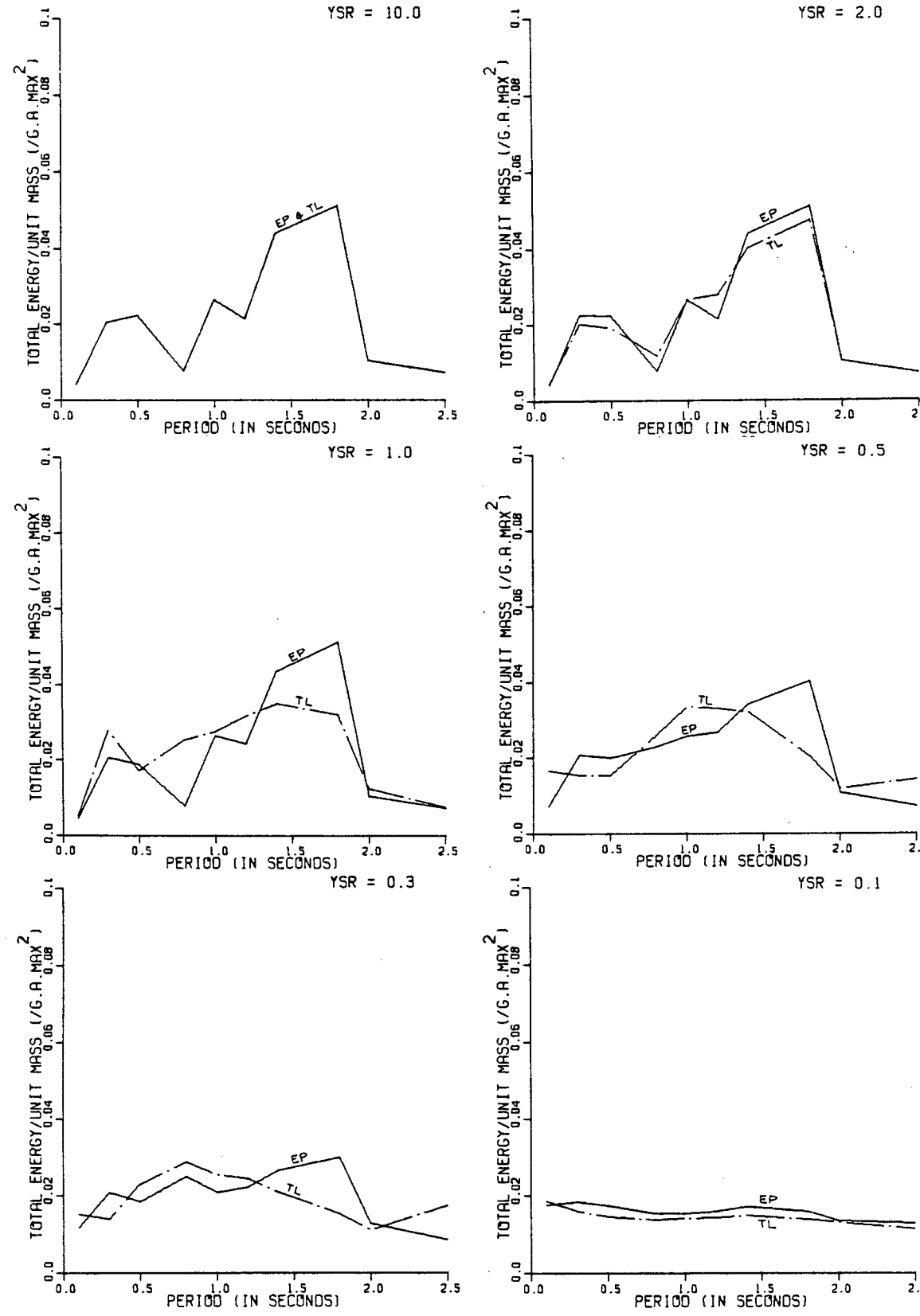


FIG. 3.14 EFFECT OF MATERIAL HYSTERSIS ON TOTAL ENERGY DISSIPATED. SYSTEMS SUBJECTED TO PACOIMA S16E WITH 1% VISCOUS DAMPING.

3.2.4. Effect of Viscous Damping on Total Energy Dissipated

The effect of varing amounts of viscous damping on the total energy dissipated is shown in figs. 3.15, 3.16, 3.17 and 3.18.

The general effect of increasing damping from 0 to 5% is seen to be small and of the order of 10% to 20% for the majority of systems studied. The effect of damping is more important for the stronger systems. For one or two isolated systems in this strong range the effect of increasing damping from 0% to 1% can increase the total energy dissipated by a factor of four. However these are exceptions that do not fit into the general pattern produced in the majority of systems.

For systems having YSR less than 1.0 the effect of varying damping is very small. For this range also the systems having higher values of viscous damping form an upper bound on the total energy dissipated.

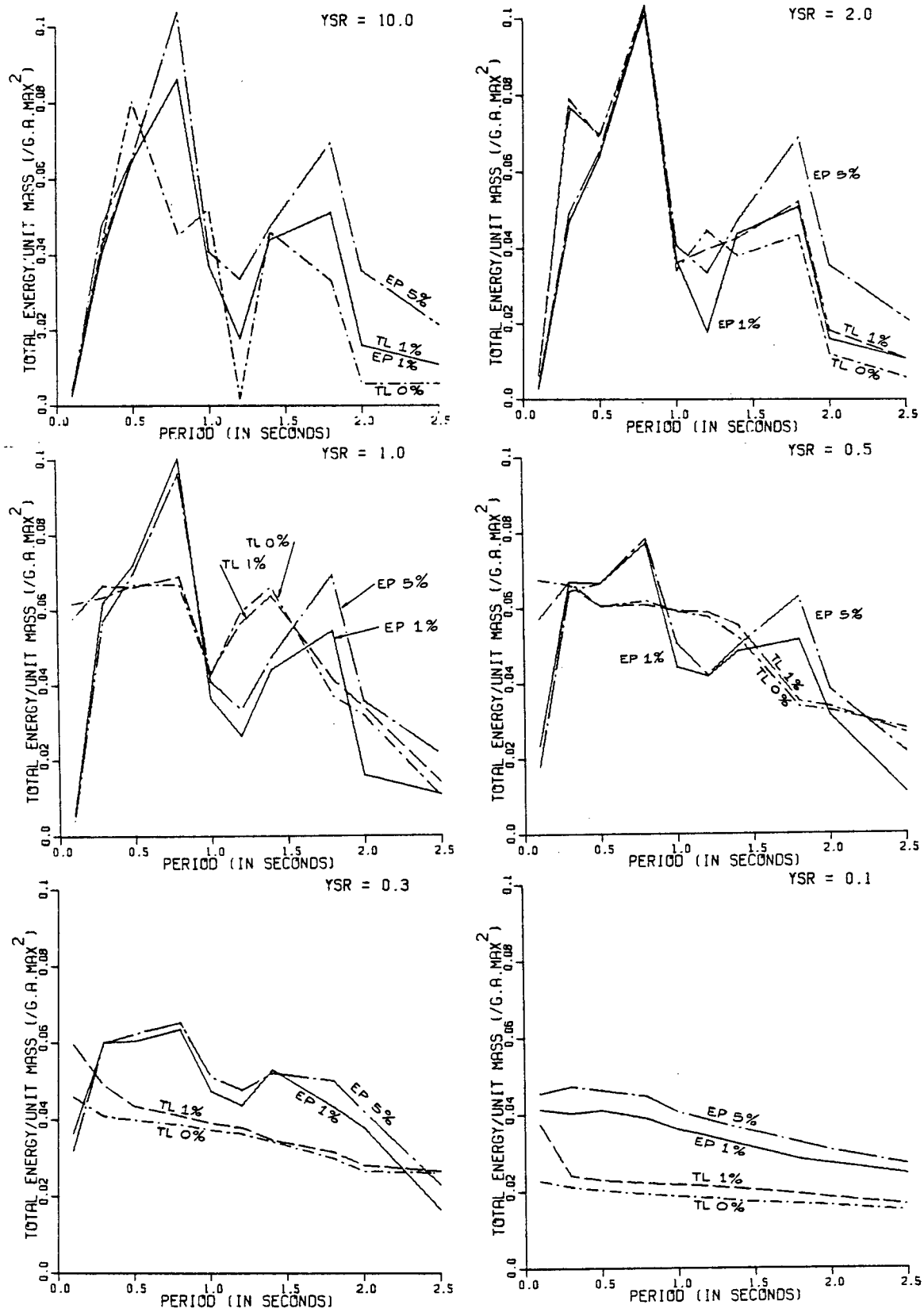


FIG. 3.15 EFFECT OF VISCOUS DAMPING ON TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO TAFT N69W.

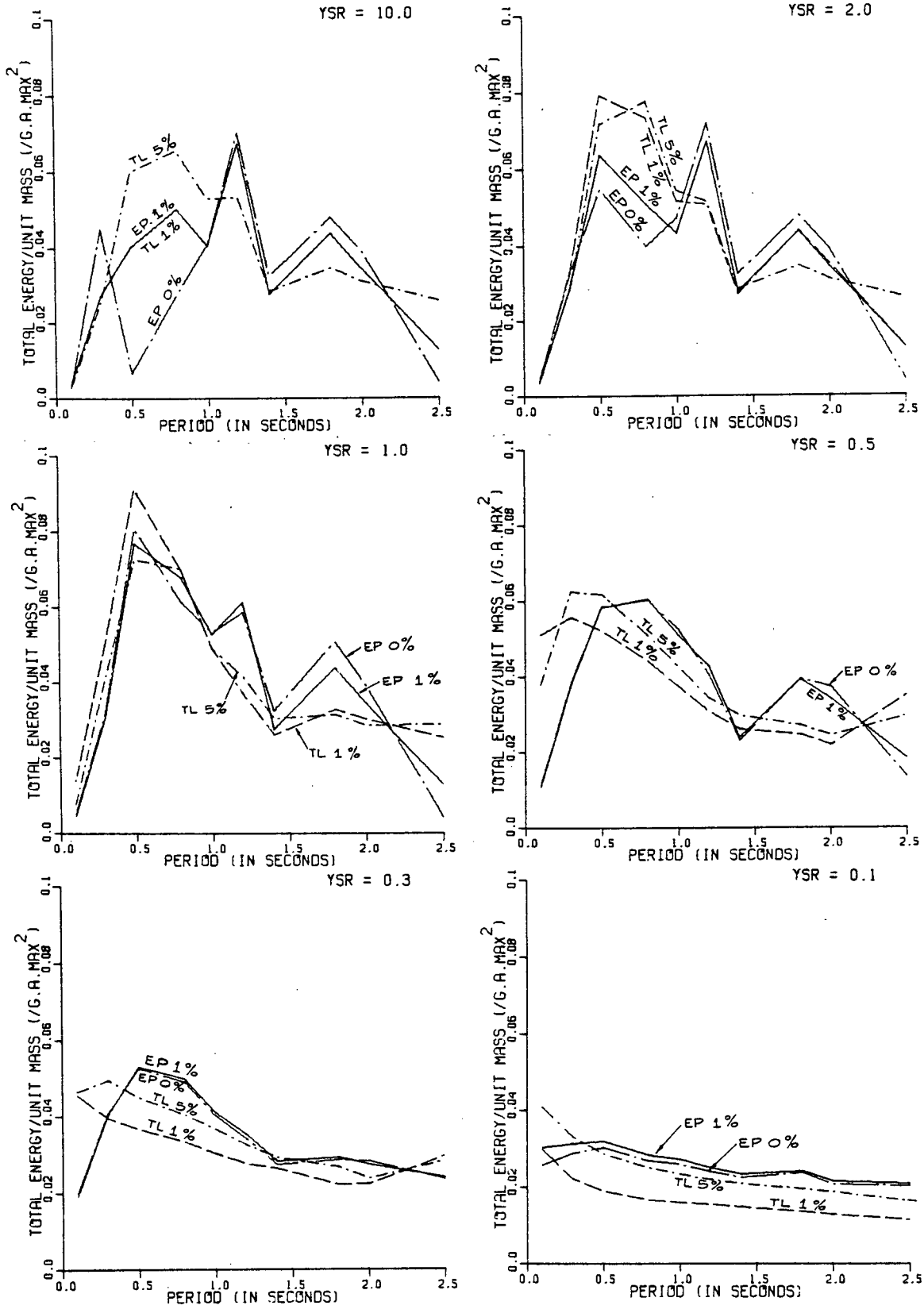


FIG. 3.16 EFFECT OF VISCOUS DAMPING ON TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO EL CENTRO N.S.

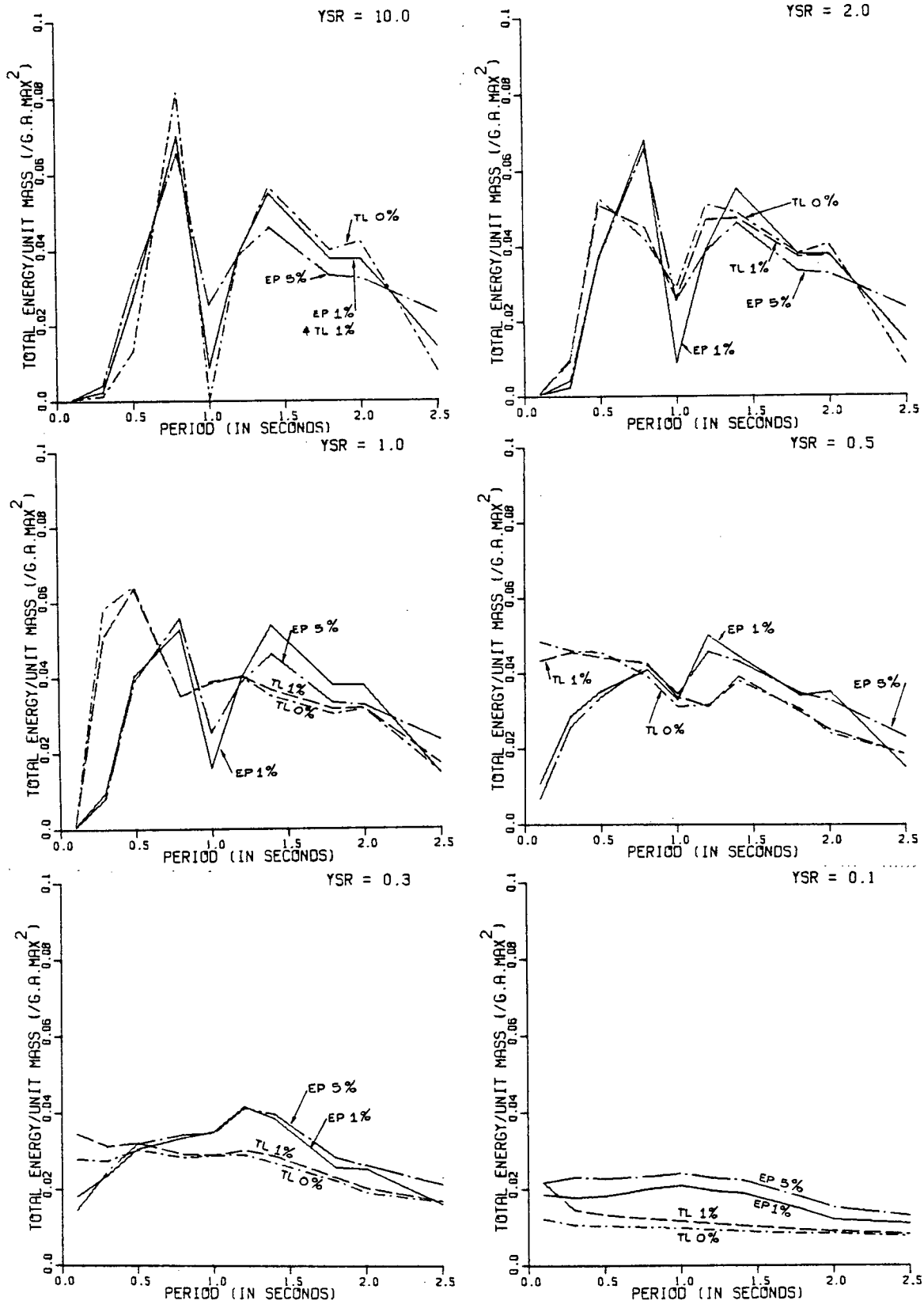


FIG. 3.17 EFFECT OF VISCOUS DAMPING ON TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO PARKFIELD N65E.

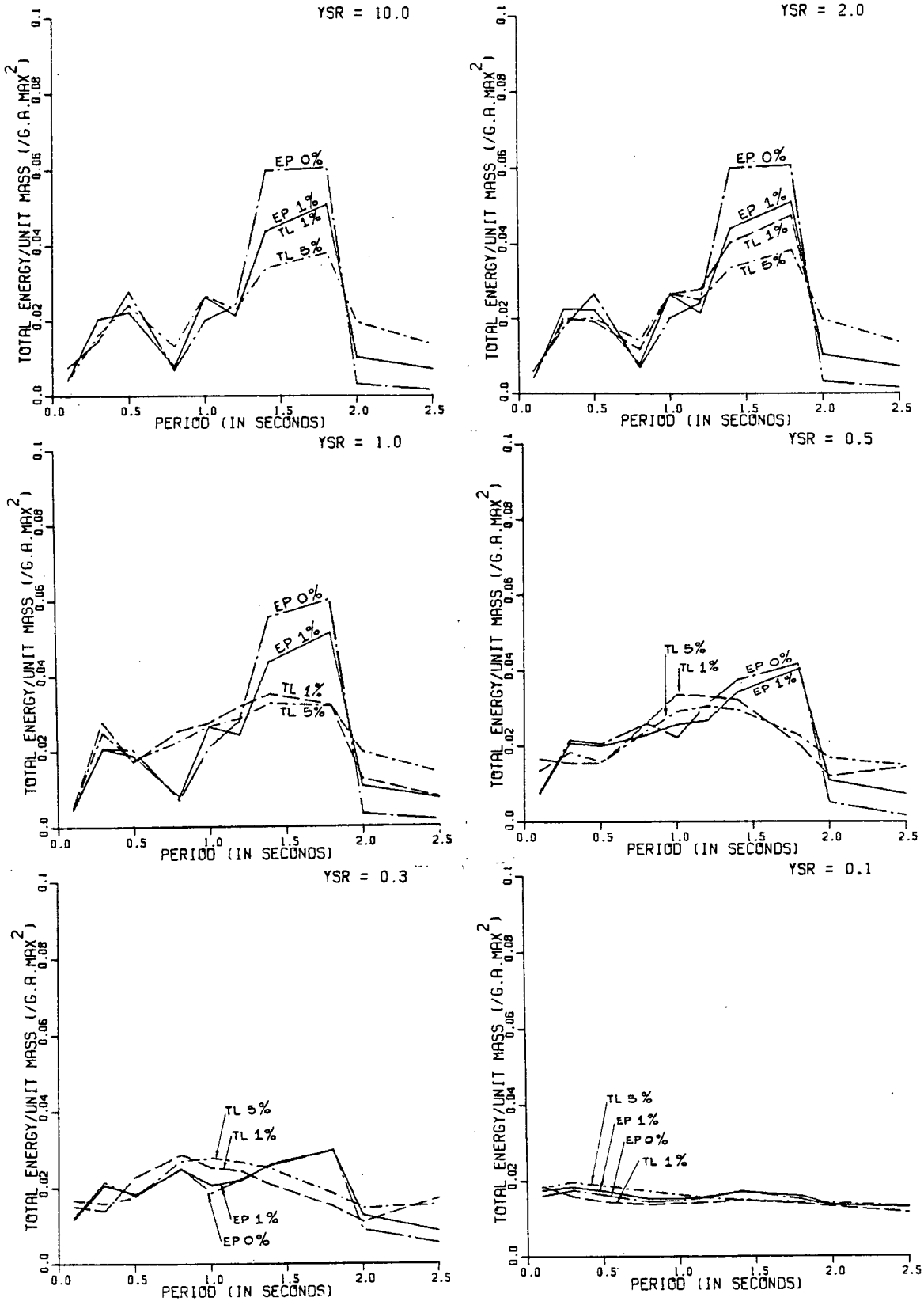


FIG. 3.18 EFFECT OF VISCOUS DAMPING ON TOTAL ENERGY DISSIPATED, FOR ALL SYSTEMS SUBJECTED TO PACOIMA S16E.

3.3 Distribution of Energy Within the Systems

Of equal importance to the amount of total energy to be dissipated within the system, is the distribution of the energy to the various dissipating mechanisms which make up the system. There are two principal dissipating mechanisms in the systems considered in this present study. These are the energy dissipated by the hysteretic behaviour of the spring elements, and the energy dissipated by viscous dampers.

The distribution of the total energy dissipated to these mechanisms, and the manner and extent to which the distribution is affected by changes in the input parameters is studied in this section.

3.3.1. Effect of Yield Strength Ratio on Distribution of Energy Within Systems

The general effect of reducing the YSR is to increase the percentage of energy dissipated by hysteretic behaviour. However this general trend needs to be qualified for systems with YSR less than 1.0 depending on hysteretic properties, damping and period. These are discussed further in sections 3.3.3 and 3.3.4.

These trends can be seen for individual systems in fig. 3.19 and appendix A. When considering means for a number of combinations the trends still hold good as can be seen in figs. 3.20 and 3.21.

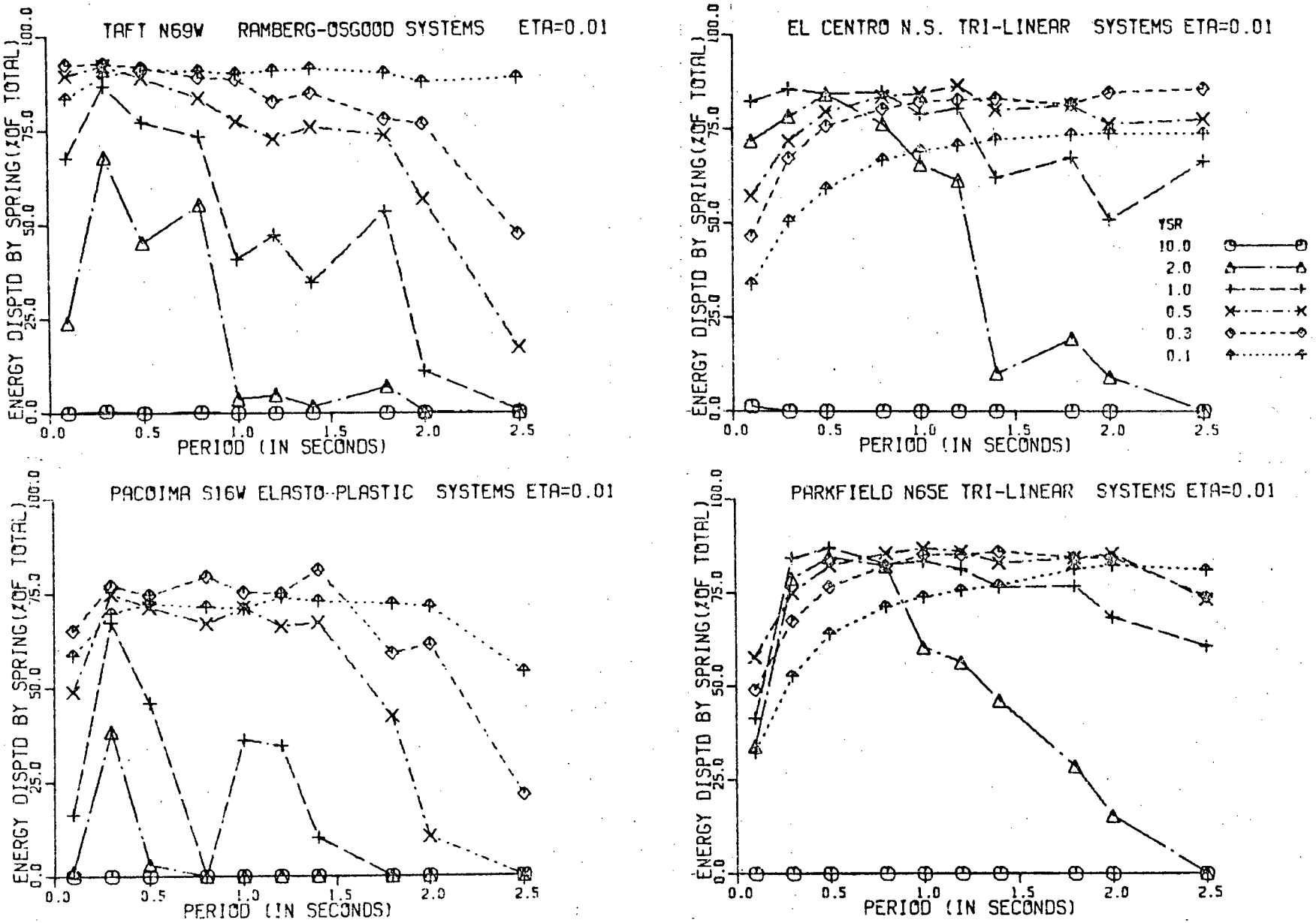


FIG. 3.19 EFFECT OF YIELD STRENGTH RATIO ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS. SOME TYPICAL RESULTS.

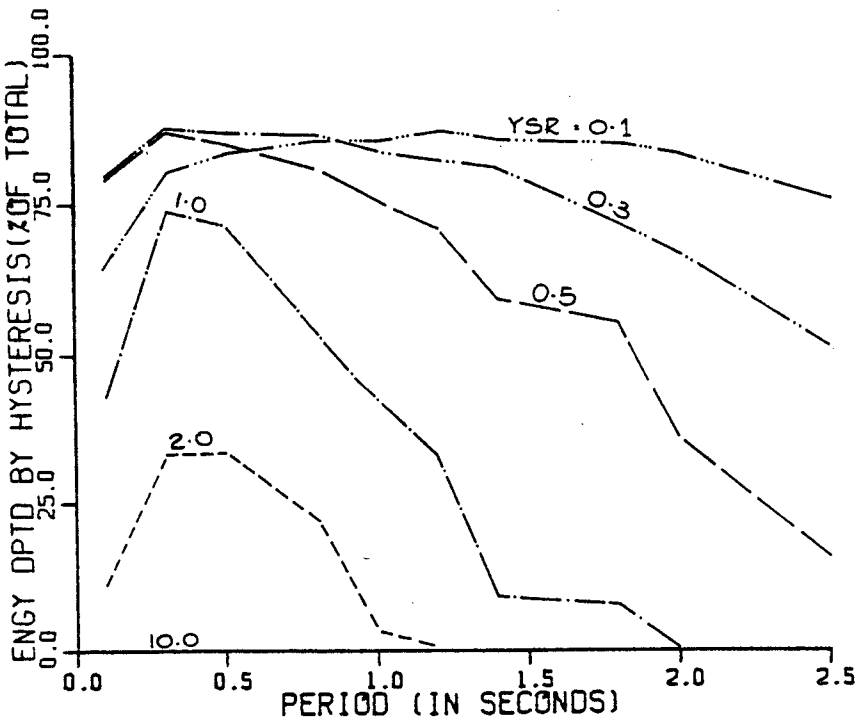


FIG. 3.20 EFFECT OF YSR ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS. MEANS FOR ALL ELASTO-PLASTIC SYSTEMS WITH 1% DAMPING.

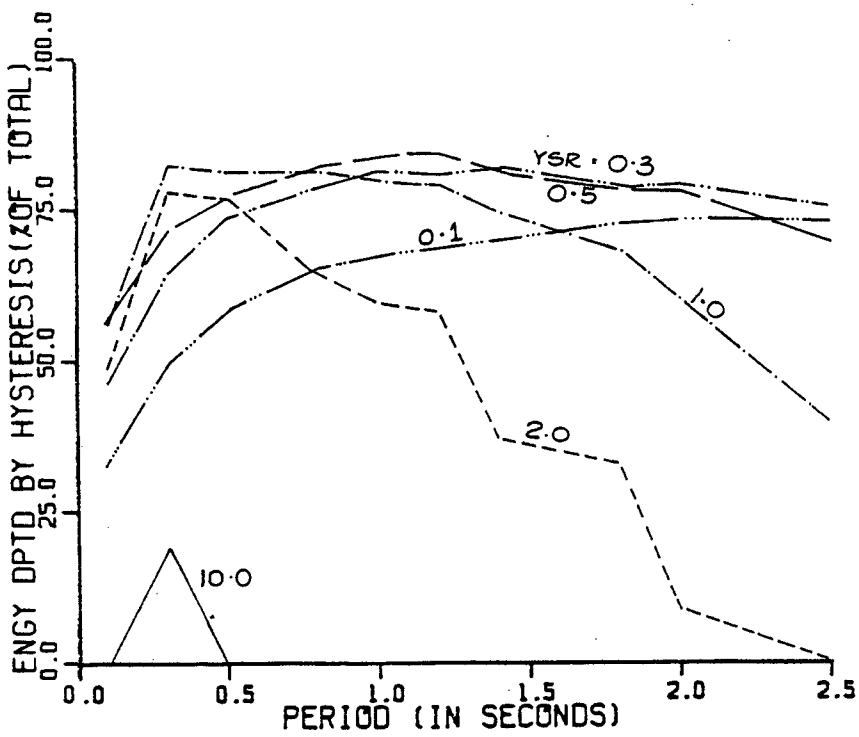


FIG. 3.21 EFFECT OF YSR ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS. MEANS FOR ALL TRI-LINEAR SYSTEMS WITH 1% DAMPING.

3.3.2 Effect of Earthquake Record on Distribution of Energy Within Systems

The effect of different earthquake records on the distribution of energy within the systems is shown in figs. 3.22 and 3.23. The distribution is seen to be relatively independent of the earthquake record used. In most instances it is observed that the results for the Pacoima S16E record form a lower bound. The curves representing the percentage of total energy dissipated in hysteresis are seen to fall into well defined patterns for each YSR and hysteretic property used. This fact is of great importance when considering the form of a design procedure based on energy considerations, and is elaborated upon in section 3.9.

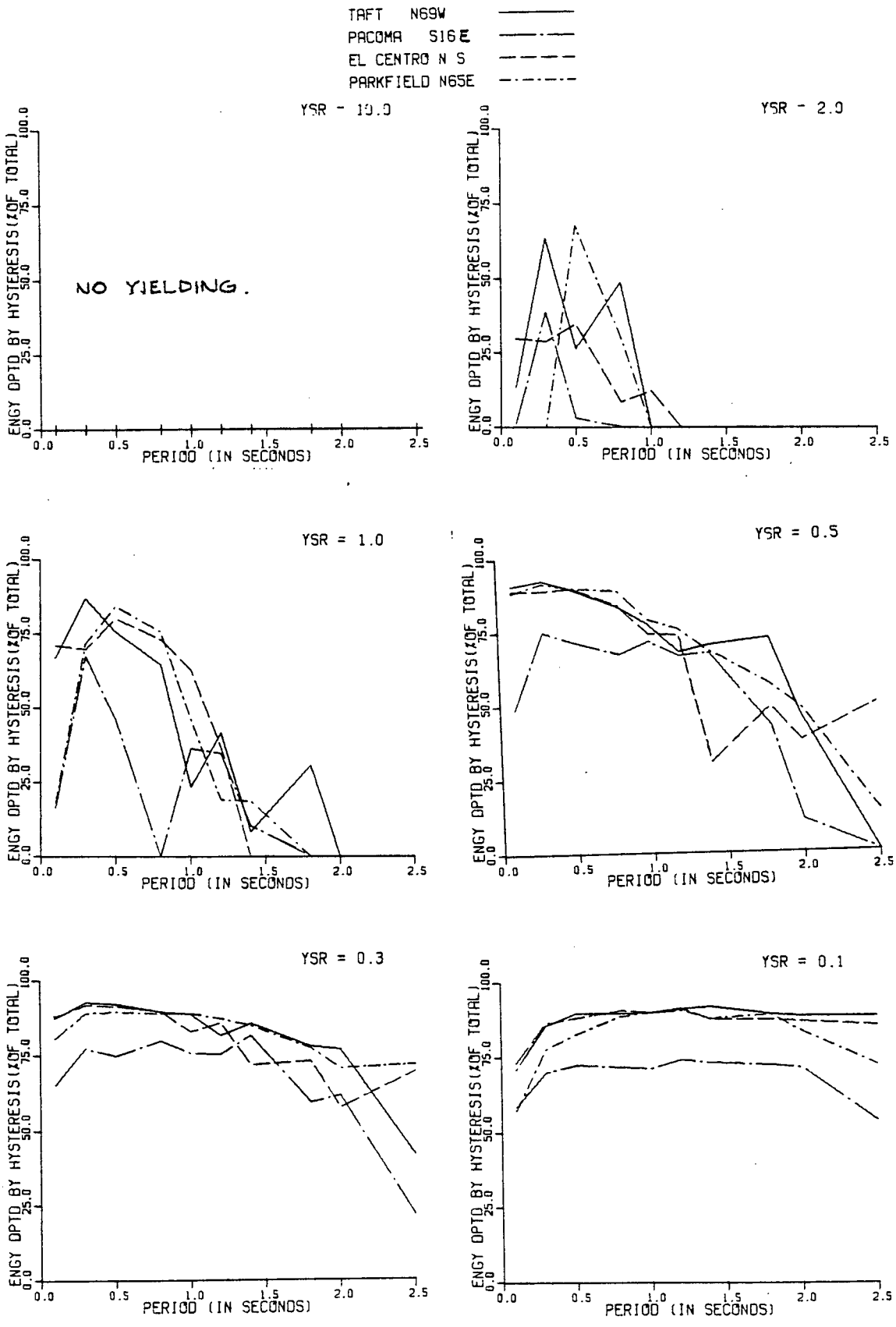


FIG. 3.22 EFFECT OF EARTHQUAKE RECORD ON DISTRIBUTION OF ENERGY WITHIN ELASTO-PLASTIC SYSTEMS WITH 1% VISCOUS DAMPING.

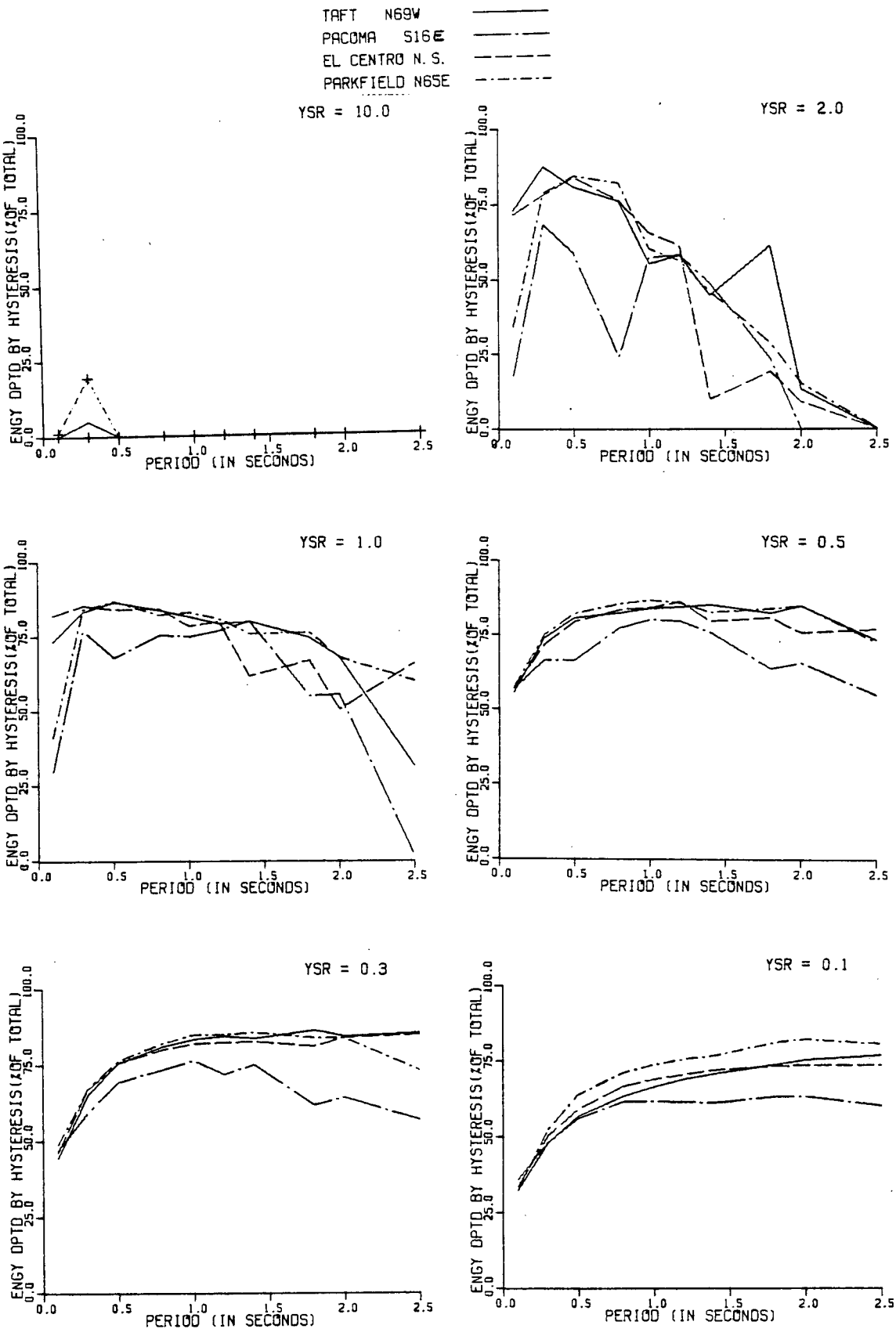


FIG. 3.23 EFFECT OF EARTHQUAKE RECORD ON DISTRIBUTION OF ENERGY WITHIN TRI-LINEAR SYSTEMS WITH 1% VISCOUS DAMPING.

3.3.3. Effect of Material Hysteretic Properties on Distribution of Energy Within Systems

A comparative study of the proportions of total energy dissipated by systems with different hysteretic properties is presented in figs. 3.24, 3.25, 3.26 and 3.27.

For the stronger systems, ie YSR = 2.0 and 1.0, the Tri-linear systems dissipate more energy in hysteresis than the Elasto - Plastic and Ramberg - Osgood systems. This difference reduces with reduction in YSR. For systems with YSR = 0.5 and 0.3 the Tri-linear systems form the upper bound for periods greater than 1.0 - 1.5 secs. The reverse of this is true for systems with periods less than 1.0 - 1.5 secs. and the Elasto-Plastic systems form the upper bound. The upper bound for the systems with YSR = 0.1 is seen to be the Elasto - Plastic and Ramberg - Osgood systems. These observations are true for the results of all four earthquake records studied.

The Ramberg - Osgood and Elasto - Plastic systems dissipate essentially the same proportions of energy. This is especially true for weaker systems where it can be observed that the two are for all practical purposes identical.

The difference between the results produced by the degrading and non-degrading stiffness systems is observed to be such that any consideration of percentage of total energy dissipated must include the hysteretic properties of the spring elements as a variable.

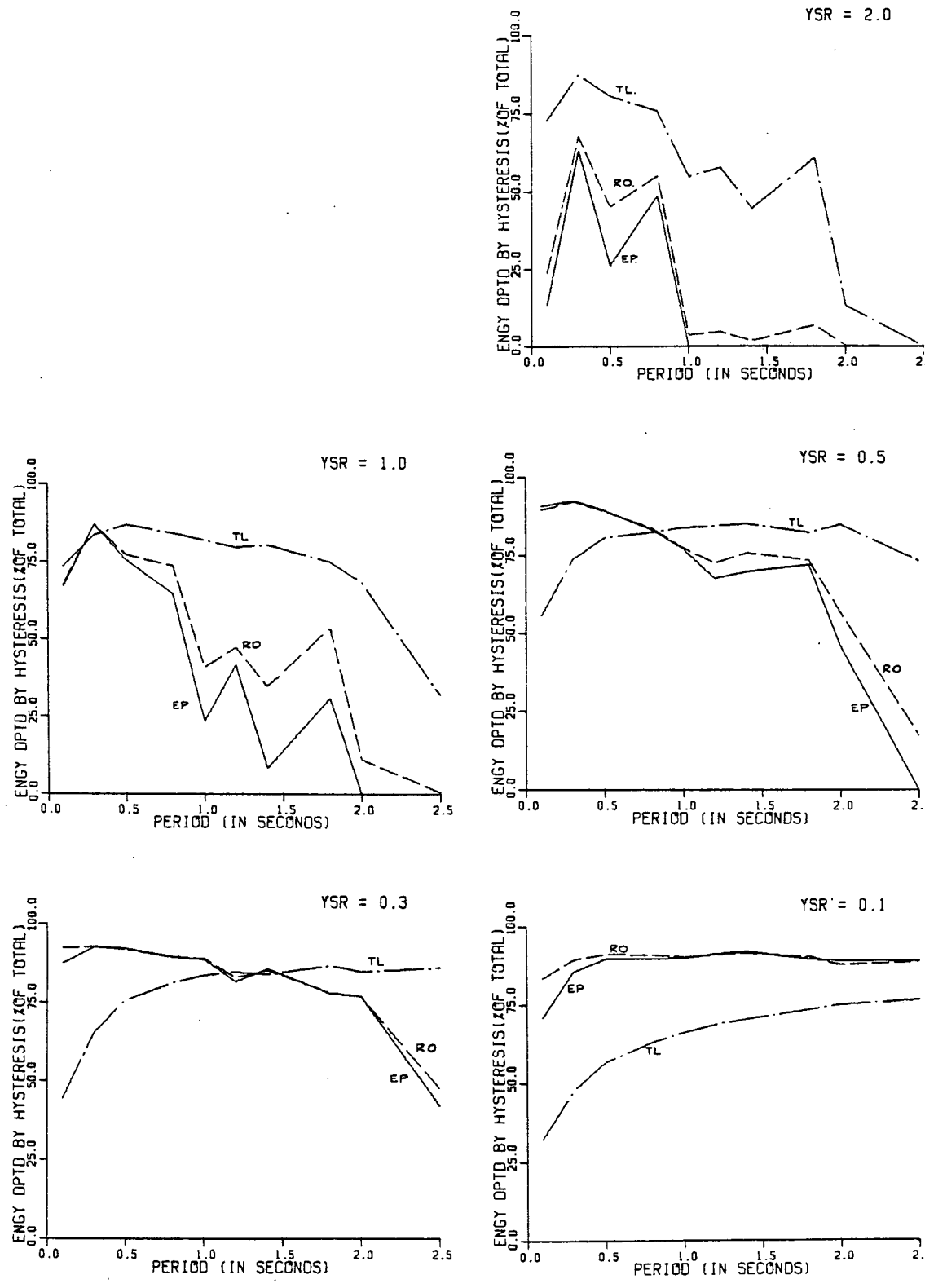


FIG. 3.24 EFFECT OF MATERIAL HYSTERETIC PROPERTIES ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS. FOR ALL SYSTEMS SUBJECTED TO TAFT N69W WITH 1% DAMPING.

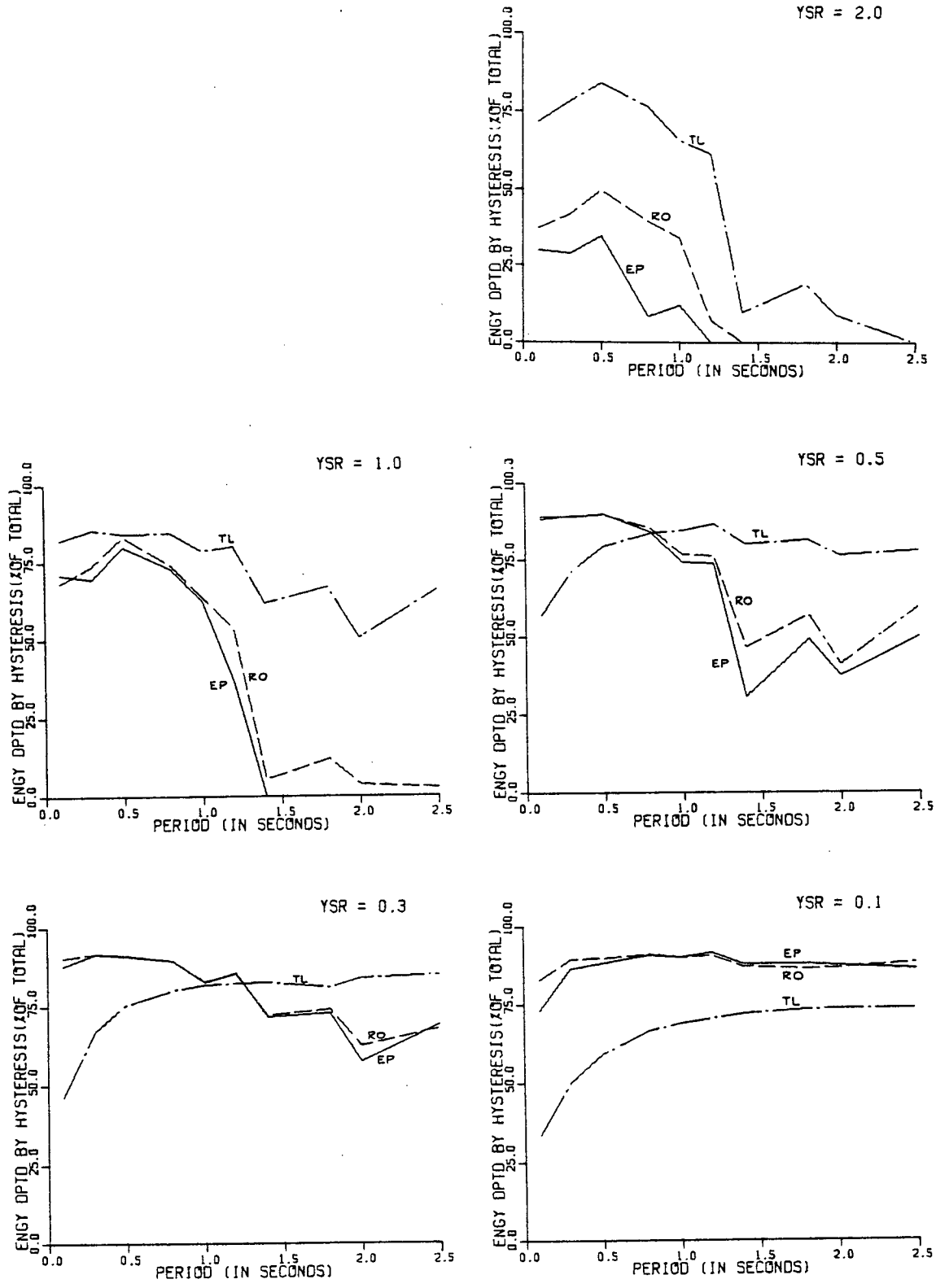


FIG. 3.25 EFFECT OF MATERIAL HYSTERETIC PROPERTIES ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS. FOR ALL SYSTEMS SUBJECTED TO EL CENTRO N.S. WITH 1% DAMPING.

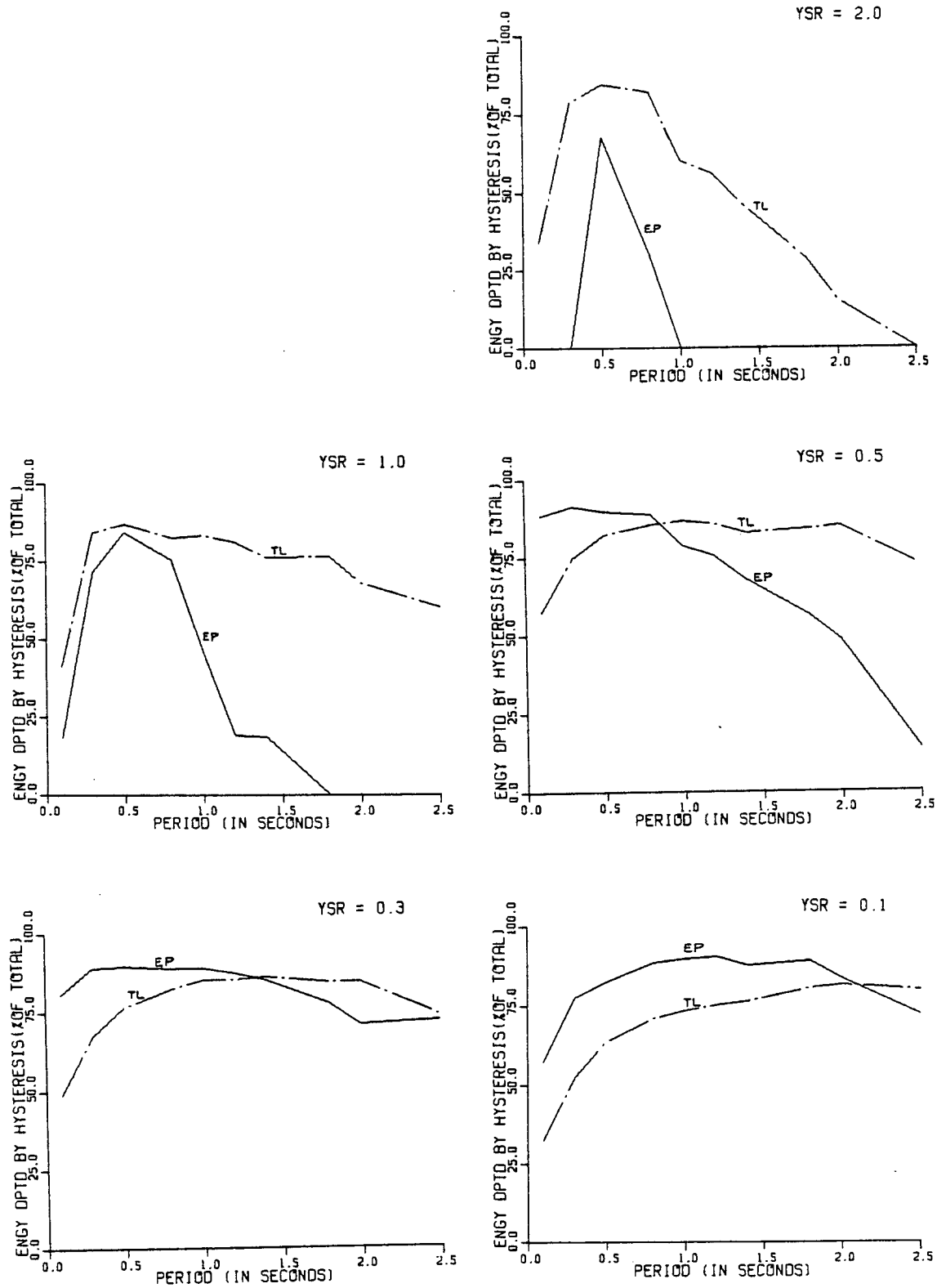


FIG. 3.26 EFFECT OF MATERIAL HYSTERETIC PROPERTIES ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS. FOR ALL SYSTEMS SUBJECTED TO PARKFIELD N65E WITH 1% DAMPING.

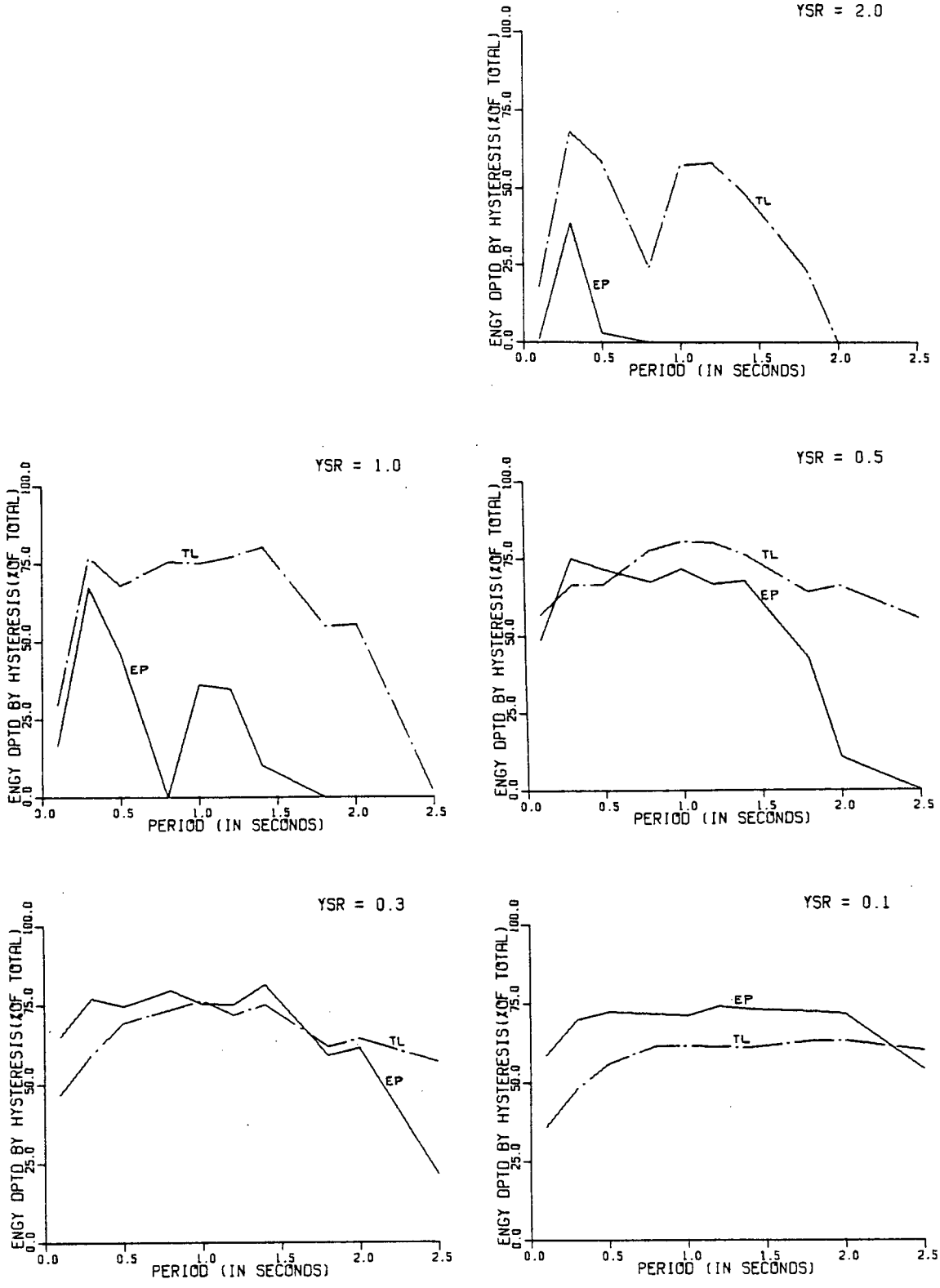


FIG. 3.27 EFFECT OF MATERIAL HYSTERETIC PROPERTIES ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS. FOR ALL SYSTEMS SUBJECTED TO PACOIMA S16E WITH 1% DAMPING.

3.3.4 Effect of Viscous Damping on Distribution of Energy Within Systems

The effect of varying amounts of viscous damping on the distribution of the total energy to be dissipated within systems is shown in figs. 3.28, 3.29, 3.30 and 3.31.

It is clear that increased amounts of viscous damping reduce the proportion of total energy dissipated by hysteresis. The extent of the reduction depends also on the hysteretic properties used and the period of the system.

The effect of variations in damping is considerably greater for the stronger systems having YSR = 1.0 or greater. Also the Tri-linear systems are more sensitive to changes in damping ratio.

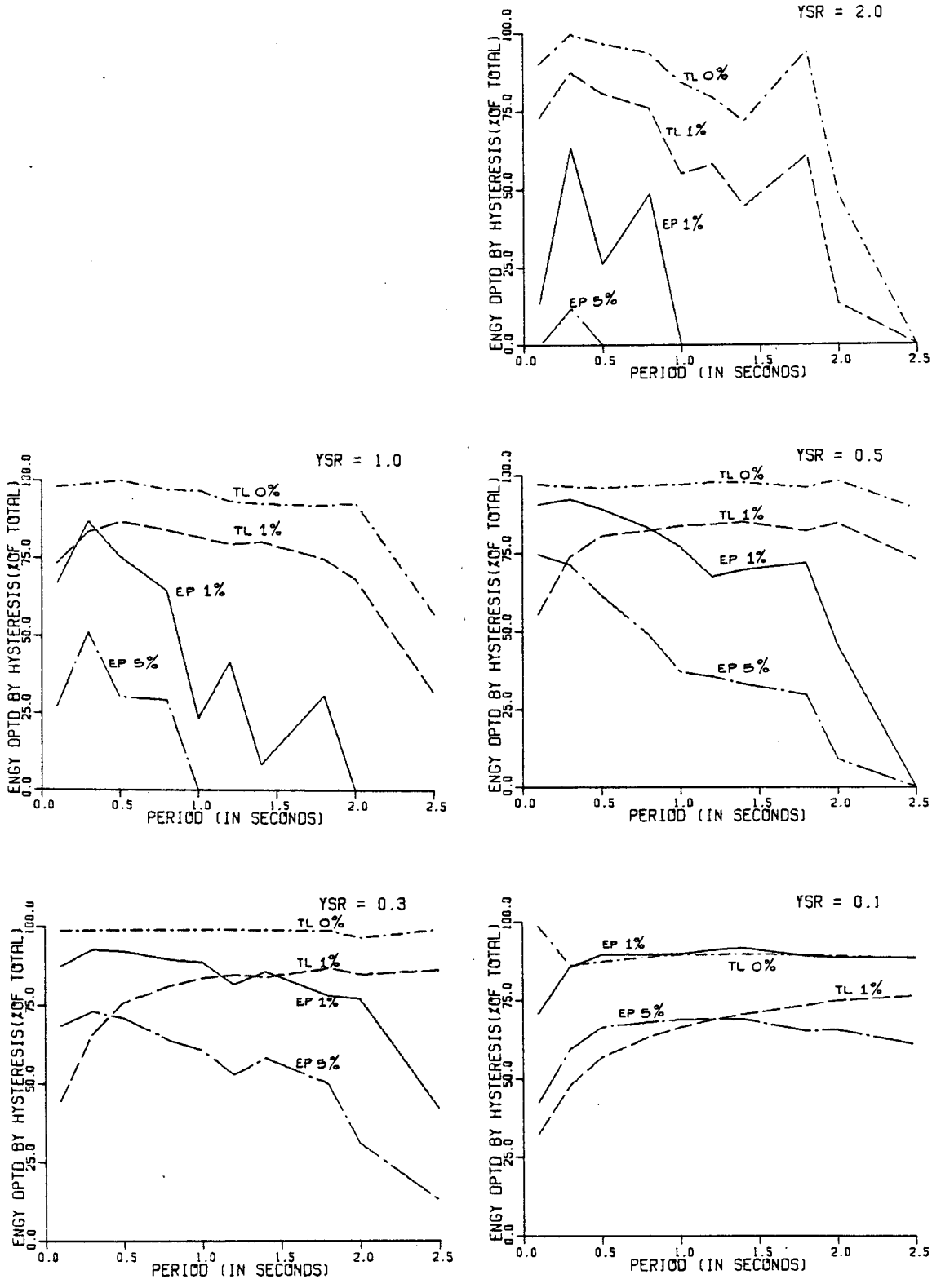


FIG. 3.28 EFFECT OF VISCOUS DAMPING ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS SUBJECTED TO TAFT N69E.

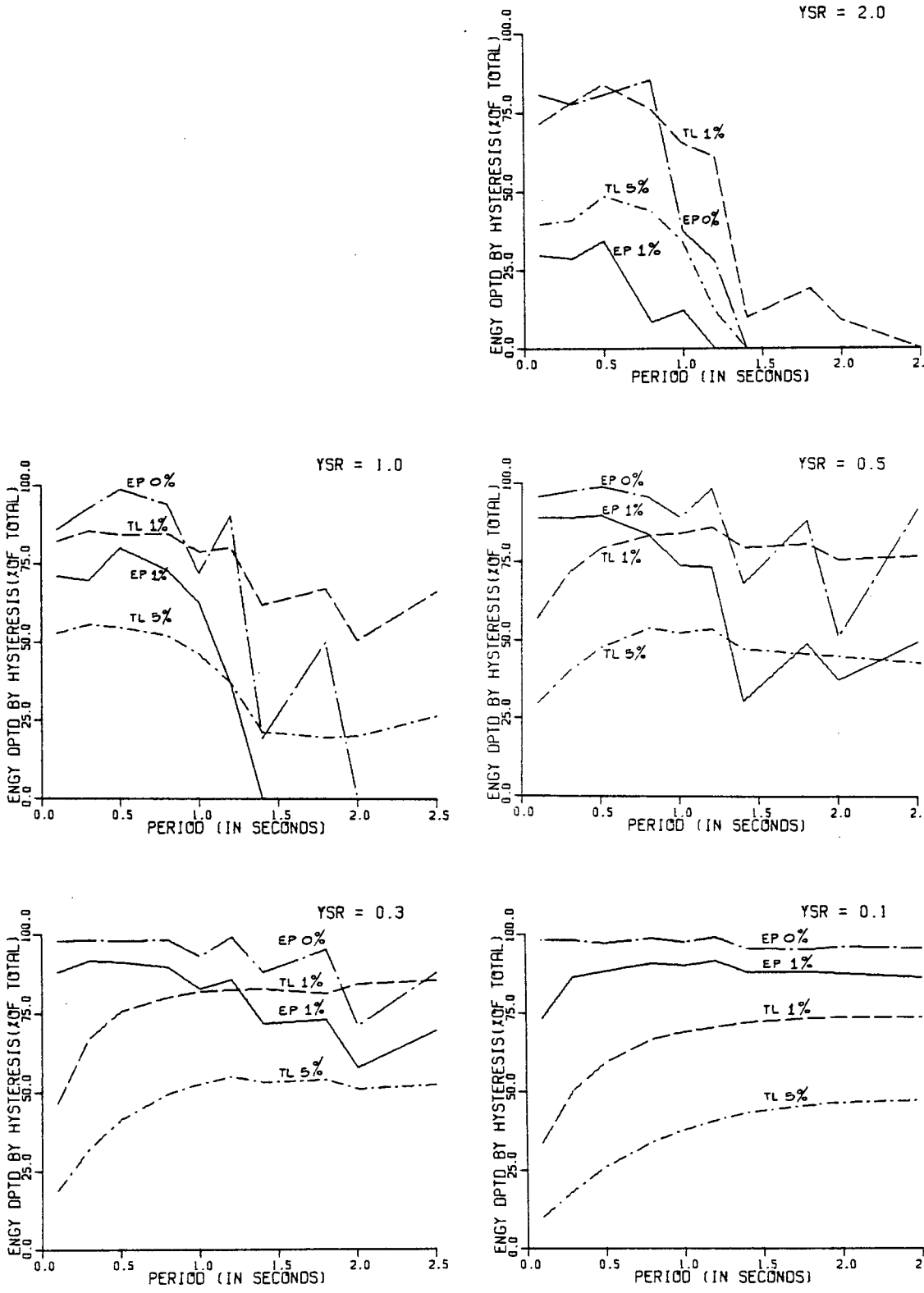


FIG. 3.29 EFFECT OF VISCOUS DAMPING ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS SUBJECTED TO EL CENTRO N.S.

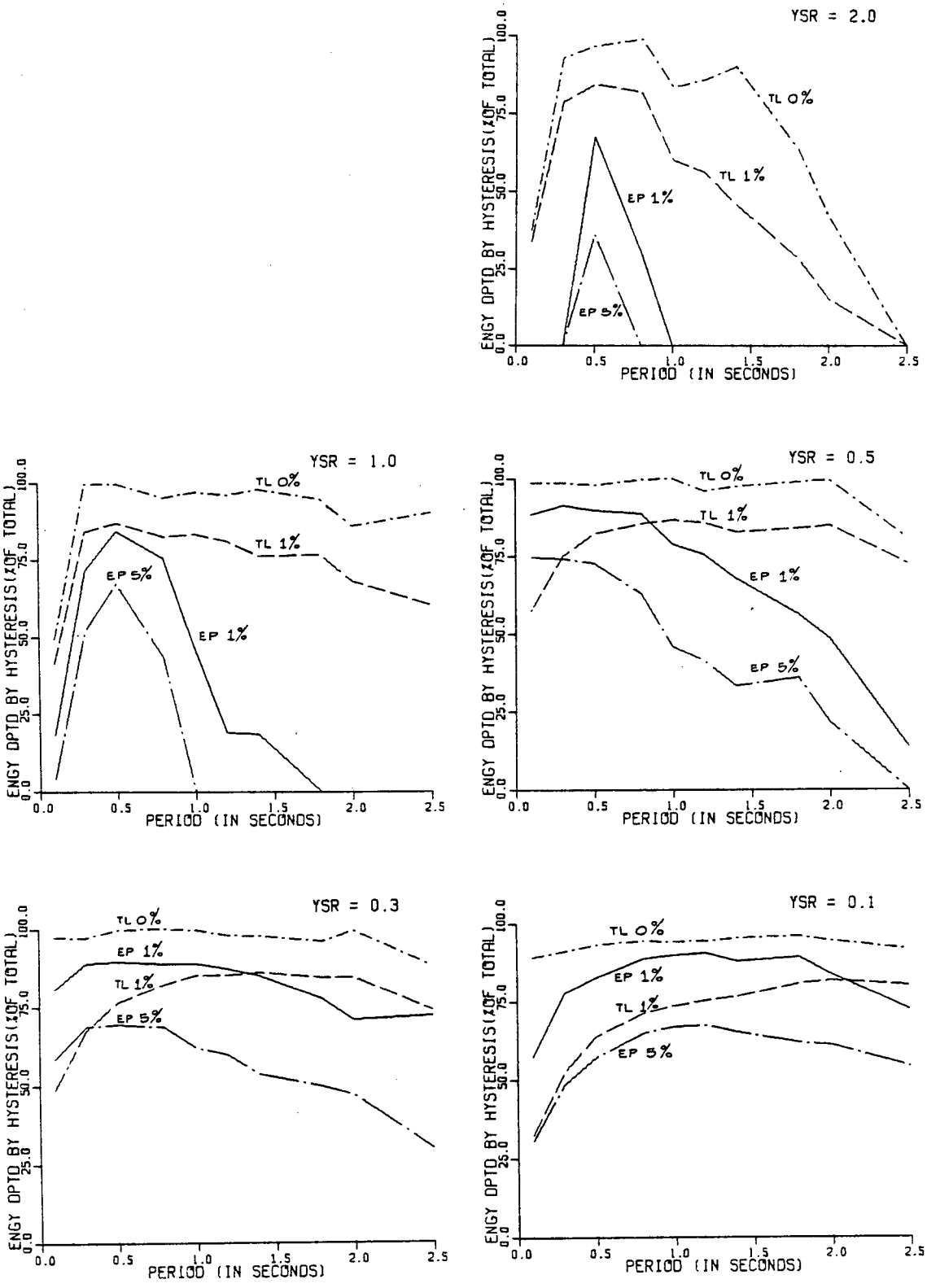


FIG. 3.30 EFFECT OF VISCOUS DAMPING ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS SUBJECTED TO PARKFIELD N65E.

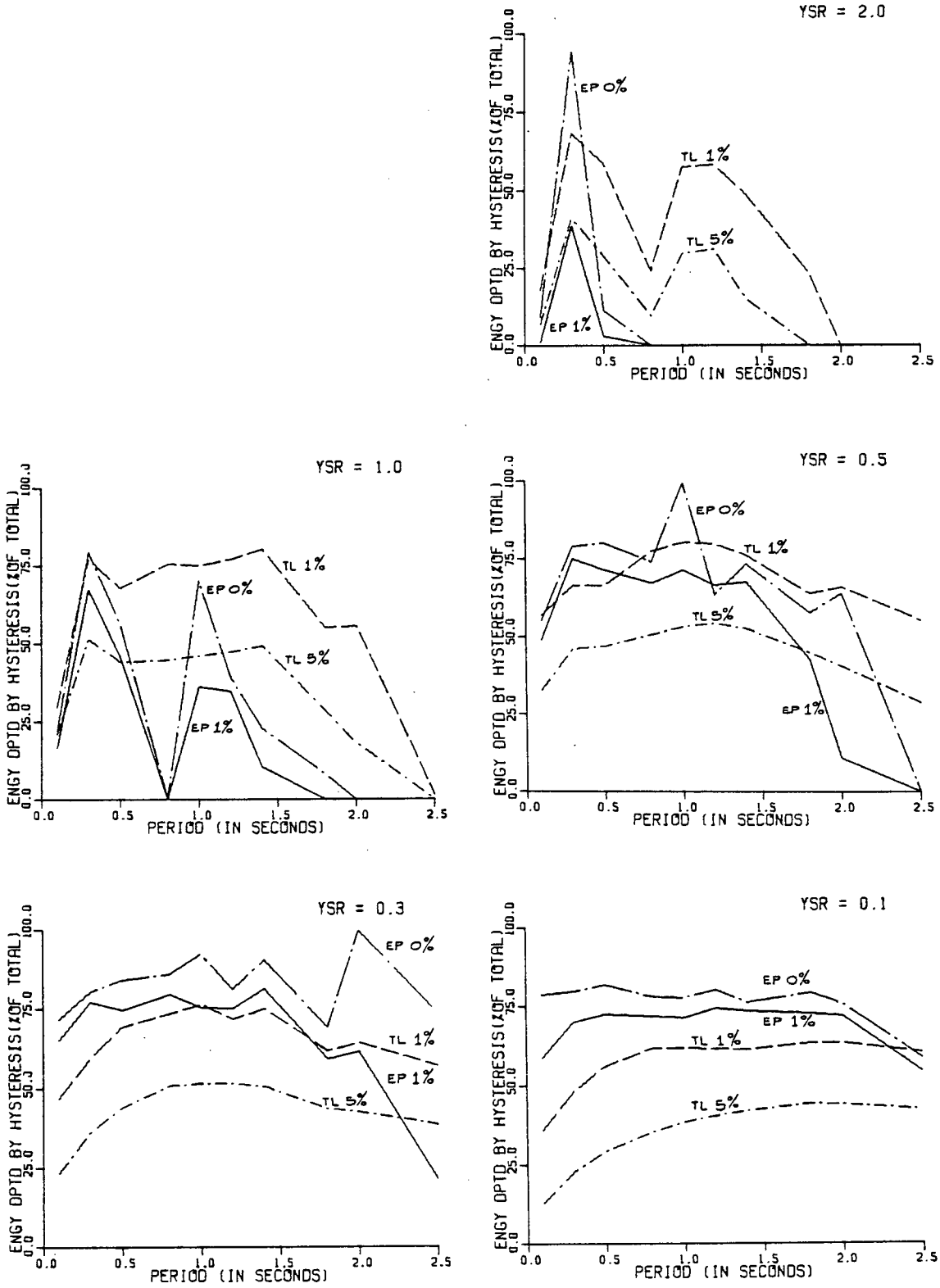


FIG. 3.31 EFFECT OF VISCOUS DAMPING ON DISTRIBUTION OF ENERGY WITHIN SYSTEMS SUBJECTED TO PACOIMA S16E.

3.3.5 Implications of these Results

The distribution of the total energy dissipated by the system, between the hysteretic and viscous mechanisms, is significantly insensitive to the individual earthquake record used, as discussed in section 3.3.2. This means that it will be possible to construct distribution data which can be applied to all earthquakes. This is an important result in terms of the design method being developed in this study.

The results studied in sections 3.3.3 and 3.3.4 provide valuable insight into the way in which the systems resist the ground motions.

The two energy dissipating mechanisms can be thought of as two resisting elements in parallel, and are shown schematically in fig. 3.32.

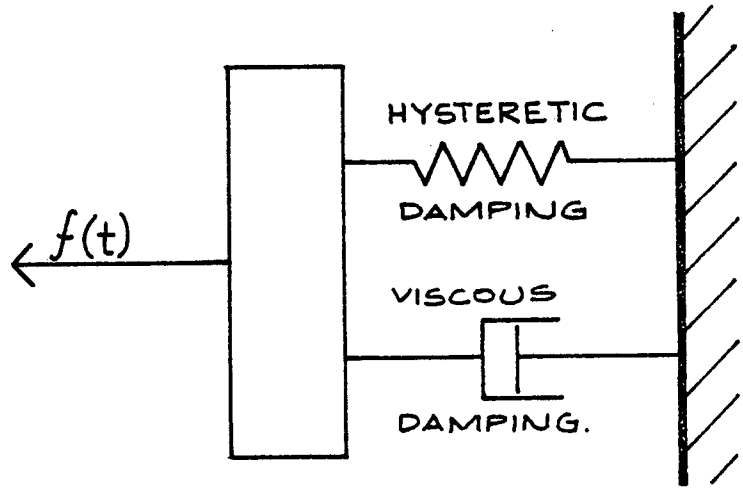


FIG. 3.32 SCHEMATIC OF TWIN PARALLEL RESISTING ELEMENT MODEL.

If the hysteretic element has large energy dissipating capacity and its YSR is such that it is the prinicipal dissipating device then the majority of the energy will be dissipated by hysteresis.

For the stronger systems with YSR $\geq$ 1.0, which remain essentially elastic during the response, the principal dissipating device is the viscous damping and hence the response is going to be greatly influenced by the percentage of critical damping used.

The weaker systems, having YSR < 1.0, provide the hysteretic mechanisms as principal dissipating devices and the response is less sensitive to variation in damping, provided that the balance between the viscous and hysteretic dampers is not affected greatly.

However in the case of the Tri-linear stiffness degrading model, the original energy dissipating capacity may well be such that at the start of the response it is the principal dissipating device. During the response, as the stiffness degrades, this capacity is reduced to such an extent that the viscous dampers take over as the principal dissipating device, and the percentage of energy dissipated by hysteresis is reduced in these systems. This becomes evident in the fact that the Elasto-Plastic and Ramberg-Osgood systems are less sensitive to variation in damping than the Tri-linear systems.

3.4 Spectral Displacements

The displacement response of single degree of freedom systems to earthquake ground motions has been the subject of many exhaustive studies in the past and the results are well known. In this section the results obtained in this study are discussed briefly, with particular emphasis placed on the effect of varying the YSR. The following effects are discussed with reference to figs. 3.33, 3.34, 3.35 and 3.36.

3.4.1 Effect of Varying Yield Strength Ratio on Spectral Displacements

The effect of varying yield strength ratio for all systems with YSR between 10.0 and 1.0 is small. However as the YSR is further reduced there is an increasing difference between the elastic and non-linear displacement response.

For systems with YSR = 0.5 to 0.3 it is seen that the non-linear response is in general similar to the elastic response for systems having periods greater than 0.5 sec. Ultimately at YSR = 0.1 there is only agreement between the elastic and non-linear response in the long period systems. (ie. period equal to 1.5 Sec. or greater.) The shorter period systems having displacements far larger than would be predicted by the equal displacement criterion.

The extent of these effects is influenced by material type, earthquake record type, and proportion of viscous damping used. However the effects of varying YSR are similar for all systems.

3.4.2 Effect of Earthquake Record on Spectral Displacement

It is observed that the equal displacement criterion is defined more clearly in the response of systems subjected to the far field ground motion records, ie Taft N69W and El Centro N.S. In the response of systems subjected to the near source impulsive type of motions, Pacoima SI6E and Parkfield N65E, the difference between the non-linear and elastic displacement response is greater than for far field records.

3.4.3 Effect of Material Hysteretic Properties on Spectral Displacements

The effect of material hysteretic properties on the spectral displacements is most pronounced in the systems having YSR = 0.5 and lower. For systems stronger than this the displacements are close to the elastic system displacements.

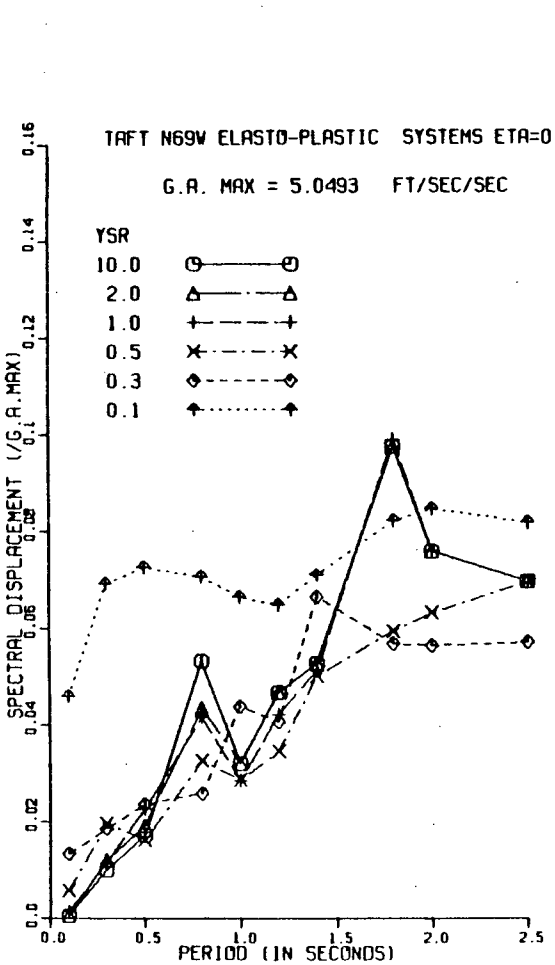
In the systems having YSR = 0.5 and lower with periods less than 1.5 sec., it is seen that the displacements for the Tri-linear systems are greater than the elastic system displacements. For these systems the deviation from the equal displacement criterion is greater than for systems with Elasto- Plastic or Ramberg-Osgood hysteresis properties.

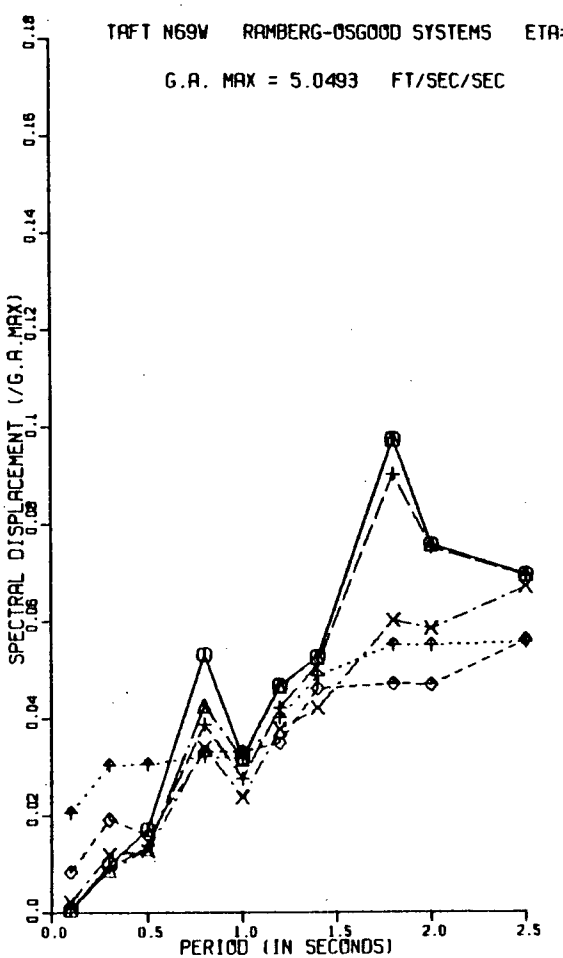
3.4.4 Effect of Viscous Damping on Spectral Displacements

The effect of viscous damping on the spectral displacements is well known and the following observations are in agreement with previous studies.

Increasing viscous damping from 0% to 1% of critical had a general effect of reducing displacements by 10% to 20%. Further increasing viscous damping from 1% to 5% of critical reduced displacements by a further 20% to 30%.

Another well defined effect of increasing damping was to improve the compliance of the non-linear systems to the equal displacement criterion. This was found to be the case for systems with all yield strength values.





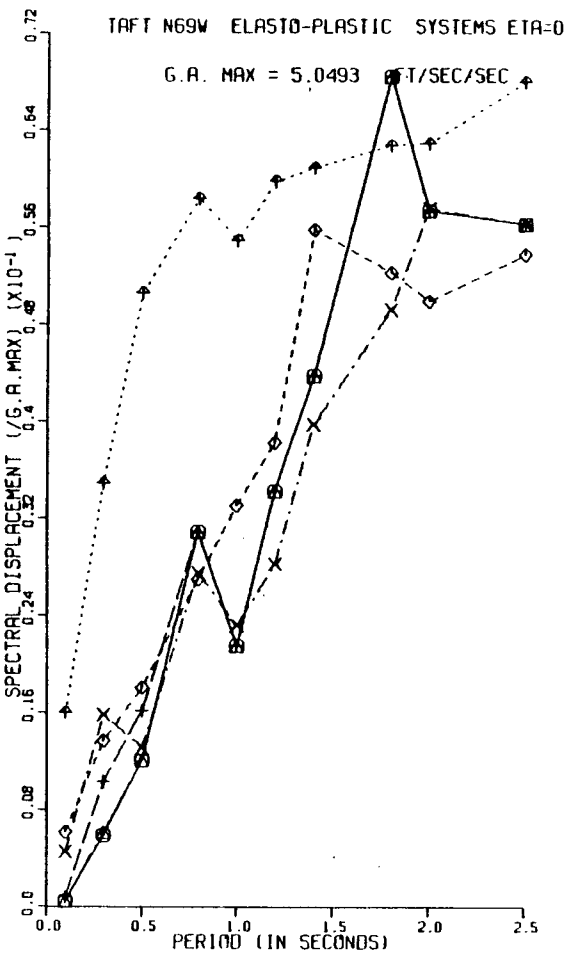
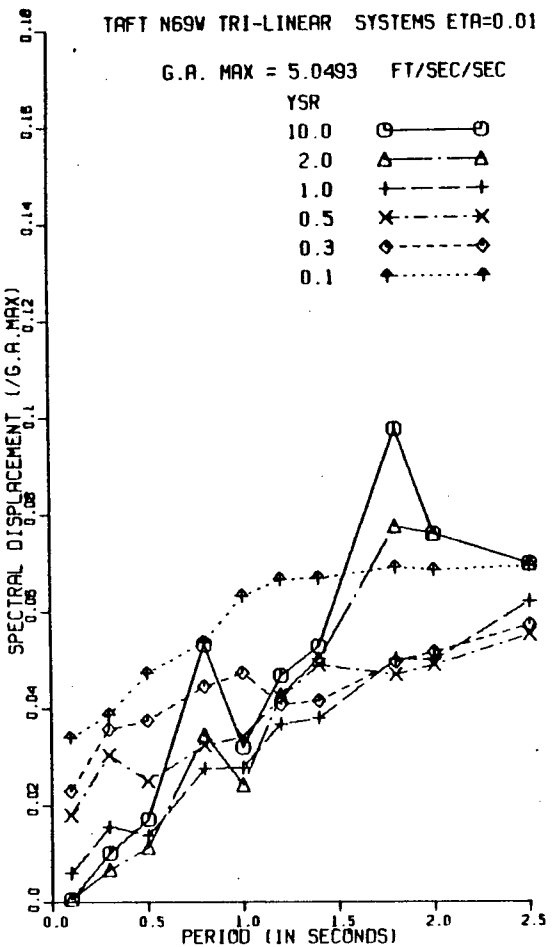


FIG. 3.33 SPECTRAL DISPLACEMENTS FOR SYSTEMS SUBJECTED TO TAFT N69W.



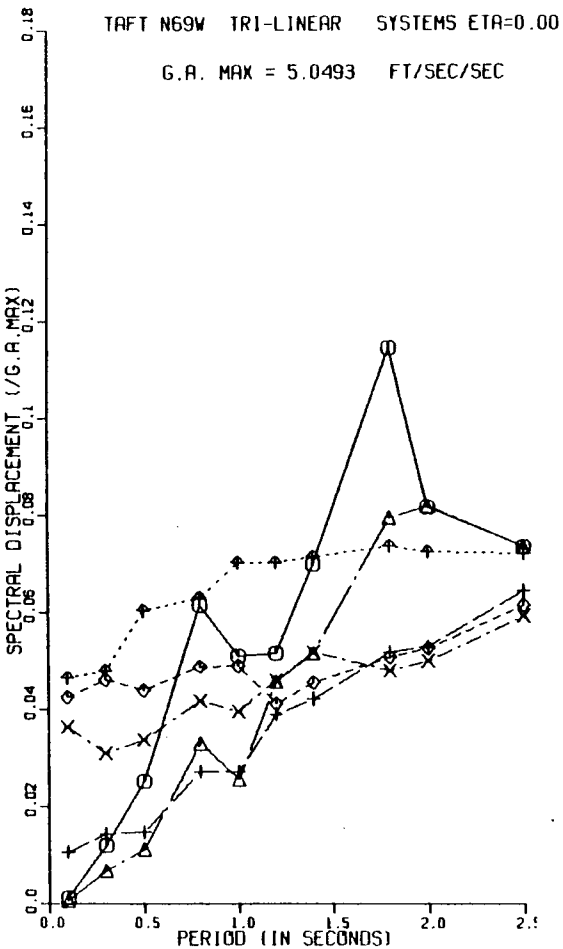


FIG. 3.33 CONTINUED

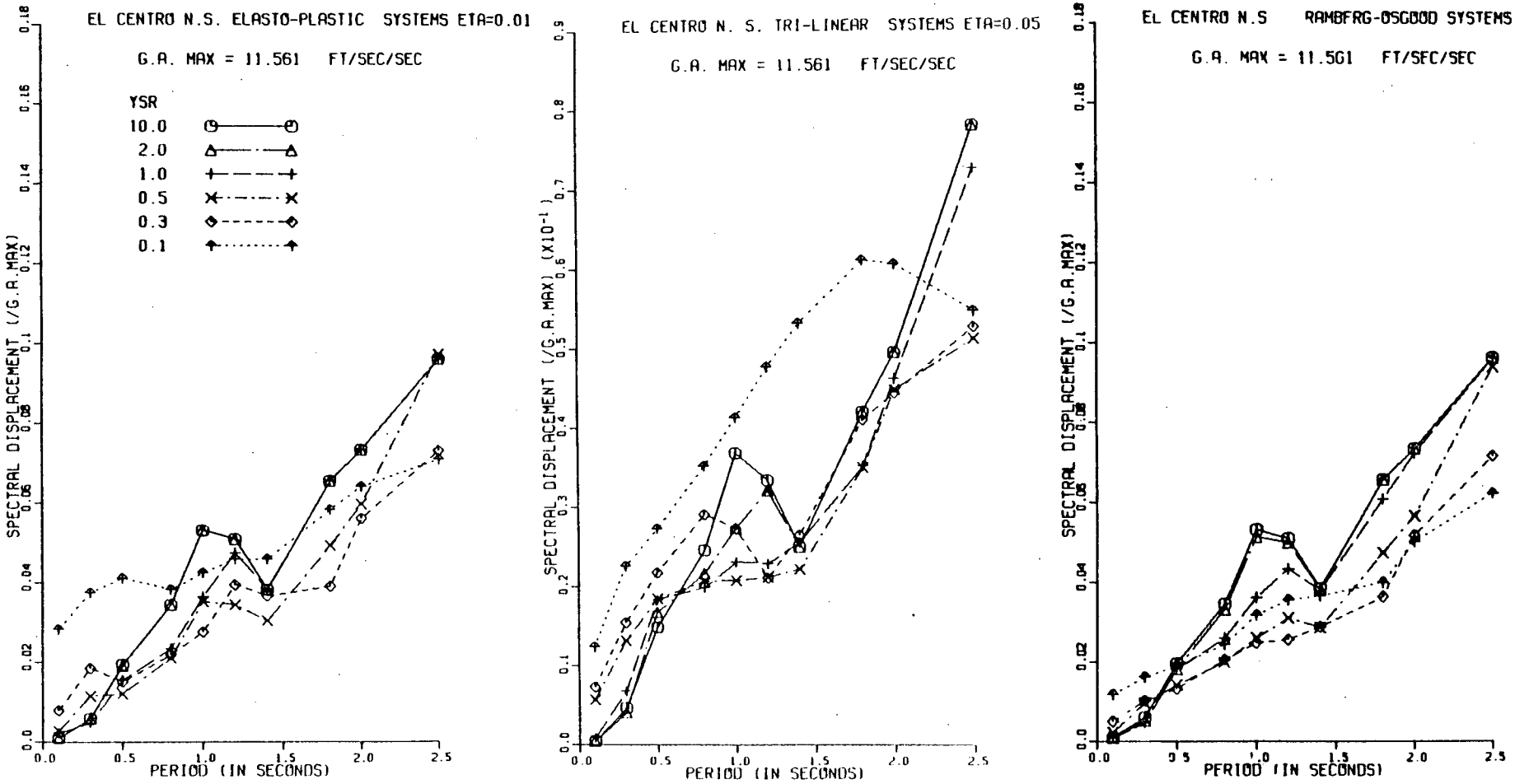
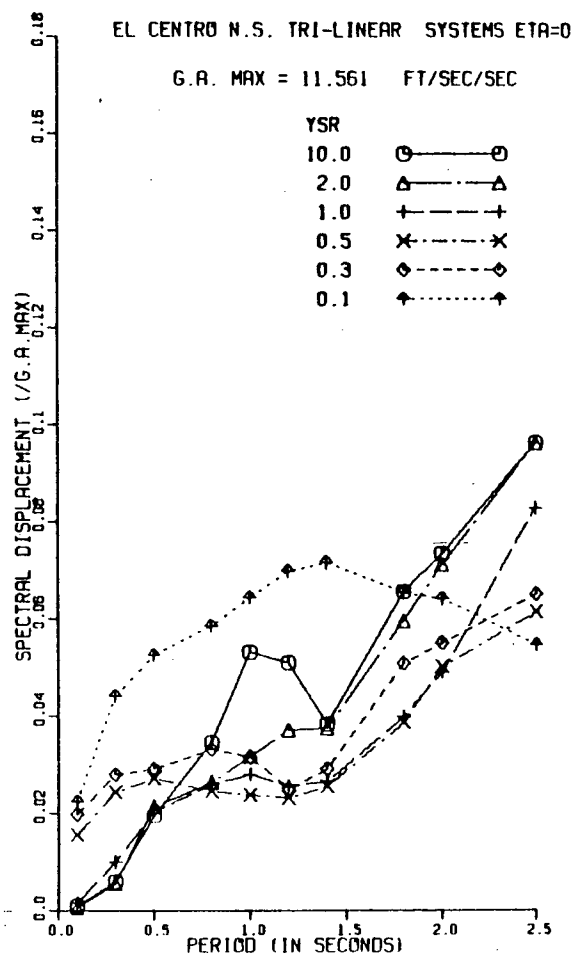


FIG. 3.34 SPECTRAL DISPLACEMENTS FOR SYSTEMS SUBJECTED TO EL CENTRO N.S.



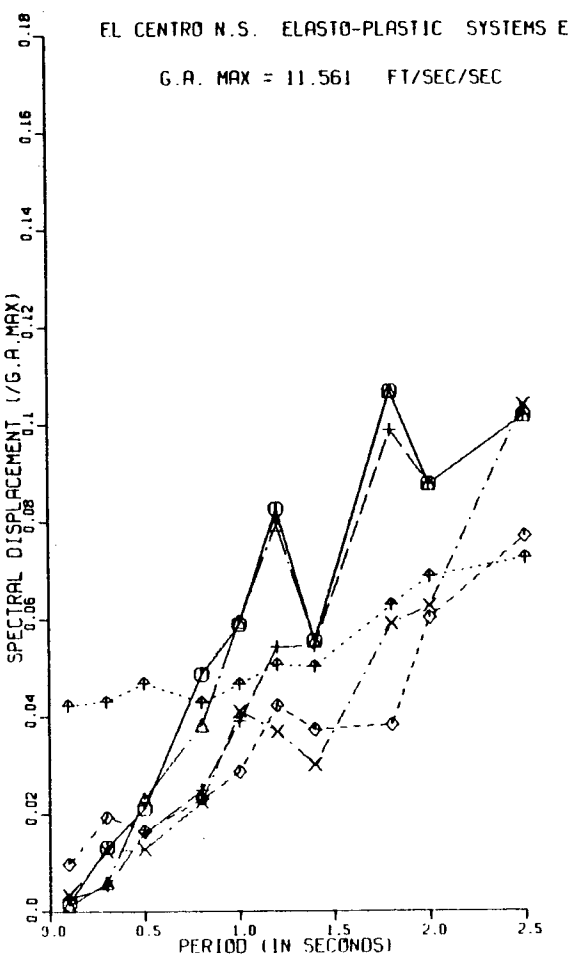
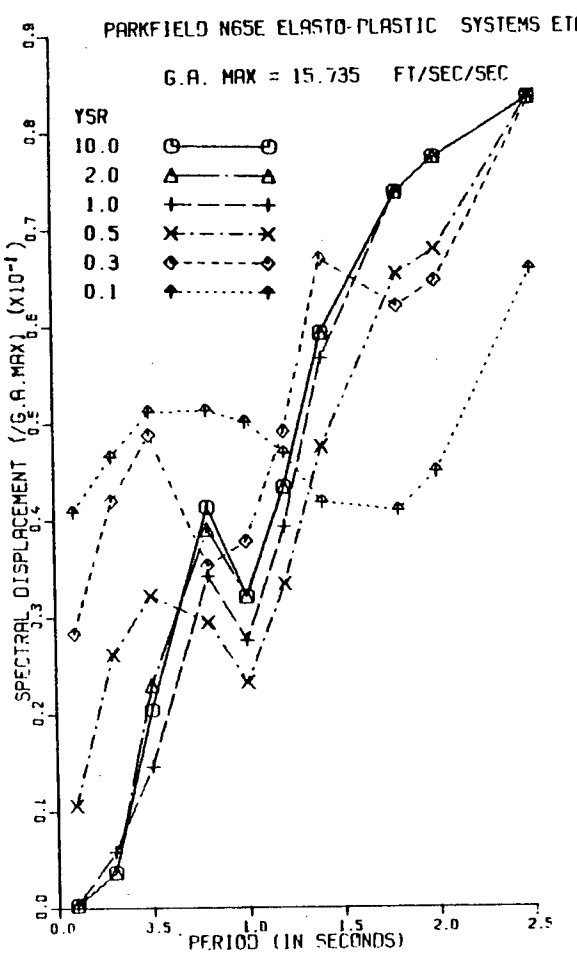


FIG. 3.34 CONTINUED



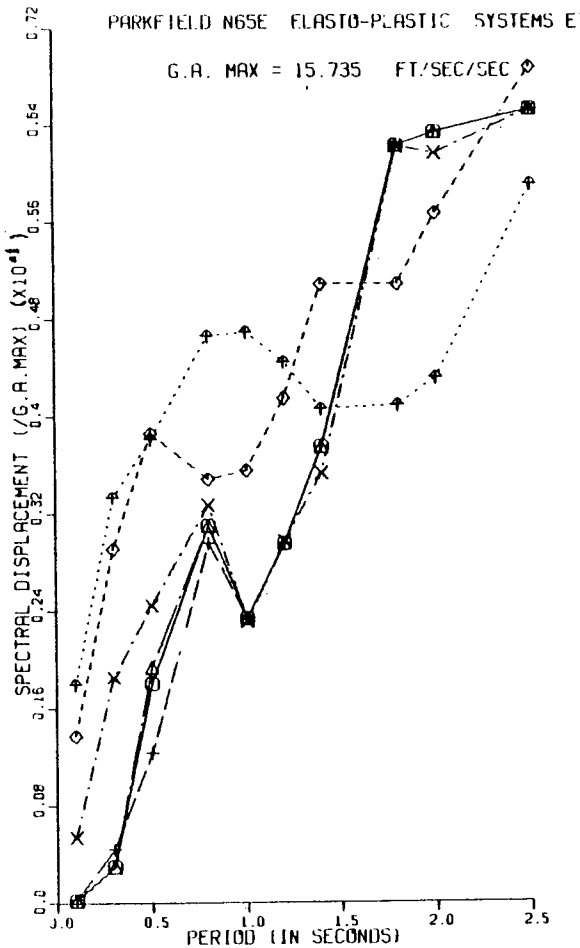
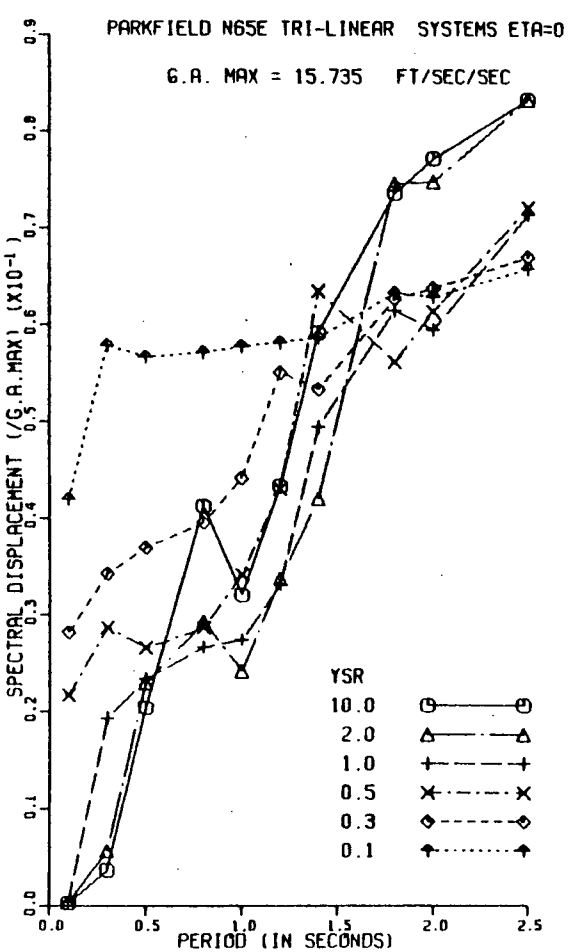


FIG. 3.35 SPECTRAL DISPLACEMENTS FOR SYSTEMS SUBJECTED TO PARKFIELD N65E.



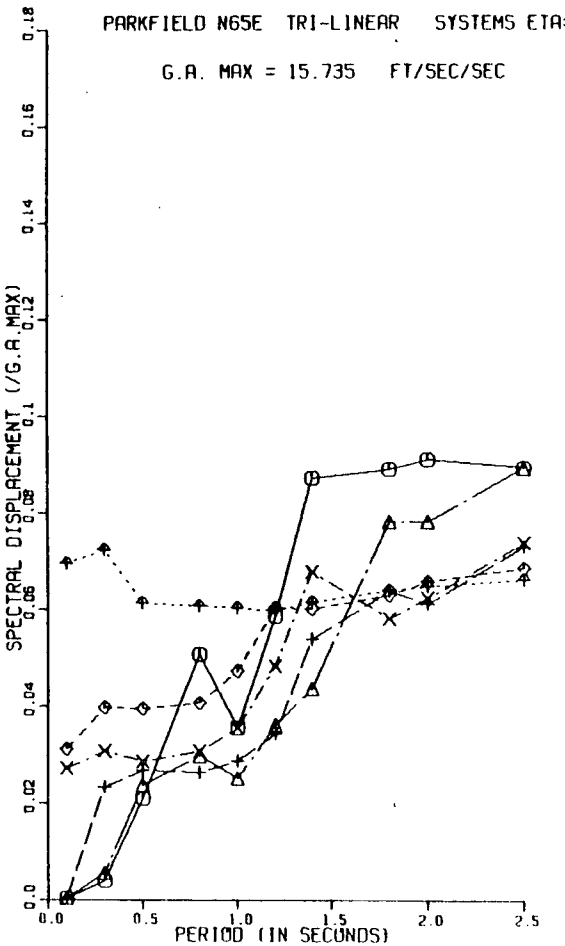
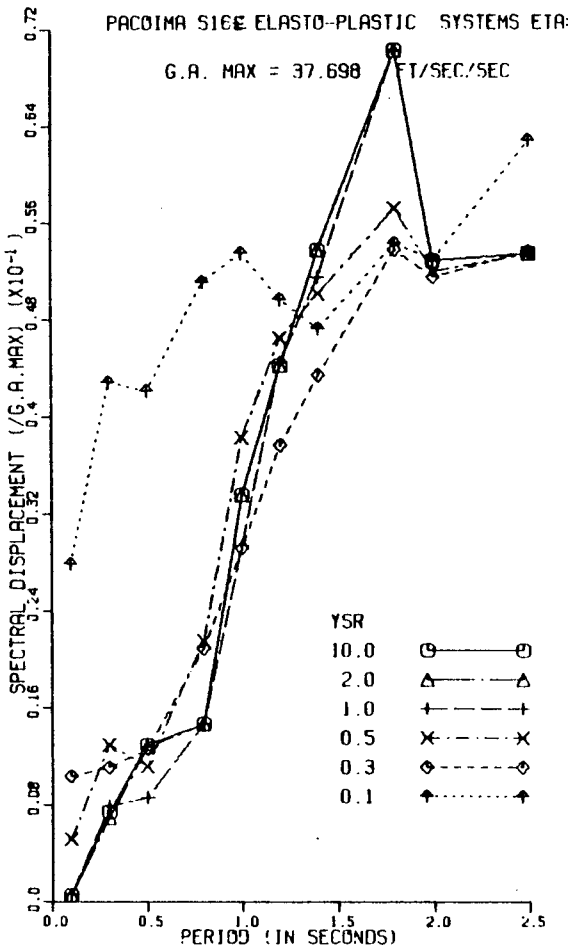


FIG. 3.35 CONTINUED



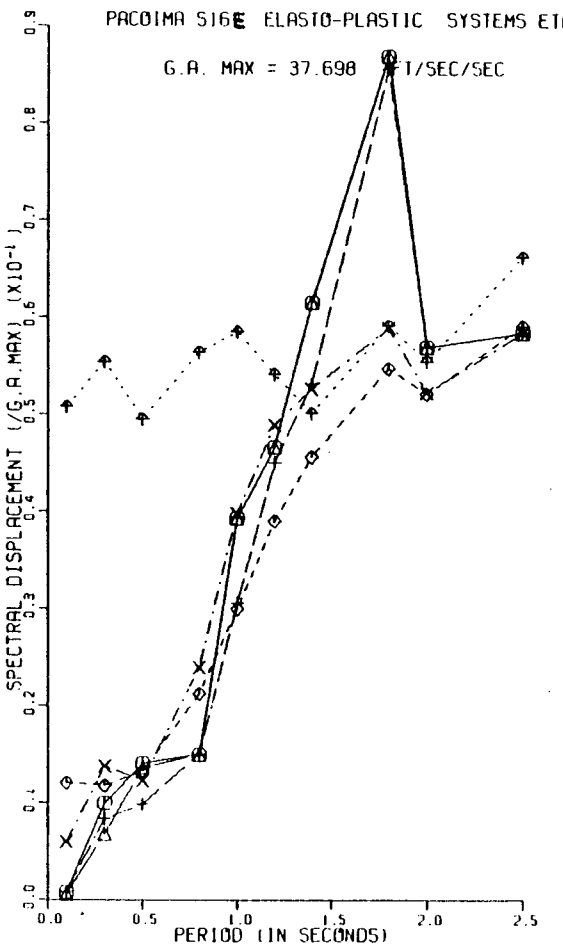
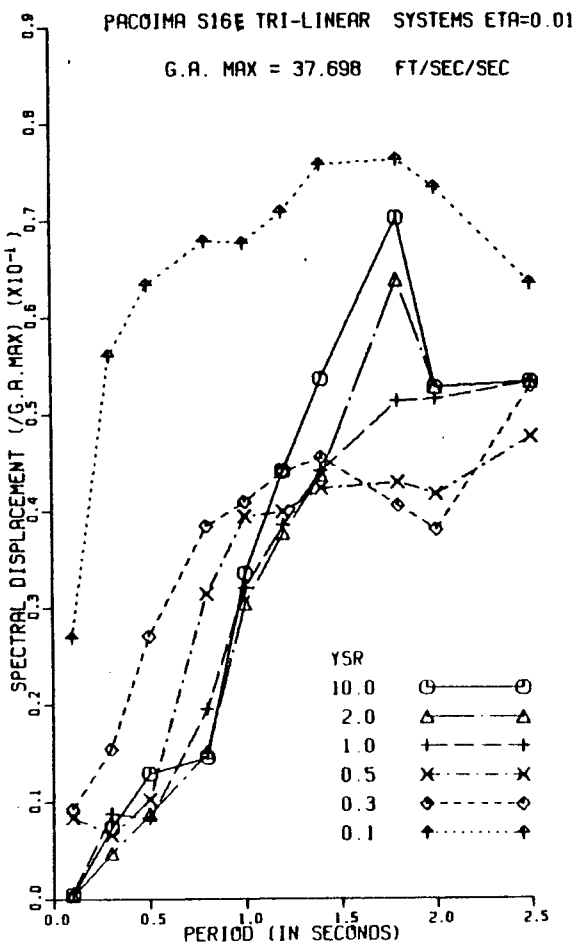


FIG. 3.36 SPECTRAL DISPLACEMENTS FOR SYSTEMS SUBJECTED TO PACOIMA S16E



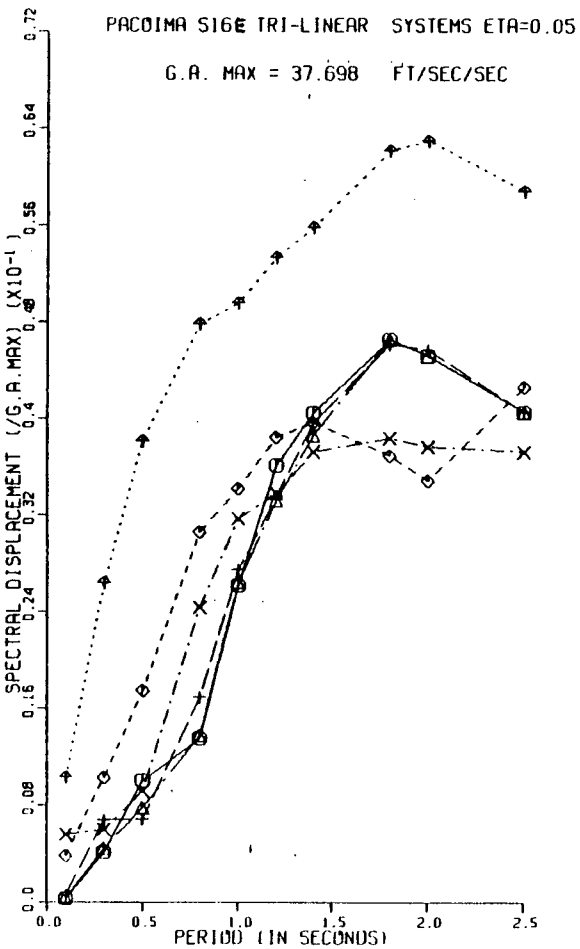


FIG. 3.36 CONTINUED

3.5 Displacement Ductilities

Displacement ductility of non-linear single degree of freedom systems has been studied in great depth over the last twenty years, and the results are well known. They are among the most important produced in earthquake engineering to date. Here displacement ductility is discussed in the context of the yield strength ratio parameter. The following effects are discussed with reference to figs. 3.37, 3.38, 3.39 and 3.40.

3.5.1 Effect of Yield Strength Ratio on Displacement Ductility

Reduction in yield strength ratio produces in all systems studied an increase in displacement ductility. This effect is greater for the short period systems than the longer period ones. Displacement ductilities decrease with increasing periods. This effect is seen to be the most clearly defined and consistent of all aspects of response investigated in this study.

The following general observations are found for each yield strength ratio.

YSR = 10.0	No systems yielded. (All displacement ductilities are < 1.0)
YSR = 2.0	Majority of systems with periods less than 1.0 sec. yielded. Others were close to yield ductility. No major yield excursions occured. Max. displacement ductility is of order 2 or 3.
YSR = 1.0	Most systems with periods less than 1.5 sec. yielded. Systems with very short periods showed displacement ductilities of the order 6 - 10 for periods of 0.1 sec.
YSR = 0.5	All systems yielded except the Tri-linear systems with periods greater than 1.5 sec. Short period systems with T = 0.1 and 0.3 sec. show extremely high displacement ductility ie >10. All other ductilities were less than 10.
YSR = 0.3	All systems yielded except the Tri-linear systems with periods greater than 1.5 secs. Systems with periods less than 0.8 sec. show displacement ductilities greater than 6. Some short period systems have huge ductilities ie. > 100.
YSR = 0.1	All systems yielded. Systems with periods less than 1.5 sec. show excessive displacement ductility.

3.5.2 Effect of Earthquake Record on Displacement Ductility

The variation in displacement ductilities for systems subjected to the four earthquake records used in this study was found to be small. This indicates that when the earthquake record and structural systems are non-dimensionalised as in this study the displacement ductility is not significantly affected by different ground motion inputs.

3.5.3 Effect of Varying Material Hysteretic Properties on Displacement Ductility

Displacement ductilities for the Ramberg-Osgood and Elasto-Plastic systems are almost identical except for systems with YSR = 0.3 and 0.1, and all systems with period less than 0.5 sec. For these two groups of systems the differences can be of the order 50 - 100%, with the Elasto-Plastic systems having the larger displacement ductilities.

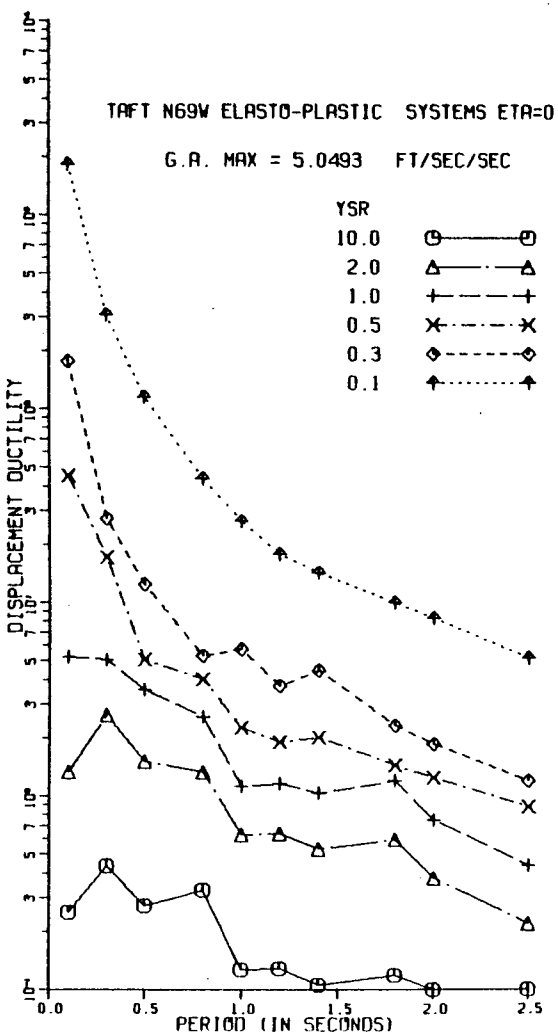
The Tri-linear systems responded to the ground motions with considerably lower displacement ductilities than the systems with Elasto-Plastic hysteretic properties. The displacement ductilities for the Tri-linear systems is generally of the order of 1/2 to 1/4 of the Elasto-Plastic displacement ductilities. However, it must be noted that the yield displacement for the Tri-linear systems is greater than that for the comparable Elasto-Plastic systems. See fig. 3.1.

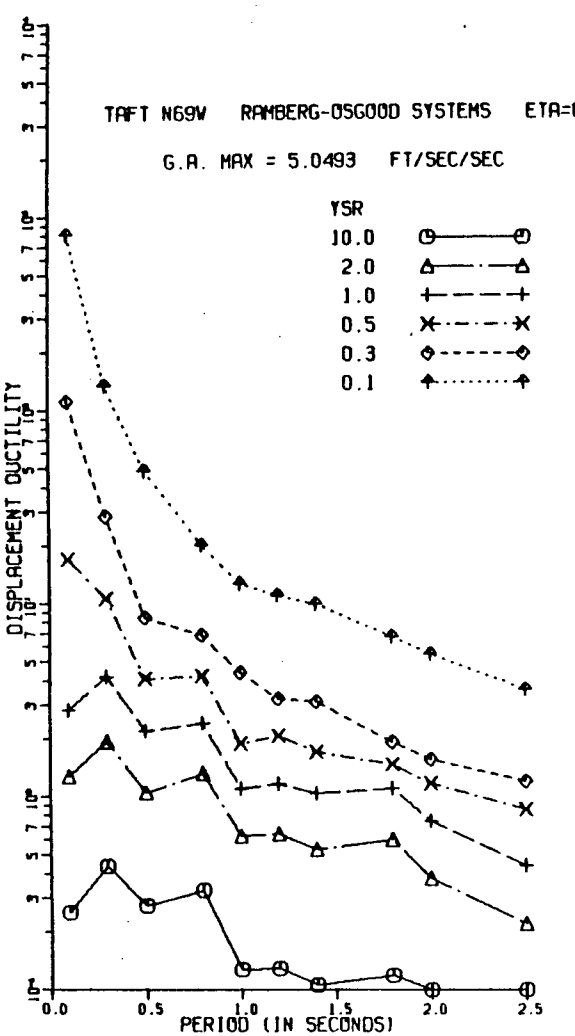
3.5.4 Effect of Viscous Damping on Displacement Ductility

It is seen that increasing the proportion of viscous damping reduces the displacement of all systems. The extent of this reduction is dependent upon the hysteretic properties, yield strength ratio and period of the systems. The effect is found to be greater for the short period systems and for the Elasto-Plastic systems.

For Elasto-Plastic systems an increase in damping from 0 to 1% of critical produced a 20% reduction in displacement ductilities for systems with YSR < 1.0 and 20 - 80% for systems with YSR > 1.0 Further increasing damping from 1% to 5% shows general reduction of 20 - 50% for systems with period > 1.0 and a reduction of 50 - 100% for systems with period < 1.0.

For Tri-linear systems an increase in damping from 0 to 1% of critical produced a reduction in displacement ductilities of the order 10% - 20% for systems with period > 1.0 sec. and 20 - 100% for systems with period < 1.0 sec. Further increasing damping from 1% to 5% shows a general reduction of displacement ductility of 80% for systems with period 0.5. This reduction reduces to 20% for systems with periods of 2.5 sec. the transition being approximately linear. The systems with YSR < 1.0 and periods < 0.5 sec. showed reductions of the order 1/2 to 1/3.





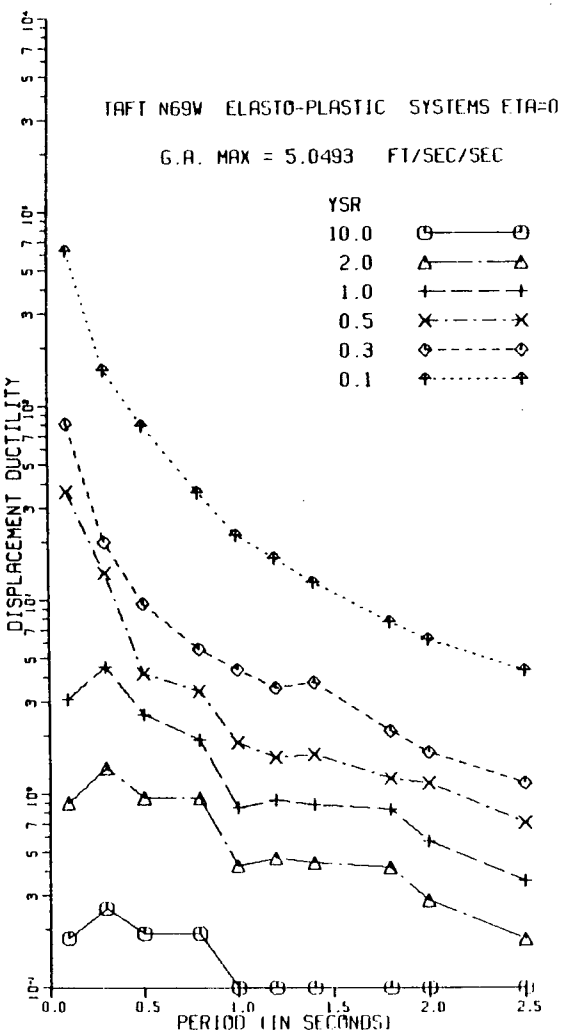
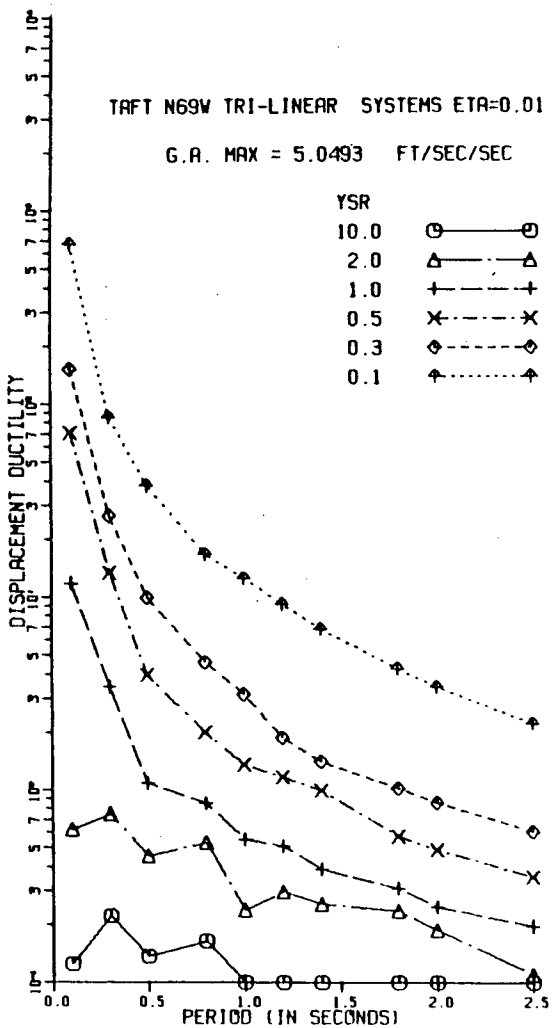


FIG. 3.37 DISPLACEMENT DUCTILITIES FOR SYSTEMS SUBJECTED TO TAFT N69W.



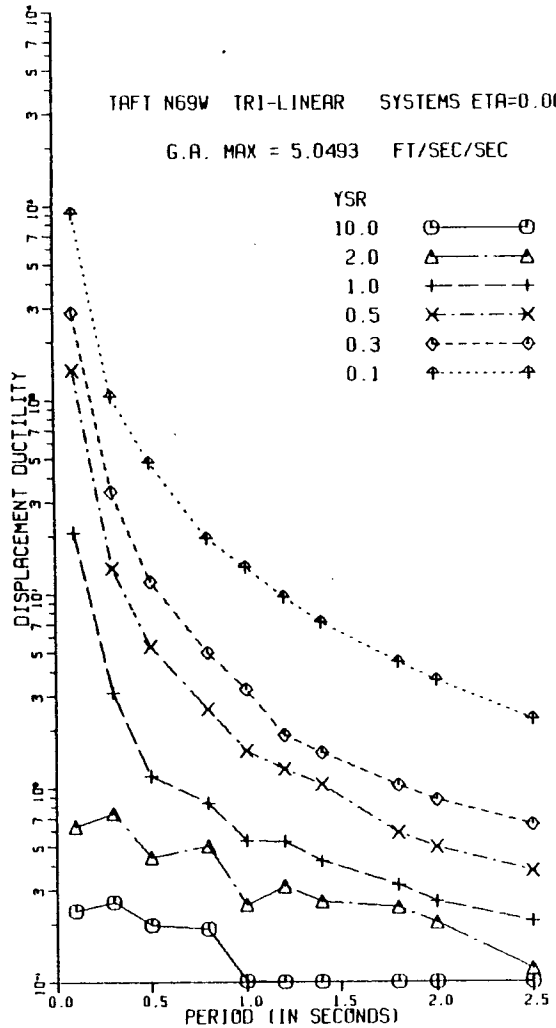


FIG. 3.37 CONTINUED

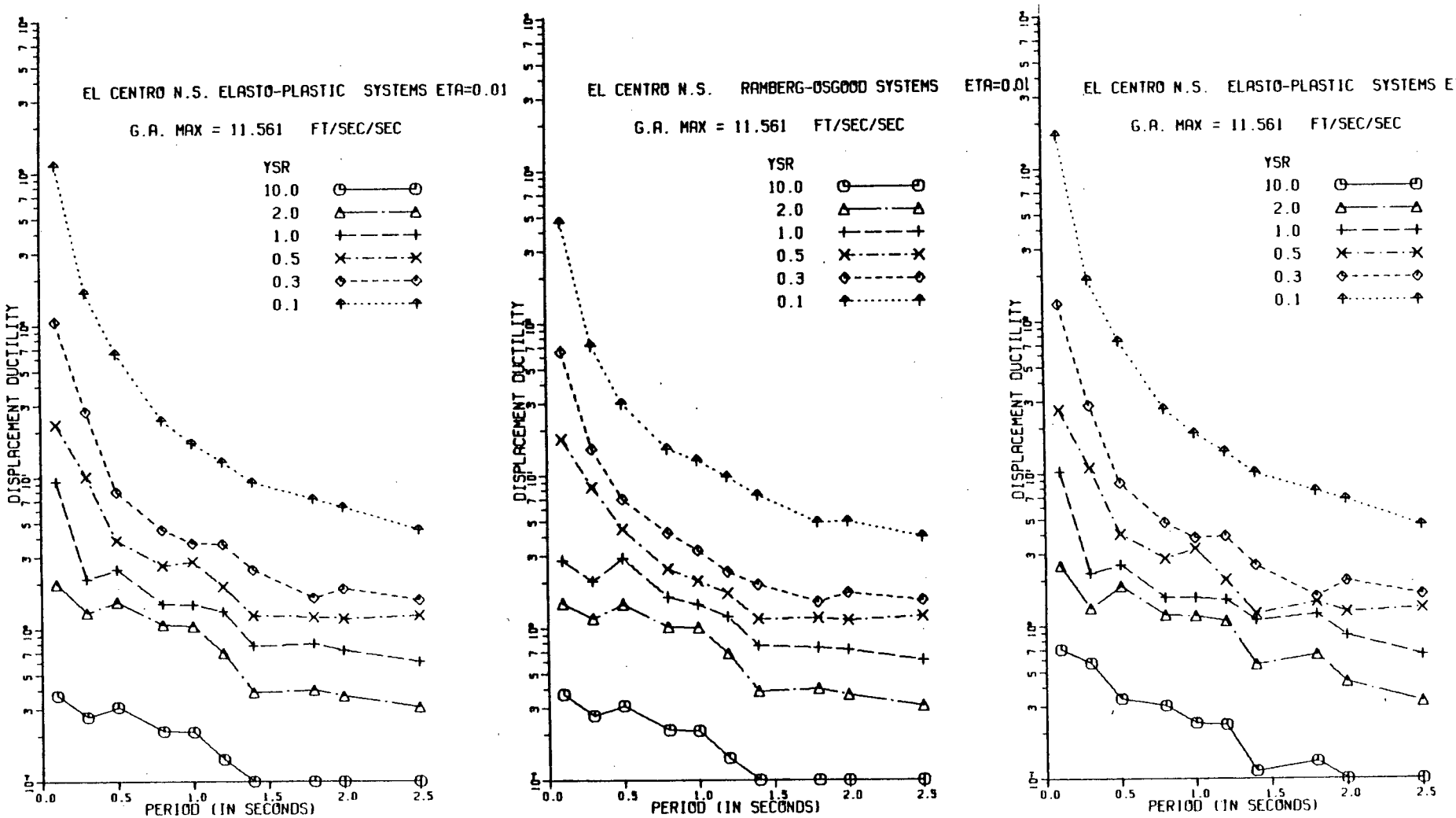
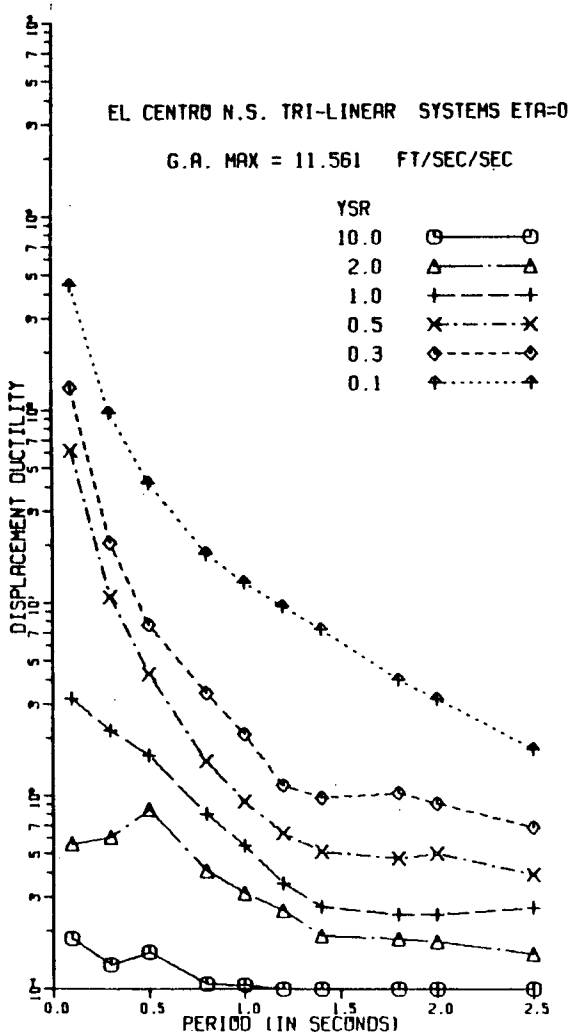


FIG. 3.38 DISPLACEMENT DUCTILITIES FOR SYSTEMS SUBJECTED TO EL CENTRO N.S.



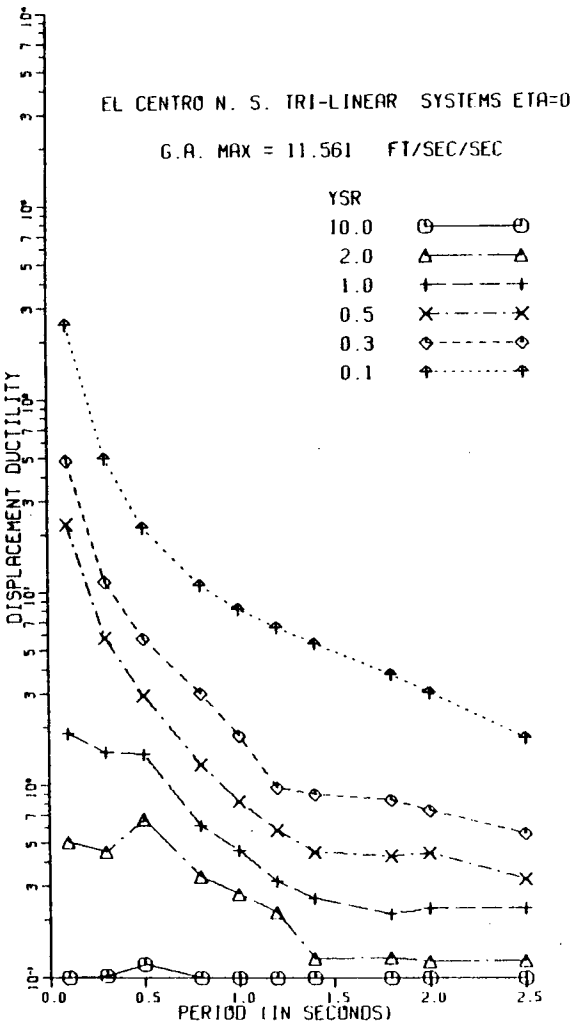
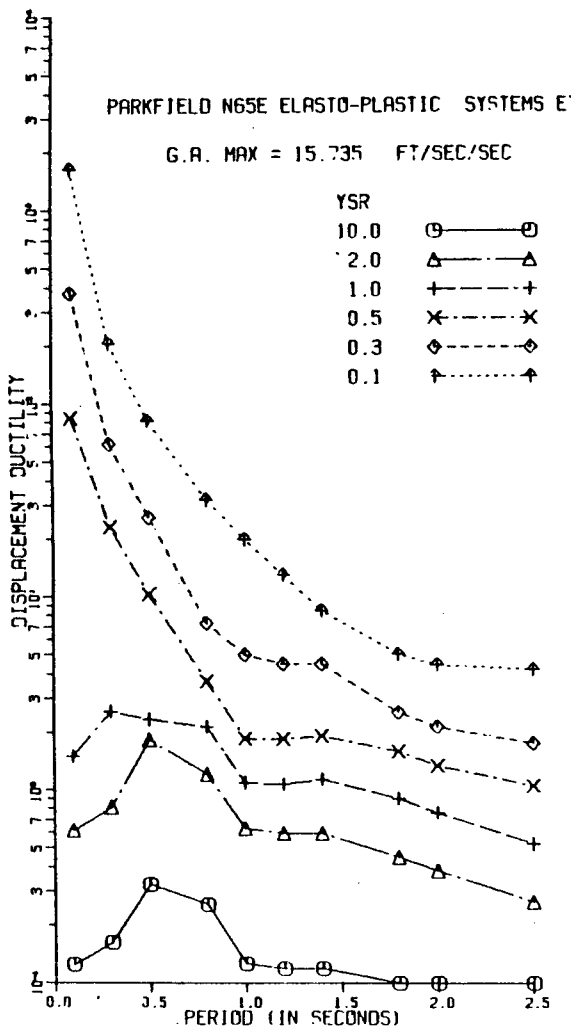


FIG. 3.38 CONTINUED



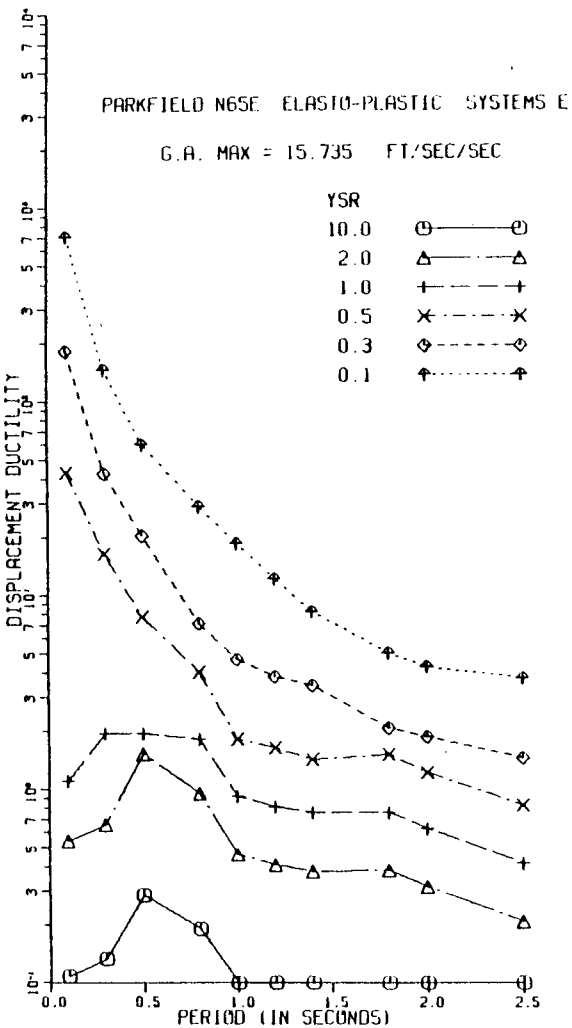
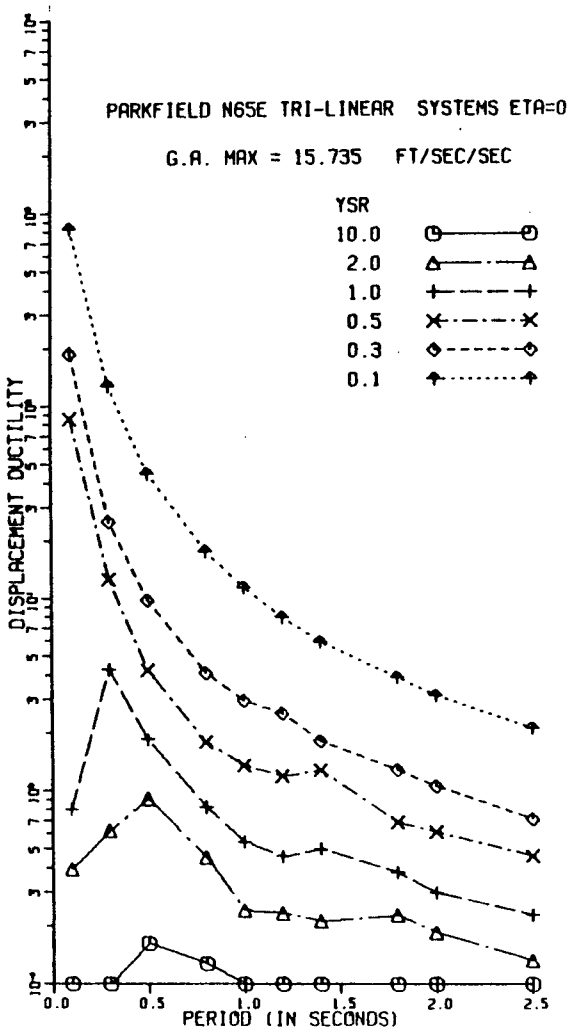


FIG. 3.39 DISPLACEMENT DUCTILITIES FOR SYSTEMS SUBJECTED TO PARKFIELD N65E.



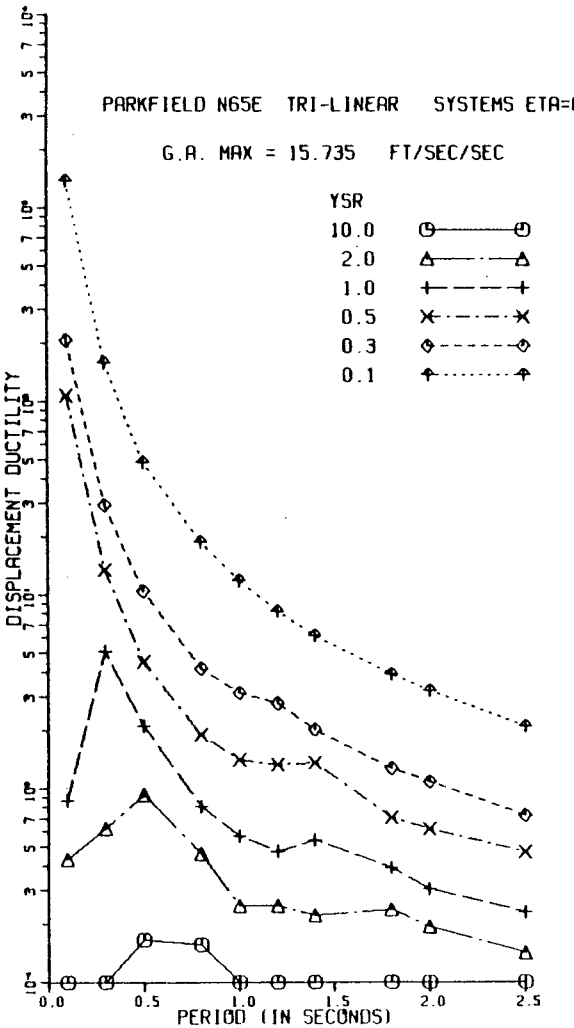
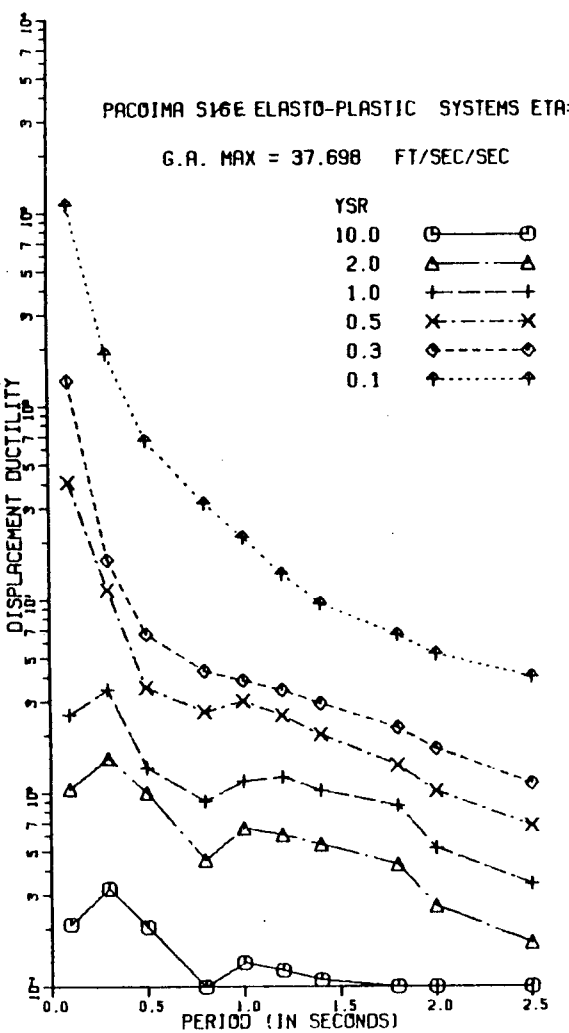


FIG. 3.39 CONTINUED



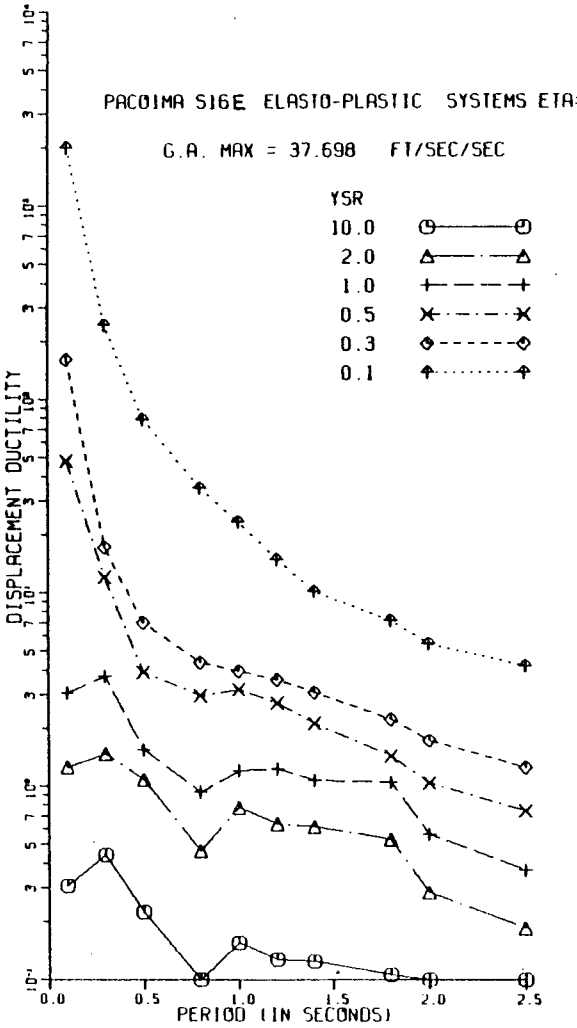
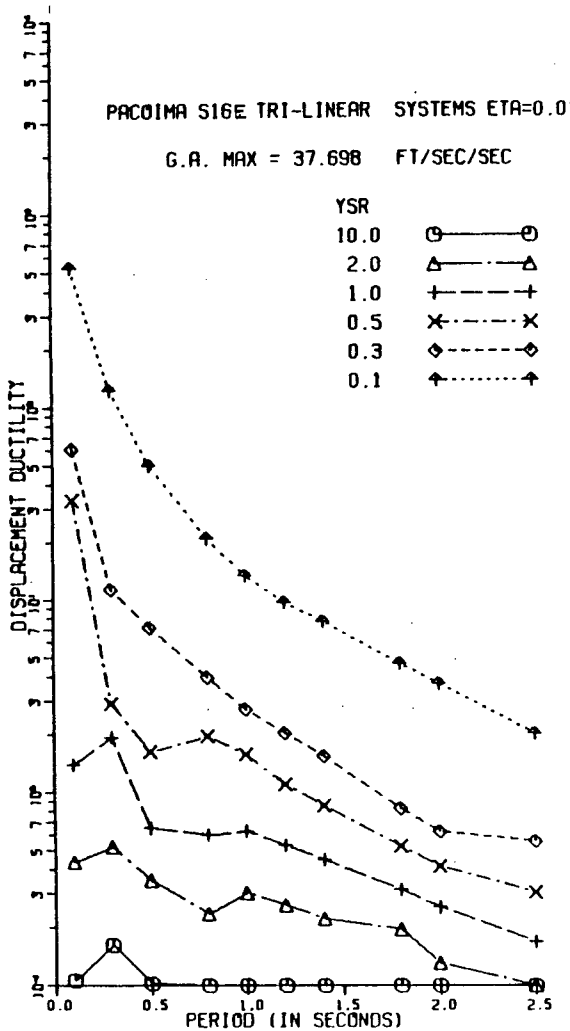


FIG. 3.40 DISPLACEMENT DUCTILITIES FOR SYSTEMS SUBJECTED TO PACOIMA S16E.



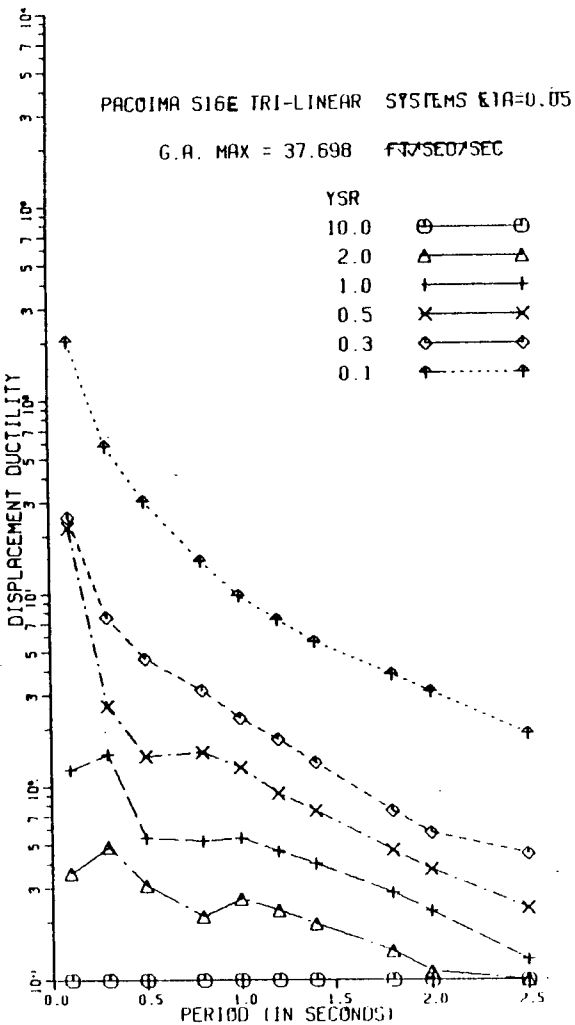


FIG. 3.40 CONTINUED

3.6 Permanent Sets

The results of this study for permanent sets showed that there was no clear pattern to this response parameter as was the case for displacements or displacement ductilities. As pointed out in section 2.6, the permanent set can be thought of as the net result of the yield excursion experienced by the system during the response. The lack of pattern in the results indicates that the net effect of the yield excursions is very sensitive to the nature and history of the response.

While there is no detailed pattern in the results, on a more general level it can be said that the permanent set results do follow a similar pattern to the displacement ductility results. In fact it is possible to say that the permanent sets in general are of the order of about 1/4 of the displacement ductility results. However it is emphasised that there are wide fluctuations from this norm. The following effects are discussed with reference to figs. 3.41, 3.42, 3.43 and 3.44.

3.6.1 Effect of Yield Strength Ratio on Permanent Sets.

Reduction in YSR has a general effect of increasing the permanent set of the systems. However this effect is not clearly defined as is the case for other parameters studied. The effect of reducing the YSR is greater for the short period systems than for long period systems.

The following general observations are found for each yield strength ratio:

YSR = 10	All permanent sets are of an order less than 10% of yield displacement.
YSR = 2	Ditto except for some short period systems where permanent set can be 50 - 60% of yield displacement, and in one case 100%.
YSR = 1	Significant permanent sets in many systems with period less than 0.8 sec. Some values up to 3.0 times yield displacement.
YSR = 0.5	Ditto for periods less than 1.5 sec. Some peak values up to 30.
YSR = 0.3	Ditto for periods less than 2.0 sec. Some peak values up to 100.
YSR = 0.1	Significant permanent sets in all systems. Some peak values up to 1000.

3.6.2 Effect of Earthquake Record on Permanent Sets

The effect of varying the earthquake ground motion on permanent sets was found to be small. This result is similar to that found for displacement ductility. In general terms it can be concluded that the permanent sets of systems non-dimensionalised as in this study are not signficantly affected by different ground motion inputs.

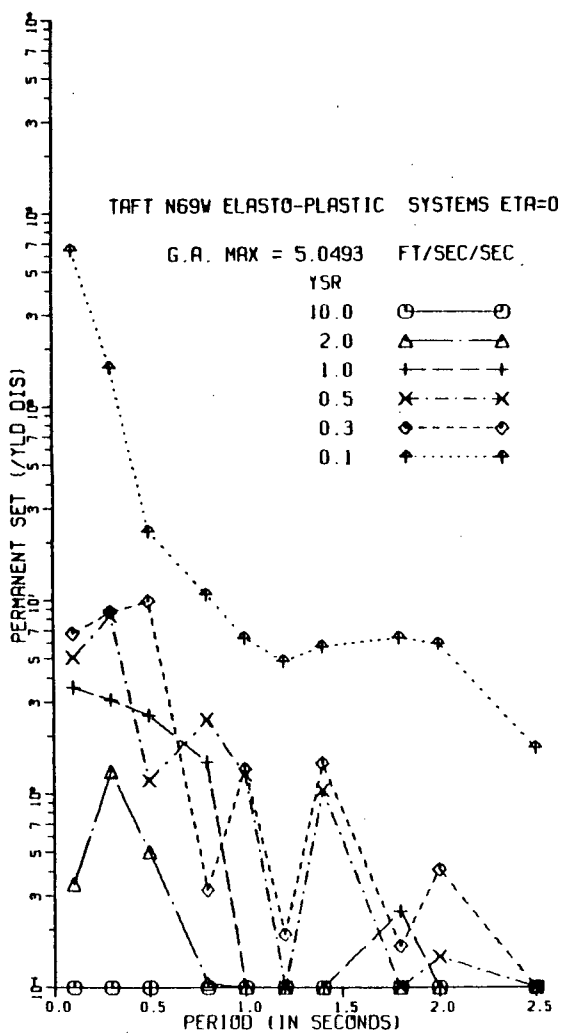
3.6.3 Effect of Material Hysteretic Properties on Permanent Sets

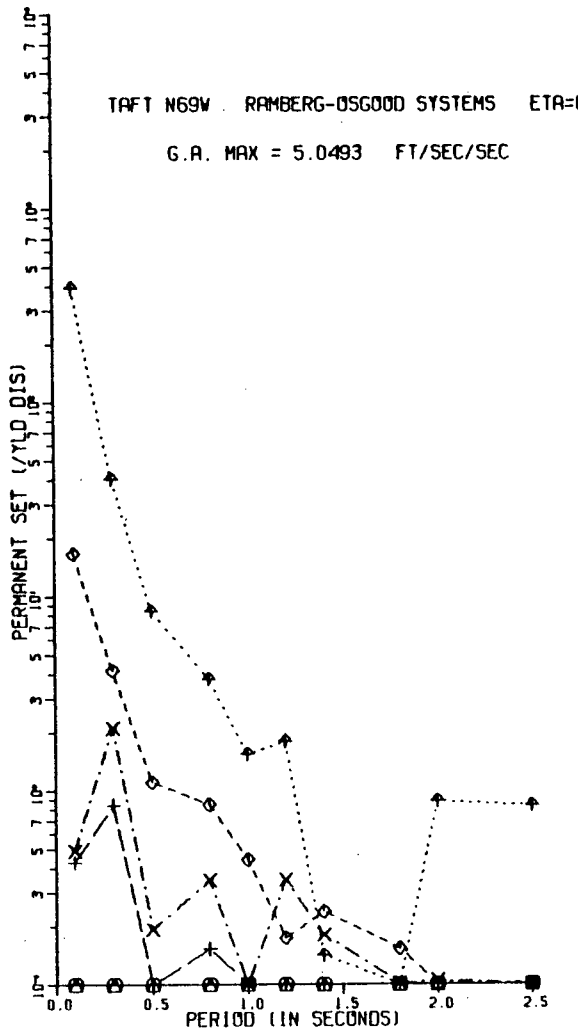
Permanent sets for the Elasto-Plastic and Ramberg-Osgood systems show no significant difference. The permanent sets for the Tri-linear systems are in general of an order of 1/2 to 1/4 the values obtained for the Elasto-Plastic systems. It is noted that the yield displacement for the Tri-linear systems is greater than that for the comparable Elasto-Plastic systems. See fig. 3.1.

3.6.4 Effect of Viscous Damping on Permanent Sets

Increasing the percentage of viscous damping from 0% to 1% of critical showed only a minor reduction in the permanent sets. The most significant reduction was 40% in a few cases, but the majority of systems showed reductions considerably less than this.

Further increasing damping from 1% to 5% produced a general reduction in permanent sets of approximately 40%. However, there was wide variations in this in some instances. One extreme case showed a reduction of one tenth, and others showed a 40% increase in permanent set.





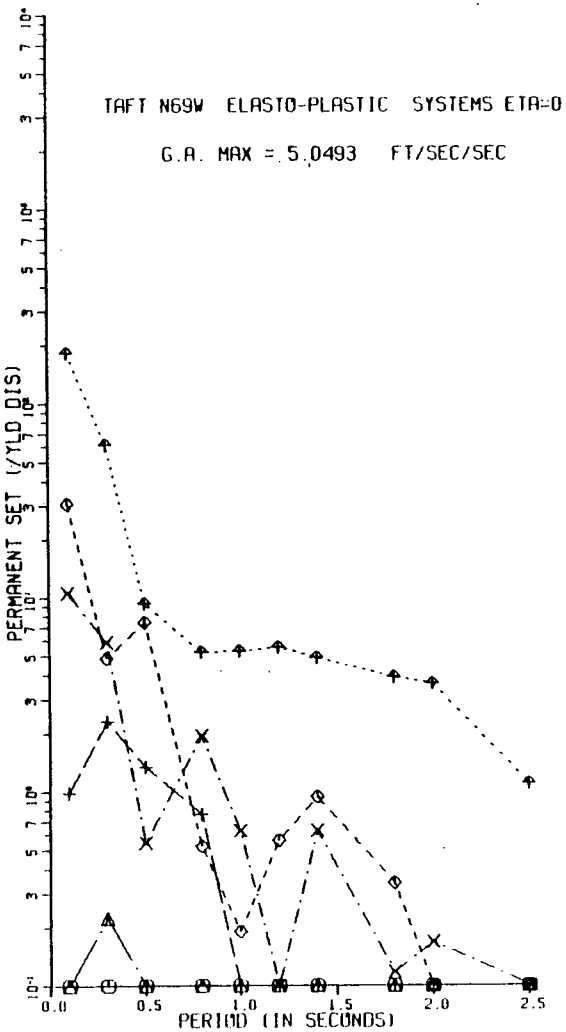
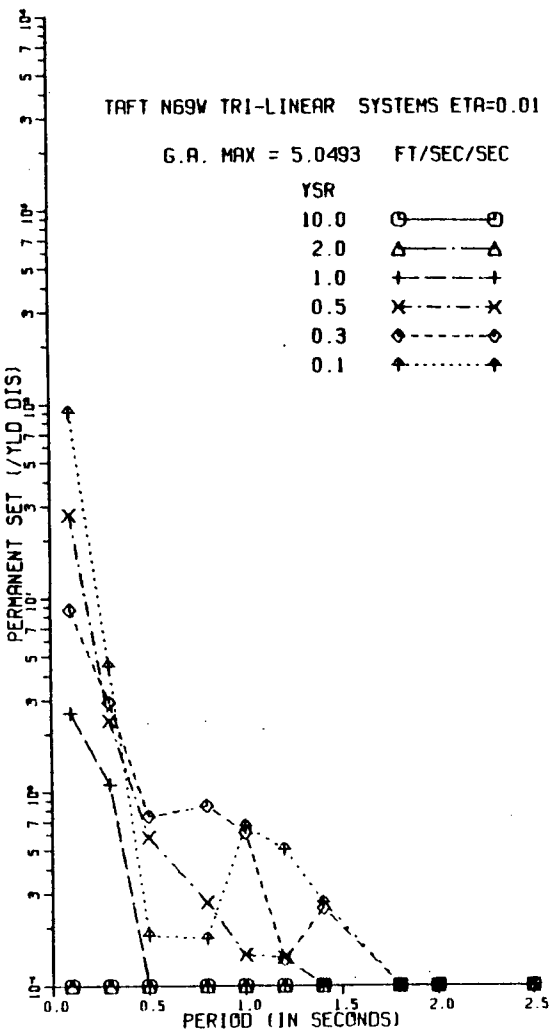


FIG. 3.41 PERMANENT SETS FOR SYSTEMS SUBJECTED TO TAFT N69W.



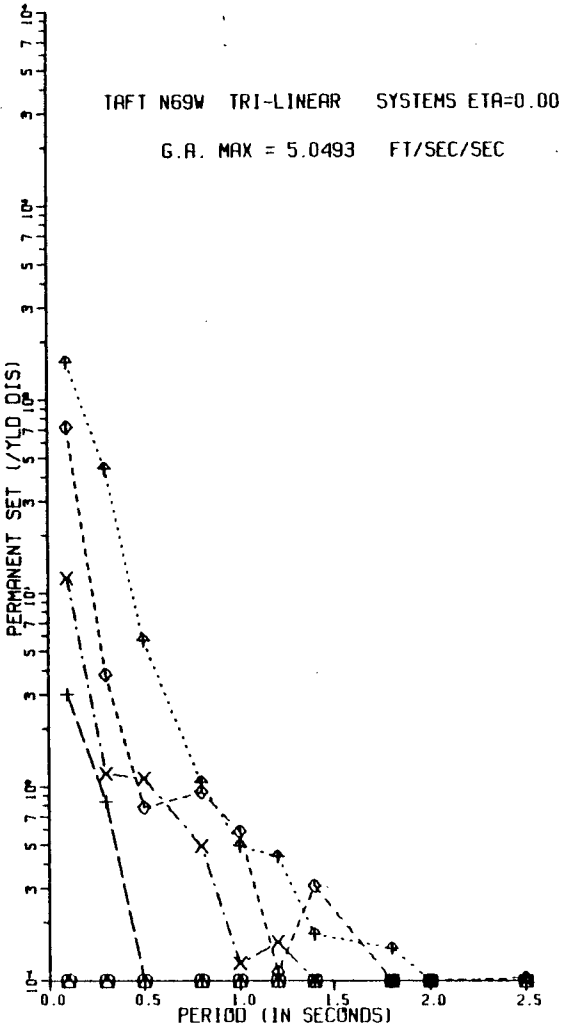


FIG. 3.41 CONTINUED

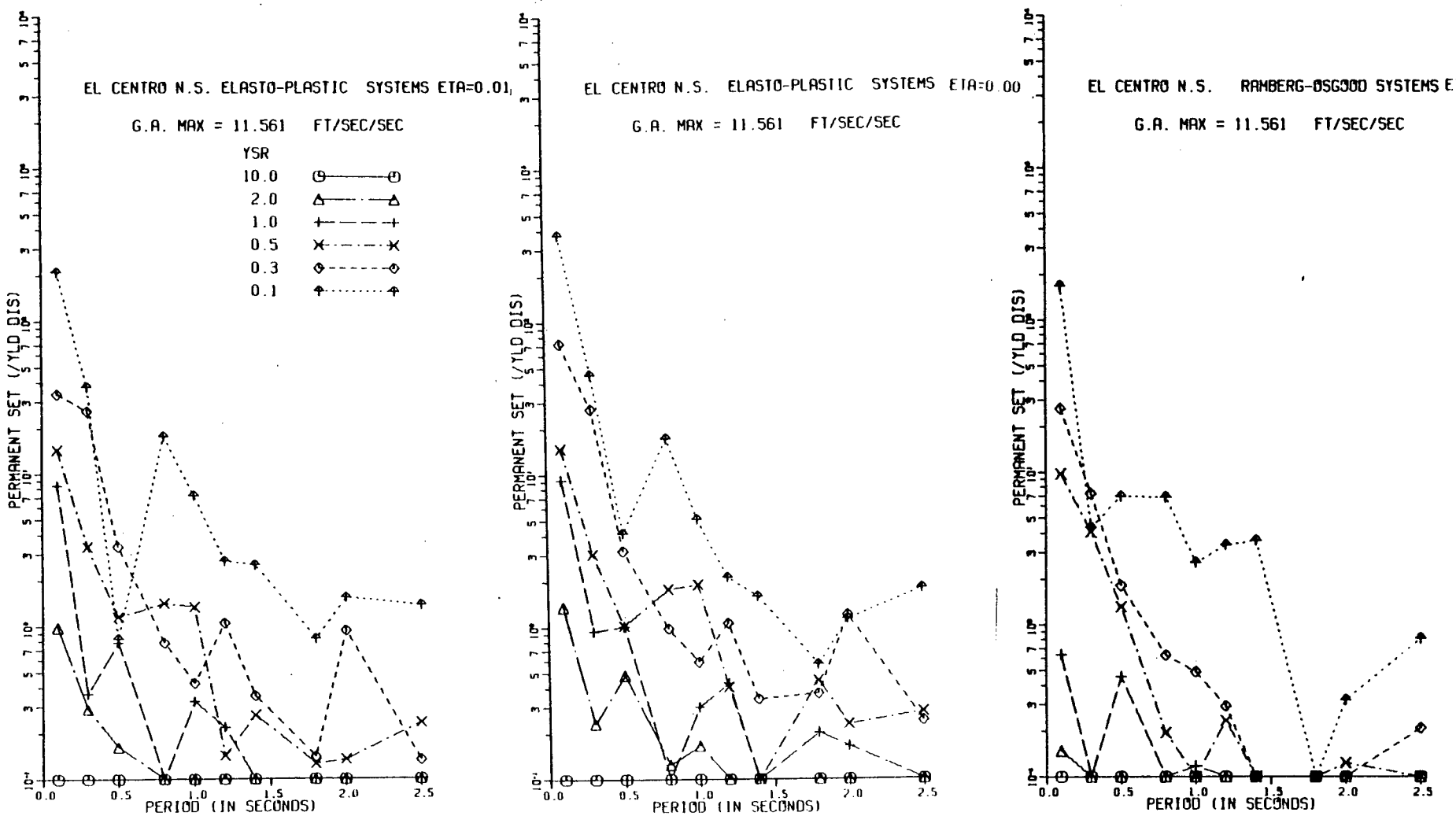
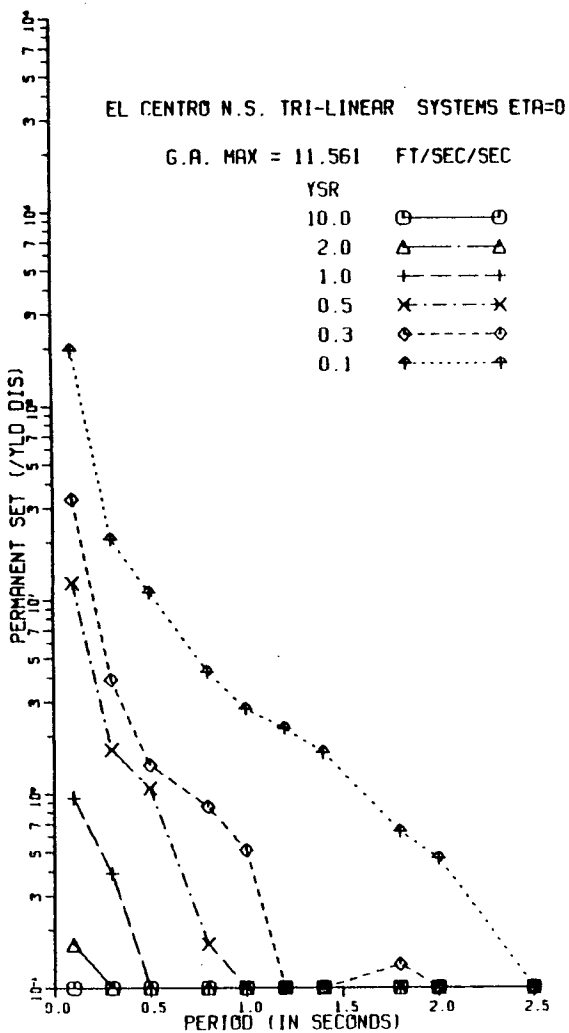


FIG. 3.42 PERMANENT SETS FOR SYSTEMS SUBJECTED TO EL CENTRO N.S.



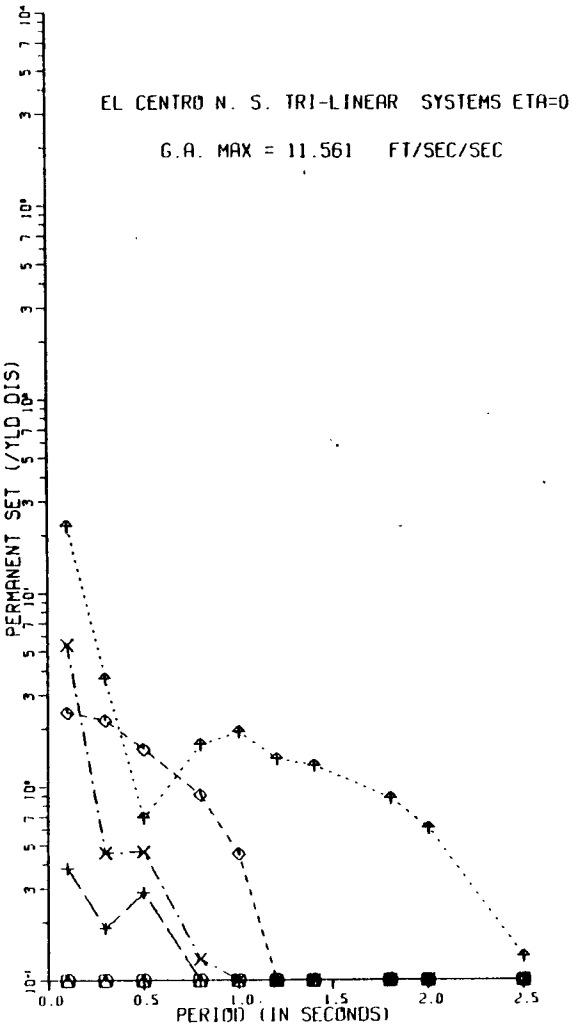
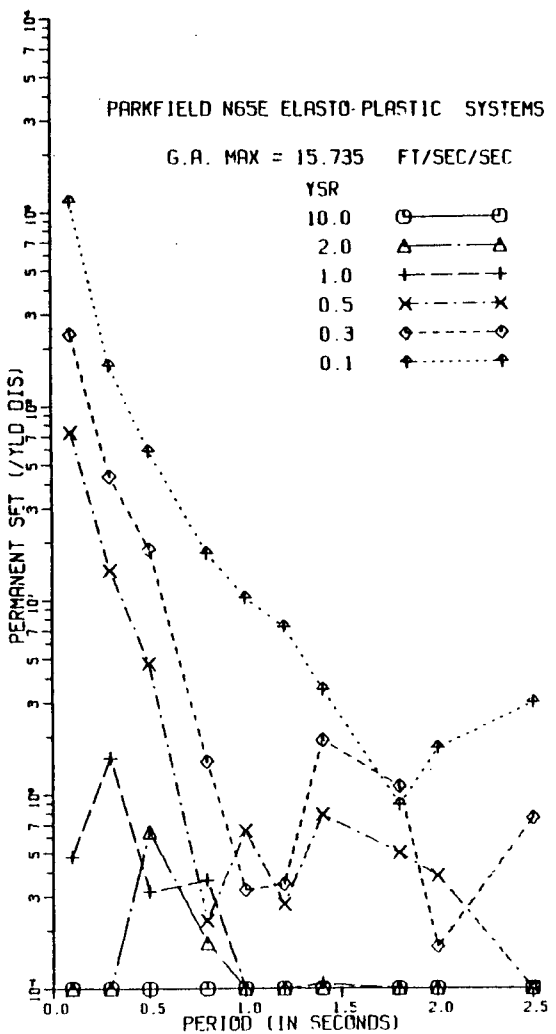


FIG. 3.42 CONTINUED



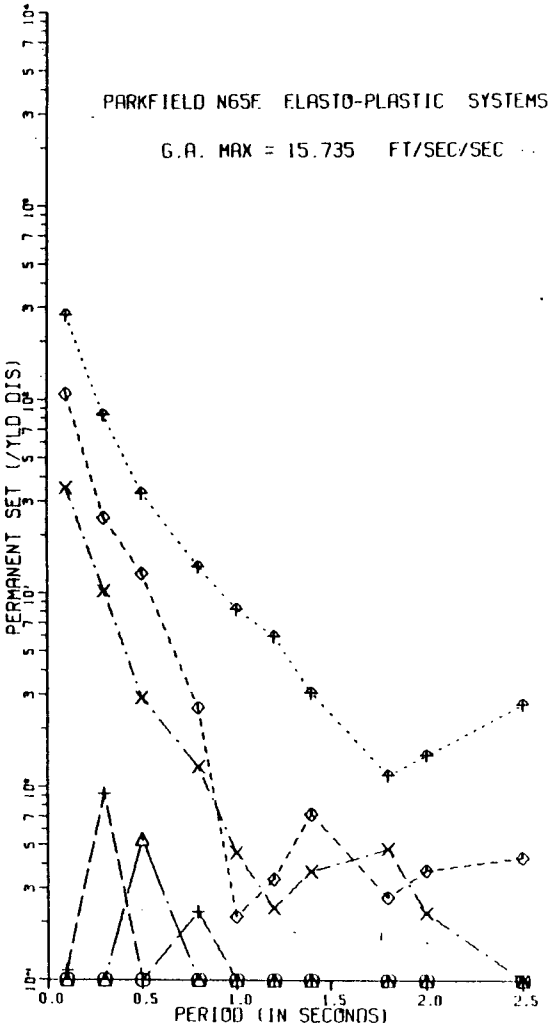
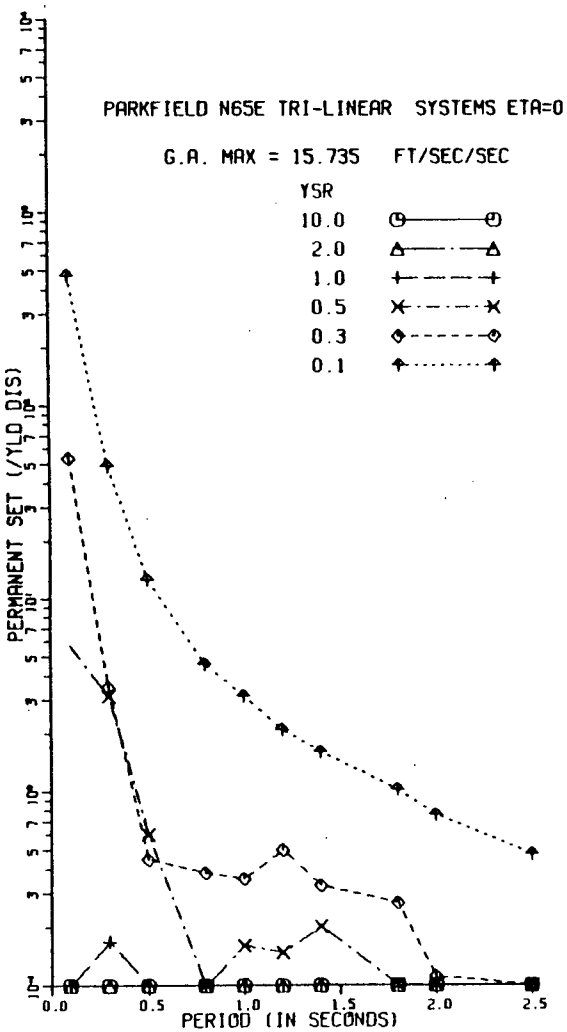


FIG. 3.43 PERMANENT SETS FOR SYSTEMS SUBJECTED TO PARKFIELD N65E.



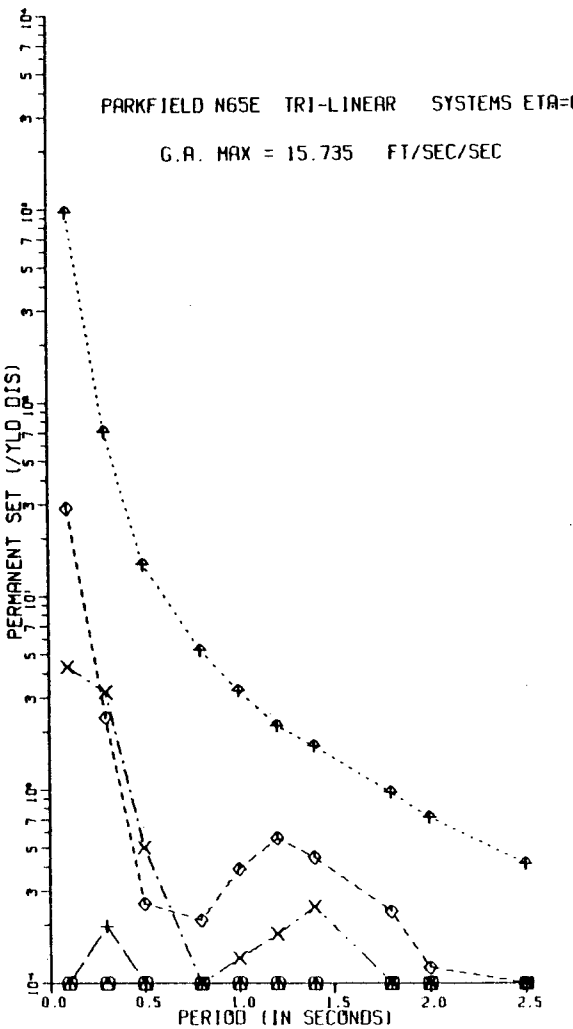
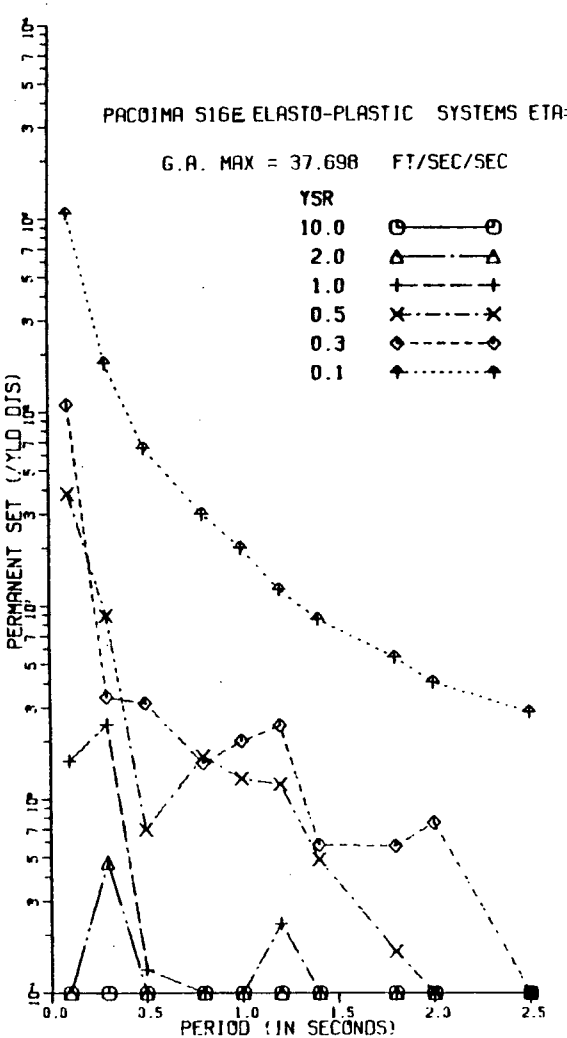


FIG. 3.43 CONTINUED



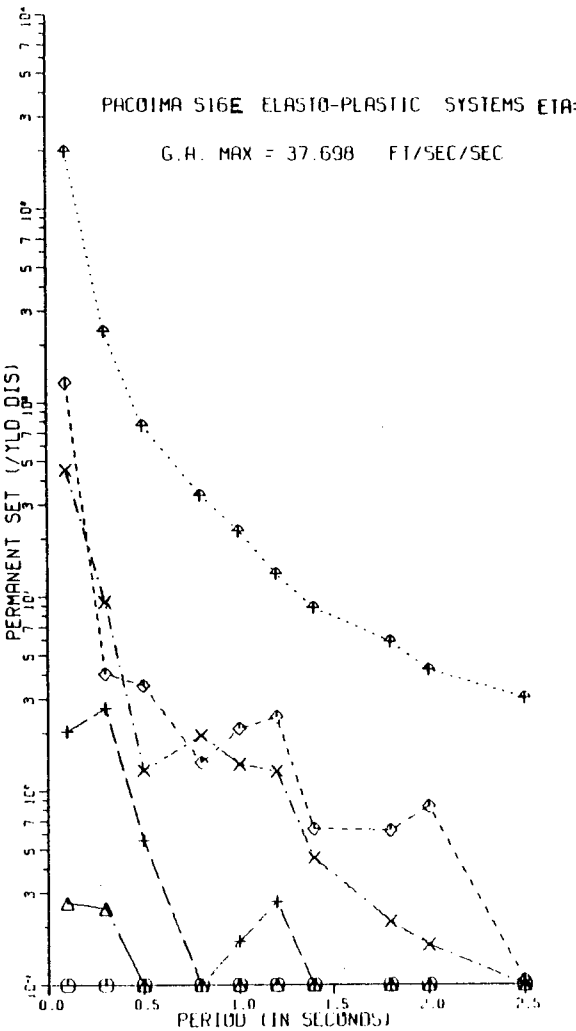
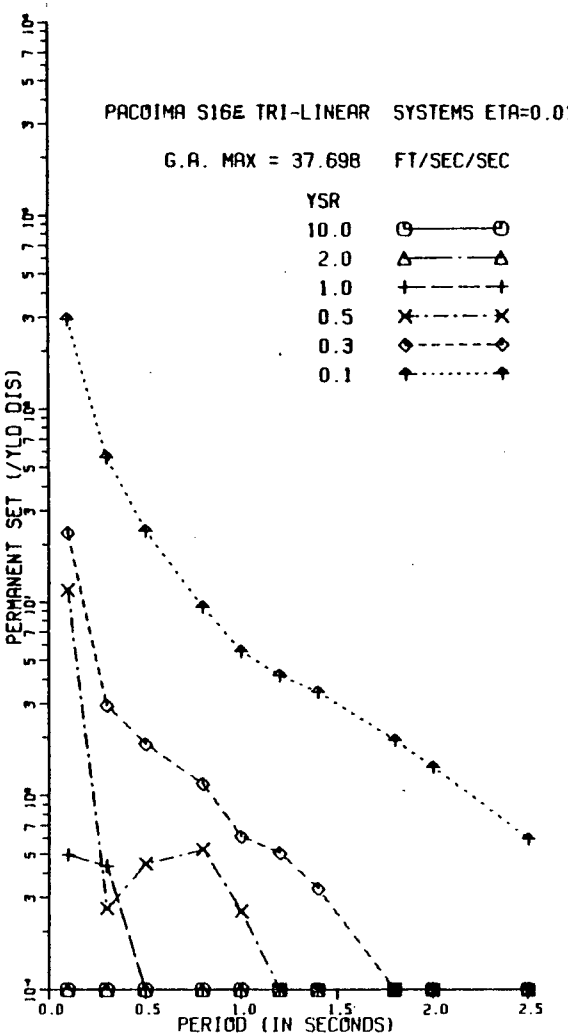


FIG. 3.44 PERMANENT SETS FOR SYSTEMS SUBJECTED TO PACOIMA S16E.



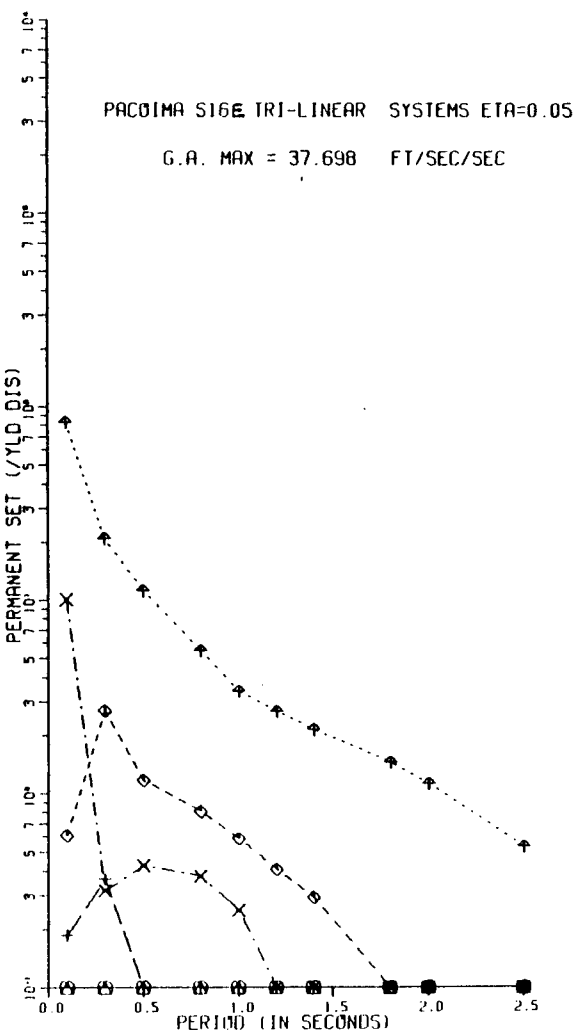


FIG. 3.44 CONTINUED

3.7 Classification of Structures by Yield Strength Ratio

The results studied in the previous sections of this chapter clearly show that this parameter has a marked effect upon the extent and the manner in which similar systems respond to the same base excitations. There was a general pattern from all results that was well defined and has led to the following strength classification of systems into three groups.

1) Strong Systems (Y.S.R. ≈ 10.0 - 1.0)

a) Response is predominantly elastic with no major yield excursions.

b) Energy is very sensitive to variations in period and varies with frequency content of E/Q.

c) Equal displacement criterion is good for periods greater than 0.5 sec. for systems with 1% damping and greater.

d) Displacement ductilities in range 1 - 10 except for one case of a Tri-linear system subjected to Taft (25 @ T = 0.1 sec.).

e) Permanent sets are generally less than yield displacement.

f) Structures fall within range of code designed systems.

2) Moderate Systems (Y.S.R. ≈ 1.0 - 0.3)

a) Major yield excursions occur in response of all systems. RESPONSE IS SIGNIFICANTLY DIFFERENT FROM ELASTIC SYSTEMS.

b) Energy varies with period, but is not strongly dependent on period as is the case for strong systems.

c) Equal displacement criterion is good for periods greater than 0.5 secs. This trend is particularly well defined for systems with non-degrading stiffness characteristics. For the degrading stiffness models and systems with small amounts of damping the equal displacement criterion does not hold.

d) Displacement ductilities in range 10 - 400 for periods = 1.0 secs. However, for periods greater than 1.0 sec. these systems have demand ductilities less than 10.

e) Permanent sets are generally about 1/4 of displacement ductility values.

f) These systems are within the range of code designed buildings.

3) Weak Systems (Y.S.R. < 0.3)

a) Excessive ductilities for all systems.

b) Energy demand is constant for all periods.

c) Equal displacement does not apply.

d) Systems are outside the range of code designed buildings.

3.7.1 Correlation of Yield Strength Ratio to Code Implied Strengths

In order to gain some physical appreciation for this strength parameter it is useful to correlate it with typical strengths implied by standard building codes. A correlation was carried out for comparison with the National Building Code of Canada (1975) using the arguments and notation employed in reference 24.

In ref. 24 it is shown that the maximum peak ground acceleration can be equated as:

$$\text{G.A. max.} = \frac{\text{ASKIF } \lambda\mu}{\beta D}$$

and the yield level base acceleration = ASKIF λ

$$\text{YSR} = \frac{\text{YIELD ACCELN}}{\text{G.A. Max.}} = \frac{\beta D}{\mu}$$

where: A, S, K, I, F are standard code symbols.

λ = Load factor

μ = Ductility factor

β = Ratio of the average acceleration of a structure to the spectral acceleration of the first dominant mode of the structure.

D = Response spectrum amplification factor.

Using figs. 1 and 2 of ref. 24 it is found that:

upper bound on strength ratio implied by code

$$= \frac{1.0 \times 3.0}{2.0} = 1.5$$

Lower bound on strength ratio implied by code

$$= \frac{0.6 \times 2.0}{4.0} = 0.3$$

Average value for a typical 10 storey frame structure

$$= \frac{0.75 \times 3.0}{4} = 0.56$$

or $$= \frac{0.75 \times 2.0}{4} = 0.4$$

From this it was concluded that an upper bound on the strength ratio implied by the code is approximately 1.5, whilst a lower bound of 0.3 is found. For a typical 10 story frame structure the yield strength ratio is of the order of 0.5.

3.7.2 Some Implications of These Results

In order to ensure that ductility demands are kept within reasonable limits the following general conclusions can be expressed in terms of the classification outlined in this section.

All structures with periods less than 1.0 sec. should be designed as strong systems with yield strength ratios at least equal to the maximum peak ground acceleration.

All structures with periods greater than 1.0 sec. should be designed as moderate systems with yield strength ratios between 1.0 and 0.3 times the maximum peak ground acceleration.

In fact the present codes probably do this implicitly because of the way they have been developed, and the fact that stiffness and yield strength of systems are inherently inter-related. So whilst the type of restriction given above is not checked explicitly by the present codes it is covered in a combination of other implicit factors.

3.8 Approximations for Total Energy Dissipated

In section 3.2 a detailed study was made of the factors affecting the total energy to be dissipated by systems subjected to earthquake ground motions. There it was stated that this parameter would be fundamental to a design method based upon energy dissipation considerations. In which case it would be most valuable to be able to approximate the total energy to be dissipated by such systems.

In this section some first attempts at these approximations are reported, and discussed in the context of the classification system presented in section 3.7.

3.8.1 Approximations for Total Energy Dissipated by Strong Systems

In considering the results for the total energy dissipated for all strong systems of the eighteen data sets produced, it is observed that the spread is too wide to obtain a useful average or upper bound. Therefore it was expedient to consider strong systems in groups for the four earthquake records studied. In these four groups the calculated total energy dissipated by the systems was compared to predictions produced from elastic response spectrum analysis.

In this comparison energies were produced by considering the elastic spectral velocity as a basis for calculating the " Elastic Spectral Kinetic Energy", as suggested by Housner[7,25]

ie. E.S.K.E. $= \frac{S_v^2}{2}$ per unit mass.

It was observed that this approximation formed a reasonable upper bound for all systems with initial period greater than 0.8 sec. However for shorter initial periods the E.S.K.E. underestimates the calculated energy demands. This is particularly true for the case of short period systems with degrading stiffness properties. For these systems the total energy dissipated is more consistent with longer period elastic systems. A bi-linear upper bound for all systems is provided by:

For $T < .5$ sec. $\quad E = 0.02 + 0.12\ T$

For $T \geq 0.5$ sec. $\quad E = 0.0925 - 0.025\ T$

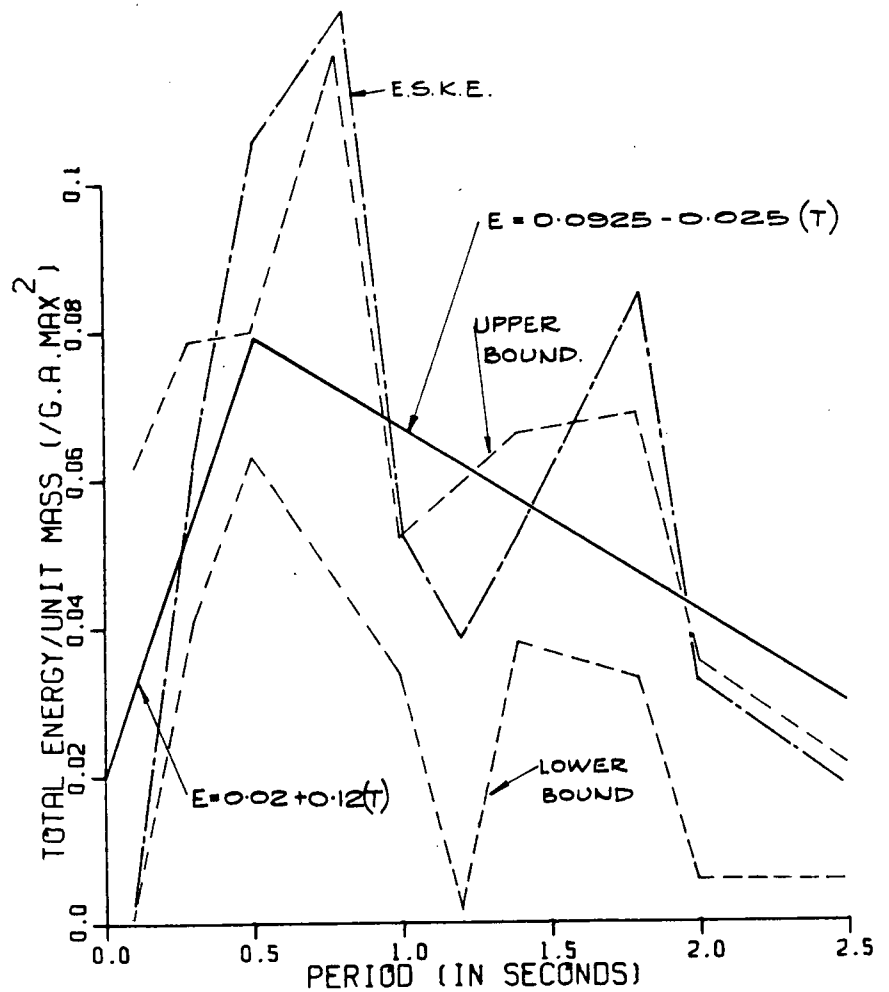
This upper bound is reasonable for all strong systems subjected to the Taft, El Centro and Parkfield ground motion records. However, this is found to be excessively conservative for the Pacoima results where the following upper bound is indicated.

For $T \leq 1.8$ sec. $\quad E = 0.02 + 0.022\ T$

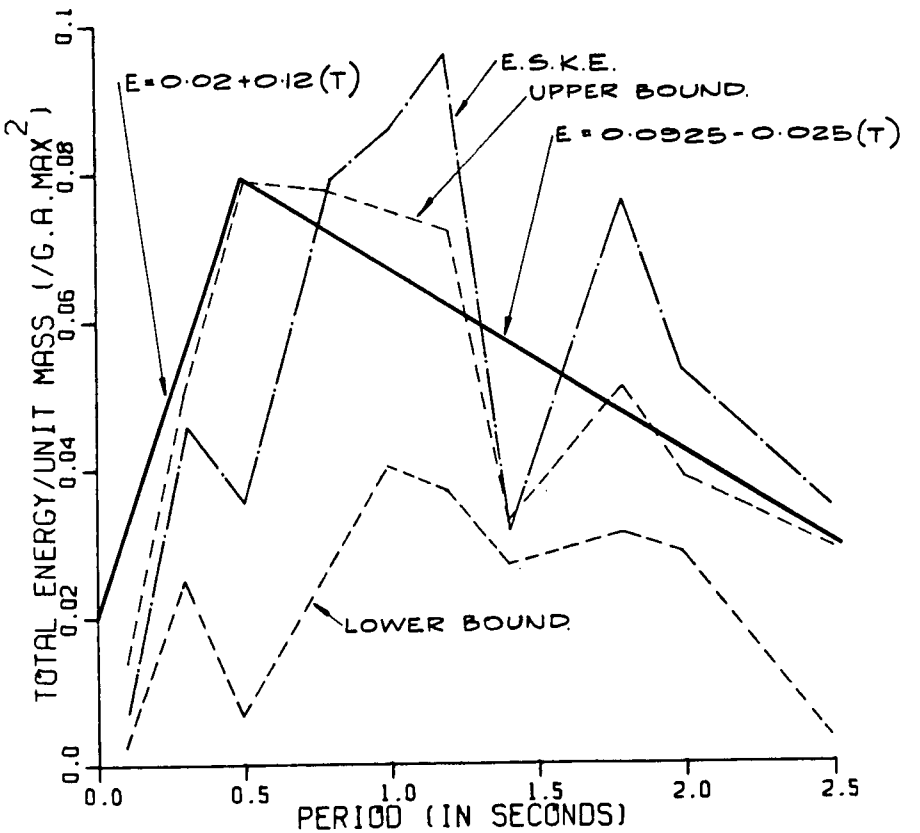
For $T > 1.8$ sec. $\quad E = 0.19 - 0.071\ T$

These approximations are shown in figs. 3.45.

A bi-linear approximation for the mean energy of all eighteen sets of strong systems studied is given in fig. 3.46.

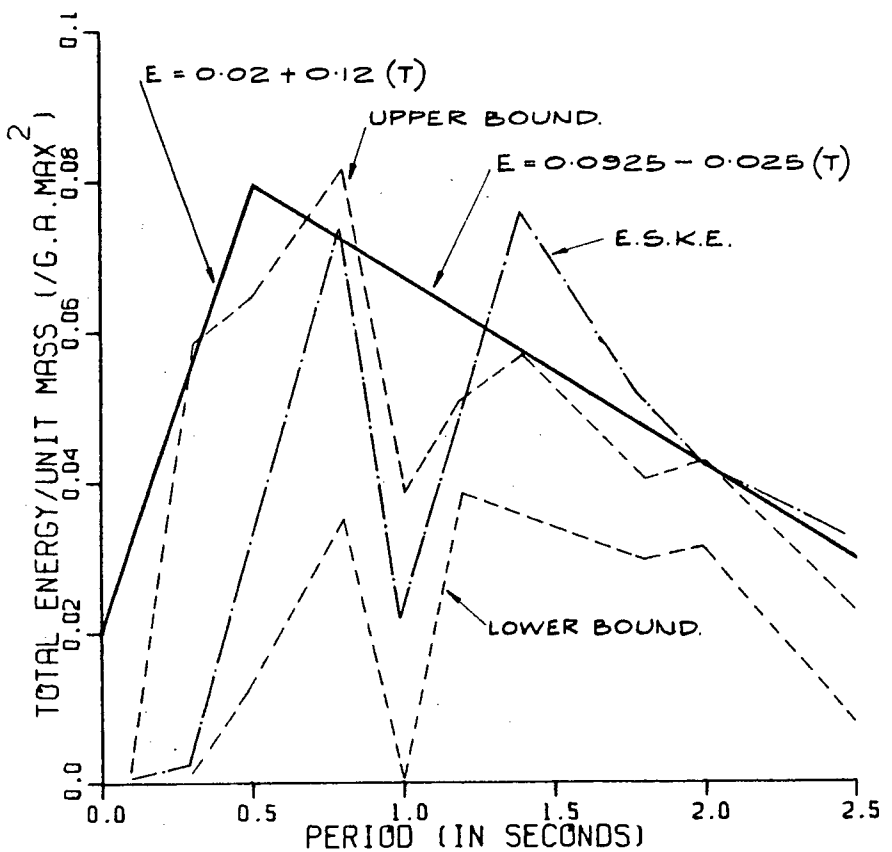


(a) STRONG SYSTEMS SUBJECTED TO TAFT N69W.

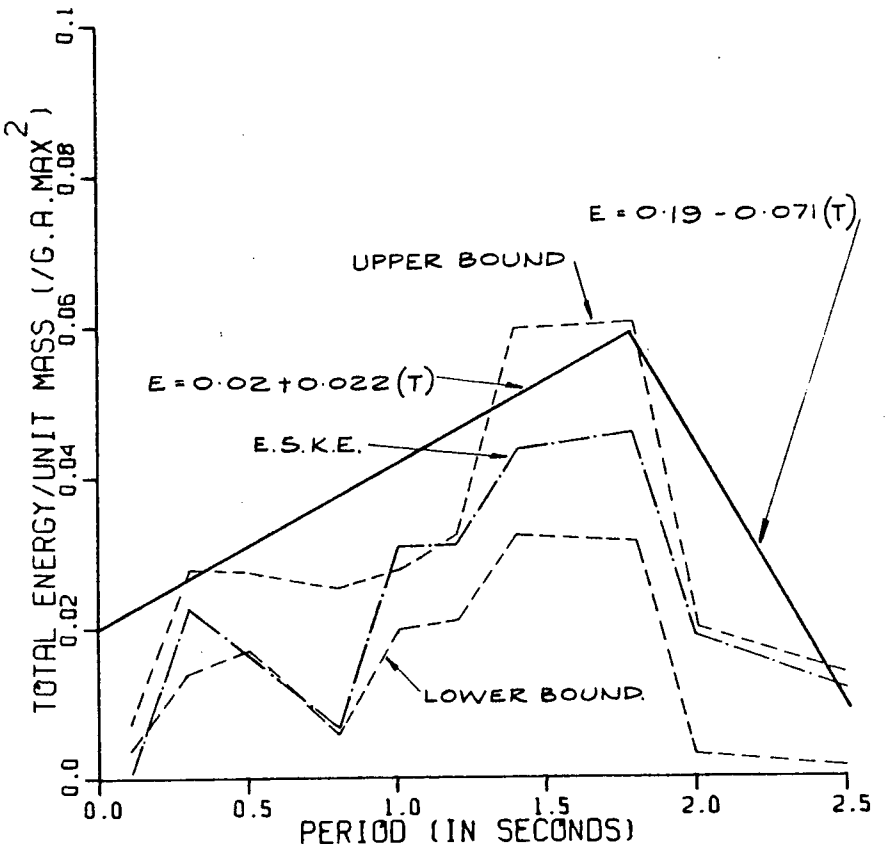


(b) STRONG SYSTEMS SUBJECTED TO EL CENTRO N.S.

FIG. 3.45 APPROXIMATIONS FOR TOTAL ENERGY DISSIPATED BY STRONG SYSTEMS.



(c) STRONG SYSTEMS SUBJECTED TO PARKFIELD N65E.



(d) STRONG SYSTEMS SUBJECTED TO PACOIMA SIGE.

FIG. 3.45 CONTINUED

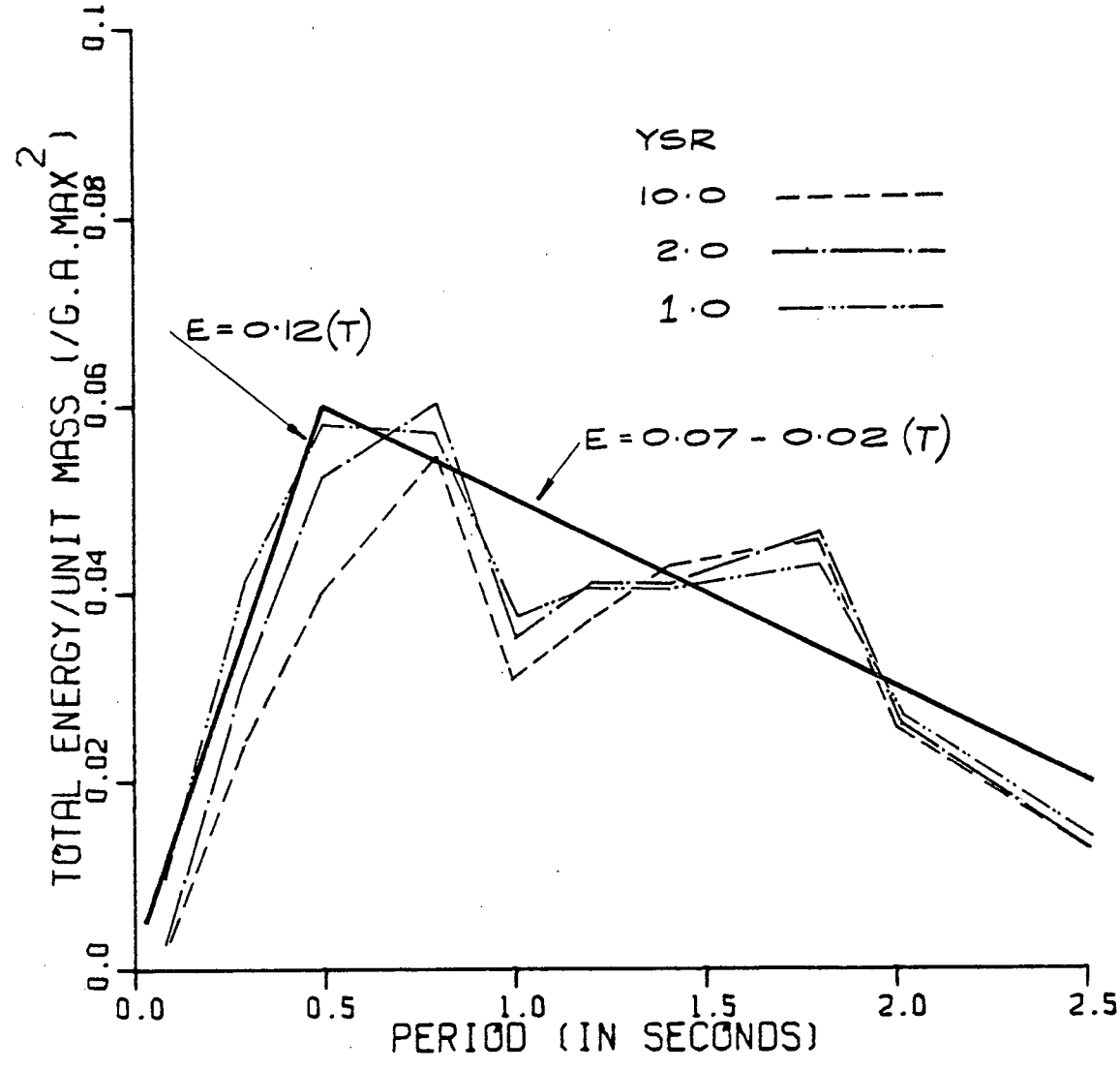


FIG. 3.46 APPROXIMATIONS FOR MEANS OF TOTAL ENERGY DISSIPATED BY ALL STRONG SYSTEMS.

3.8.2 Approximations for Total Energy Dissipated by Moderate Systems

For the results of the moderate systems it was found that the total energy dissipated for all hysteretic properties, damping values, and earthquake ground motions form a reasonably narrow band and fall into a consistent pattern. For these results it is possible to produce expressions for approximations to the mean energy by bi-linear regression.

For systems with YSR = 1.0 a bi-linear regression gives the following results for mean energies.

For $T \leq 0.5$ sec. $\quad E = 0.0011 + 0.118\ (T)$

For $T > 0.5$ sec. $\quad E = 0.0673 - 0.0197\ (T)$

For systems with YSR = 0.5

For $T \leq 0.5$ sec. $\quad E = 0.022 + 0.056\ (T)$

For $T > 0.5$ sec. $\quad E = 0.062 - 0.016\ (T)$

For systems with YSR = 0.3

For $T \leq 0.5$ sec. $\quad E = 0.026 + 0.312\ (T)$

For $T > 0.5$ sec. $\quad E = 0.049 - 0.012\ (T)$

Similarly by carrying out a bi-linear regression analysis at energy values corresponding to the mean plus one standard deviation for data at each period, it is possible to construct an upper bound which corresponds approximately to a confidence level of 83.7%.

The results for this upper bound regression analysis are given below:

For systems with YSR = 1.0

For $T \leq 0.5$ sec. $E = 0.016 + 0.135\ (T)$

For $T > 0.5$ sec. $E = 0.094 - 0.028\ (T)$

For systems with YSR = 0.5

For $T \leq 0.5$ sec. $E = 0.042 + 0.056\ (T)$

For $T > 0.5$ sec. $E = 0.079 - 0.021\ (T)$

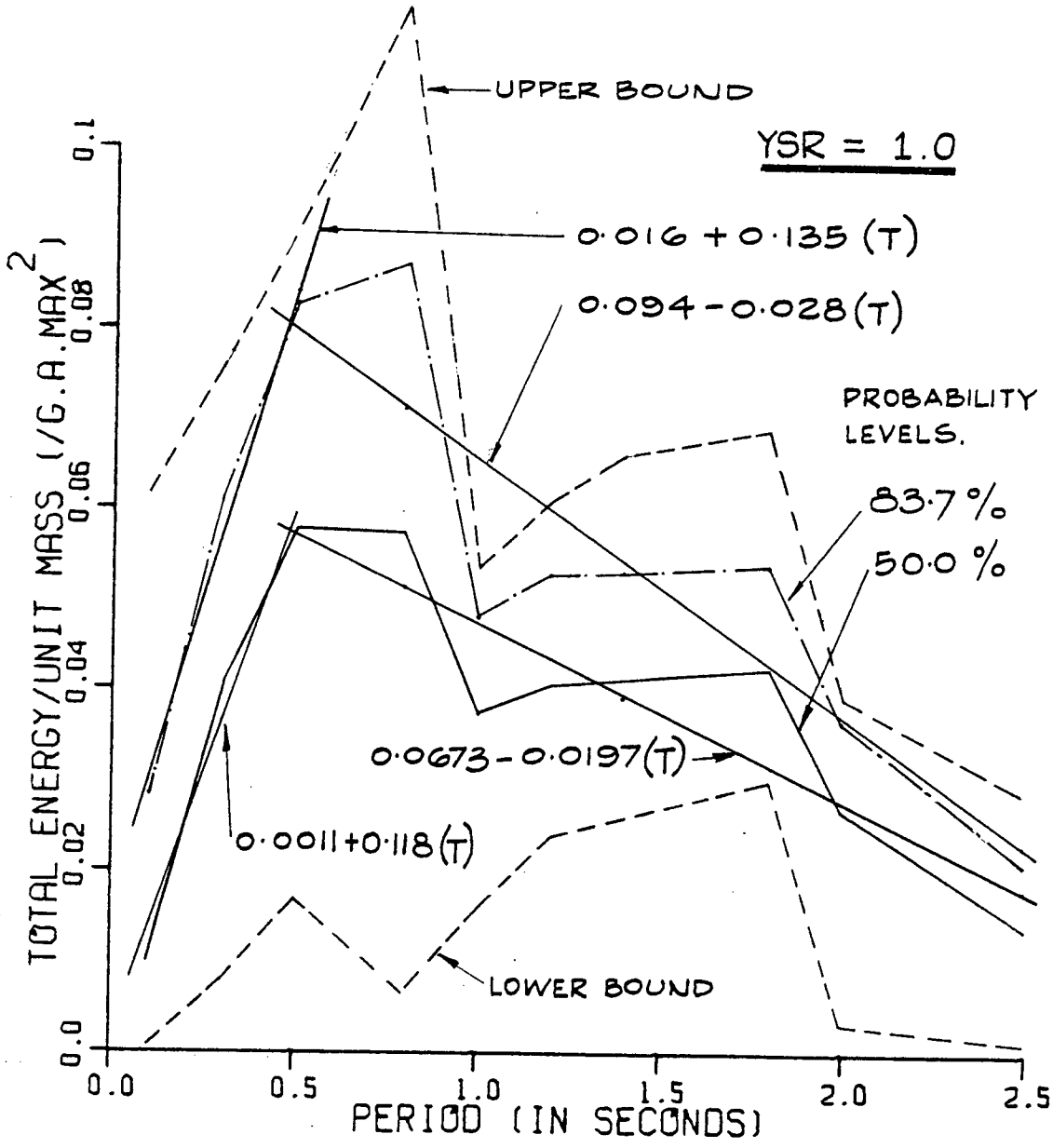
For systems with YSR = 0.3

For $T \leq 0.5$ sec. $E = 0.04 + 0.037\ (T)$

For $T > 0.5$ sec. $E = 0.063 - 0.015\ (T)$

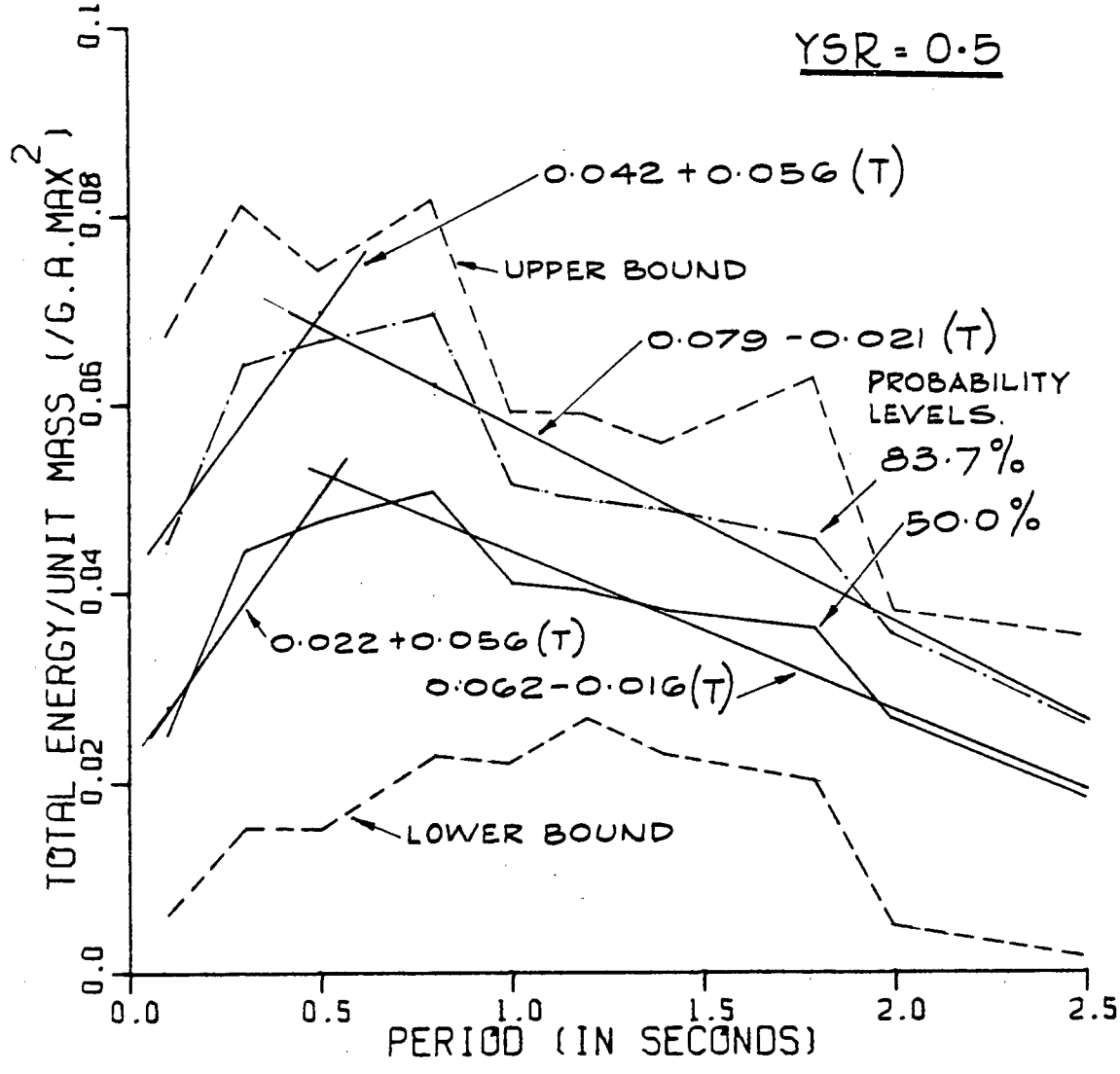
The regression analysis for all these systems leads to similar expressions which suggests that one expression for the mean energies can be used for all moderate systems.

These results are shown in fig. 3.47.



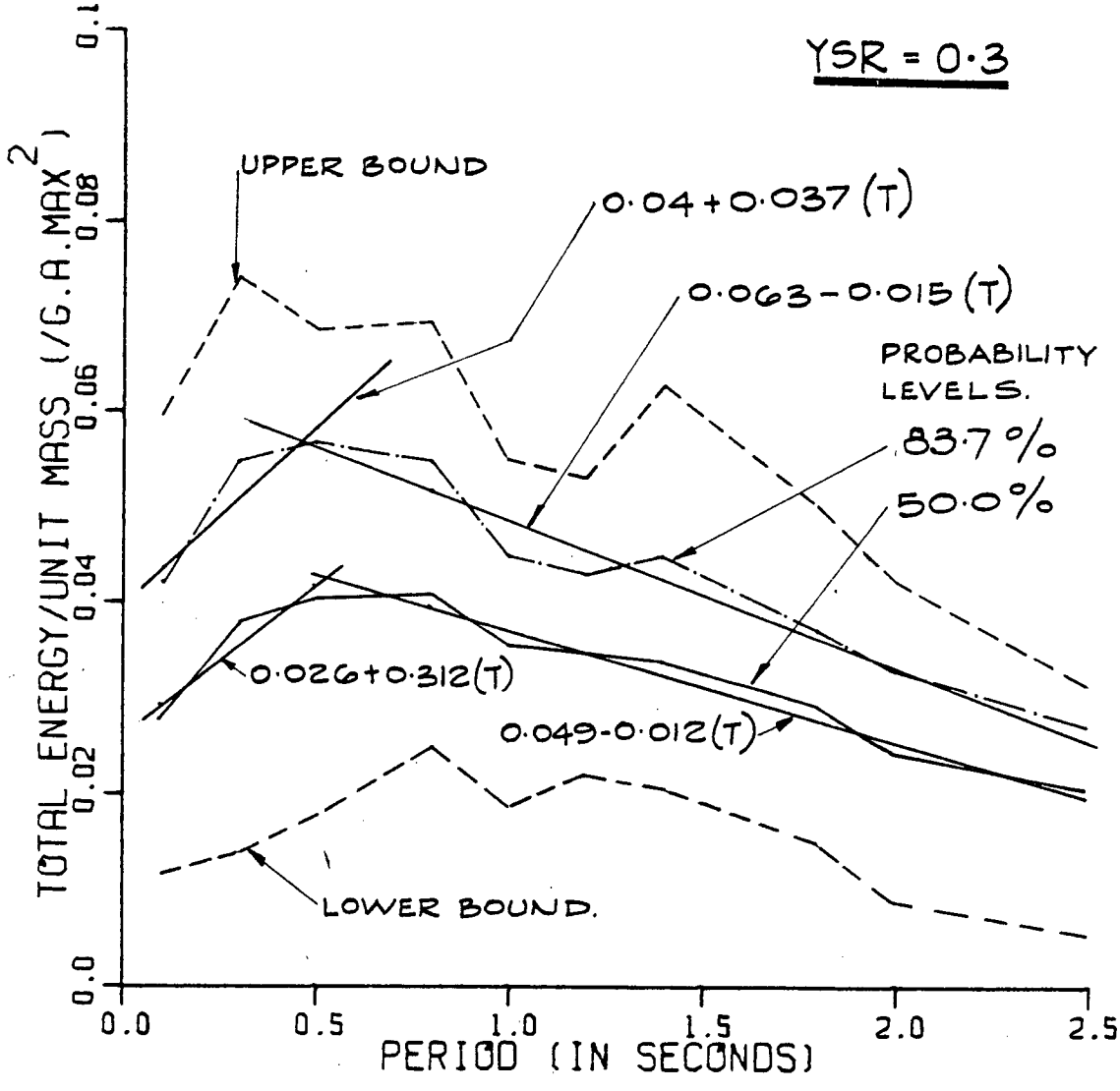
(A)

FIG. 3.47 APPROXIMATIONS FOR TOTAL ENERGY DISSIPATED BY MODERATE SYSTEMS.



(B)

FIG. 3.47 CONTINUED



(C)

FIG. 3.47 CONTINUED

3.8.3 Approximations for Total Energy Dissipated by Weak Systems

For these systems it is found that the total energy dissipated decreases linearly with period, and is essentially independent of viscous damping and earthquake excitation used. The spread in these results is in large measure a function of the way the earthquake records are non-dimensionalised.

A simple linear regression analysis produced excellent correlation with the mean energy values as:

$E = 0.028 - 0.005\,(T)$ for all periods.

A similar regression analysis for mean plus one standard deviation energy values produced an approximate 83.7% confidence level upper bound as:

$E = 0.041 - 0.008\,(T)$ for all periods.

These results are shown in fig. 3.48. This energy represents the energy required to effectively destroy the systems. In terms of energy dissipation capacity, these values can be considered the maximum energies that can be dissipated by the system during the earthquake. Additional energies from the earthquake can not be absorbed.

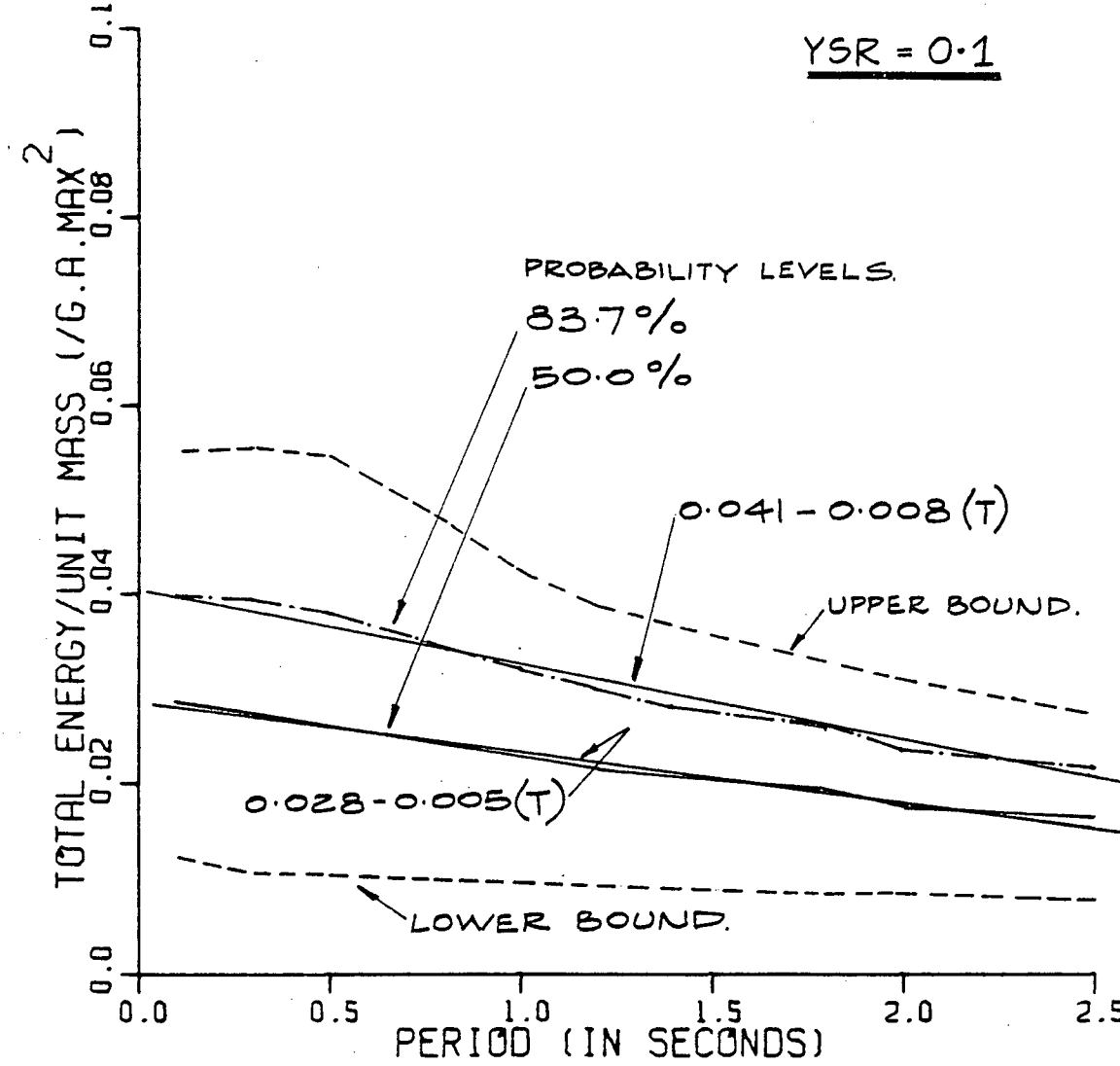


FIG. 3.48 APPROXIMATIONS FOR TOTAL ENERGY DISSIPATED BY WEAK SYSTEMS.

3.9 Approximations for Distribution of Energy Within Systems

The results for the distribution of energy within systems were given in section 3.3. There it was shown that the percentage of total energy dissipated by hysteresis is independent of earthquake record. Further, once these results are considered in terms of hysteresis model and proportion of viscous damping, they fall into narrow well defined patterns.

Because of the clear pattern produced by these results it is possible to approximate the distribution of energy within the systems by simply taking the mean values of the results for the corresponding combinations of parameters.

These results are shown in figs. 3.49 and 3.50 for Elasto-Plastic and Tri-linear systems respectively.

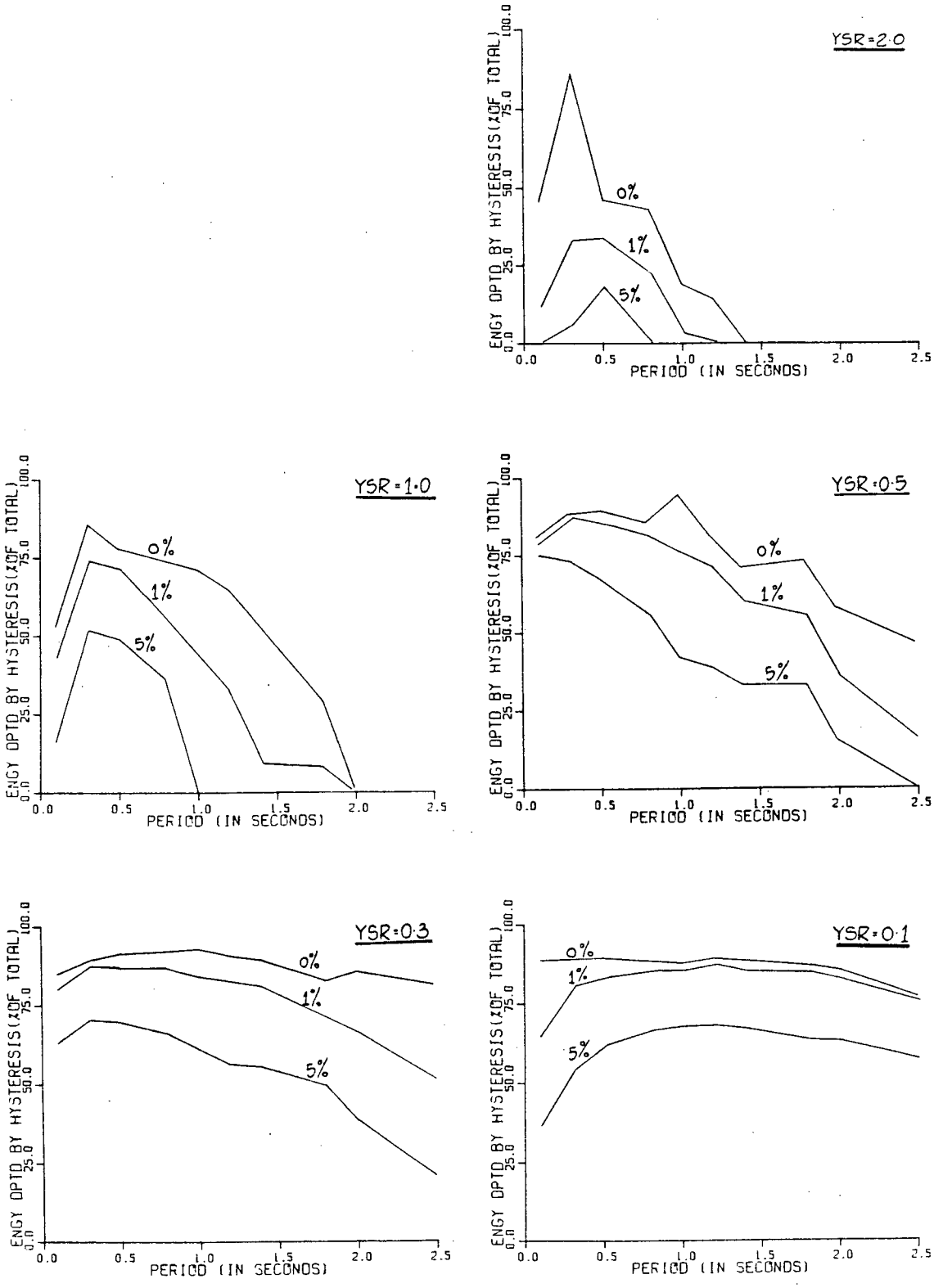


FIG. 3.49 APPROXIMATIONS FOR DISTRIBUTION OF ENERGY WITHIN SYSTEMS FOR ELASTO-PLASTIC SYSTEMS.

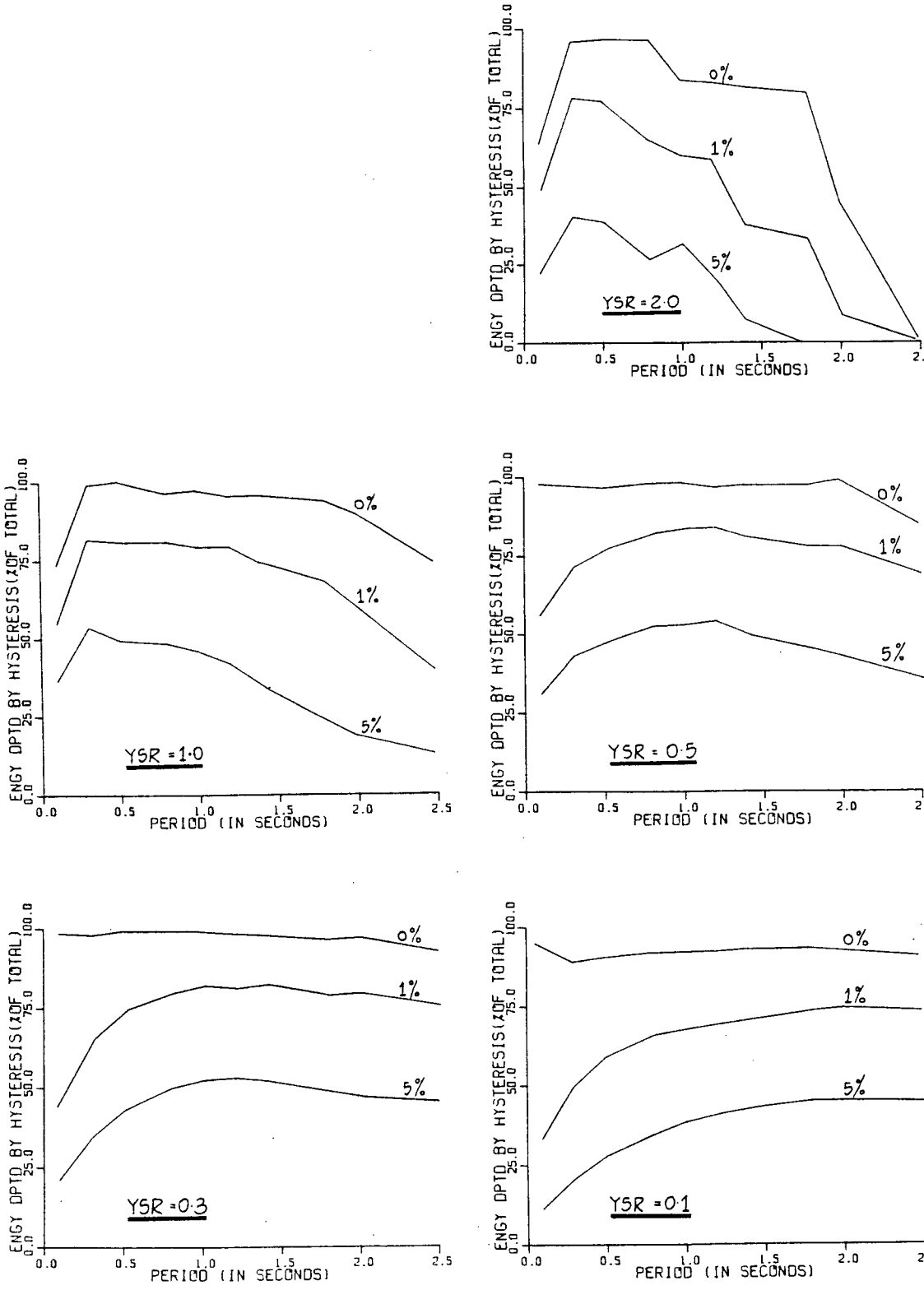


FIG. 3.50 APPROXIMATIONS FOR DISTRIBUTION OF ENERGY WITHIN SYSTEMS FOR TRI-LINEAR SYSTEMS.

CHAPTER 4

DEVELOPMENT AND VERIFICATION OF DESIGN METHOD FOR SINGLE DEGREE OF FREEDOM SYSTEMS

4.1 Introduction

In this chapter the intention is to incorporate the results and insight obtained in chapter 3 into a design method, based on energy dissipation requirements, which would be suitable for inclusion in a limit state design code. Due to the time limitations upon this work it was not possible to conduct as thorough an investigation into this aspect of the research as was hoped. However, sufficient information is available to enable preliminary conclusions to be made, and a tentative form of a design method is outlined.

The results of the detailed study of chapter 3 give insight into the total energy to be dissipated by single degree of freedom systems. Also the manner in which the total energy to be dissipated is distributed between the hysteretic and viscous damping mechanisms within the system was studied. To date the study has shown that the total energy and its distribution within the system depends upon the following five parameters.

(i) yield strength ratio

(ii) period

(iii) hysteretic model

(iv) viscous damping

(v) earthquake type

There is a wide spread in some of the results with respect to individual earthquake records, and it is possible that the influence of the other parameters may not, in comparison with this spread, need to be given a very refined treatment in a design method. However, in chapter 3, it was shown that it was possible to construct spectral curves of total energy and distribution of energy for systems in terms of all these parameters.

The present generation of design codes, based on a limit state philosophy, requires a two level investigation of earthquake resistance. The intention is to ensure minor damage occuring in a moderate earthquake, and to prevent collapse in a severe earthquake. Although this general intent has long been established in the provisions of design codes, the explicit nature of the limit state requirements presents a new challenge. In this context the yield strength ratio, and the strength classification system discussed in chapter 3 are most useful.

4.2 Requirements for an Earthquake Design Method

In the design of buildings the serviceability and architectural requirements predetermine the layout, and to a large extent the structural framing. Thus the stiffness of the structure is largely fixed by the time aseismic considerations are taken up. Hence the initial period is fixed and is only modified slightly by engineering choice of construction system and design strength. The two main parameters that the engineer can vary are the structural system to be used and the yield strength of the members.

The design method should concentrate on the effects of varying the construction system and yield strength and checking that the response and energy dissipating capacities are satisfactory.

A most critical parameter in measuring response is displacement, because this can be related directly to damage.

The structure must, at all times during the earthquake, be capable of dissipating the energy imparted to it by the ground motion. A check for this adequacy is imperative. This means that the structure must be designed and detailed to ensure that the Required Energy Capacity is provided.

The design method can take the form of an optimization process in which the materials and strengths are varied and energy capacity, peak displacements and permanent sets are checked for acceptable levels.

4.3 Yield Strength Ratio and Damage Control

It has long been the philosophy in designing structures to withstand earthquake motions to permit limited amounts of damage consistent with economic considerations. It is uneconomic to try and design for no damage, but at the same time, excessive damage must be avoided. A spectral analysis using assumed ductility factors to produce design forces can at best only meet the designers philosophic goals in a general sense. In order to improve upon our analysis technique, we must include an additional parameter which is based explicitly on strength considerations. In the single degree of freedom study it is shown that a strength variation has marked effects upon all significant parameters. ie. total energy dissipated, displacement ductility, displacement and permanent sets.

By including explicitly a strength parameter in the analysis and design procedure it is possible to meet the goals of the design philosophy in a far more specific manner. Having completed a design with a specific

strength parameter, the designer will be able to predict with reasonable accuracy the displacement ductility and displacements to be expected from a moderate or a severe ground motion. The displacement ductility and displacement predictions can then be related to expected damage levels which must be chosen to comply with economic requirements. In this way the designer has far more control over the consquences he inherently builds into his design and an optimum solution to the problem becomes possible.

4.4 Some Notes on Energy Dissipation Versus Time

For a design method based upon energy dissipating characteristics it is important not only to know the amount of energy to be dissipated by each individual mechanism, but also the manner and the rate at which this energy is dissipated throughout the excitation. Insight into this aspect of the response was gained from studying the time histories of the displacement, energy input to system, energy dissipated by viscous damping and energy dissipated by hysteresis in conjunction with the force/displacement history of each system. From these sets of data for individual systems a general picture of the energy dissipating mechanisms can be built up. Some typical sets of these results are given in figs. 4.1, 4.2, 4.3 and 4.4. A summary of the results of this study is presented in table 4.1.

From these studies it was found that the most useful parameter for application in a design method is to consider the fraction of hysteretic energy dissipated in the spring during the largest half loop yield excursion. In order to be able to proportion the amount of hysteretic energy to be dissipated in this "principal half loop" a number of systems were studied. From these preliminary studies it has been found that the magnitude of the prinicipal half loops can be generally categorized as follows:

(i) For all systems subjected to Pacoima S16E, a near source impulsive earthquake, and for strong systems subjected to Taft N69W, a far field earthquake, the largest yield excursions dissipate up to 50% of the total energy dissipated in hysteresis. ie. such systems experience 2 or 3 major yield excursions.

(ii) For moderate systems subjected to Taft N69W, a far field earthquake, the largest yield excursions dissipate from 20% to 33% of the hysteretic energy.
ie. such systems experience 3 - 5 major excursions.

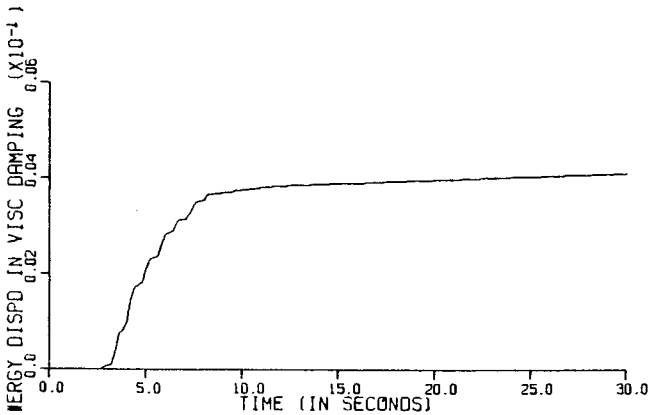
The rate at which energy is dissipated by viscous damping is in general either a linear or parabolic function of time. For some systems energy is dissipated by the viscous dampers in a few isolated pulses, up to 20%. However, for the very weak systems subjected to the Pacoima S16E record these pulses can be as large as 55%.

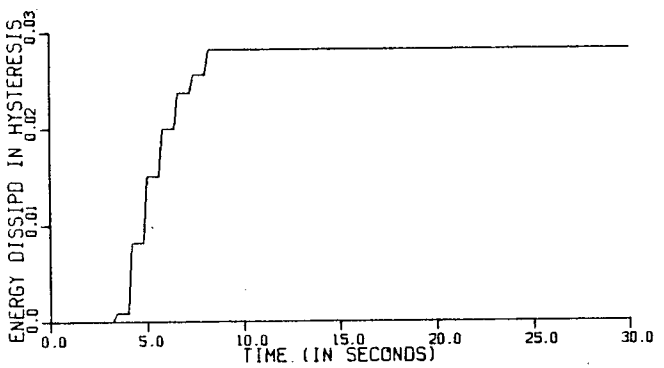
SYSTEM					Percentage of Hysteretic Energy In Principal Half Loop	Shape of Viscous Damping Energy Vs. Time Curve
Record	HYST.	YSR.	Period	Viscous Damping		
Taft	E/P	1.0	0.8	1%	30%	Linear
Taft	E/P	1.0	1.5	1%	40%	Linear
Taft	E/P	0.5	0.8	1%	25%	Linear (10% Pulse)
Taft	E/P	0.5	1.5	1%	21%	Linear
Taft	T/L	1.0	0.8	1%	14%	Linear (20% Pulse)
Taft	T/L	1.0	1.4	1%	15%	small steps/Linear
Taft	T/L	0.5	0.8	1%	16%	small steps/Linear
Taft	T/L	0.5	1.4	1%	18%	small steps/Linear
Pacoima	E/P	1.0	0.8	1%	Elastic	Parabolic
Pacoima	E/P	1.0	1.4	1%	48%	Parabolic
Pacoima	E/P	0.5	0.8	1%	41%	Linear
Pacoima	E/P	0.5	1.4	1%	54%	Parabolic
Pacoima	T/L	1.0	0.8	1%	24%	Linear (15% Pulse)
Pacoima	T/L	1.0	1.4	1%	26%	Parabolic
Pacoima	T/L	0.5	0.8	1%	47%	Parabolic
Pacoima	T/L	0.5	1.4	1%	26%	Parabolic
Taft	E/P	.64	0.8	1%	33%	Linear (10% Pulse)
Taft	E/P	.64	1.6	1%	25%	Linear
Taft	E/P	1.3	1.6	1%	60%	Linear
Taft	E/P	1.3	0.8	1%	55%	Linear
Pacoima	E/P	0.17	0.8	1%	42%	35% Pulse
Pacoima	E/P	0.17	1.6	1%	56%	55% Pulse
Pacoima	E/P	0.08	0.8	1%	38%	55% Pulse
Taft	E/P	.64	0.8	5%	57%	Linear
Taft	E/P	.64	1.6	5%	30%	Parabolic
Pacoima	E/P	.25	0.8	5%	44%	28% (Pulse)

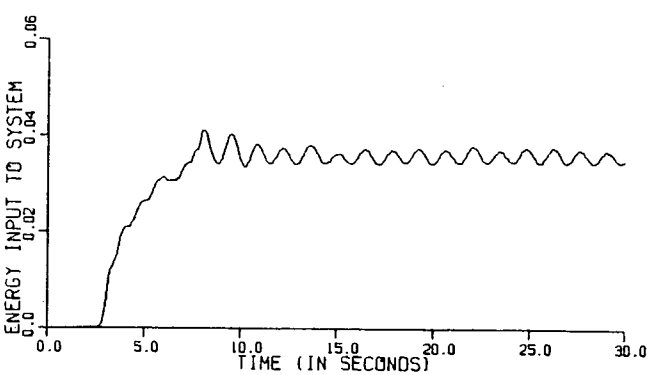
TABLE 4.1

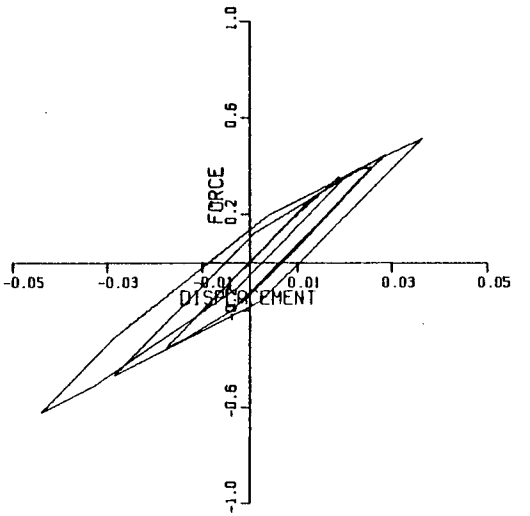
ENERGY DISSIPATION VERSUS TIME

FOR SINGLE DEGREE OF FREEDOM SYSTEMS









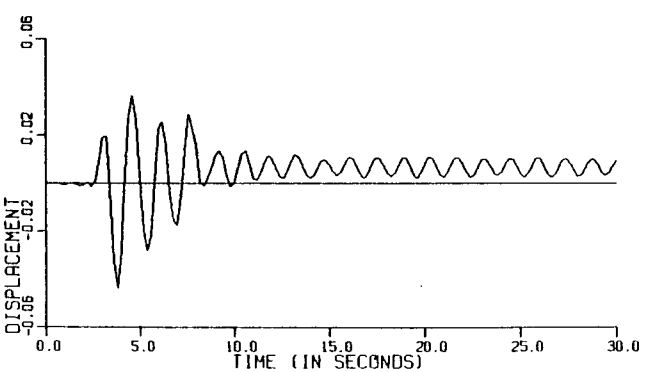
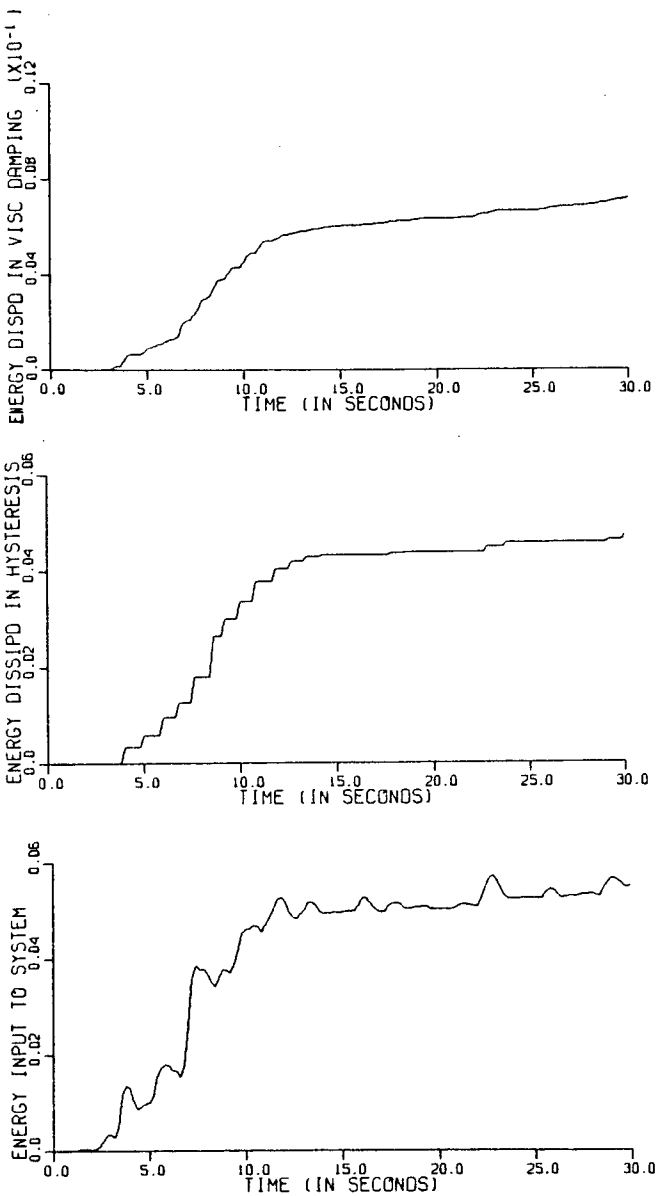
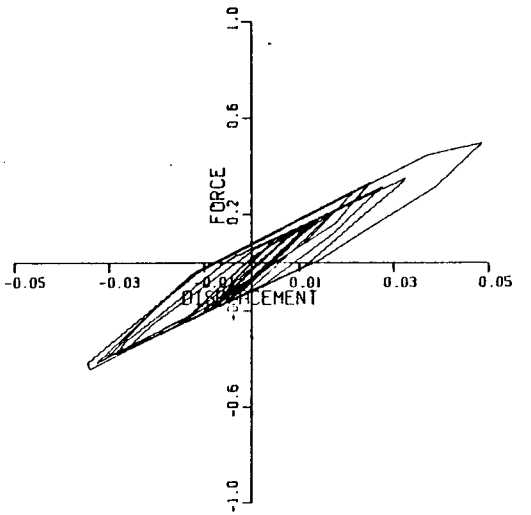


FIG. 4.1 TIME HISTORY OF ENERGY DISSIPATION FOR A TRI-LINEAR SYSTEM YSR = 1.0, PERIOD = 1.4 SEC., 1% VISC. DMPG. SUBJECTED TO PACOIMA S16E.





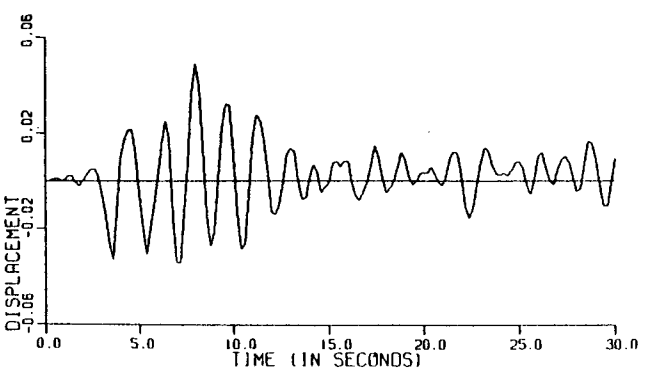
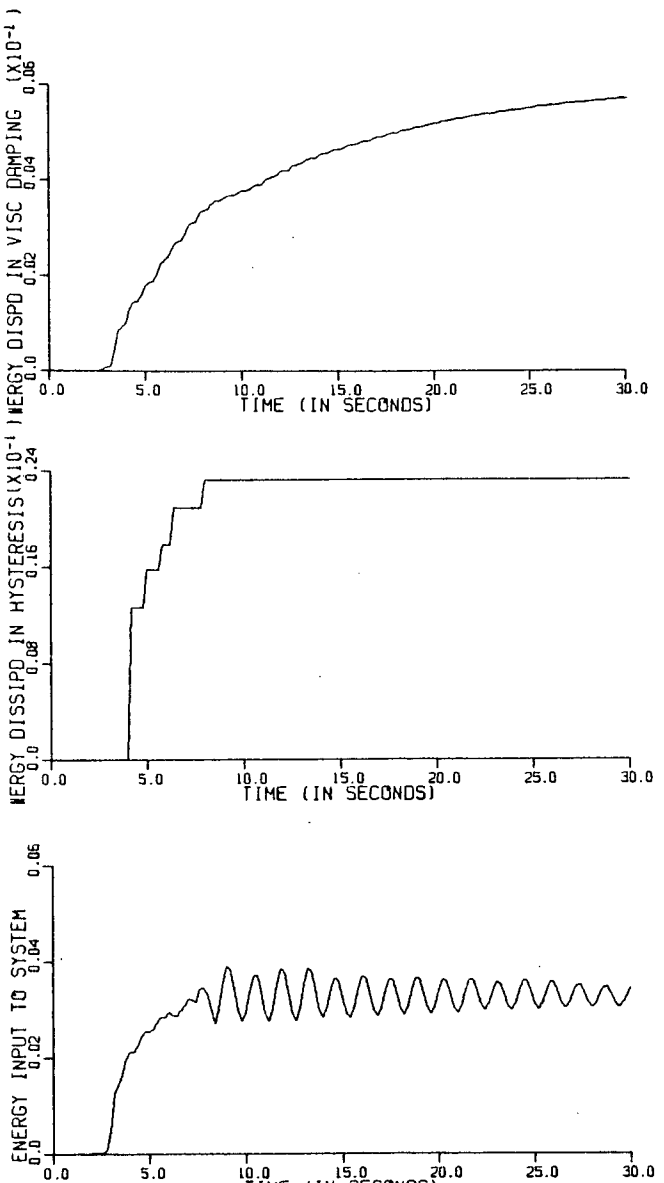


FIG. 4.2 TIME HISTORY OF ENERGY DISSIPATION FOR A TRI-LINEAR SYSTEM
YSR = 0.5, PERIOD = 1.4 SEC., 1% VISC. DMPG. SUBJECTED TO TAFT N69W.



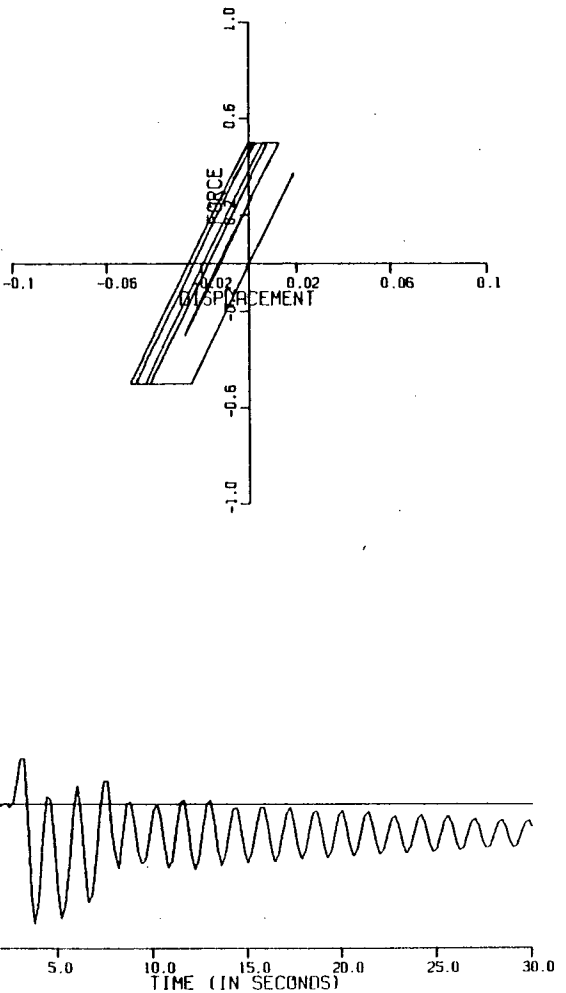
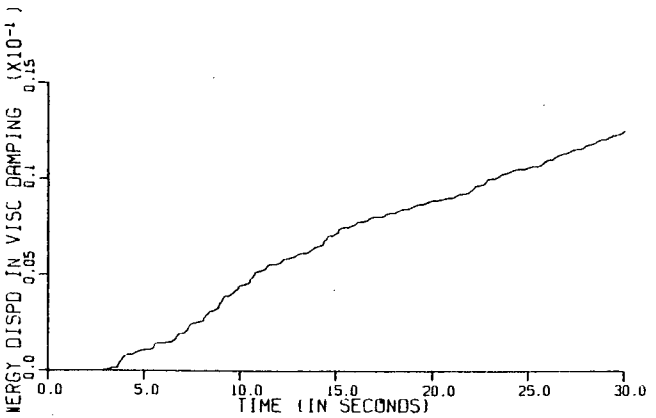
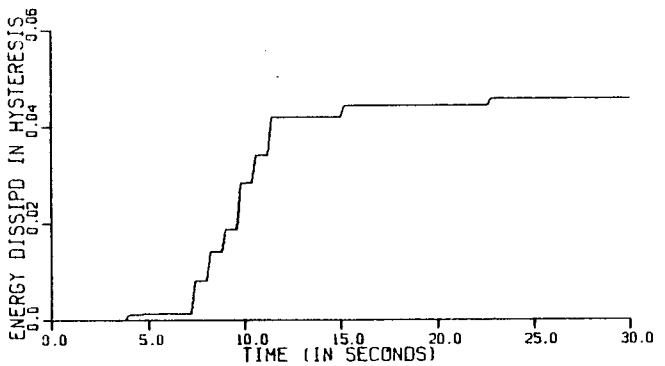
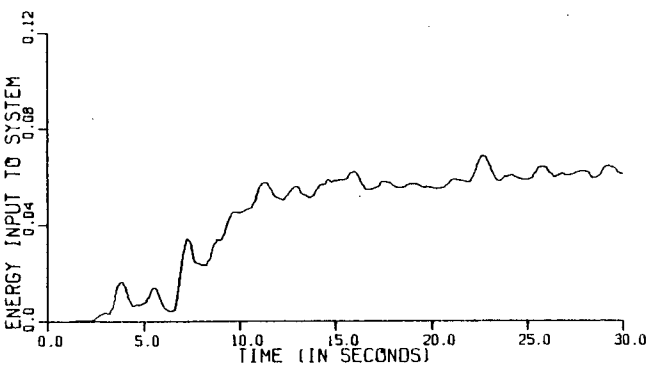
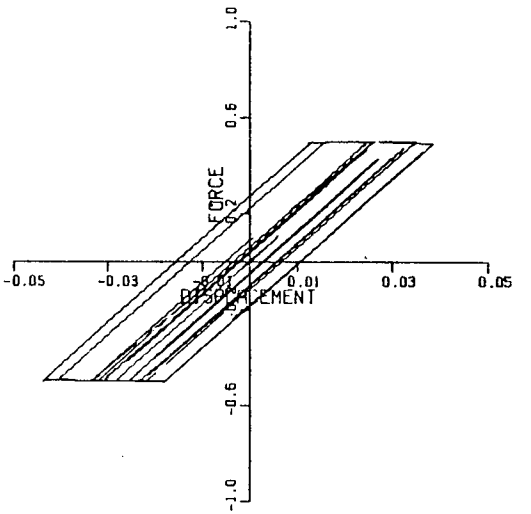


FIG. 4.3 TIME HISTORY OF ENERGY DISSIPATION FOR AN ELASTO-PLASTIC SYSTEM YSR = 0.5, PERIOD = 1.4 SEC., 1% VISC. DMPG. SUBJECTED TO PACOIMA S16E.









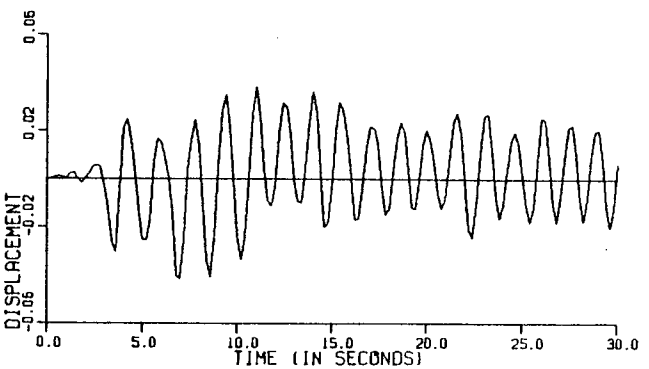


FIG. 4.4 TIME HISTORY OF ENERGY DISSIPATION FOR AN ELASTO-PLASTIC SYSTEM YSR = 0.5, PERIOD = 0.8 SEC., 1% VISC. DMPG. SUBJECTED TO TAFT N69W.

4.5 Outline of the Design Method and Examples

With the information obtained so far it is now possible to outline the form of a design method which could be used in a limit state design code.

The analysis procedure can be divided into two broad areas. First, a check that the Required Energy Capacity is provided forms a check upon the safety of the structure against collapse. Secondly, checks upon the displacement and displacement ductility provide information on the damage levels to be expected from the earthquake.

It should be noted that all the input parameters required for this method can be calculated or estimated with reasonable confidence. No assumption about ductility factor need be made, because in this method, the displacement ductility is given explicitly as an output parameter. It thus removes the uncertainity common to all present design methods.

In the context of the two level limit state philosophy of the new generation of building codes, this method is outlined as follows:

OUTLINE OF DESIGN METHOD

1 (a) Establish type of design earthquake for a given site.

(b) Estimate maximum ground acceleration expected during a moderate earthquake. (Say a 25 year return period).

(c) Estimate maximum ground acceleration expected during a severe earthquake. (Say a 100 year return period).

(d) Estimate proportion of viscous damping in system.

(e) Calculate period of first mode of system.

(f) Assuming yield moments and collapse mechanism, calculate yield strength of the system.

N.B. The following procedures, steps 2 through 8, are carried out twice. Once for the moderate earthquake and once for the severe earthquake.

2 Establish Yield Strength Ratio

From spectrum for strong, moderate or weak system obtain:

(a) Total energy to be dissipated by system.
(From figs. 3.45, 3.46, 3.47 and 3.48 or other).

(b) Proportion of energy dissipated by hysteresis.
(From figs. 3.49 and 3.50 or other).

3 Estimate the energy to be dissipated by hysteresis in the principal half loop.

4 Calculate the displacement required to dissipate this energy in one half loop.

5 From spectra obtain displacement ductility and permanent set values in terms of yield displacement. (See figs. 3.37 to 3.44 and appendix A).

6 Calculate yield displacement of system.

7 Calculate maximum displacement.

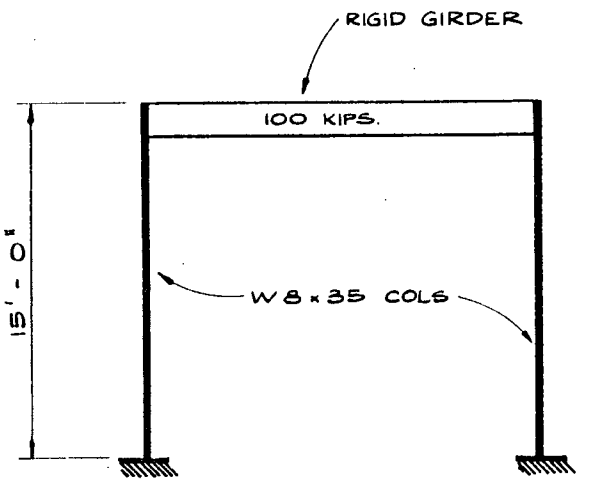
8 Check if response is within design criteria. Iterate to obtain a satisfactory solution.

In the method outlined above steps 2, 3 and 4 can be categorized as strength and safety checks. Steps 5, 6 and 7 can be considered damage or serviceability checks.

By performing separate sets of calculations for each of the earthquake severity levels, a detailed understanding of the response and expected damage levels is provided.

The following example illustrates the use of the above method, and a summary of several typical calculations for single degree of freedom systems is given in table 4.2.

EXAMPLE



DETAILS OF FRAME USED IN EXAMPLE

(1A) IN GENERAL A DESIGN EARTHQUAKE WOULD BE ESTABLISHED BASED UPON STUDIES OF THE PARTICULAR SITE SEISMICITY. FOR PURPOSES OF THIS EXAMPLE, SPECTRA FOR THE TAFT N69W, AND PACOIMA S16E, RECORDS WILL BE USED. THIS PERMITS DIRECT COMPARISONS WITH TIME STEP CALCULATIONS.

(1B) ESTIMATE MAXIMUM GROUND ACCELN. FOR 25 YEAR RETURN PERIOD. USE TAFT N69W. MAX GRND ACCELN = 5.04 FT/SEC^2.

(1C) ESTIMATE MAXIMUM GROUND ACCELN. FOR 100 YEAR RETURN PERIOD. USE PACOIMA S16E MAX GRND ACCELN =37.7 FT/SEC^2.

(1D) ASSUME 1% OF CRITICAL VISCOUS DAMPING TO REPRESENT THE NON-STRUCTURAL DAMPING IN THE SYSTEM.

EXAMPLE CONTINUED

(1E) FUNDAMENTAL PERIOD.

$$K = 2 \times \frac{12EI}{L^3} = \frac{2 \times 12 \times 30{,}000 \times 126}{180^3} = \underline{\underline{15.55}} \text{ KIPS/INCH.}$$

$$T = 2\pi\sqrt{\frac{100}{386 \times 15.55}} = \underline{\underline{0.81}} \text{ SEC.}$$

(1F) YIELD STRENGTH OF SYSTEM.

PLASTIC MOMENT IN W8 X 35 YIELD STRESS = 44 K.S.I

Z_{XX} = 34.7 IN^3 $M_P = \frac{34.7 \times 44}{12}$ = 127 KIP FT.

HORIZONTAL SHEAR IN COLS AT YIELD = $\frac{127 \times 2}{15}$ = 16.95 KIPS.

TOTAL HORIZONTAL SHEAR AT YIELD = 33.9 KIPS.

HORIZONTAL ACCELN OF MASS REQD TO PRODUCE THIS SHEAR.

$$= \frac{33.9}{100} = 33.9\%_g = 10.91 \text{ FT/SEC}^2$$

EXAMPLE CONTINUED

DESIGN FOR MODERATE EARTHQUAKE

(2) YIELD STRENGTH RATIO $= \frac{10.91}{5.05} = 2.16$

$\therefore$ STRONG SYSTEM.

THE TOTAL ENERGY TO BE DISSIPATED BY THE SYSTEM CAN BE APPROXIMATED FROM DESIGN SPECTRA SUCH AS FIGS 3.45 - 3.48. HOWEVER TO PERMIT DIRECT COMPARISON WITH TIME STEP CALCULATIONS THE SPECTRA FOR TAFT N69W OF FIG A.1 WILL BE USED.

(2A) TOTAL ENERGY TO BE DISSIPATED BY THE SYSTEM

$= 0.1 \times 5.05^2 \times 144 \times 0.259 = 95$ KIP INS

SPECTRAL VALUE $\times$ $(G.A.MAX)^2$ $\times$ MASS

(2B) ENERGY TO BE DISSIPATED IN HYSTERSIS

$= 95 \times 0.50 = 47.5$ KIP INS

(3) FROM SECTION 4.4 IT IS KNOWN THAT HYSTERETIC ENERGY WILL BE DISSIPATED IN TWO OR THREE MAJOR YIELD EXCURSIONS

ENERGY TO BE DISSIPATED IN EACH MAJOR EXCURSION

$= \frac{47.5}{2} = 23.8$ KIP INS

EXAMPLE CONTINUED

DESIGN FOR MODERATE EARTHQUAKE

(4) ENERGY DEMAND PER JOINT

WITH FOUR PLASTIC HINGES $= \frac{23.8}{4} = 5.94$ KIP INS/JOINT

JOINT ROTATION REQUIRED TO DISSIPATE THIS ENERGY

$= \frac{5.94}{127 \times 12} = 0.0039$ RADIANS

DISPLACEMENT AT TOP OF COLUMN DURING MAX YIELD EXCURSION

$= 0.0039 \times 15 \times 12 = \underline{\underline{0.702}}$ INS

(5) DISPLACEMENT DUCTILITY (FROM SPECTRUM)

$= \underline{\underline{1.5}}$

(6) HORIZONTAL DISPLACEMENT OF BEAM AT YIELD IN COLS.

$= \frac{P_Y}{K} = \frac{33.9}{15.55} = \underline{\underline{2.18}}$ INS

(7) MAXIMUM DISPLACEMENT $= 1.5 \times 2.18 = \underline{\underline{3.27}}$ INS

(8) PERMANENT SET $= 0.17 \times 2.18 = \underline{\underline{0.37}}$ INS

EXAMPLE CONTINUED

DESIGN FOR SEVERE EARTHQUAKE.

(2) YIELD STRENGTH RATIO $= \frac{10.91}{37.7} = 0.3$

$\therefore$ MODERATE SYSTEM

THE TOTAL ENERGY TO BE DISSIPATED BY THE SYSTEM CAN BE APPROXIMATED FROM DESIGN SPECTRA SUCH AS FIG 3.45 - 3.48.
HOWEVER TO PERMIT DIRECT COMPARISON WITH TIME STEP CALCULATIONS THE SPECTRA FOR PACOIMA S16E OF FIG A.2 WILL BE USED.

(2A) TOTAL ENERGY TO BE DISSIPATED BY THE SYSTEM

$= 0.025 \times 37.698^2 \times 144 \times 0.259 = 1330$ KIP INS

SPECTRAL VALUE $\times$ (G.A.MAX)^2 $\times$ MASS

(2B) ENERGY TO BE DISSIPATED IN HYSTERESIS

$= 1330 \times 0.8 = 1064$ KIP INS.

(3) FROM SECTION 4.4 IT IS KNOWN THAT HYSTERETIC ENERGY WILL BE DISSIPATED IN TWO OR THREE MAJOR YIELD EXCURSIONS.

$\therefore$ ENERGY TO BE DISSIPATED IN EACH MAJOR EXCURSION

$= \frac{1064}{2} = 532$ KIP INS.

EXAMPLE CONTINUED

DESIGN FOR SEVERE EARTHQUAKE

(4) ENERGY DEMAND PER JOINT

WITH FOUR PLASTIC HINGES $= \frac{532}{4} = 133$ KIP INS.

JOINT ROTATION REQUIRED TO DISSIPATE THIS ENERGY.

$= \frac{133}{127 \times 12} = 0.087$ RADIANS.

DISPLACEMENT AT TOP OF COLUMN DURING MAX YIELD EXCURSION

$= 0.087 \times 15 \times 12 = \underline{15.7}$ INS.

(5) DISPLACEMENT DUCTILITY (FROM SPECTRUM)

$= \underline{5.5}$

(6) HORIZONTAL DISPLACEMENT OF BEAM AT YIELD IN COLS.

$= \frac{P_Y}{K} = \frac{33.9}{15.55} = \underline{2.18}$ INS.

(7) MAXIMUM DISPLACEMENT $= 5.5 \times 2.18 = \underline{12.0}$ INS.

(8) PERMANENT SET $= 2.5 \times 2.18 = \underline{5.45}$ INS.

SYSTEM			Period Sec.	YSR	Type	MAX DISPLACEMENT (INS)			PERMANENT SETS		
Earthquake	Material	Damping				Elastic[1]	Plastic[2]	Time Step[3]	Plastic[2]	Time Step[3]	
Pacoima	E/P	0.01	.8	.3	Mod.	6.7	12.0	10.74	5.45	0.9	+
Pacoima	E/P	0.05	.8	.3	Mod.	6.1	7.12	8.30	2.62	1.9	
Pacoima	E/P	0.05	1.0	.2	Weak	11.6	10.2	11.75	7.0	2.3	
Taft	E/P	0.01	.8	1.85	Strong	3.4	3.27	2.91	0.37	0.11	+
Taft	E/P	0.01	1.25	0.96	Mod.	2.9	2.42	2.50	0.6	1.23	
Taft	E/P	0.01	1.41	0.8	Mod.	4.5	3.36	3.52	1.86	1.86	
Pacoima	T/L	0.01	.8	.3	Mod.	6.7	18.8	10.91	5.64	0.73	
Taft	T/L	0.01	.8	1.85	Strong	3.4	2.64	2.86	.18	0.43	
Taft	T/L	0.01	1.41	0.8	Mod.	4.5	4.35	3.72	.62	1.15	

1. ELASTIC SPECTRAL ANALYSIS 5% DMPG.
2. METHOD GIVEN IN THIS CHAPTER
3. NON-LINEAR TIME STEP CALCS. MADE WITH DRAIN - $2D^{22}$

\+ See example in section 4.5 for detailed calculations.

TABLE 4.2

DISPLACEMENTS AND PERMANENT SETS FOR SYSTEMS ANALYZED BY THE METHOD GIVEN IN CHAPTER 4.

CHAPTER 5

THEORY AND PROGRAMMING CONSIDERATIONS FOR MULTI-DEGREE OF FREEDOM SYSTEMS

5.1 Mathematical Model for Multi-Degree of Freedom Studies

The model used for the multi-storey structure analysis is the simple shear beam model. See fig. 5.1. For each storey there is one lateral degree of freedom only. The girders are assumed to have infinite stiffness, and the columns are assumed to be fixed at the foundations. The important influence of gravity loads[26] on energy dissipation is not considered in this preliminary study.

The numerical parameters of the model are defined for each storey by the mass, initial stiffness, yield strength ratio, and the viscous damping. In the computer program the input is arranged so that the data for each floor is defined in relation to the values for the first, or lowest, storey. The viscous damping can be defined as mass or stiffness damping or a combination of the two. In the case of stiffness damping the damping factors are related to the initial stiffness of the system throughout the entire excitation.

In the present study both Elasto-Plastic and the Tri-Linear degrading stiffness models of hysteresis were used. These are similar to the models described in section 3.1.

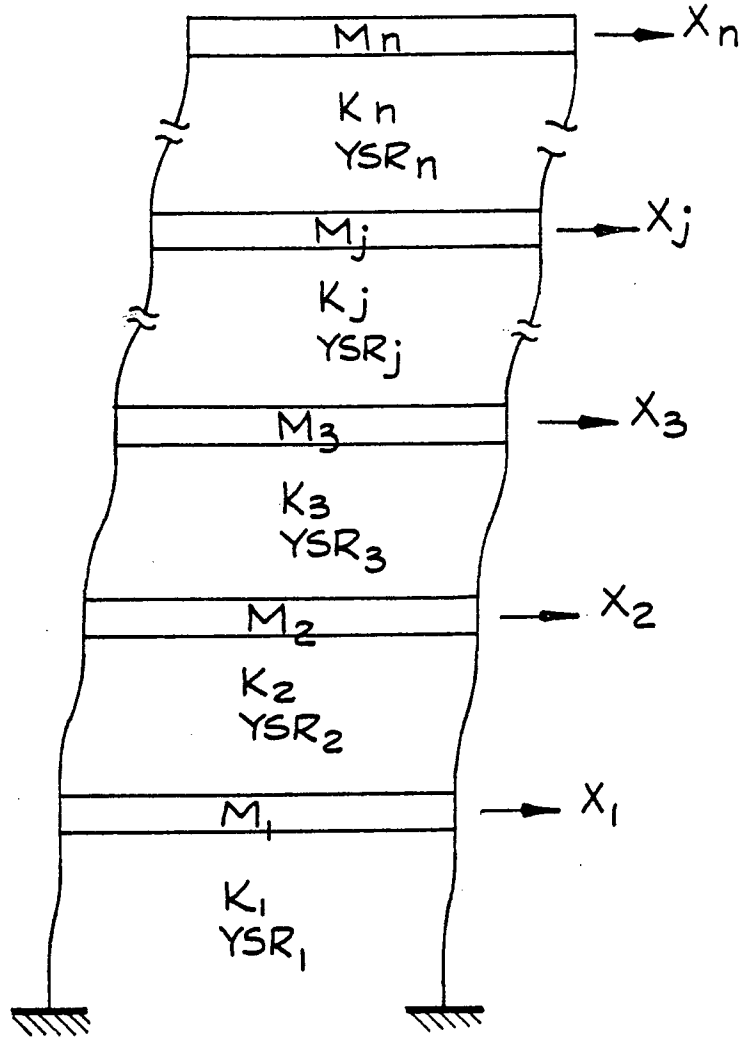


FIG. 5.1
MULTI-DEGREE OF FREEDOM MODEL

5.2 Equations of Motion for Multi-Degree of Freedom Systems.

The equations of motion for the multi-degree of freedom systems were integrated using the constant average acceleration time step scheme. The development of this scheme for multi-degree of freedom systems is similar to that given in Chapter 2 for single degree of freedom systems. In matrix notation the incremental equation of motion for multi-degree of freedom systems can be written as:

$$\left[\frac{4}{\Delta t^2} [M] + \frac{2}{\Delta t} [C] + [K]_T \right] \{\Delta x\}$$

$$= -[M]\{1\}\,\Delta g_a + [M]\{2\ddot{x}_o + \frac{4}{\Delta t}\dot{x}_o\} + [C]\{2\dot{x}_o\}$$

... Eqn.(5.1)

where $[M]$, $[C]$ and $[K]_T$ are the mass, damping and stiffness matricies for the system.

$\ddot{x}_o$ is the acceleration of each node at the start of the time increment.

$\dot{x}_o$ is the velocity of each node at the start of the time increment.

x_o is the displacement of each node at the start of the time increment.

Δg_a is the change in base acceleration for each increment.

Δt is the duration of each increment in seconds.

If it is assumed that the viscous damping can be represented as a combination of mass-dependent and initial stiffness-dependent effects, the damping matrix can be replaced by:

$$[C] = \alpha [M] + \beta [K]_I \qquad \text{....Eqn.(5.2)}$$

Introducing this into the incremental equation of motion and collecting terms gives:

$$\left[\left\{\frac{4}{\Delta t^2} + \frac{2}{\Delta t}\right\}\alpha [M] + \frac{2}{\Delta t}\beta[K]_I + [K]_T\right]\{\Delta x\}$$

$$= [M]\left\{-\Delta g_a + 2\ddot{x}_o + \left(\frac{4}{\Delta t} + 2\alpha\right)\dot{x}_o\right\} + 2\beta\{\dot{x}_o\}[K]_I$$

....Eqn. (5.3)

This is the form of the equation used in the computer program for this study. The equation was integrated using time steps of 0.01 sec. for systems with periods greater than 0.5 sec. and 0.005 sec. for shorter period systems.

Equilibrium checks were made at the end of each time step, and corrective forces applied when required. This procedure was similar to that given in detail in section 2.3.

5.3 Energy Calculations

The calculation of energies within the multi-degree of freedom systems is similar to the single degree of freedom system calculations. In the computer subroutine for multi-degree of freedom systems the calculations are made in the following sequence at the end of each time step.

1. For each degree of freedom in system.
   - (a) Calculate the energy stored and dissipated by each spring.
   - (b) Calculate the kinetic energy for each mass.
   - (c) Calculate energy dissipated by mass proportional viscous damping.
   - (d) Calculate energy dissipated by initial stiffness proportional viscous damping.
   - (e) Sum component energies for each degree of freedom.
2. Sum all energies stored within the system to this point.
3. Calculate the total energy input to the structure to this point.

Total Energy Input

$$= \sum_{i=1}^{NDF} \text{MASS}_i \ * \ \text{TOTAL ACCEL.}_i \ * \ \text{GROUND DISPLACEMENT}$$

The total acceleration for each mass is taken as the average total acceleration during the time step.

4. Energy balance checks are made by equating the stored and input energies.

CHAPTER 6

TOTAL ENERGY DISSIPATED IN MULTI-DEGREE OF FREEDOM SYSTEMS

6.1 INTRODUCTION

Details of a preliminary study of energy dissipation mechanisms in multi-degree of freedom systems is reported in this, and the following chapter. Ultimately, the objective of such a study would be to gain sufficient understanding of the energy dissipation mechanisms involved in such systems, to enable the formulation of a design method based upon this knowledge. Obviously, such a task would require a major research effort, and is beyond the resources of the present study. Nevertheless, in this study sufficient insight is gained about the nature of the dissipation mechanisms to justify optimism about the suitability of such an approach for multi-degree of freedom systems.

The present chapter deals with the total energy dissipated by these systems. In particular, the possibility of obtaining the total energy to be dissipated by multi-degree of freedom systems, by extrapolation of the results for single-degree of freedom systems, reported in chapter 3, is studied. Also the effects of different hysteretic models and forms of viscous damping, mass proportional or stiffness proportional or combinations of both, upon the total energy dissipated is investigated.

The distribution of the energy within the multi-degree of freedom systems is reported in the next chapter. Detailed results of this study are reproduced in Appendix C.

6.2 Structures Used in This Study

In this study six different structures are used. They are intended to cover as wide a variety of structural types as possible. All six structures were investigated using different ground motion records, and both Elasto-Plastic and Stiffness Degrading hysteretic models. Details of the structures are given in fig 6.1 and discussed briefly below.

STRUCTURE 1

This is a three storey structure with increasing mass, stiffness and yield strengths from top to bottom stories. This system is intended to represent the standard structural arrangement that would be obtained from a building code analysis.

STRUCTURE 2

A three storey structure with constant mass, stiffness and yield strength for each storey.

STRUCTURE 3

A three storey structure similar to structure 2 having identical mass and stiffness but with one-third the yield strength of structure two.

STRUCTURE 4

This three storey structure represents a soft first storey system. Each floor is assumed to have equal mass, the stiffness and yield strength

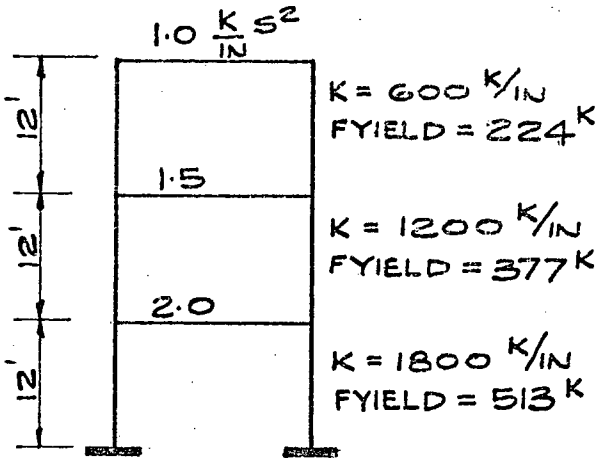
of the lowest storey are one-half of the values for the upper two floors.

STRUCTURE 5

Another soft first storey structure similar to structure four, but with the stiffness and yield values of the lowest floor equal to one-third of the values for the upper floors.

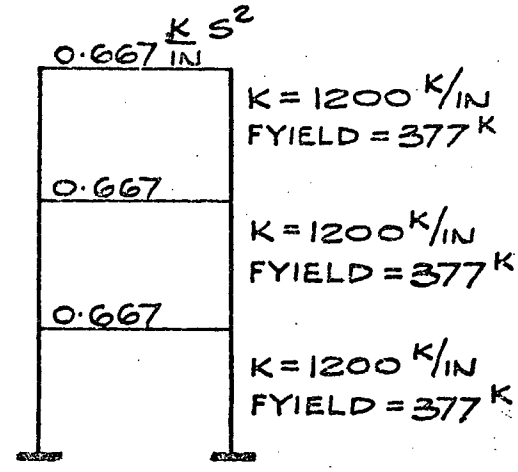
STRUCTURE 6

A ten storey structure with equal mass stiffness and yield strength at each storey.



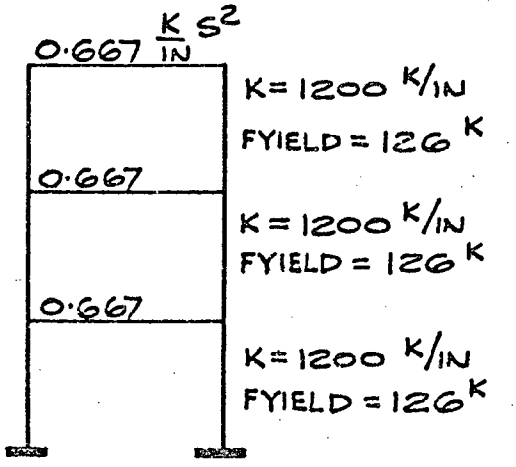
STRUCTURE 1

$T_1 = 0.433$ SEC. $T_2 = 0.202$ SEC.



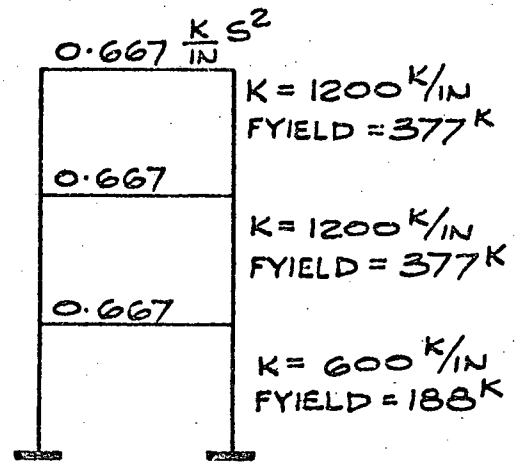
STRUCTURE 2

$T_1 = 0.333$ SEC. $T_2 = 0.119$ SEC.



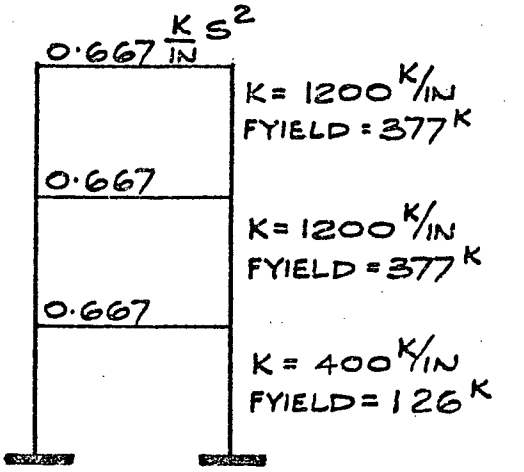
STRUCTURE 3

$T_1 = 0.333$ SEC. $T_2 = 0.119$ SEC.



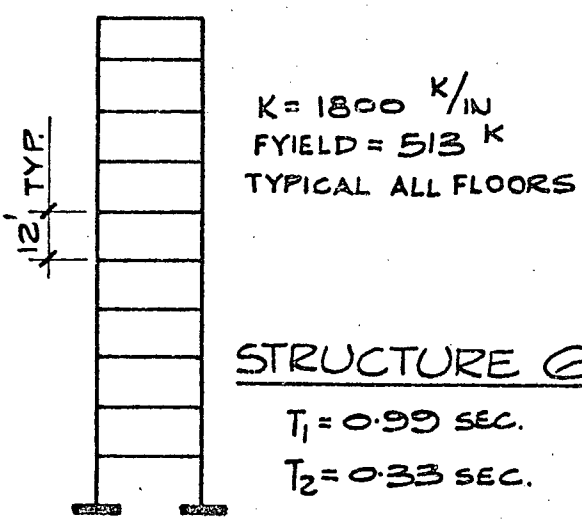
STRUCTURE 4

$T_1 = 0.47$ SEC. $T_2 = 0.17$ SEC.



STRUCTURE 5

$T_1 = 0.58$ SEC. $T_2 = 0.21$ SEC.



STRUCTURE 6

$T_1 = 0.99$ SEC.

$T_2 = 0.33$ SEC.

FIG. 6.1

STRUCTURES USED IN M.D.F. STUDY

6.3 Total Energy Dissipated in Elasto-Plastic Multi-Degree of Freedom Systems

The results of this study for the total energy dissipated by Elasto-Plastic multi-degree of freedom systems investigated are summarised in table 6.1.

From these results, it can be seen that the estimates of total energy to be dissipated, obtained from single degree of freedom spectra, (see Appendix A), are in good agreement with the calculations obtained using the multi-degree of freedom computer model. It is noted that the agreement in results from the two methods was poor for the case of strong systems where interpolation of the spectral results was required. However, when the results of the single degree of freedom systems with corresponding parameters to the multi-degree of freedom systems are used, the agreement is close as can be seen in the table. This shows that the difficulty is not in extrapolation, but in the coarse data mesh used for the single degree of freedom spectra.

The general close agreement in the two sets of results suggests that the multi-degree of freedom systems respond predominantly in the fundamental mode.

The effect of various forms of viscous damping, mass or stiffness proportional or both, upon the total energy dissipated by the systems is seen to be small, provided that the percentage of critical damping in the system remains constant.

A comparison of total energy dissipated by multi-degree of freedom systems with the single degree of freedom system results is shown in fig 6.2.

Structure	Number of Stories	Fund^{L} Period (Sec.)	YSR	Excitation	Viscous Damping	Total Energy (Inch Kips)	
						M.D.F. Time Step	S.D.F. Spectrum
1	3	0.43	1.9	Taft N69W	1% M. & S.	1520	1803 *
1	3	0.43	1.9	Taft N69W	1% Mass	1517	1803 *
1	3	0.43	1.9	Taft N69W	1% Stiff.	1498	1803 *
1	3	0.43	1.9	Taft N69W	10% Stiff.	1260	1670 *
1	3	0.43	0.8	El Centro N.S.	1% M. & S.	3715	4330
1	3	0.43	0.8	El Centro N.S.	1% Stiff.	3700	4330
1	3	0.43	0.8	El Centro N.S.	10% Stiff.	3491	4330
1	3	0.43	0.26	Pacoima S16E	1% M. & S.	17,437	18,418
1	3	0.43	0.26	Pacoima S16E	1% Stiff.	17,557	18,418
1	3	0.43	0.26	Pacoima S16E	10% Stiff.	16,605	18,418
2	3	0.33	3.1	Taft N69W	1% M. & S.	702	785 *
2	3	0.33	1.4	El Centro N.S.	1% M. & S.	682	693 *
2	3	0.33	1.4	El Centro N.S.	1% Mass	622	693 *
2	3	0.33	0.43	Pacoima S16E	1% M. & S.	8222	8515
2	3	0.33	0.43	Pacoima S16E	1% Stiff.	8297	8515
2	3	0.33	0.43	Pacoima S16E	1% Mass	8482	8515
3	3	0.33	0.45	El Centro N.S.	1% M. & S.	1413	1539
4	3	0.47	0.68	El Centro N.S.	1% M. & S.	2356	2502
5	3	0.57	0.45	El Centro N.S.	1% M. & S.	2152	2309
6	10	0.99	0.37	El Centro N.S.	3% Mass	9005	9622
6	10	0.99	0.11	Pacoima S16E	3% Mass	35,353	33,000

Note: M. = Mass S.= Stiffness

* STRONG SYSTEMS. VALUES NOT INTERPOLATED FROM SPECTRA, BUT OBTAINED FROM CORRESPONDING S.D.F. SYSTEM.

TABLE 6.1

TOTAL ENERGY DISSIPATED BY ELASTO-PLASTIC M.D.F. SYSTEMS

6.4 Total Energy Dissipated in Stiffness Degrading Multi-Degree of Freedom Systems

The results of this study for the total energy dissipated by Stiffness Degrading multi-degree of freedom systems are summarised in table 6.2

The agreement between the results of multi-degree of freedom calculations and extrapolation from the single degree of freedom results is seen to be good. The agreement in results for strong systems is good when interpolating between spectral curves. This indicates that the strong degrading stiffness systems are less sensitive to variations in the strength parameter than was the case for the strong Elasto-Plastic systems.

A comparison of total energy dissipated by multi-degree of freedom systems with the single degree of freedom systems results is shown in fig 6.2.

Structure	Number of Stories	Fund^{l} Period (Sec.)	YSR	Excitation	Viscous Damping	Total Energy (Inch Kips)	
						M.D.F. Time Step	S.D.F. Spectrum
1	3	0.43	1.9	Taft N69W	1% M.& S.	1052.3	1156
1	3	0.43	0.8	El Centro N.S.	1% M. & S.	6,744.3	6000
1	3	0.43	0.26	Pacoima S16E	1% M. & S.	22,367.1	18,420
2	3	0.33	3.1	Taft N69W	1% M. & S.	553.0	504
2	3	0.33	1.4	El Centro N.S.	1% M. & S.	1308.5	1540
2	3	0.33	0.43	Pacoima S16E	1% M. & S.	5,773.3	6960
3	3	0.33	0.45	El Centro N.S.	1% Mass	1,946.8	1925
4	3	0.47	0.68	El Centro N.S.	1% M. & S.	2,709.6	2700
5	3	0.57	0.45	El Centro N.S.	1% M. & S.	1,908.5	1925
6	10	0.99	0.37	El Centro N.S.	3% Mass	7,356.9	7300
6	10	0.99	0.11	Pacoima S16E	3% Mass	33,493.4	33,000

Note: M = Mass S = Stiffness

TABLE 6.2

TOTAL ENERGY DISSIPATED BY DEGRADING STIFFNESS M.D.F. SYSTEMS

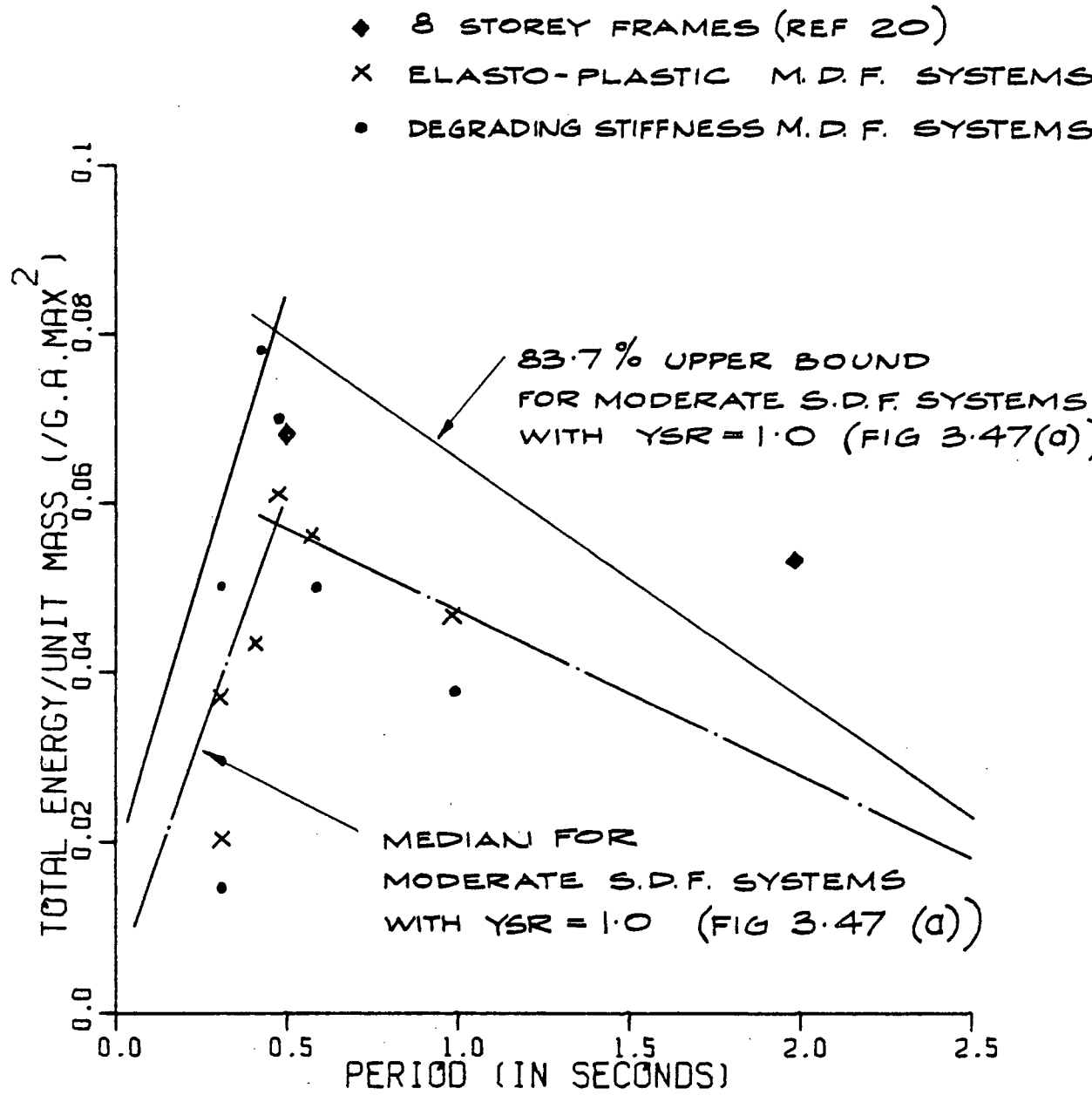


FIG. 6.2

COMPARISON OF TOTAL ENERGY DISSIPATED BY MULTI-DEGREE OF FREEDOM SYSTEMS WITH SINGLE DEGREE OF FREEDOM RESULTS

CHAPTER 7

DISTRIBUTION OF ENERGY WITHIN MULTI-DEGREE OF FREEDOM SYSTEMS

7.1 Introduction

The distribution of energy within multi-degree of freedom systems is studied in this chapter. The structures used in this study are described in section 6.2, and detailed results of the calculations are reproduced in Appendix C.

Two aspects of the energy distribution within the systems are considered. Firstly, the distribution of energy between the hysteretic and viscous damping mechanisms in the structure is considered. Principal interest is given to the possibility of extrapolating from the single degree of freedom results to the multi-degree of freedom case. The second aspect considered is the distribution of the energy dissipated by the two mechanisms at various locations within the system; there the aim is to identify general patterns and trends which could be suitable for a design method.

7.2 Distribution of Energy Between Hysteretic and Viscous Damping Mechanisms

The distribution of energy between the hysteretic and viscous

damping mechanisms in the systems studied is summarized in table 7.1 for the Elasto-Plastic systems, and in table 7.2 for the degrading stiffness systems.

It is seen from both sets of results that there is good agreement between the multi-degree of freedom calculations, and the single degree of freedom results. The single degree of freedom results given in the tables are taken from figs. 3.49 and 3.50.

In the case of the strong Elasto-Plastic systems subjected to the Taft N69W record the single degree of freedom results obtained from fig 3.49, under-estimate the proportion of energy to be dissipated in hysteresis. This difficulty can be overcome by using a finer data mesh when producing spectra for strong Elasto-Plastic systems. The results obtained from single degree of freedom systems with corresponding parameters to the multi-degree of freedom systems compare well with the multi-degree of freedom results.

Structure	Number of Stories	Fund[1] Period (Sec.)	YSR	Excitation	Viscous Damping	% Energy dissipated in Hysteresis	
						M.D.F. Time Step	S.D.F. Spectrum +
1	3	0.43	1.9	Taft N69W	1% S & M	68	45 (70)*
1	3	0.43	1.9	Taft N69W	1% Mass	65	45 (70)*
1	3	0.43	1.9	Taft N69W	1% Stiff.	61	45 (70)*
1	3	0.43	1.9	Taft N69W	10% Stiff.	0	10
1	3	0.43	0.8	El Centro N.S.	1% S & M	65	75
1	3	0.43	0.8	El Centro N.S.	1% Stiff.	75	75
1	3	0.43	0.8	El Centro N.S.	10% Stiff.	22	50
1	3	0.43	0.26	Pacoima S16E	1% S & M	71	80
1	3	0.43	0.26	Pacoima S16E	1% Stiff.	74	80
1	3	0.43	0.26	Pacoima S16E	10% Stiff.	41	60
2	3	0.33	3.1	Taft N69W	1% S & M.	20	35
2	3	0.33	1.4	El Centro N.S.	1% S & M.	34	50
2	3	0.33	1.4	El Centro N.S.	1% Mass	43	50
2	3	0.33	0.43	Pacoima S16E	1% S & M.	70	80
2	3	0.33	0.43	Pacoima S16E	1% Stiff.	72	80
2	3	0.33	0.43	Pacoima S16E	1% Mass	74	80
3	3	0.33	0.45	El Centro N.S.	1% S & M.	90	80
4	3	0.47	0.68	El Centro N.S.	1% S & M.	73	80
5	3	0.57	0.45	El Centro N.S.	1% S & M.	77	80
6	10	0.99	0.37	El Centro N.S.	3% Mass	65	70
6	10	0.99	0.11	Pacoima S16E	3% Mass	64	70

Note: M = Mass S = Stiffness

* Strong systems. Values obtained from corresponding S.D.F. system.

+ Values obtained from fig. 3.49.

TABLE 7.1

ENERGY DISSIPATED IN HYSTERESIS FOR ELASTO-PLASTIC M. D. F. SYSTEMS.

Structure	Number of Stories	Fund[1] Period (Sec.)	YSR	Excitation	Viscous Damping	% Energy Dissipated in Hysteresis	
						M.D.F. Time Step	S.D.F. Spectrum +
1	3	0.43	1.9	Taft N69W	1% S & M	86	80
1	3	0.43	0.8	El Centro N.S.	1% S & M	86	80
1	3	0.43	0.26	Pacoima S16E	1% S & M	71	70
2	3	0.33	3.1	Taft N69W	1% S & M	69	80
2	3	0.33	1.4	El Centro N.S.	1% S & M	77	80
2	3	0.33	0.43	Pacoima S16E	1% S & M	57	70
3	3	0.33	0.45	El Centro N.S.	1% Mass	74	70
4	3	0.47	0.68	El Centro N.S.	1% S & M	70	75
5	3	0.57	0.45	El Centro N.S.	1% S & M	69	75
6	10	0.99	0.37	El Centro N.S.	3% Mass	70	65
6	10	0.99	0.11	Pacoima S16E	3% Mass	50	50

Note: M = Mass S = Stiffness

\+ Values obtained from fig. 3.50

TABLE 7.2

ENERGY DISSIPATED IN HYSTERESIS FOR STIFFNESS DEGRADING M. D. F. SYSTEMS.

7.3 Distribution of Energy in Elasto-Plastic Multi-Degree of Freedom Systems

7.3.1 Effect of Different Forms of Viscous Damping on Total Energy and Energy Distribution

Some appreciation of the effect of different types of viscous damping, stiffness or mass proportional, or a combination of both, upon the total energy dissipated by the systems under study, and the distribution of the energy within the systems, was obtained from a parametric study. Some typical results for systems subjected to the Taft N69W and Pacoima S16E ground motion records are presented in table 7.3.

It can be seen that the effect of the three types of viscous damping is only marginal on the total energy dissipated, and on the distribution of the energy within the systems. The use of average values for these systems is practical.

STRUCTURE 1

ELASTO-PLASTIC

30 SECONDS TAFT N69W

Viscous Damping	Total Energy (Inch Kips)	Energy Dissipated By Hysteresis %	Energy Distribution %		
			Storey 1	Storey 2	Storey 3
1% M & S	1520	68	41.5	16.8	9.7
1% Stiff.	1495	60.6	33.1	21.7	5.8
1% Mass	1517	64.8	39.3	15.4	10.0
Mean.	1511	64.5	38.0	18.0	8.5

STRUCTURE 2

ELASTO-PLASTIC

30 SECONDS PACOIMA S16E

Viscous Damping	Total Energy (Inch Kips)	Energy Dissipated By Hysteresis %	Energy Distribution %		
			Storey 1	Storey 2	Storey 3
1% M & S	8222.6	69.3	61.9	7.3	0.1
1% Stiff.	8297.0	71.3	63.4	7.8	0.1
1% Mass	8483.0	73.8	64.8	8.5	0.5
Mean.	8334.2	71.5	63.4	7.9	0.23

TABLE 7.3

EFFECT OF VARIOUS FORMS OF VISCOUS DAMPING ON ENERGY DISTRIBUTION WITHIN ELASTO-PLASTIC M.D.F. SYSTEMS.

7.3.2 Summary of Results for Structure 1

Elasto-Plastic Model

For the Elasto-Plastic systems with 1% of critical viscous damping it was found that the distribution of energy between the hysteretic and viscous mechanisms is relatively insensitive to different values of yield strength ratio. For example it can be seen from table 7.4 that when this structure is subjected to the Taft N69W record it responds as a strong structure with YSR = 1.9 and dissipates 67% of the total energy in hysteresis. The same structure subjected to the Pacoima S16E record is a weak structure with YSR = 0.26, and in this case 75% of the total energy is dissipated in hysteresis.

The results for the systems with 10% of critical viscous damping show that the yield strength ratio has a distinct effect upon the energy distribution within the system. This can be clearly seen in table 7.5.

In general it is noted that for the systems in which the energy is dissipated prinicipally in the hysteretic mechanisms the majority of the energy is dissipated in the lowest storey. When the viscous damping forms the principal dissipating mechanism the majority of the energy is dissipated in the upper stories. These results are summarized in tables 7.4 and 7.5.

STRUCTURE 1 ELASTO-PLASTIC

1% VISCOUS DAMPING

Earthquake	YSR Category	Energy Dissipated In Hysteresis (%)	Energy Dissipated In Viscous Damping (%)
Taft N69W	1.9 Strong	67	33
El Centro N.S.	0.8 Mod.	70	30
Pacoima S16E	0.26 Weak	75	25

DISTRIBUTION OF HYSTERETIC ENERGY WITHIN SYSTEM

Storey	Taft	El Centro	Pacoima
3	10	3	9
2	20	15	16
1	37	52	50
Σ	67%	70%	75%

DISTRIBUTION OF ENERGY DISSIPATED BY VISCOUS DAMPING

Storey	Taft	El Centro	Pacoima
3	18	15	6
2	10	10	9
1	5	5	10
Σ	33%	30%	25%

TABLE 7.4

DISTRIBUTION OF ENERGY IN STRUCTURE 1
ELASTO-PLASTIC MODEL 1% VISCOUS DAMPING.

STRUCTURE 1 — ELASTO-PLASTIC

10% VISCOUS DAMPING

Earthquake	YSR Category	Energy Dissipated In Hysteresis (%)	Energy Dissipated In Viscous Damping (%)
Taft N69W	1.9 Strong	0	100
El Centro N.S.	0.8 Mod.	22	78
Pacoima S16E	0.26 Weak	40	60

DISTRIBUTION OF HYSTERETIC ENERGY WITHIN SYSTEM

Storey	Taft	El Centro	Pacoima
3	0	0	2
2	0	4	12
1	0	18	26
Σ	0%	22%	40%

DISTRIBUTION OF ENERGY DISSIPATED BY VISCOUS DAMPING

Storey	Taft	El Centro	Pacoima
3	54	38	20
2	34	27	20
1	12	13	20
Σ	100%	78%	60%

TABLE 7.5

DISTRIBUTION OF ENERGY IN STRUCTURE 1
ELASTO-PLASTIC MODEL 10% VISCOUS DAMPING.

7.3.3 Summary of Results for Structure 2

Elasto-Plastic Model

The results for this structure subjected to different ground motions show that the distribution of energy within the systems is greatly dependent upon the yield strength ratio. These results for systems with 1% of critical viscous damping are considerably more sensitive to variations in this parameter than those reported for structure 1 in the previous section. The results for this structure are summarized in table 7.6.

STRUCTURE 2 ELASTO-PLASTIC

1% VISCOUS DAMPING.

Earthquake	YSR Category	Energy Dissipated In Hysteresis (%)	Energy Dissipated In Viscous Damping (%)
Taft N69W	3.1 Strong	19	81
El Centro N.S.	1.4 Strong	38	62
Pacoima S16E	0.43 Mod.	70	30

DISTRIBUTION OF HYSTERETIC ENERGY WITHIN SYSTEM

Storey	Taft	El Centro	Pacoima
3	0	0	0
2	0	0	8
1	19	38	62
Σ	19%	38%	70%

DISTRIBUTION OF ENERGY DISSIPATED BY VISCOUS DAMPING

Storey	Taft	El Centro	Pacoima
3	43	32	11
2	28	22	11
1	10	8	8
Σ	81%	62%	30%

TABLE 7.6

DISTRIBUTION OF ENERGY IN STRUCTURE 2
ELASTO-PLASTIC MODEL 1% VISCOUS DAMPING

7.3.4 Comparison of Energies in Structures 1, 2, 3, 4 and 5. Elasto-Plastic Model

This comparison considers the total energy and energy distribution in structures 1, 2, 3, 4 and 5, with all systems having 1% mass and stiffness proportional viscous damping, and subjected to 30 secs. of El Centro N.S. The results are presented in table 7.7.

The large variation in the amount of total energy dissipated by these systems is a result of variations in period and yield strength ratio. In all cases (except for structure 2), hysteresis forms the prinicipal dissipating mechanism, and the majority of the hysteretic energy is dissipated in the lowest storey. This is true not only for the systems having a 'soft first storey', but also when there is a strong first storey as in structure 1. This shows that the first storey is a major factor in determining the adequacy of a system in earthquake excitation.

In all cases the majority of the energy dissipated by viscous damping is located in the upper stories.

All five of the three storey structures considered in this study exhibit a predominantly first mode response. The effect of higher modes is not significant in any of these systems.

Structure	Period (Sec.)	YSR	Total Energy (Inch Kips)	Energy Dissipated In Hysteresis (%)	Distribution			Energy Dissipated in Viscous Damping (%)	Distribution		
					1	2	3		1	2	3
1	.43	.8	3715	65.5	48.9	13.9	2.6	34.5	6.2	11.0	16.3
2	.33	1.4	682	34.0	34.0	0	0	65.0	8.2	22.0	34.8
3	.33	.45	1413	90.0	83.0	7.0	0	10.0	2.0	3.0	5.0
4	.47	.68	2356	73.0	73.0	0	0	27.0	7.0	8.0	12.0
5	.57	.45	2152	77.0	77.0	0	0	23.0	6.0	7.0	10.0

TABLE 7.7

ENERGY DISTRIBUTION IN STRUCTURES 1, 2, 3, 4 & 5 ELASTO-PLASTIC MODEL
1% VISCOUS DAMPING
SUBJECTED TO EL CENTRO N.S.

7.3.5 Summary of Results for Structure 6

Elasto-Plastic Model

A summary of the results for this structure when subjected to the El Centro N.S. and the Pacoima S16E ground motion records is presented in table 7.8. The distribution of the energy dissipated when the system is subjected to the El Centro record in which the system is of moderate strength is very similar to the distribution for the Pacoima record in which case the system is weak.

It is observed that the principal dissipating mechanism is hysteresis in both cases. Almost all the hysteretic energy is dissipated in the lower three stories of the structure. The distribution of energy dissipated by viscous damping is found to be constant for the top half of the systems, showing the effect of higher modes.

STRUCTURE 6 ELASTO-PLASTIC 3% Mass Damping					
El Centro N.S.			Pacoima S16E		
Storey	Energy Dissipated By Hysteresis	Energy Dissipated By Viscous Damping	Storey	Energy Dissipated By Hysteresis	Energy Dissipated By Viscous Damping
10	0	6.6	10	0	4.3
9	0	5.8	9	0.2	4.1
8	0	5.0	8	0.9	4.0
7	0	4.3	7	1.5	3.8
6	1.5	3.6	6	3.1	3.8
5	3.7	2.9	5	3.6	3.6
4	6.2	2.5	4	2.6	3.3
3	10.7	1.9	3	3.1	3.1
2	9.3	1.5	2	2.6	2.9
1	33.1	1.1	1	46.6	2.7
Total	64.6	35.4	Total	64.1	35.9

TABLE 7.8

DISTRIBUTION OF ENERGY IN STRUCTURE 6,
ELASTO-PLASTIC MODEL 3% VISCOUS DAMPING

7.4 Distribution of Energy in Stiffness Degrading Multi-Degree of Freedom Systems

7.4.1 Summary of Results for Structure 1 Stiffness Degrading Model

A summary of the results obtained for this structure subjected to three ground motion records is presented in table 7.9. It can be seen that the systems with stronger yield strength ratios dissipate slightly larger percentages for energy in hysteresis. For example this system when subjected to the Taft N69W record is a strong system with YSR = 1.9 and dissipates 85.9% of the energy in hysteresis. The same system subjected to the Pacoima S16E record is a weak system with YSR = 0.26 and dissipates 70.9% of the energy in hysteresis. However this difference is considered small in comparison to the change in intensity of the two records used.

An interesting trend that is found in these results is the apparent concentration of hysteretic energy dissipation in the lowest storey as the yield strength ratio of the system is reduced.

In summary it is noted that the distribution of the total energy between the hysteretic and viscous damping mechanisms is not significantly affected by the changes in YSR, but the location of the energy dissipated by the hysteretic mechanisms is very sensitive to changes in the YSR, for these stiffness degrading models.

STRUCTURE 1 STIFFNESS DEGRADING

1% VISCOUS DAMPING

Earthquake	YSR Category	Energy Dissipated In Hysteresis (%)	Energy Dissipated In Viscous Damping (%)
Taft N69W	1.9 Strong	85.9	14.1
El Centro N.S.	0.8 Mod.	86.4	13.6
Pacoima S16E	0.26 Weak	70.9	29.1

DISTRIBUTION OF HYSTERETIC ENERGY WITHIN SYSTEM

Storey	Taft	El Centro	Pacoima
3	19.1	6.2	1.2
2	33.3	29.4	3.2
1	33.6	50.8	66.5
Σ	85.9%	86.4%	70.9%

DISTRIBUTION OF ENERGY DISSIPATED BY VISCOUS DAMPING

Storey	Taft	El Centro	Pacoima
3	7.0	4.5	6.4
2	4.8	5.5	9.1
1	2.3	3.6	13.6
Σ	14.1%	13.6%	29.1%

TABLE 7.9

DISTRIBUTION OF ENERGY IN STRUCTURE 1
STIFFNESS DEGRADING MODEL 1% VISCOUS DAMPING

7.4.2 Summary of Results for Structure 2

Stiffness Degrading Model

The results for this system are summarized in table 7.10. For these systems it was found that the effect of changes in YSR is of the same order for both the distribution of energy between the two mechanisms and the location of the energy dissipated in the system. These effects are much smaller than was found for Structure 1. In all cases the lowest storey dissipates approximately the same proportion of energy in hysteresis. Also it is observed that the lowest storey dissipates the majority of the energy in viscous damping. The explanation for this lies in the lengthening of the fundamental period caused by the stiffness degradation. The energy spectrum for the Pacoima record used has an unusual concentration of energy at the long period end and the systems used are in effect moving into the higher energy periods as the stiffness degrades.

STRUCTURE 2 STIFFNESS DEGRADING

1% VISCOUS DAMPING

Earthquake	YSR Category	Energy Dissipated In Hysteresis (%)	Energy Dissipated In Viscous Damping (%)
Taft N69W	3.1 Strong	68.6	31.4
El Centro N.S.	1.4 Strong	76.6	23.4
Pacoima S16E	0.43 Mod.	56.5	43.5

DISTRIBUTION OF HYSTERETIC ENERGY WITHIN SYSTEM

Storey	Taft	El Centro	Pacoima
3	0.0	2.4	0.9
2	8.8	22.3	5.5
1	59.9	51.9	50.1
Σ	68.6%	76.6%	56.5%

DISTRIBUTION OF ENERGY DISSIPATED BY VISCOUS DAMPING

Storey	Taft	El Centro	Pacoima
3	15.5	10.6	12.3
2	10.2	8.5	12.3
1	5.7	4.3	18.9
Σ	31.4%	23.4%	43.5%

TABLE 7.10

DISTRIBUTION OF ENERGY IN STRUCTURE 2
STIFFNESS DEGRADING MODEL 1% VISCOUS DAMPING

7.4.3 Comparison of Energies in Structures 1, 2, 3, 4 and 5. Stiffness Degrading Model.

This comparison is similar to that presented for the Elasto-Plastic model in section 7.3.4. In this study all the systems have 1% mass and stiffness proportional viscous damping and are subjected to thirty seconds of the El Centro N.S. record. The results are presented in table 7.11.

In all cases it is found that hysteresis is the principal energy dissipating mechanism. In structures 1 and 2 it is noted that the second storey dissipates a significant proportion of the hysteretic energy. This is not found to be the case for the other structures studied where the lowest storey dissipates almost all of the hysteretic energy. For these systems the concept of the 'soft first storey' is found to be effective in concentrating the location of the hysteretic and viscous energy dissipation into the lowest storey.

Structure	Period (Sec.)	YSR	Total Energy (Inch Kips)	Energy Dissipated In Hysteresis (%)	Distribution			Energy Dissipated In Viscous Damping (%)	Distribution		
					1	2	3		1	2	3
1	0.43	0.8	6744.3	86.4	50.8	29.4	6.2	13.6	3.6	5.5	4.5
2	0.33	1.4	1308.5	76.6	51.9	22.3	2.4	23.4	4.3	8.5	10.6
3	0.33	0.45	1946.8	73.4	71.0	1.9	0.5	26.6	8.4	8.9	9.3
4	0.47	0.68	2709.6	70.0	67.0	3.1	0.0	30.0	18.7	5.4	5.9
5	0.57	0.45	1908.5	69.1	68.7	0.4	0.0	30.9	19.7	5.2	6.0

TABLE 7.11

ENERGY DISTRIBUTION IN STRUCTURES 1, 2, 3, 4 & 5
STIFFNESS DEGRADING MODEL 1% VISCOUS DAMPING
SUBJECTED TO EL CENTRO N.S.

7.4.4 Summary of Results for Structure 6

Stiffness Degrading Model

The results of this study are presented in table 7.12. The results show that in the El Centro response the hysteretic mechanism is the principal energy dissipator. However, when the system is subjected to the Pacoima record there is almost equal distribution of energy between the two mechanisms. It was also be seen that the reduction in YSR tends to concentrate the energy dissipated in hysteresis into the lowest storey of the structure. The distribution of energy dissipated by the viscous damping mechanism is approximately constant for the upper half of the structure.

STRUCTURE 6

STIFFNESS DEGRADING

3% MASS DAMPING

El Centro N.S.			Pacoima S16E		
Storey	Energy Dissipated By Hysteresis	Energy Dissipated By Viscous Damping	Storey	Energy Dissipated By Hysteresis	Energy Dissipated By Viscous Damping
10	0.0	5.1	10	0.0	5.5
9	1.0	4.9	9	0.1	5.5
8	2.4	4.5	8	0.3	5.4
7	3.9	4.0	7	0.4	5.4
6	5.9	3.4	6	0.6	5.2
5	7.2	2.8	5	1.2	5.2
4	8.4	2.2	4	1.6	4.9
3	9.5	1.6	3	1.6	4.7
2	14.2	1.1	2	3.8	4.5
1	17.2	0.6	1	39.8	4.2
Total	69.8	30.2	Total	49.5	50.5

TABLE 7. 12

DISTRIBUTION OF ENERGY IN STRUCTURE 6
STIFFNESS DEGRADING MODEL 3% VISCOUS DAMPING.

CHAPTER 8

CONCLUSION

8.1 Energy Dissipation in Single Degree of Freedom Systems

The system strength parameter (Yield Strength Ratio, YSR) was found to be of great significance for all aspects of response measured in this study. The total energy dissipated by systems which remained elastic during the response does not form an upper bound for the total energy dissipated by systems which undergo significant yield excursions during their response.

In terms of the YSR parameter the response for all systems can be classified into three broad groups.

1. Strong systems (YSR = 1 to 10). These would include realistic buildings, which would, in practice, tend to have short periods characteristic of shear wall systems.

   Response is predominantly elastic; ductility demand is in the order of 1 to 3 when the period is less than 0.5 secs, but there are no major yield excursions. The equal displacement criterion is good, provided that there is viscous damping at 1% of critical or greater, and the period is greater than 0.5 secs. The energy dissipated by the hysteresis in the members is very sensitive to the period and frequency content of the earthquake.

2. Moderate systems (YSR = 0.3 to 1). These would also include realistic buildings, with longer periods characteristic of frame structures.

Major yield excursions occur, with ductility demands up to 10 for periods over 1 sec. (Higher for less realistic structures with short periods). The equal displacement criterion is good for members with non-degrading stiffness, but does not hold when the stiffness degrades unless the viscous damping is high. The hysteretic energy dissipated is less strongly period dependent.

3. Weak systems (YSR < 0.3). Such systems would seldom be encountered in practice; they would tend to have very long periods.
   a) Ductility demand is excessive for all systems.
   b) Required Energy Capacity is very weakly period-dependent.
   c) The equal displacement criterion does not apply.

In investigating the time history of energy dissipated in the hysteretic mechanism it was found that the number of excursions into the yield range depends upon the type of earthquake and the Yield Strength Ratio. For impulsive earthquakes, and for strong systems in more distant earthquakes, there are generally 2 to 3 such excursions, with the largest dissipating up to 50% of the total hysteretic energy. For moderate systems in more distant earthquakes there are 3 to 5 yield excursions, with the largest dissipating up to 30% of the hysteretic energy.

8.2 The Proposed Design Method

The present study has led to the development of a design method for seismic design of structures, which considers energy dissipation as the prime design parameter. In the proposed method the total energy to be absorbed by a structure is approximated on the basis of the Yield Strength Ratio (YSR) and period; the fraction of this energy that is dissipated hysteretically can, in

turn, be predicted by means of spectra that depend upon the YSR, the proportion of viscous damping and the hysteretic model. Such spectra may be constructed from the response of single degree of freedom systems. Results so far suggest that it may be possible to predict in advance the approximate distribution of hysteretic energy dissipation though the structure; if this, with further study, proves to be practicable, the basis for a rational design method exists. It will be possible to predict the amount of hysteretic energy that must be accepted by each location in the structure, and the size of the hysteresis loop for which the detailing must provide. The form this method takes would make it most useful for incorporation into the limit state design requirements of modern building codes.

8.3 Total Energy Dissipated by Multi-Degree of Freedom Systems

The results of this study indicate that a good estimate of the total energy to be dissipated by multi-degree of freedom systems can be obtained from appropriate spectra produced with a single-degree of freedom model. The effects of various forms of viscous damping upon the total energy dissipated by the systems was found to be small.

The generally close agreement in the results suggests that the multi-degree of freedom systems respond predominantly in the fundamental mode. Further, the variables which influence energy dissipation characteristics in single-degree of freedom systems are also effective for multi-degree of freedom systems.

8.4 The Distribution of Dissipated Energy Within Multi-Degree of Freedom Systems

It was shown in chapter 7 that the distribution of energy between the hysteretic and viscous damping mechanisms is a function of the material properties, yield strength ratio, proportion of viscous damping and period. It is relatively insensitive to different ground motion records, and can be extrapolated with reasonable accuracy from the spectra produced for single degree of freedom systems.

The distribution of energy within the structure from storey to storey is found to be dependent upon the material hysteretic properties used and the mechanism considered; (whether viscous or hysteretic). The dissipation of energy by hysteresis is found to take place predominantly in the lower stories of the structures studied here. For the Elasto-Plastic model this distribution was found to be relatively independent of changes in strength and stiffness in the lower stories. The soft first storey concept did not work well for these Elasto-Plastic systems. This was not found to be the case for the stiffness degrading model systems. Here it was observed that reduction in the yield strength ratio caused a concentration of energy dissipated by hysteresis into the lowest storey. In this sense the soft first storey concept was found to be effective for these systems.

The energy dissipated by the viscous damping mechanism was found to take place mainly in the upper stories of the structures studied.

8.5 Future Work

The work reported here should be viewed as a preliminary study for an energy based analysis procedure. It is presented as a first step toward this objective. Throughout the study as wide a range of variables as possible was used in order to identify general trends and effects. Having identified the principal parameters, more detailed studies using more closely spaced data and a greater number of earthquake records can be made to expand the results obtained here.

Employing single degree of freedom models, design spectra can be produced for total energy dissipated and energy distribution using the increased input data. This would make the spectra statistically more representative of the general earthquake problem. More extensive investigation and verification of the design approach outlined in chapter 4 is needed before it can be used with confidence.

The extension of the method to multi-degree of freedom systems needs to be investigated further. Work on more detailed multi-degree of freedom computer models is required to confirm or amend the findings produced for the shear beam model used in the present study.

The use of the method given here for the design of systems which incorporate special energy dissipating devices of known characteristics is another area which could be usefully investigated in the future.

The influence of axial force combined with flexure upon the energy dissipation characteristics of both S.D.F. and M.D.F. systems can be studied with the inclusion of a suitable hysteresis relationship.

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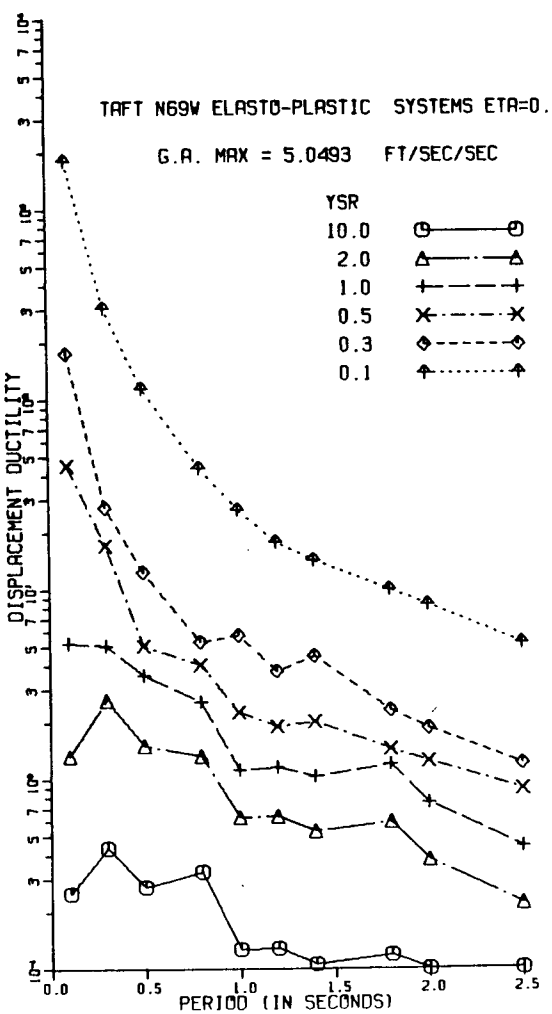
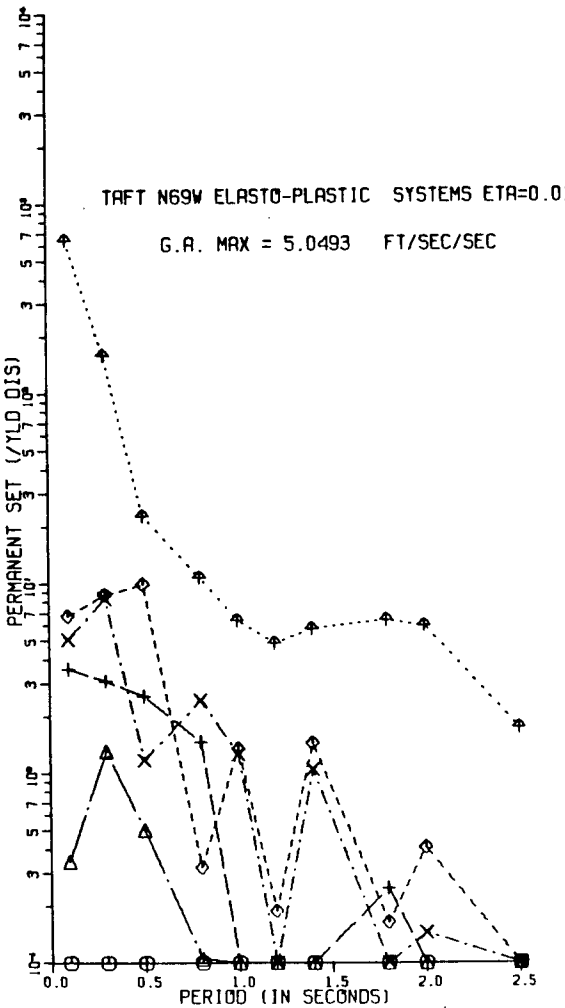
APPENDIX A

RESULTS OF SINGLE DEGREE OF FREEDOM STUDY IN ORIGINAL FORM

Complete results of the single degree of freedom study presented in Chapter 3 are given here in the original form. For an explanation of the input parameters employed and the abbreviations used see section 3.1.





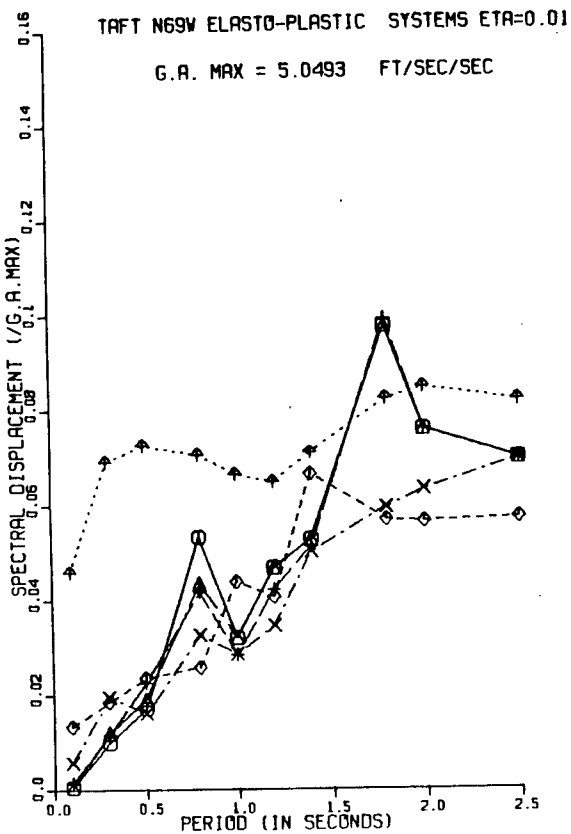
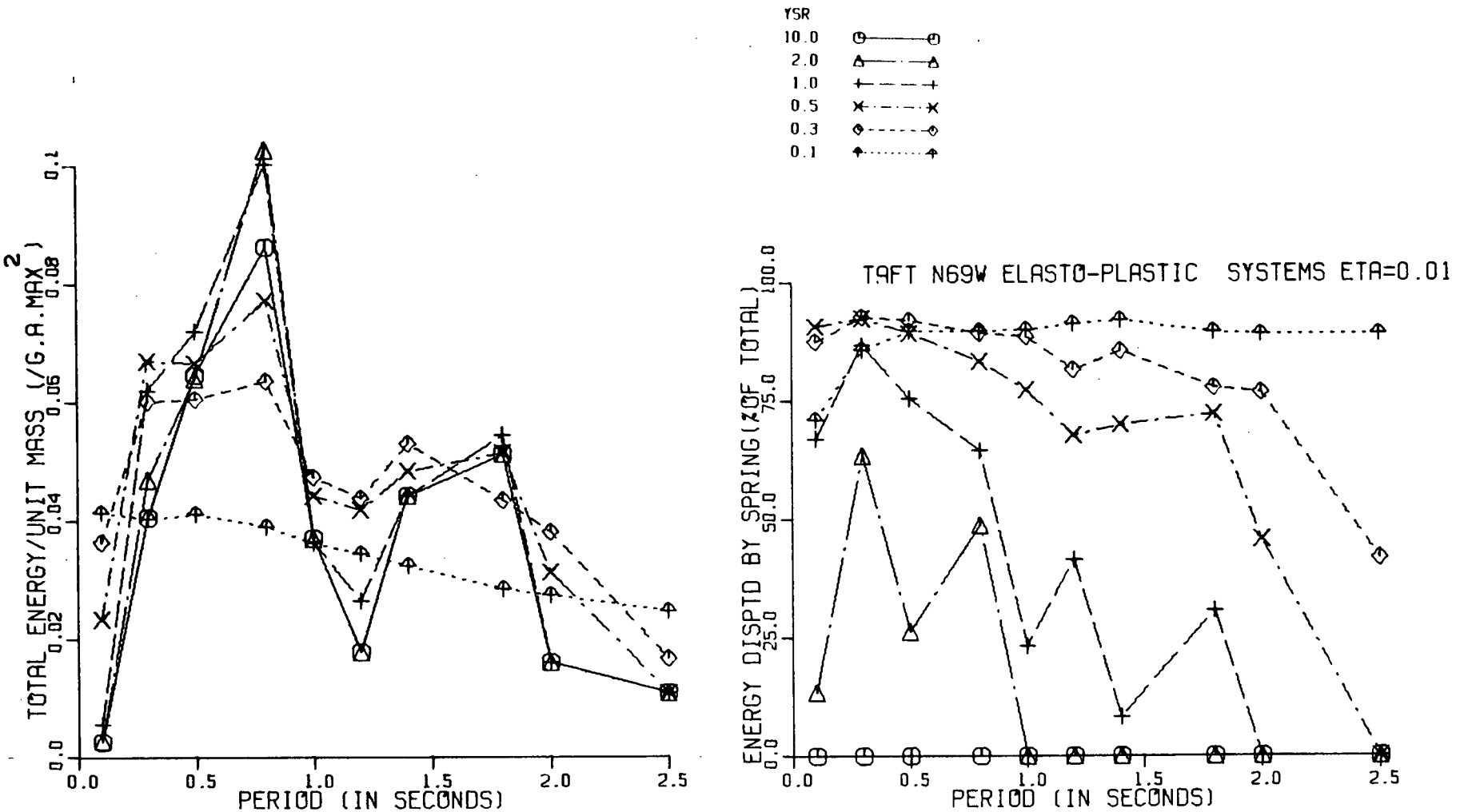


FIG. A.1 RESULTS FOR COMBINATION 1 TAFEP.01



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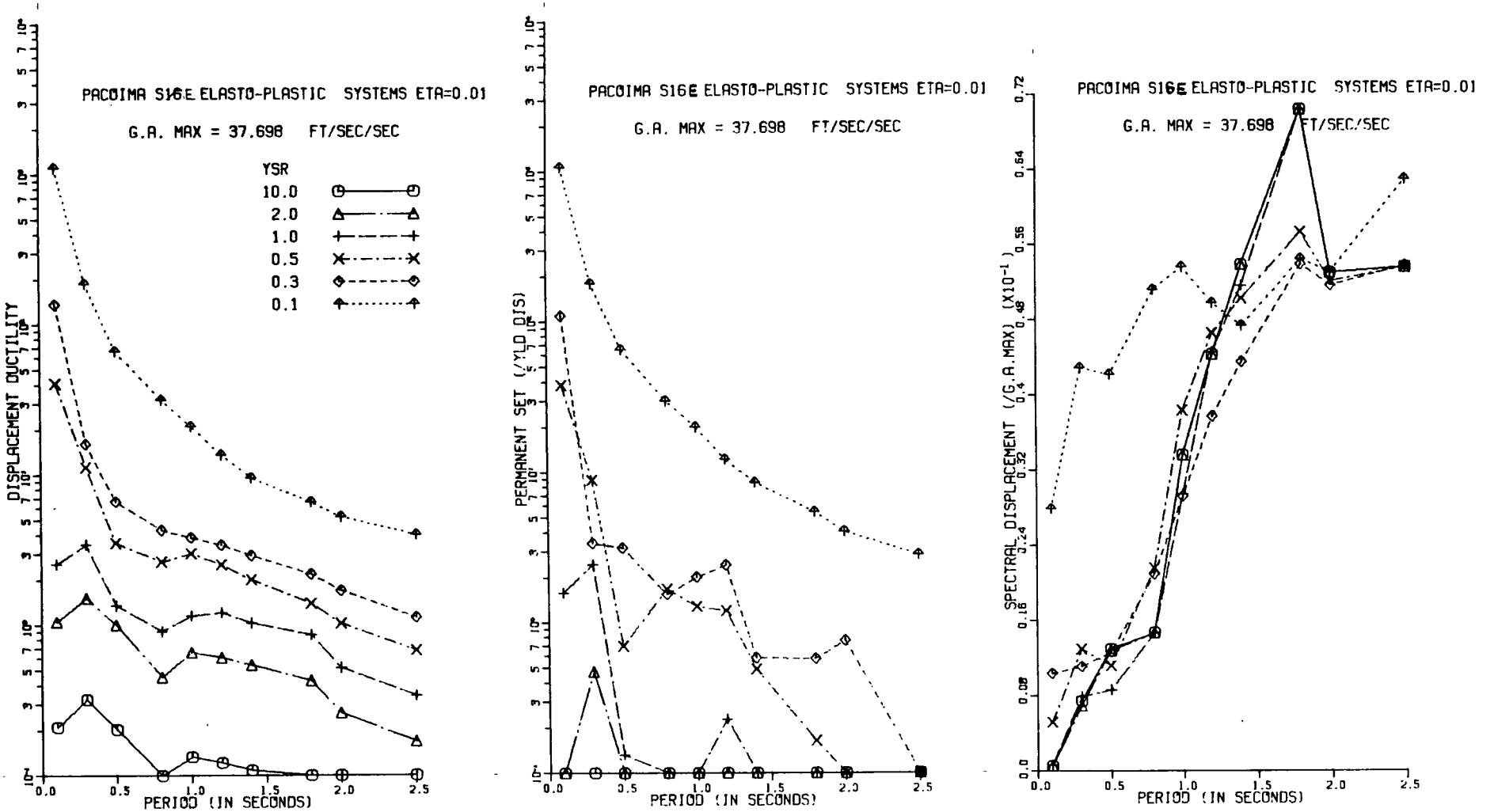

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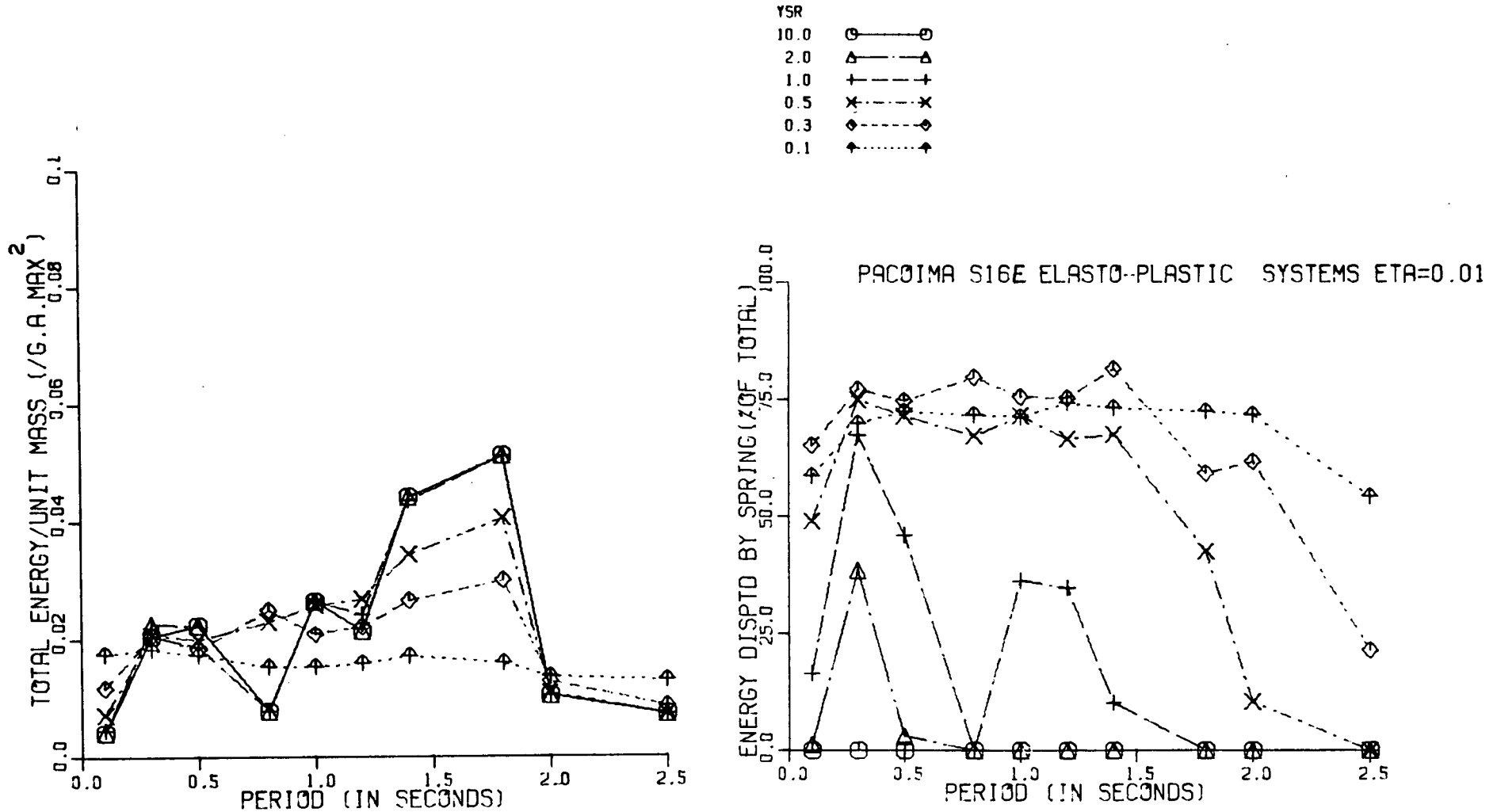


FIG. A.2 CONTINUED

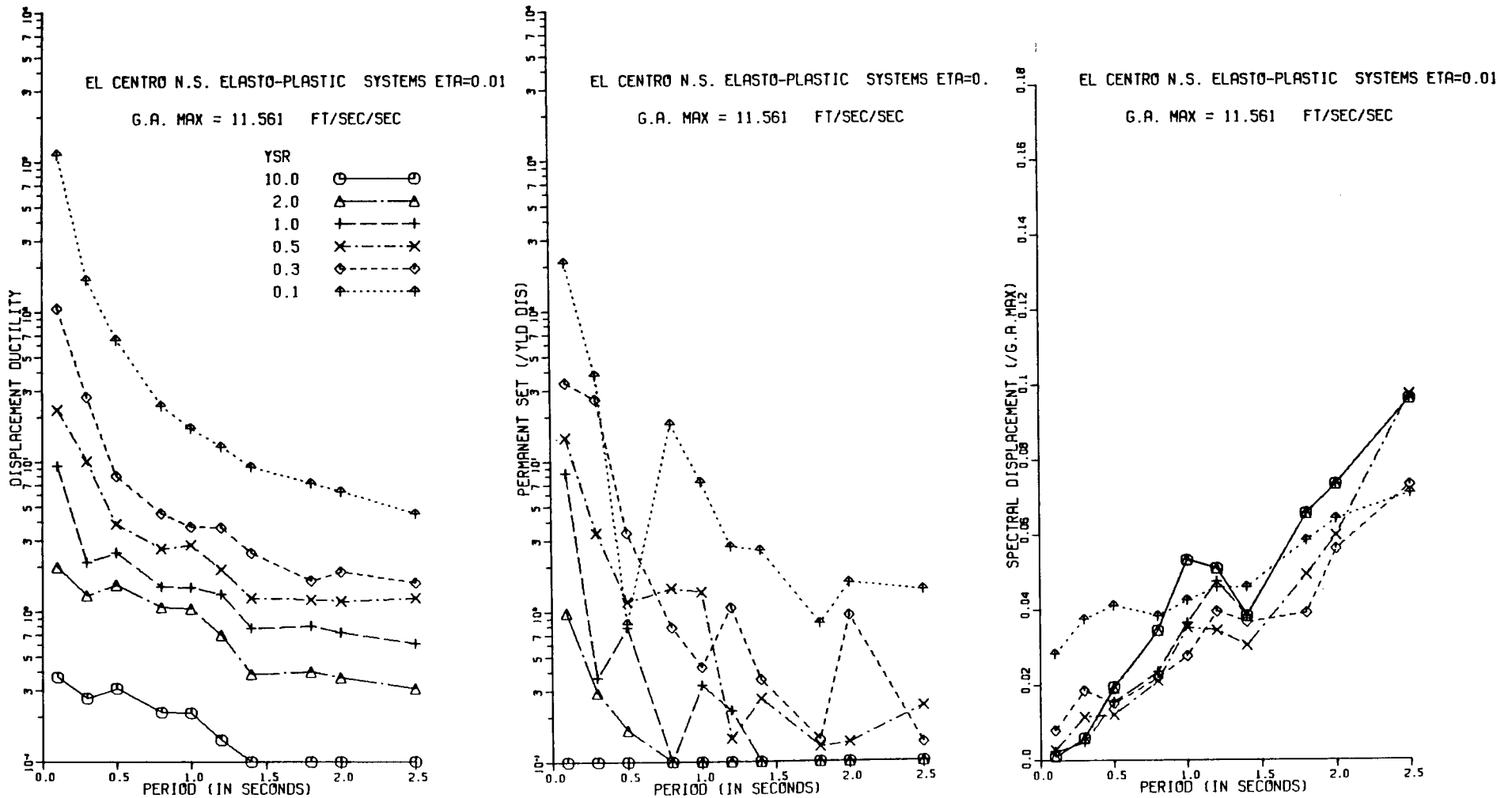
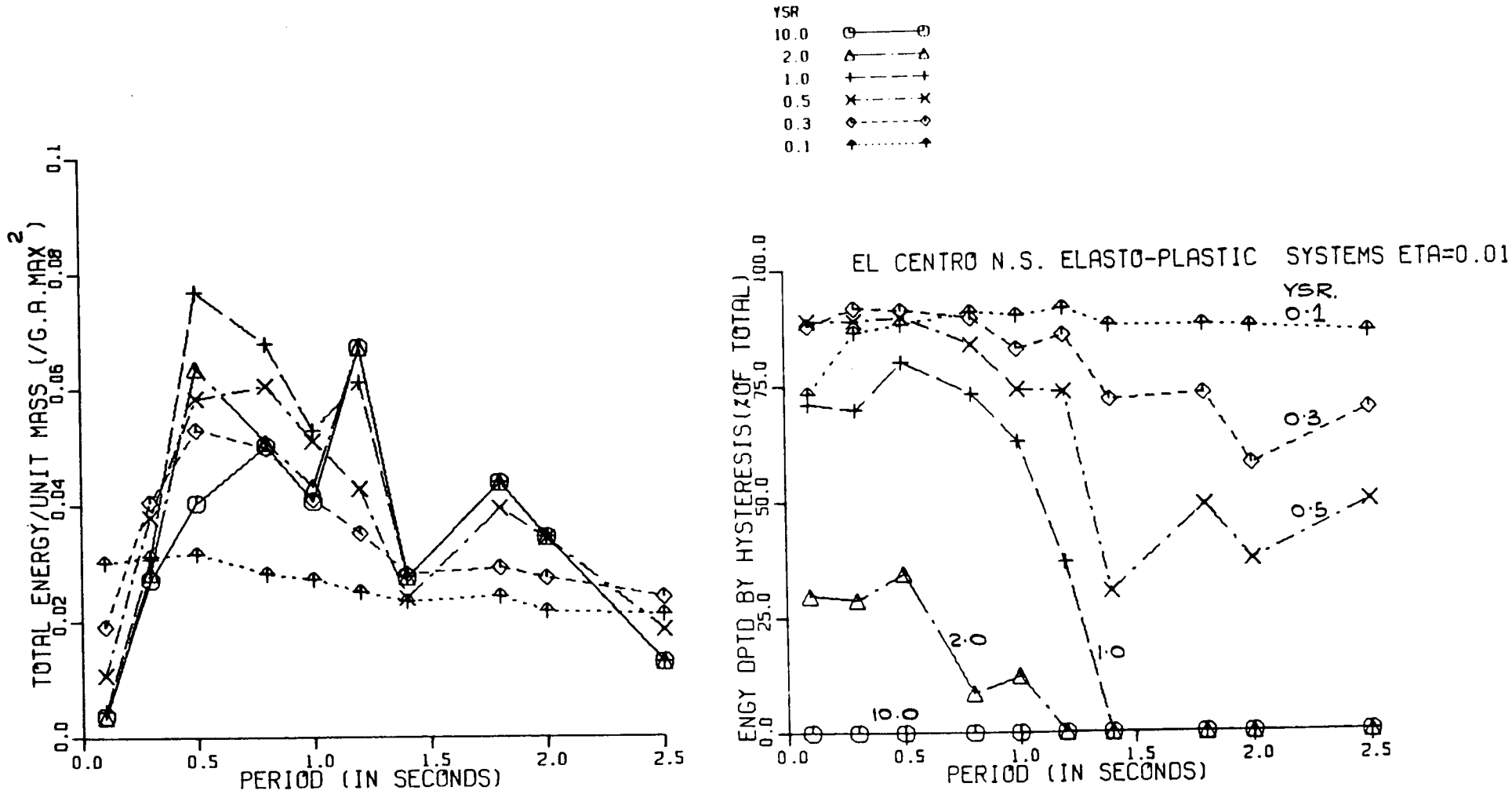


FIG. A.3 RESULTS FOR COMBINATION 3 ELCEP.01



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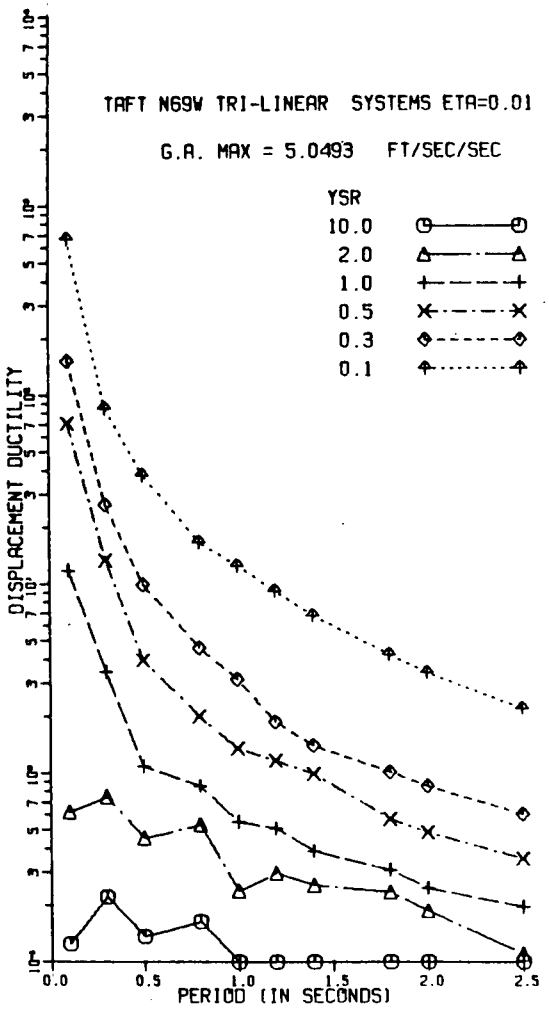

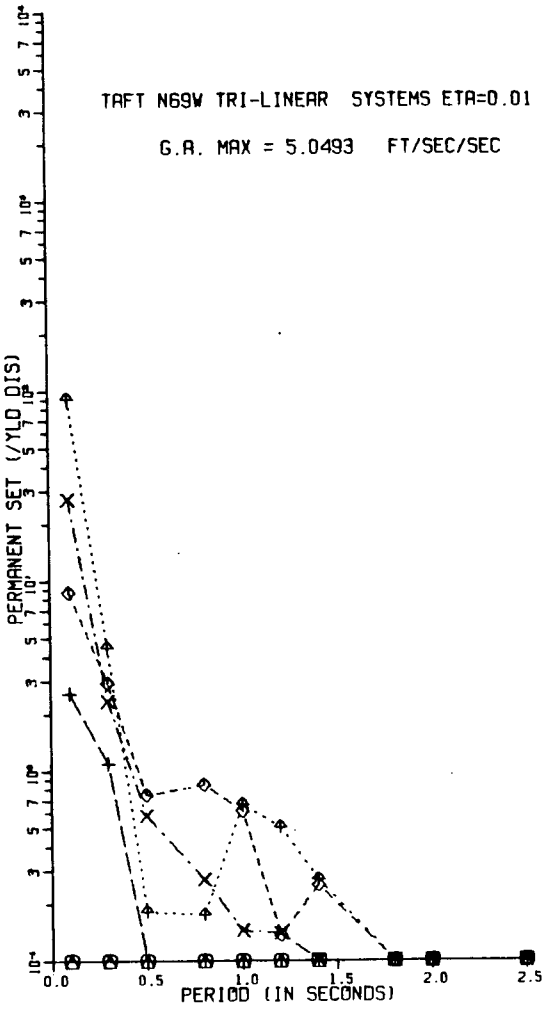

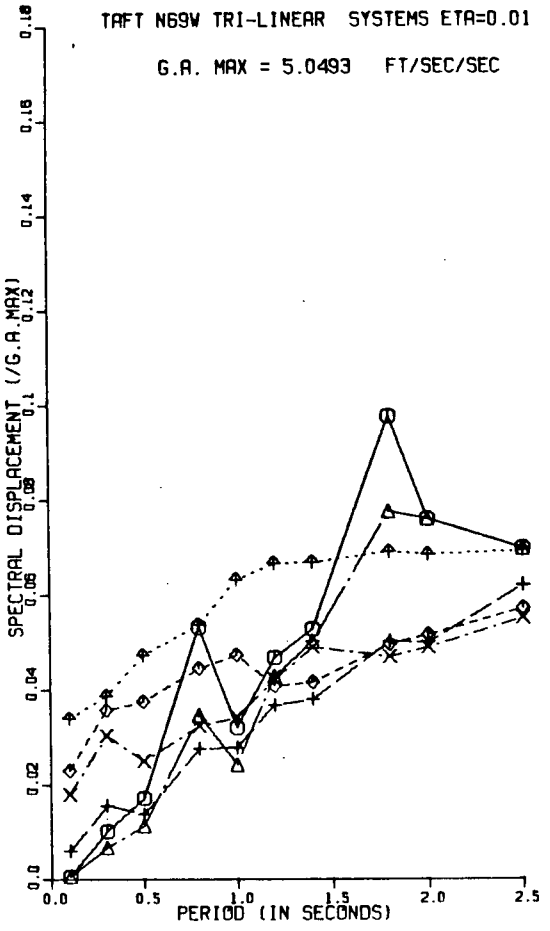

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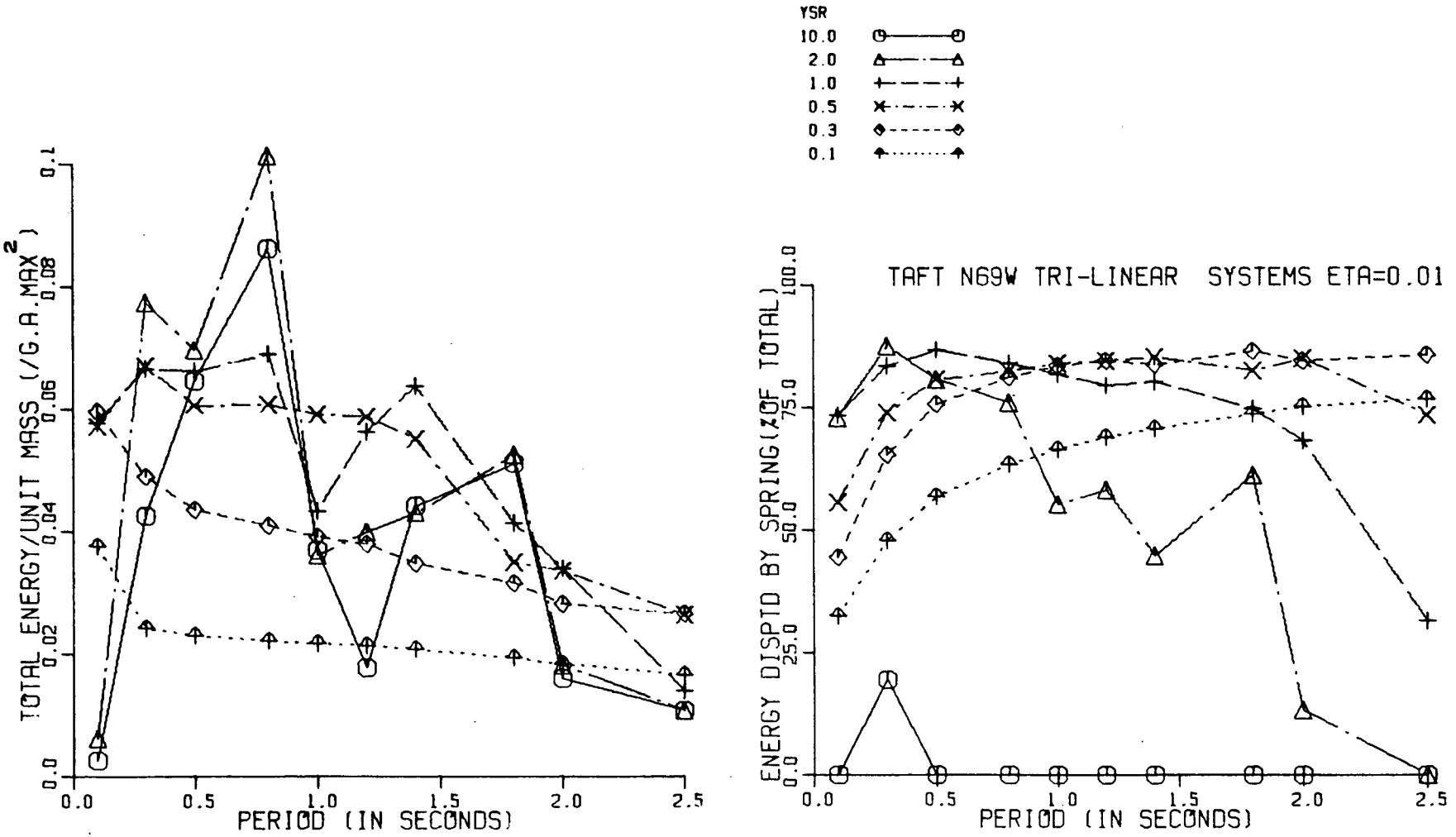

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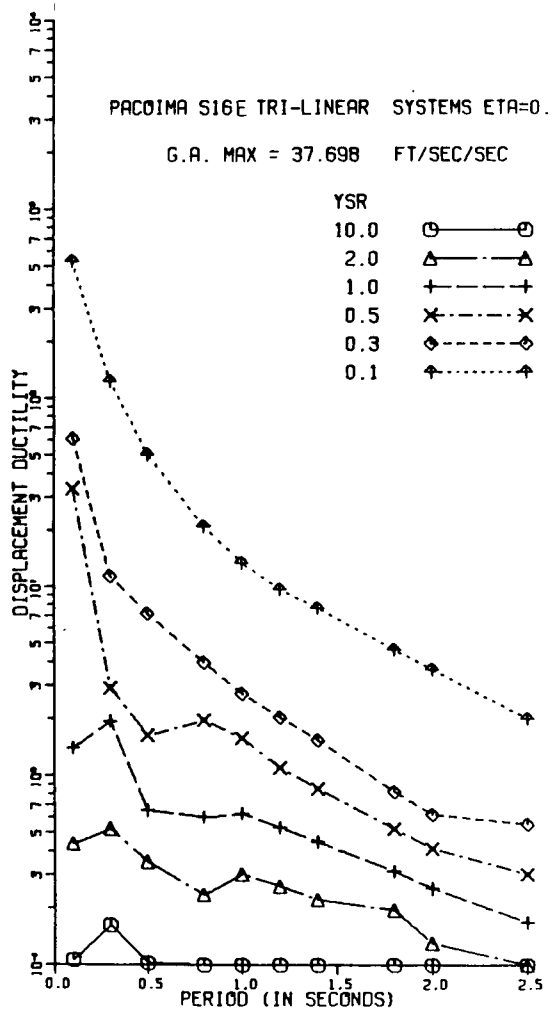
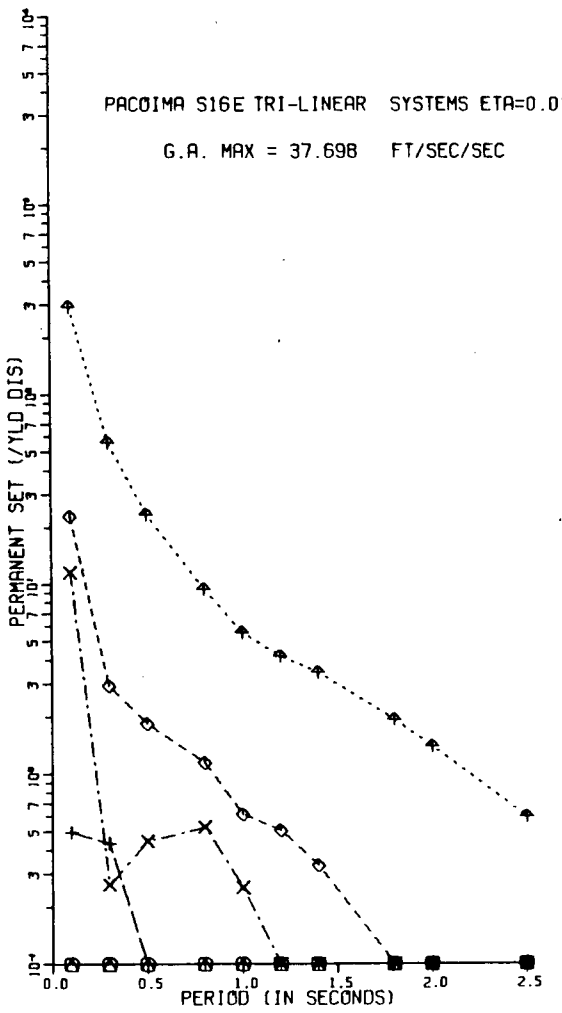




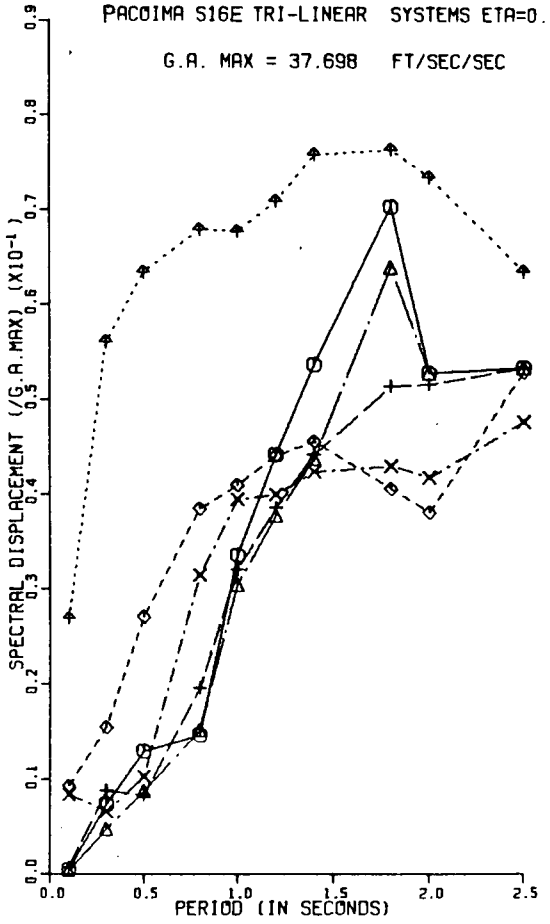
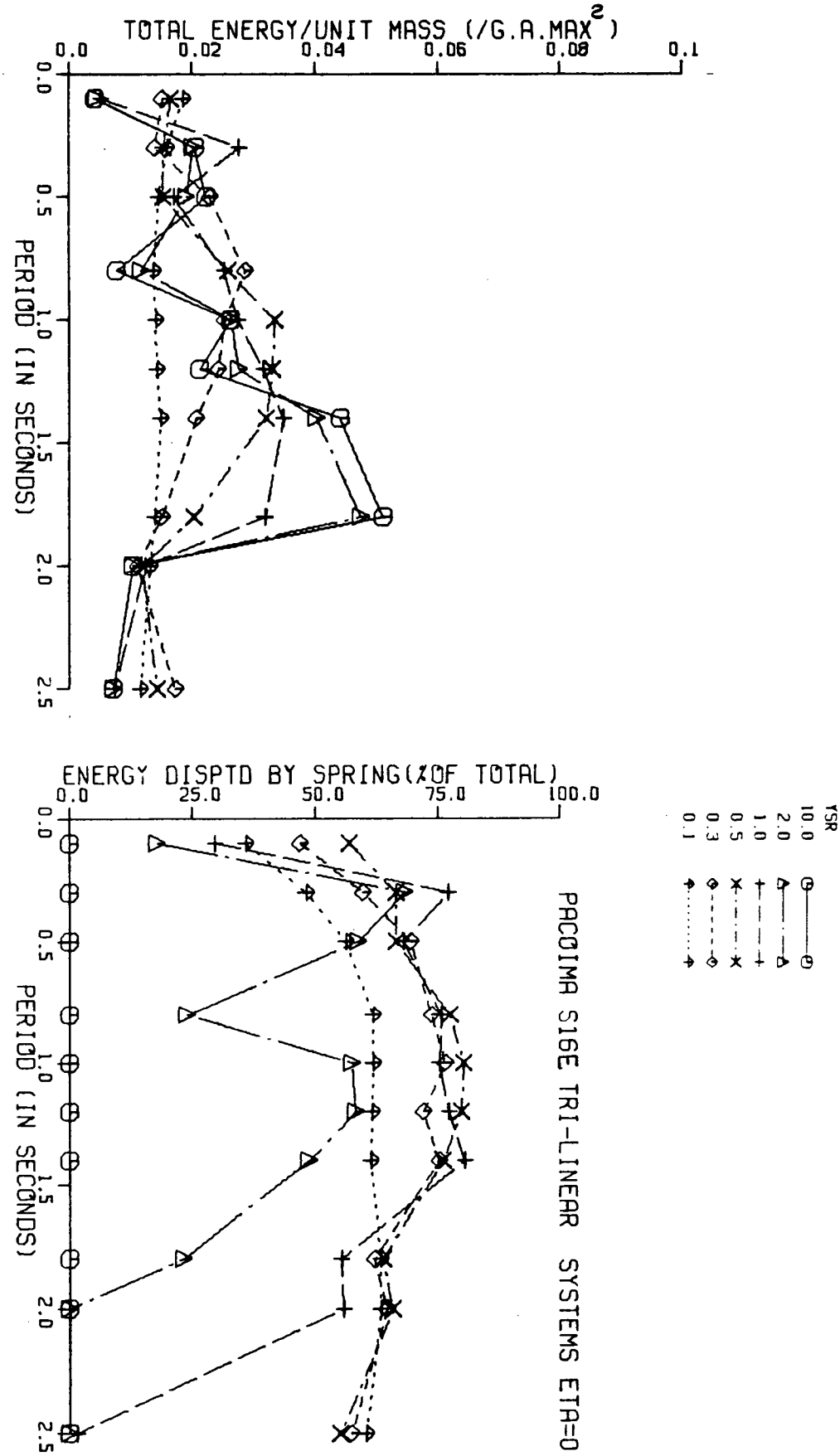


FIG. A.5 RESULTS FOR COMBINATION 5 PACTL.01



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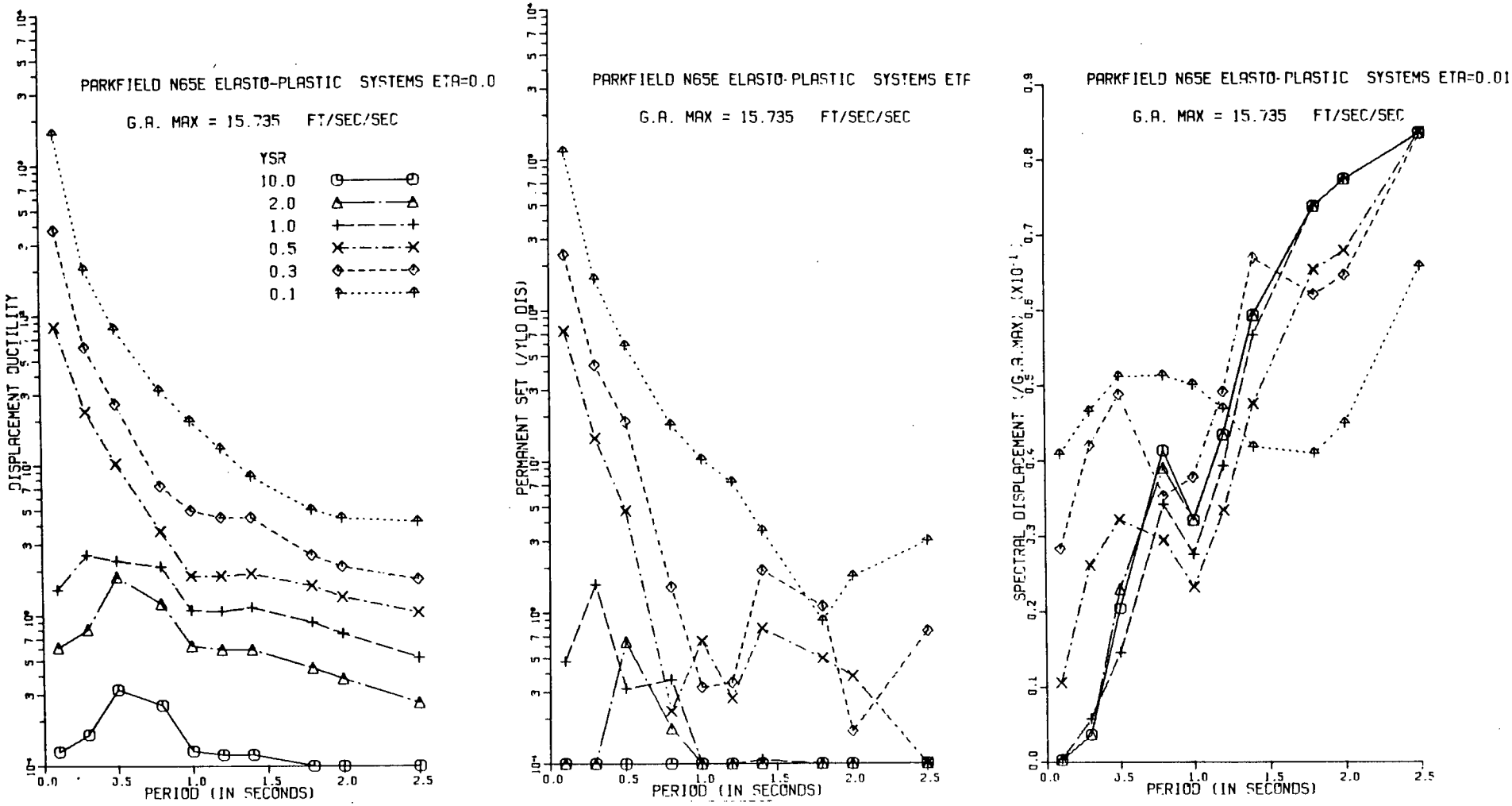

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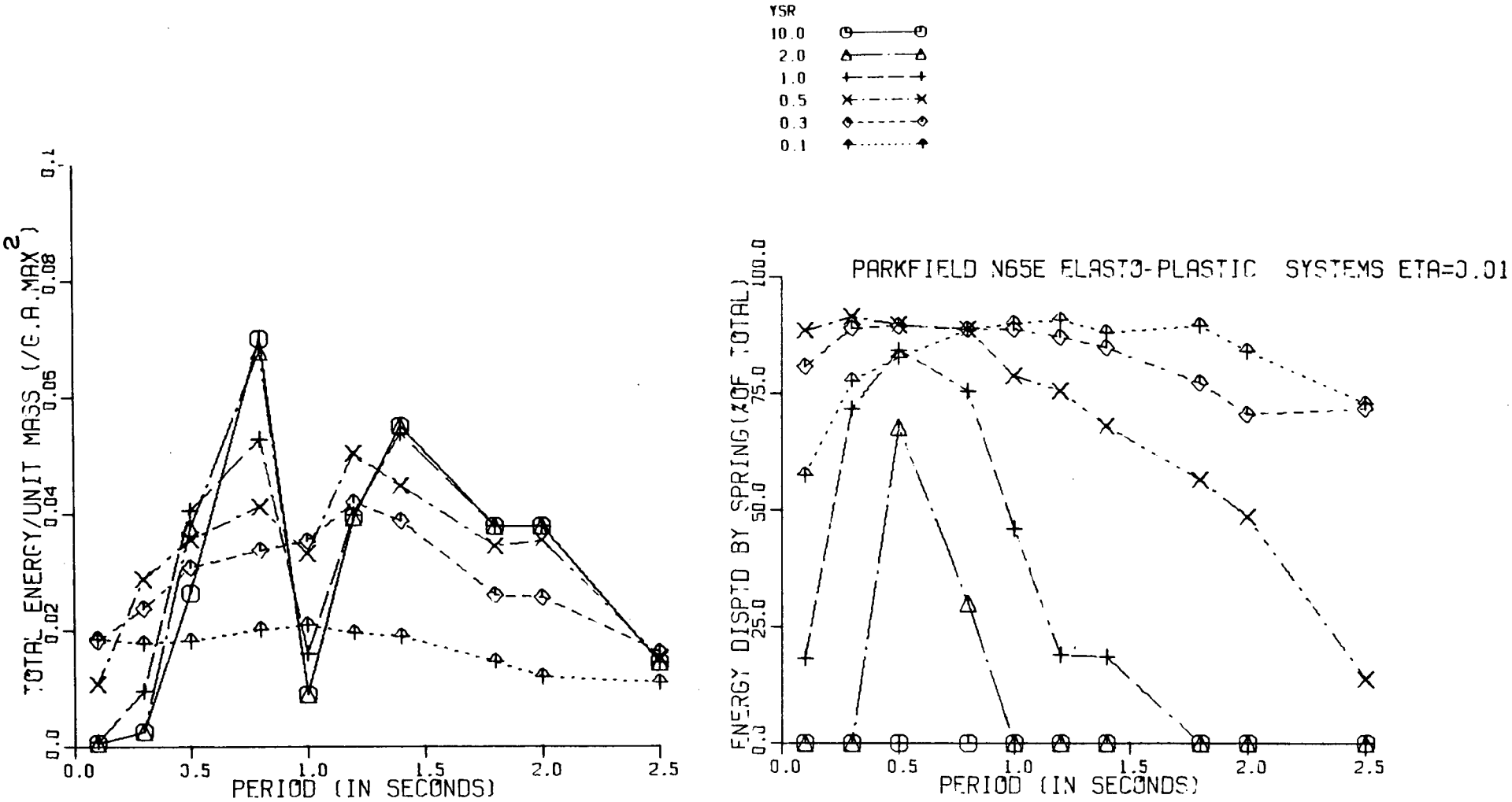

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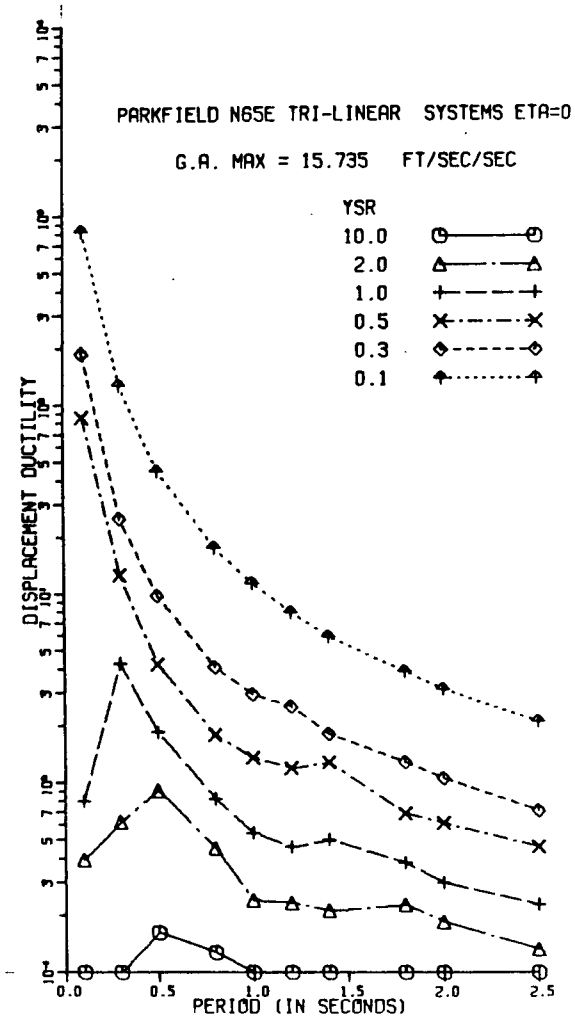

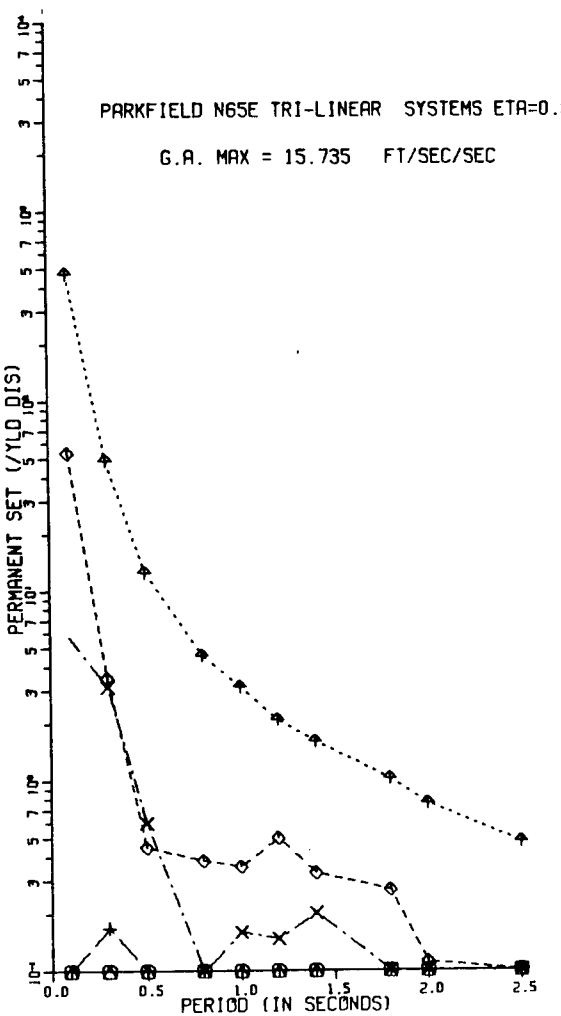

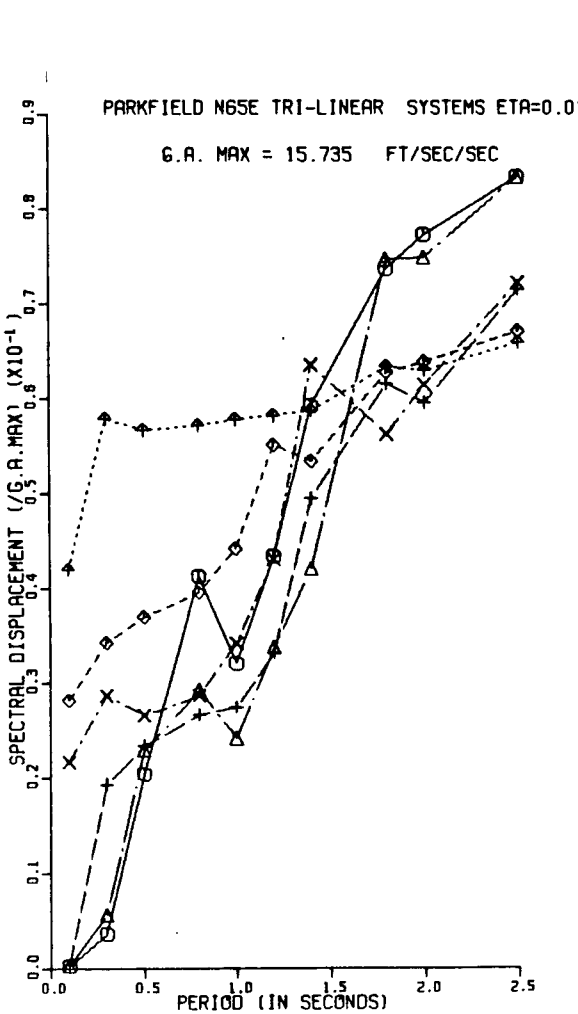

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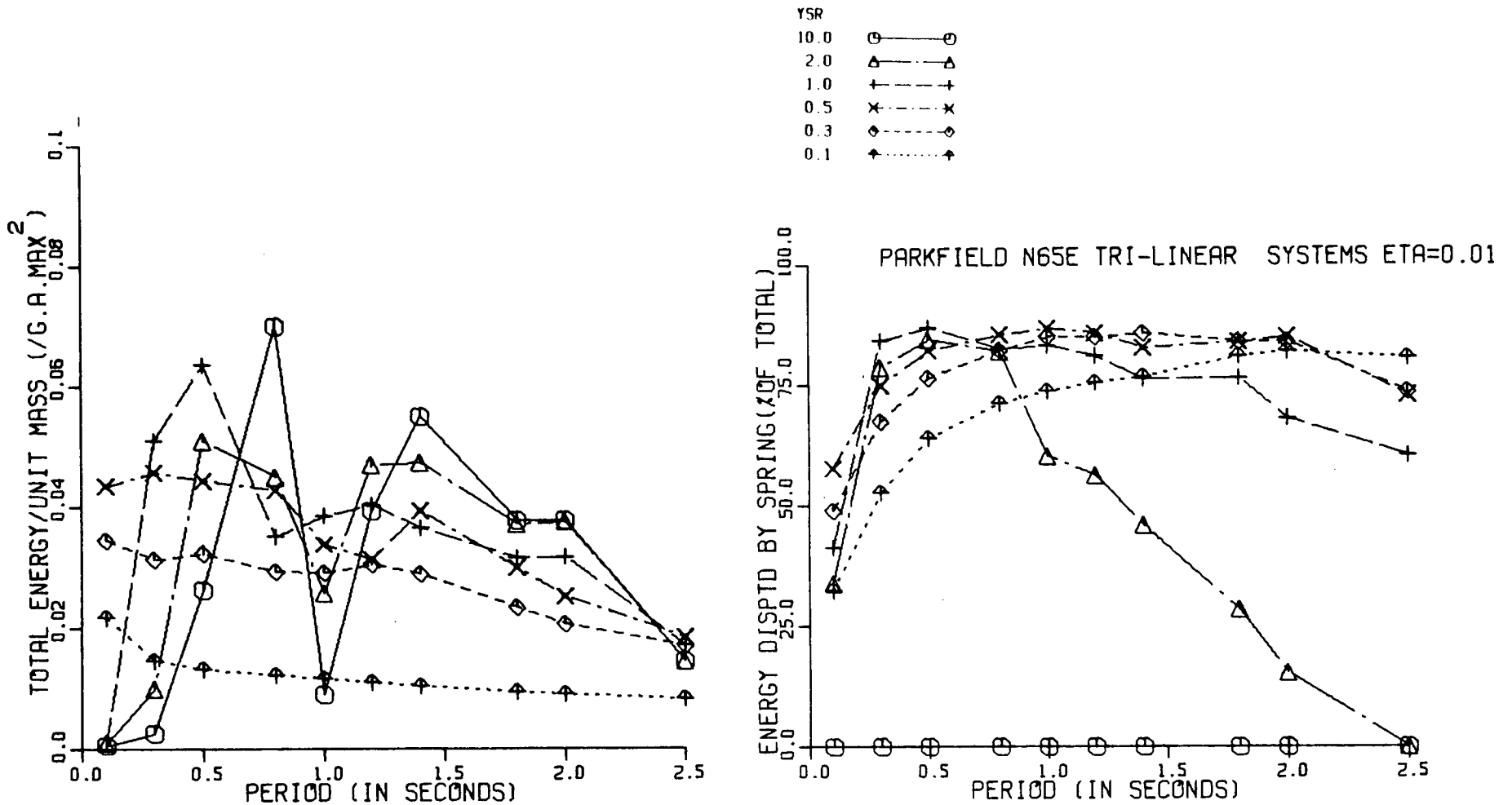

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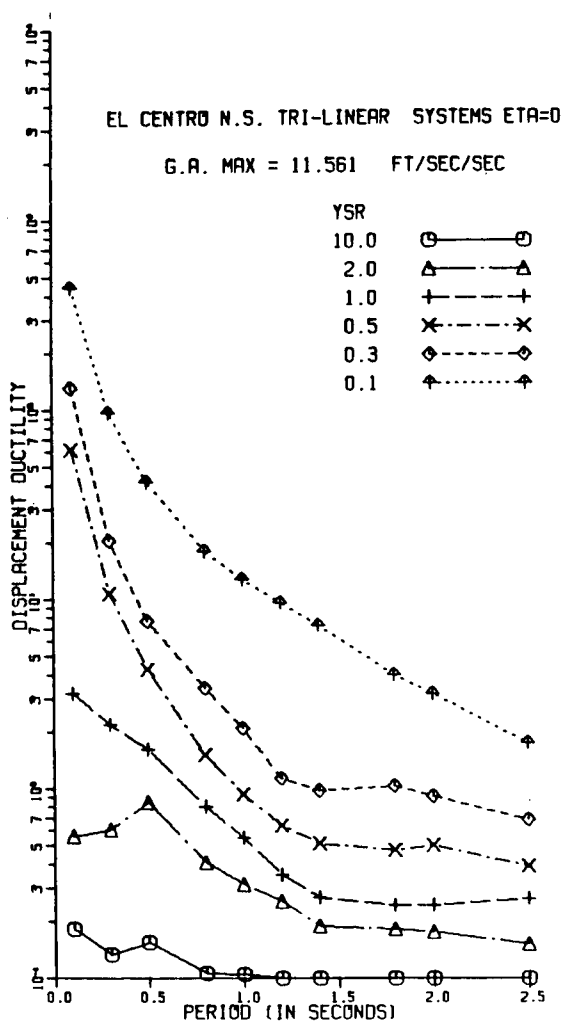

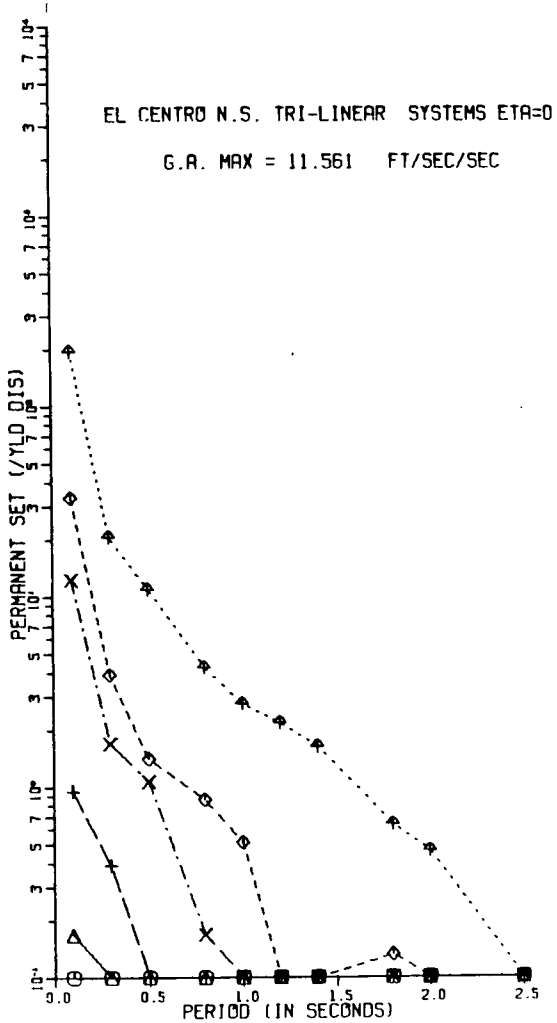

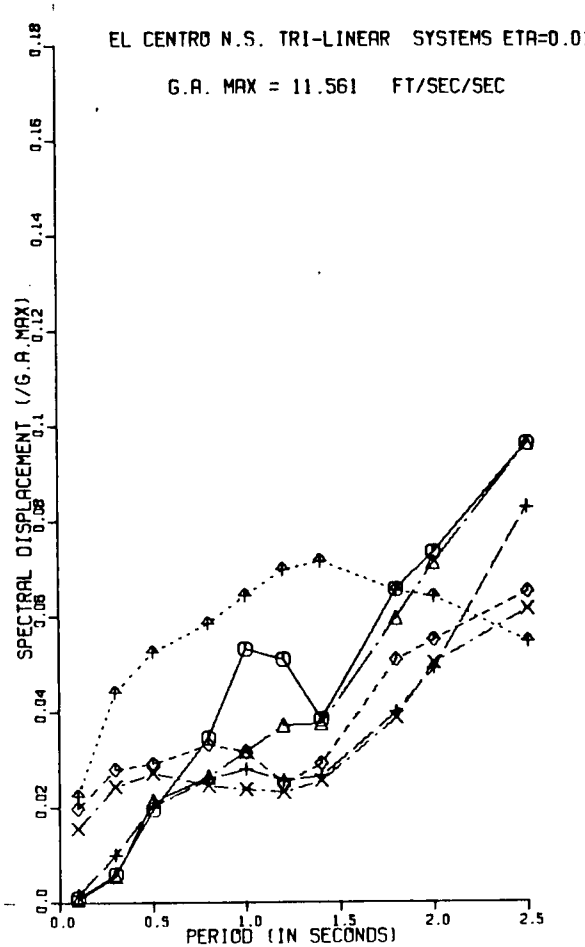

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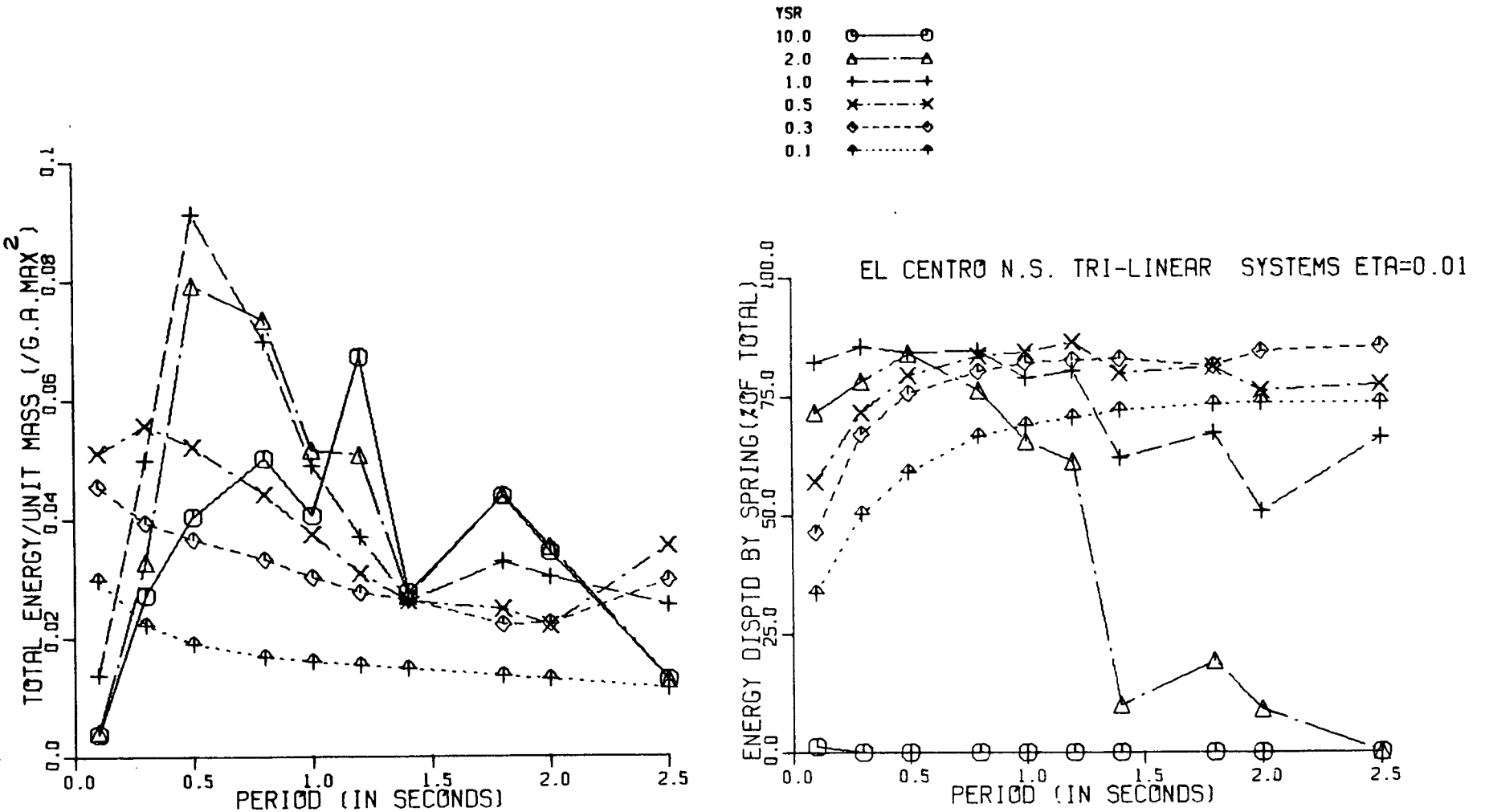

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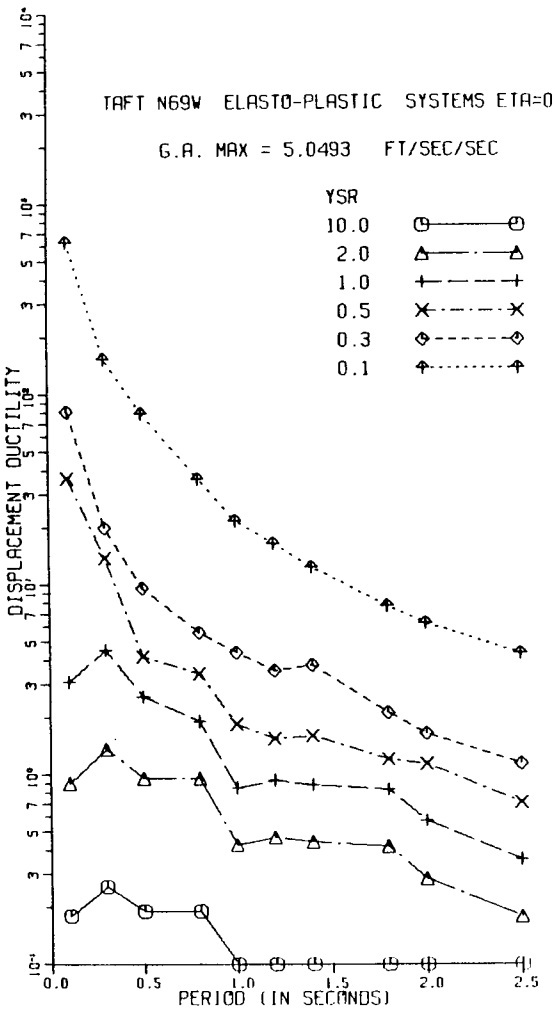

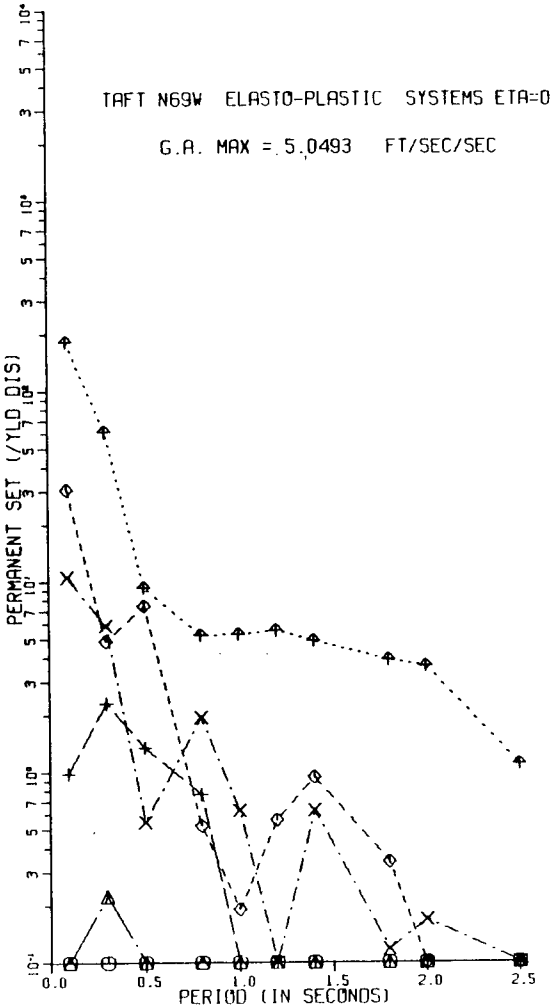

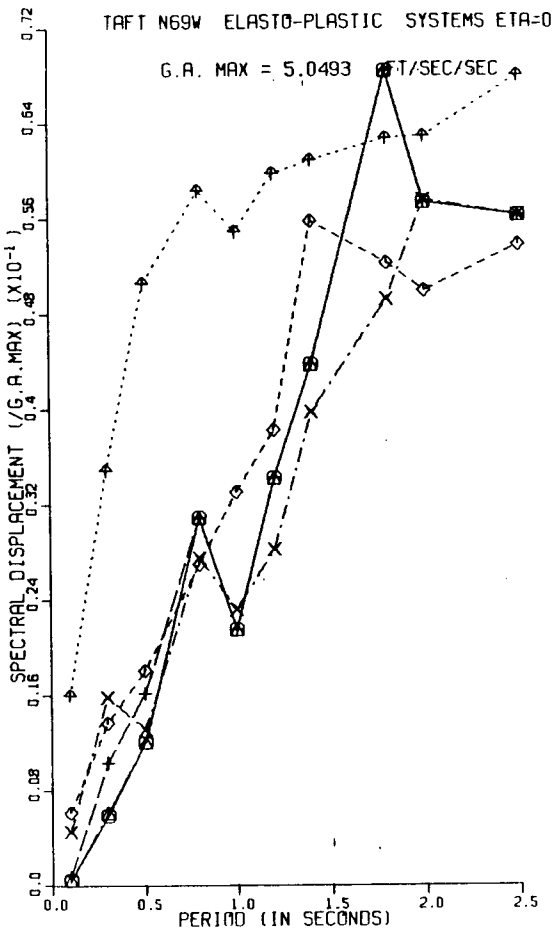

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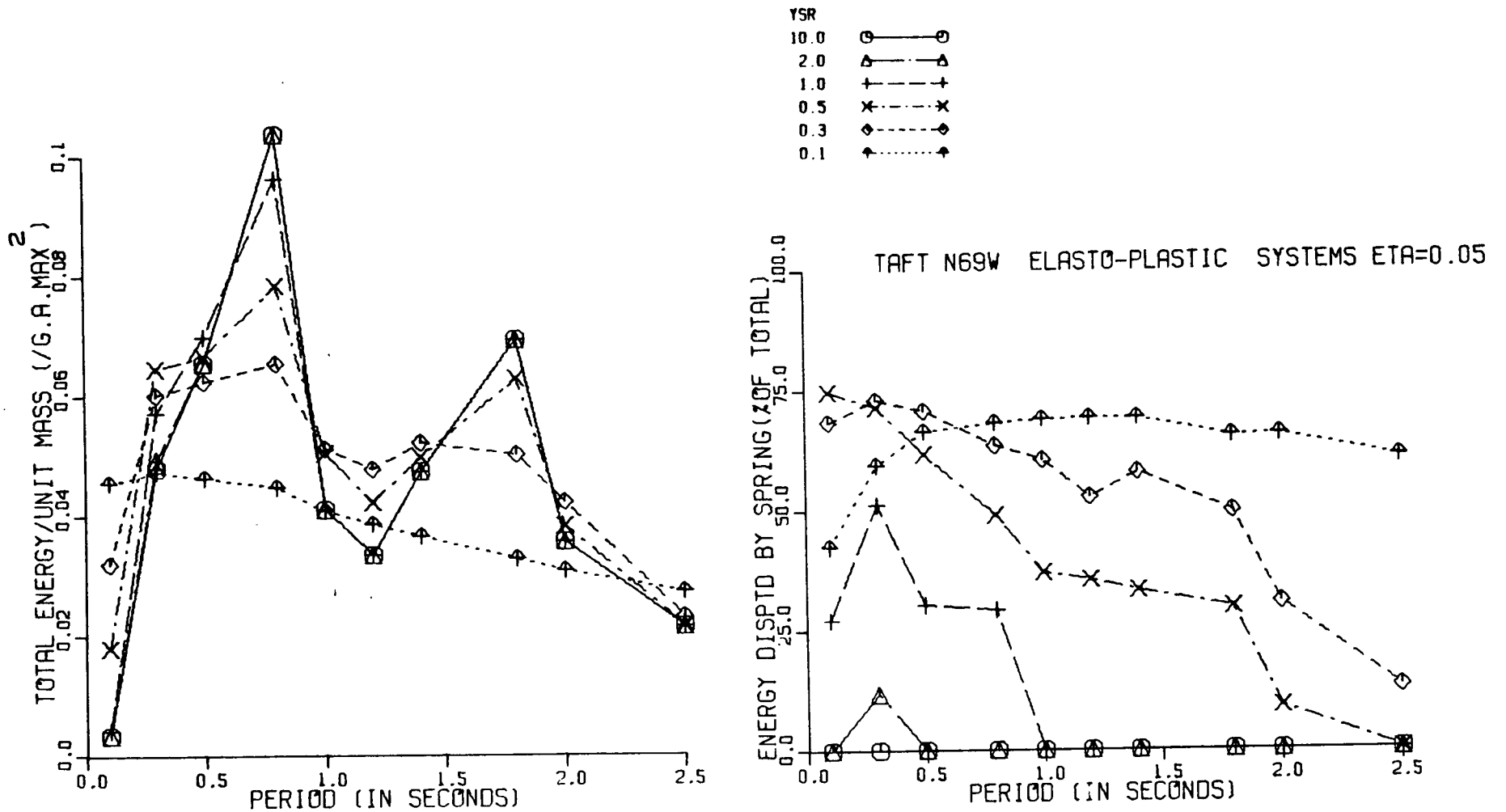

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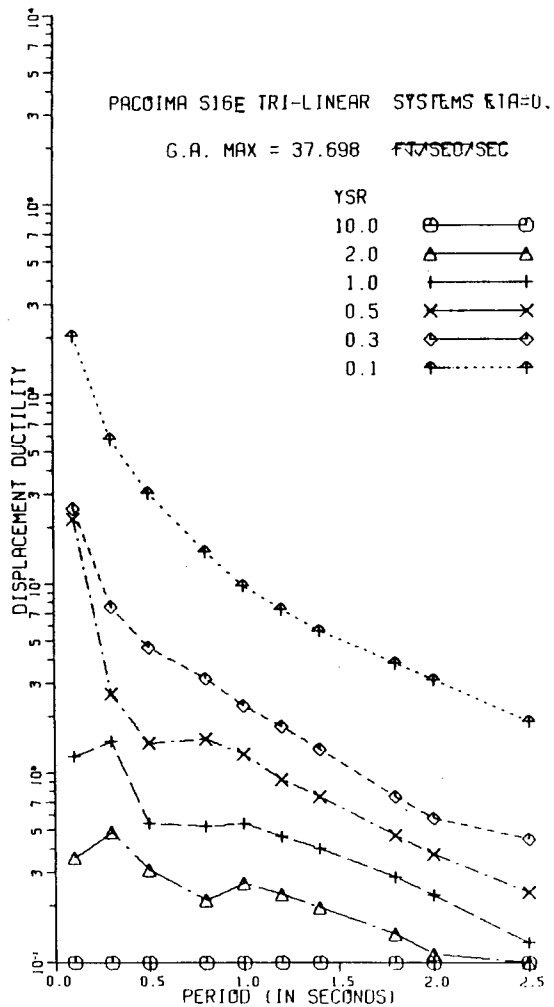

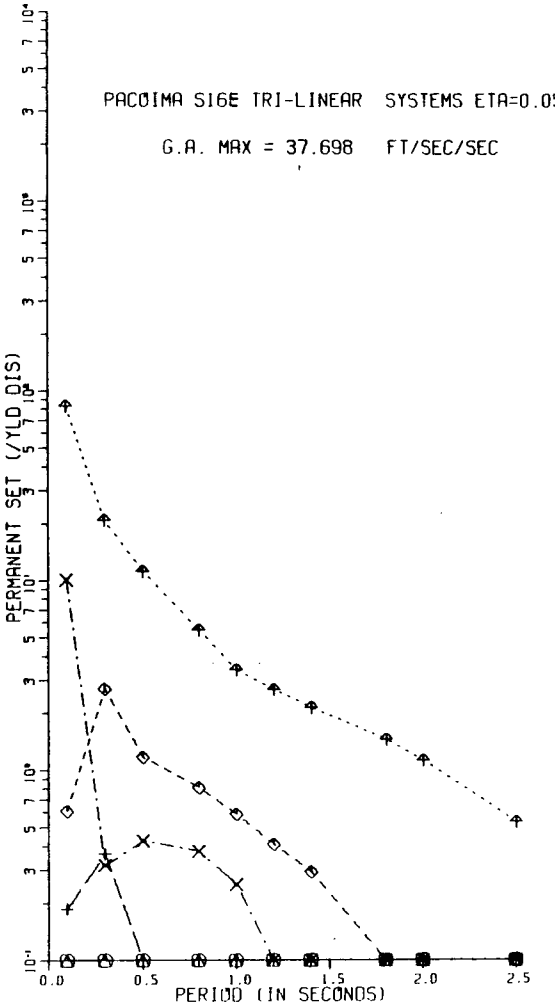

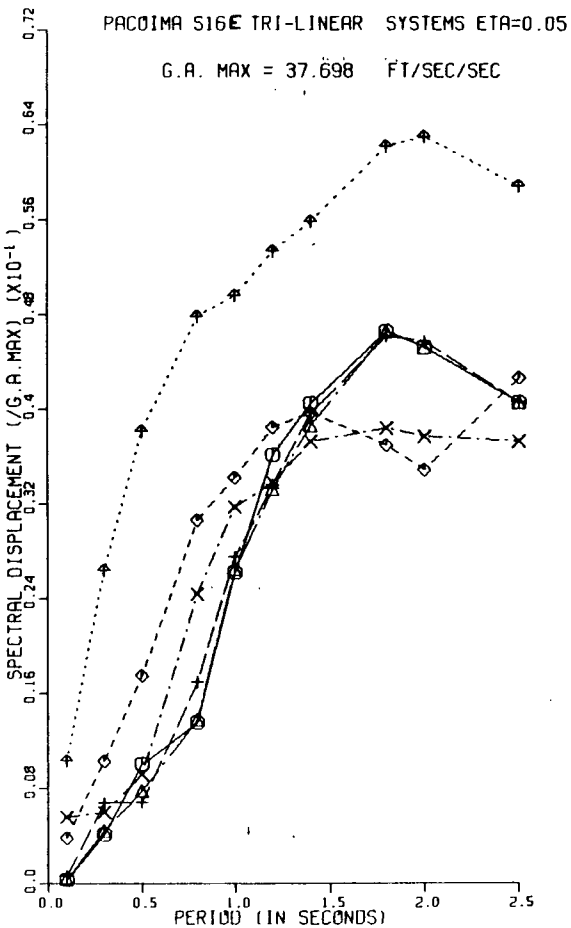

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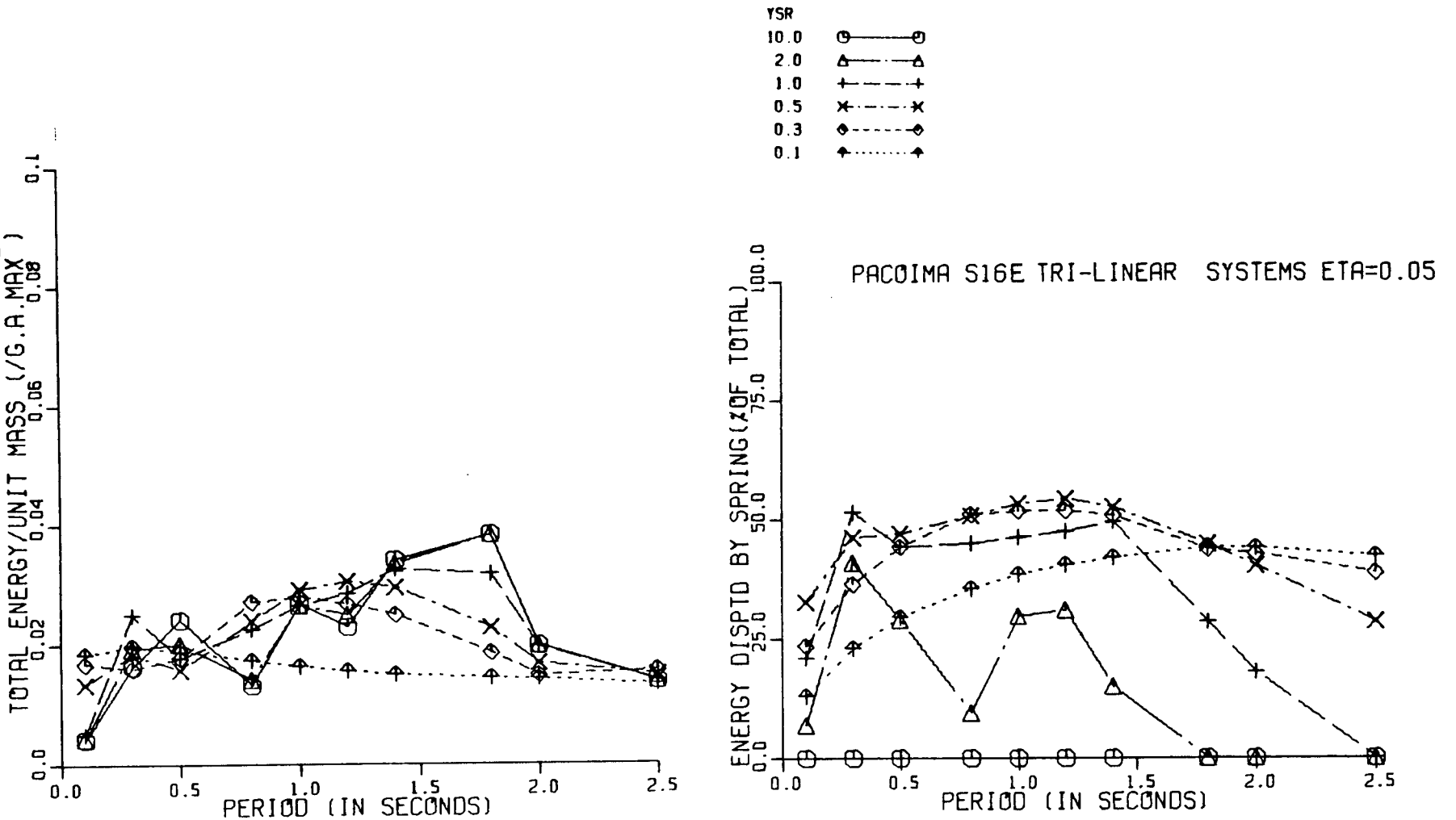

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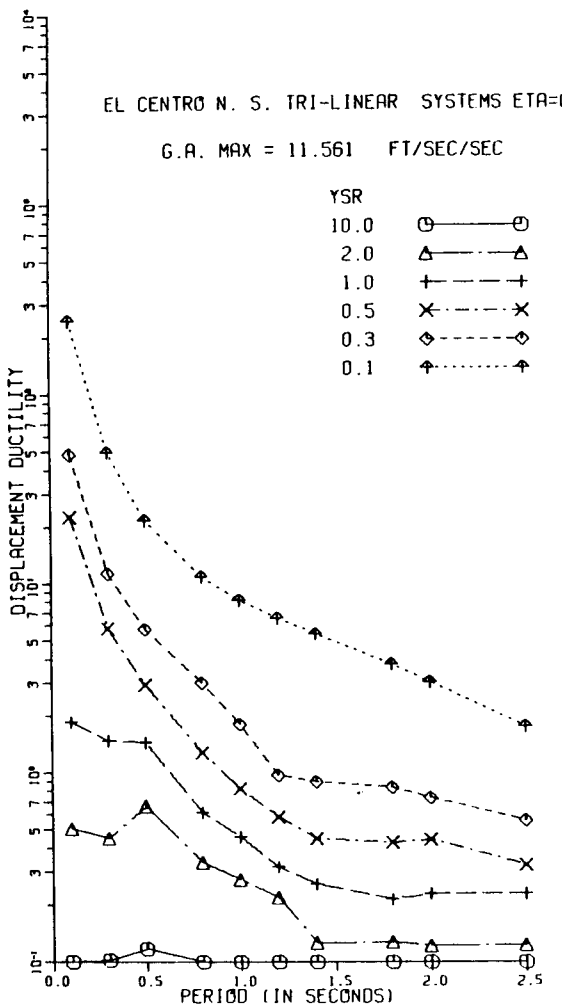

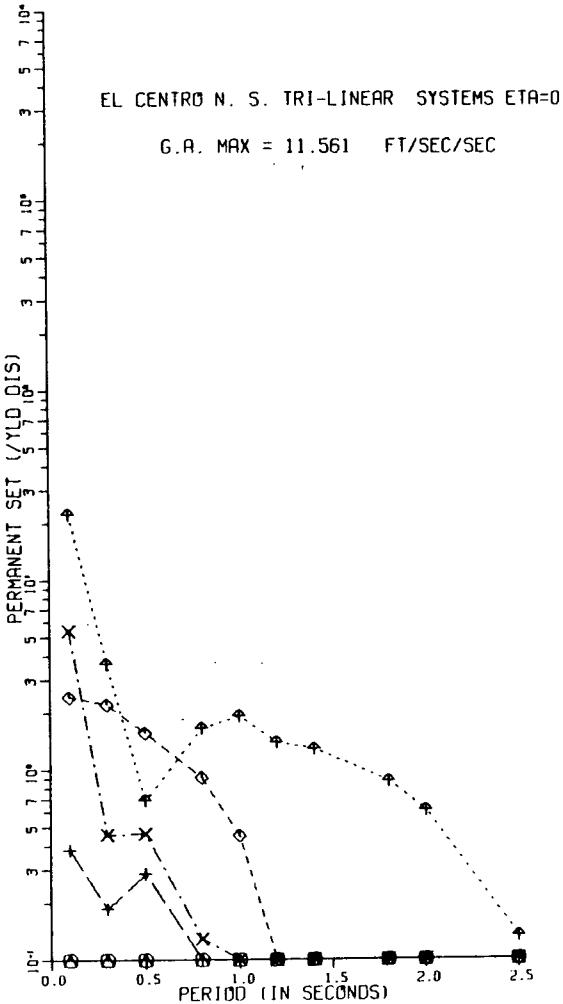

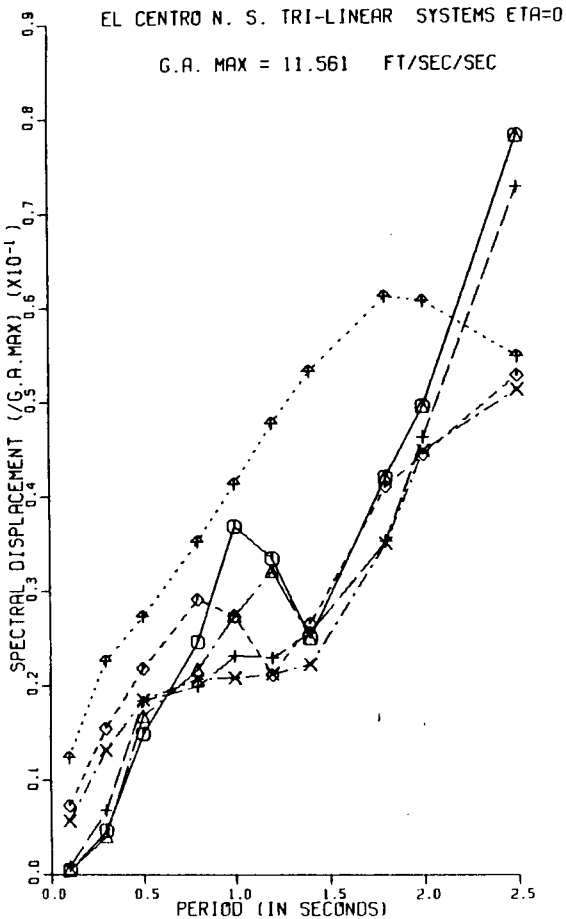

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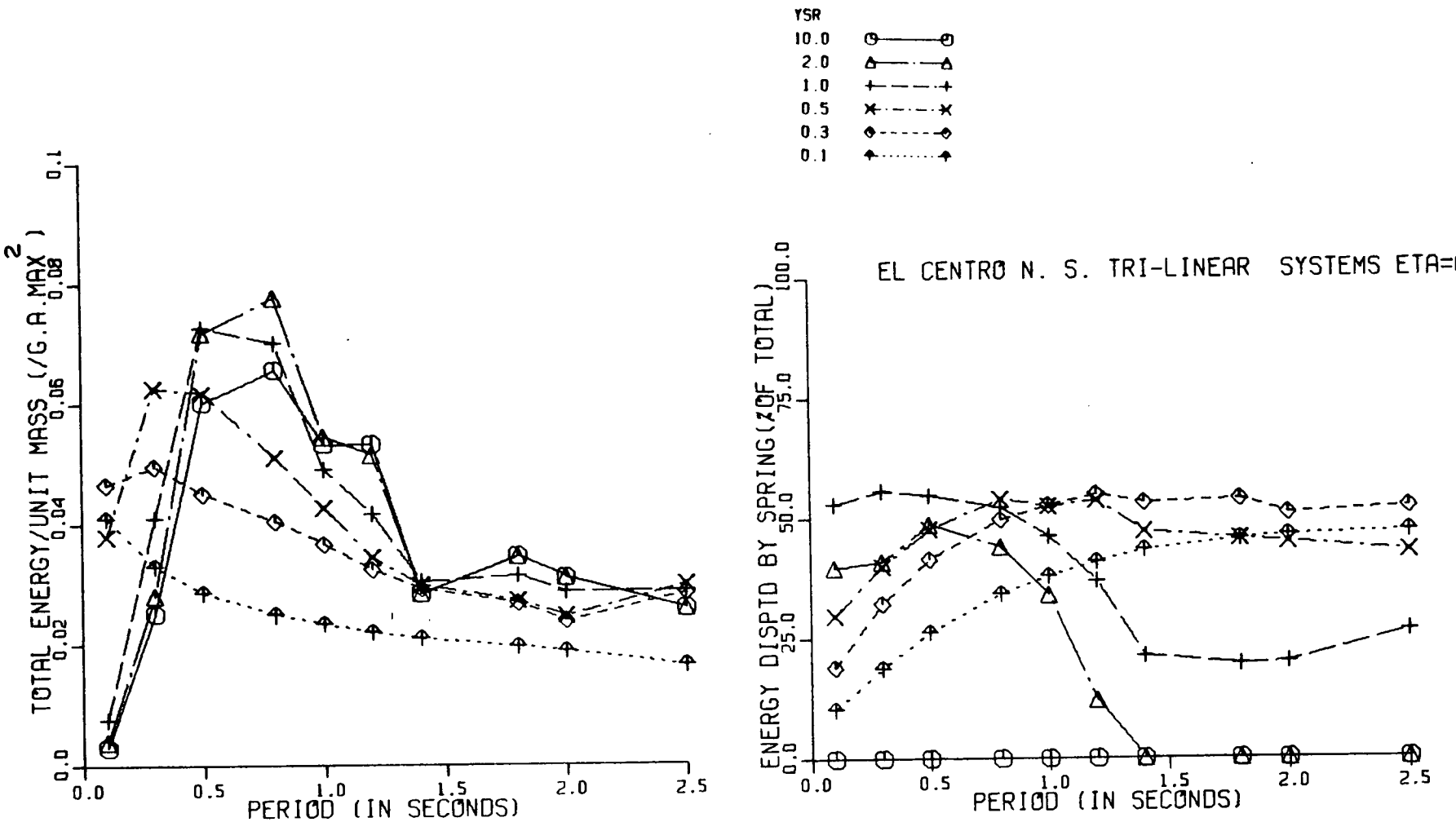

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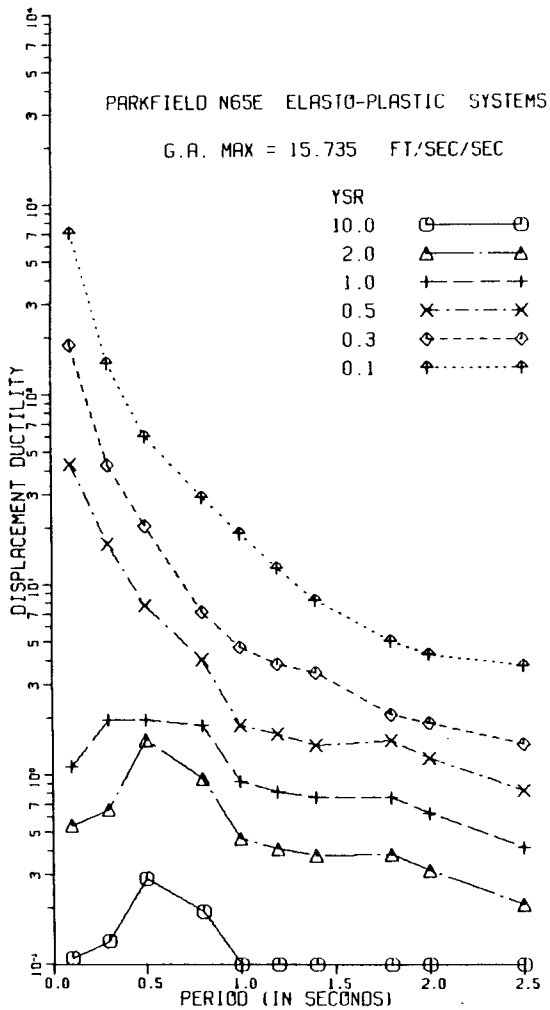

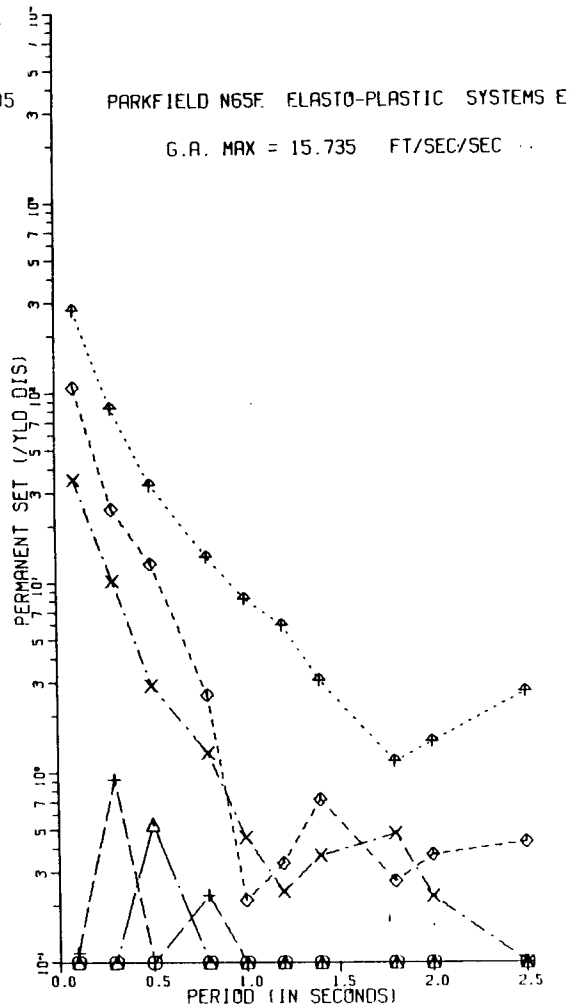

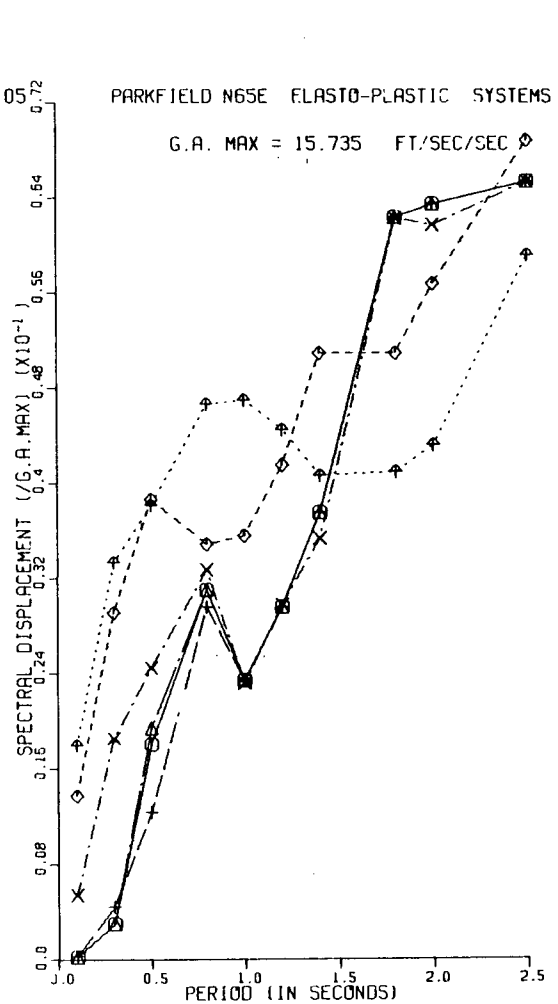

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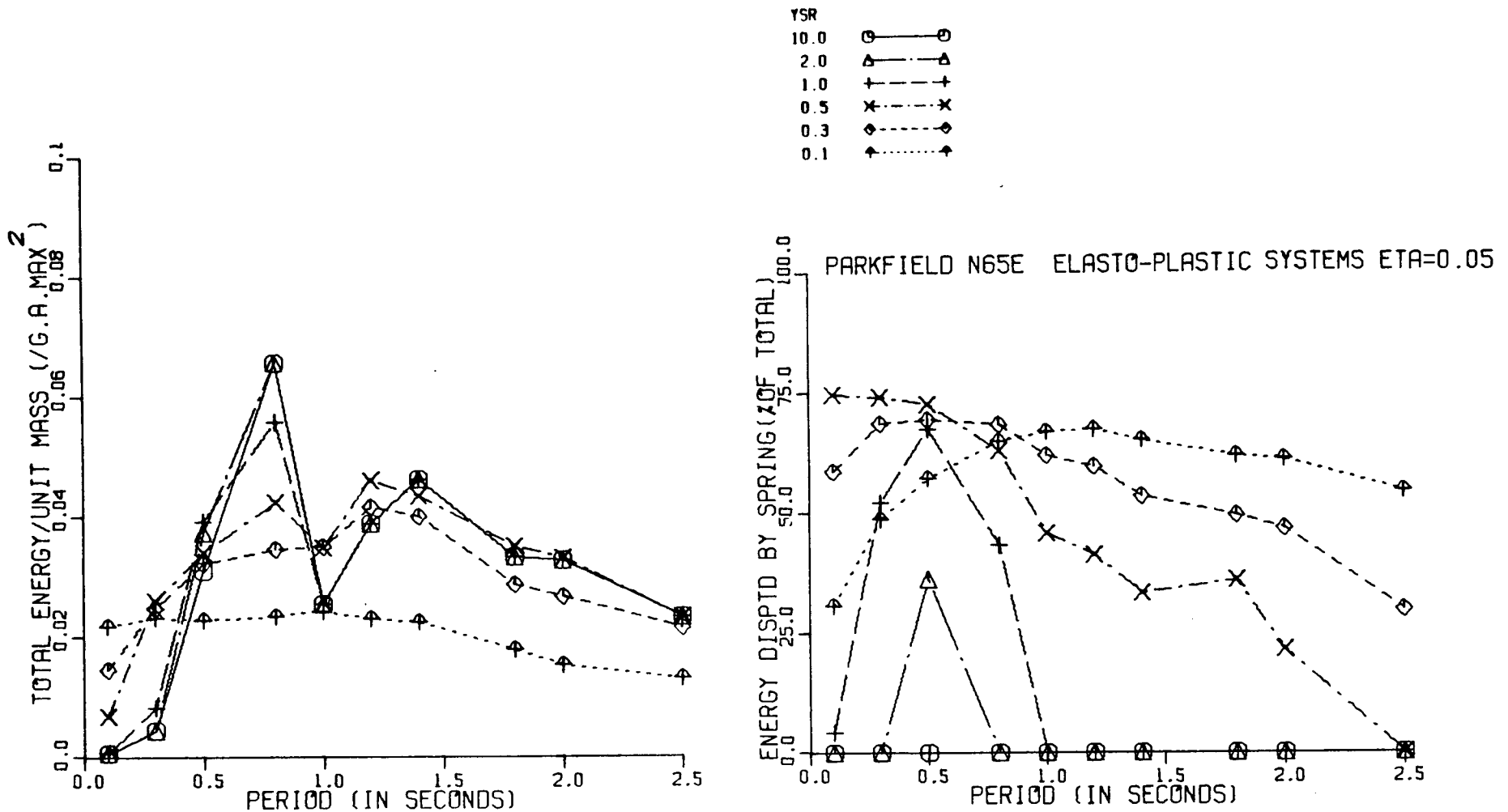

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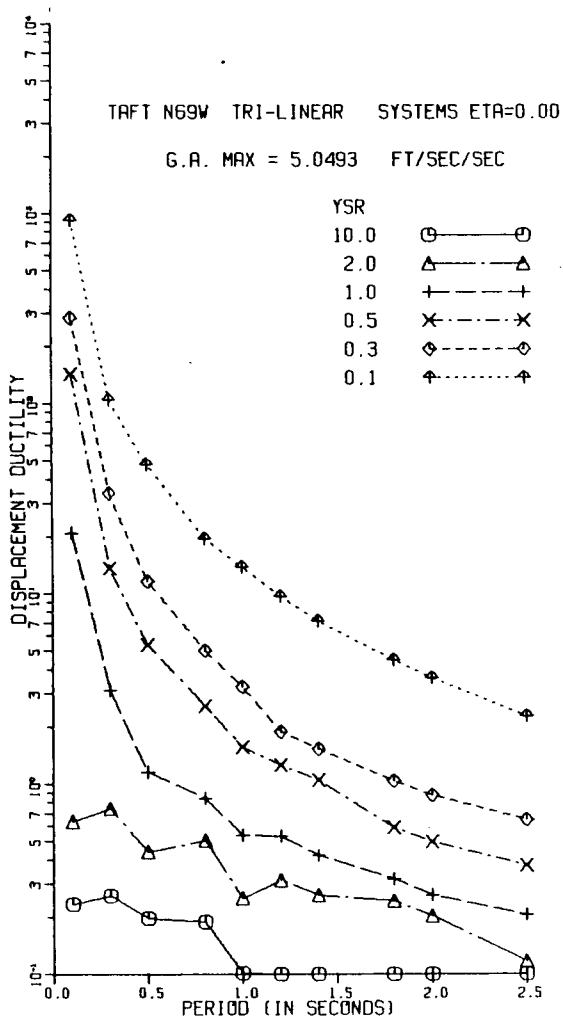
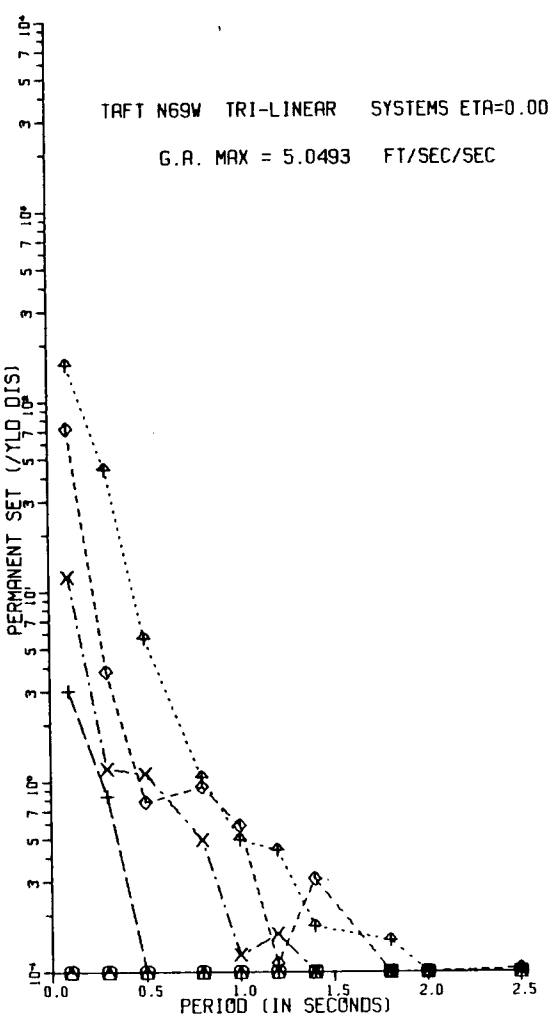




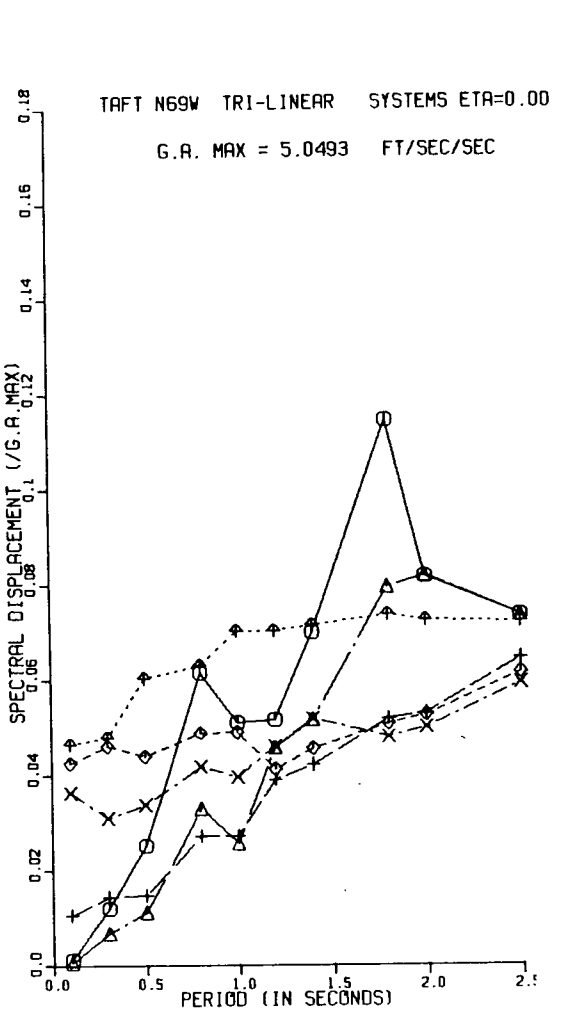


FIG. A.13 RESULTS FOR COMBINATION 13 TAFTL.00

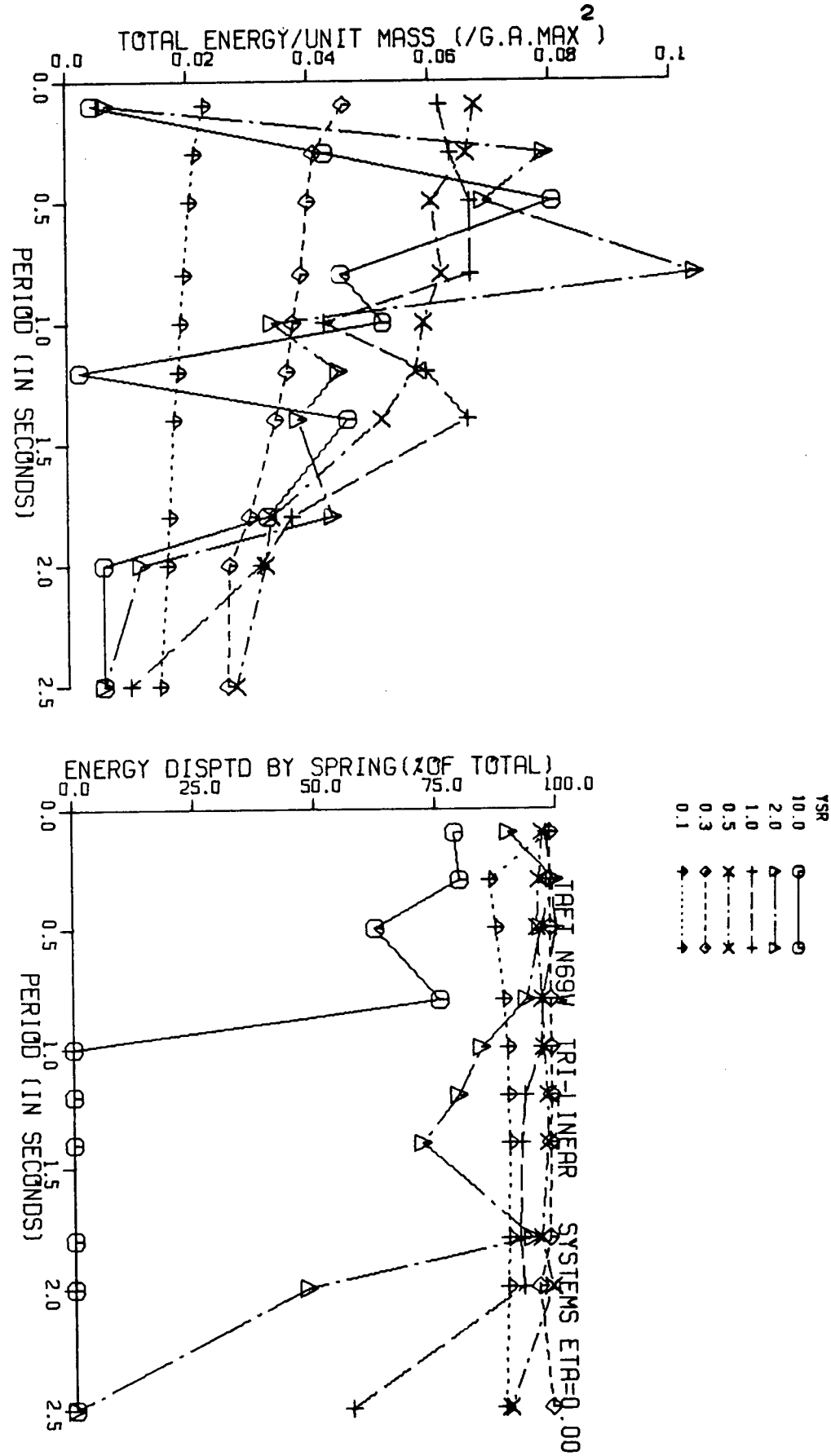


FIG. A.13 CONTINUED

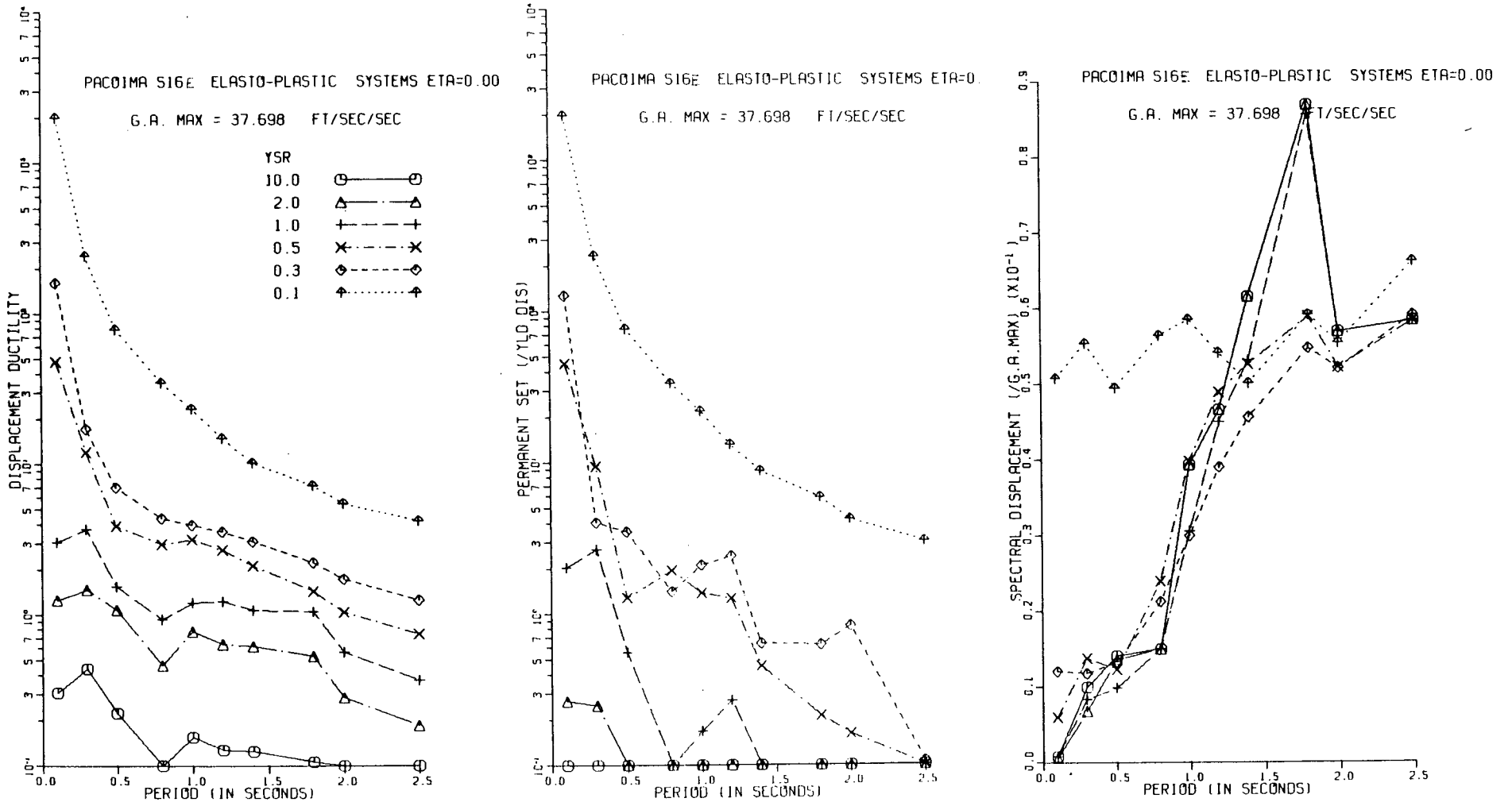


FIG. A.14 RESULTS FOR COMBINATION 14 PACEP.00

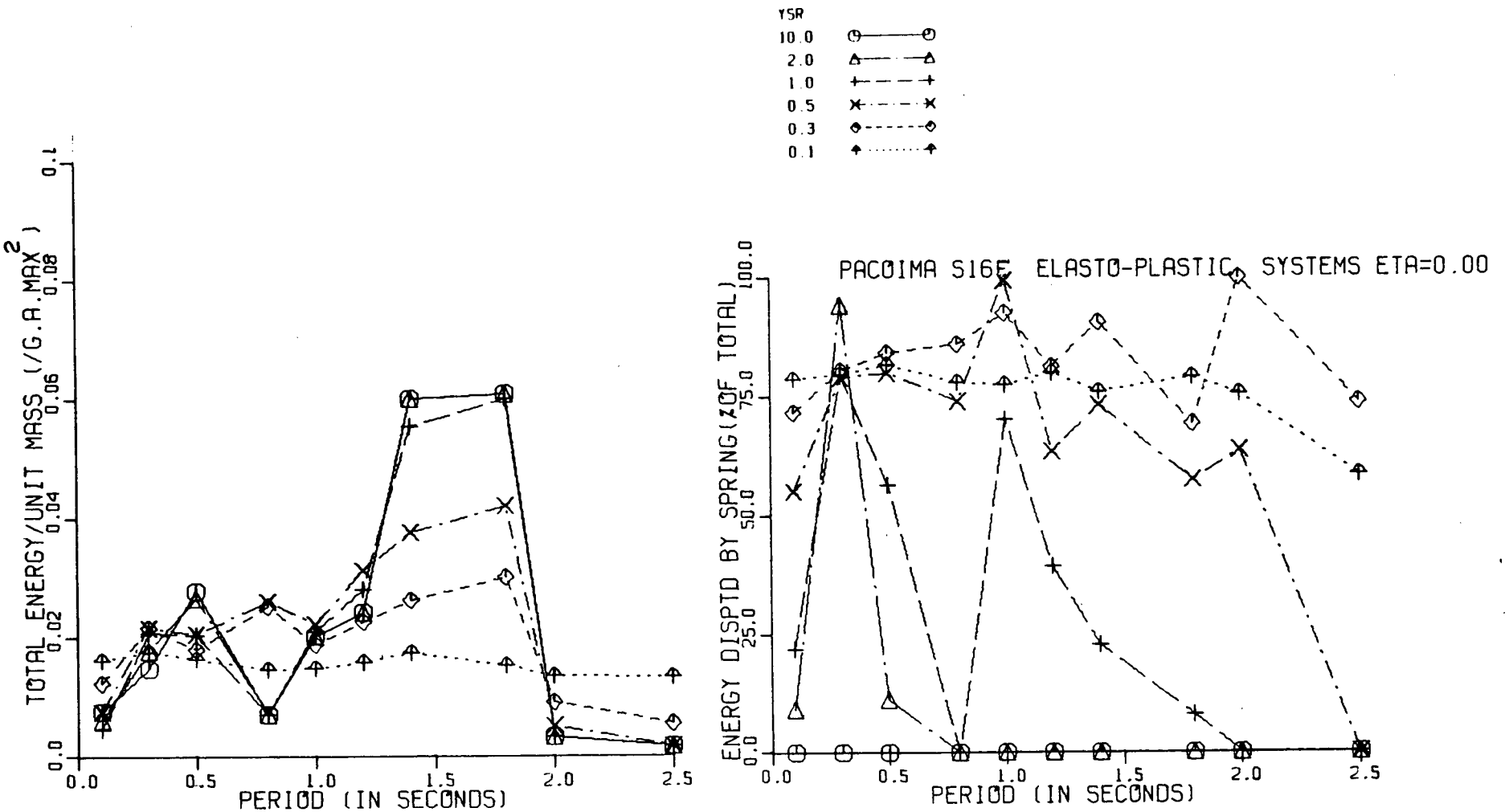
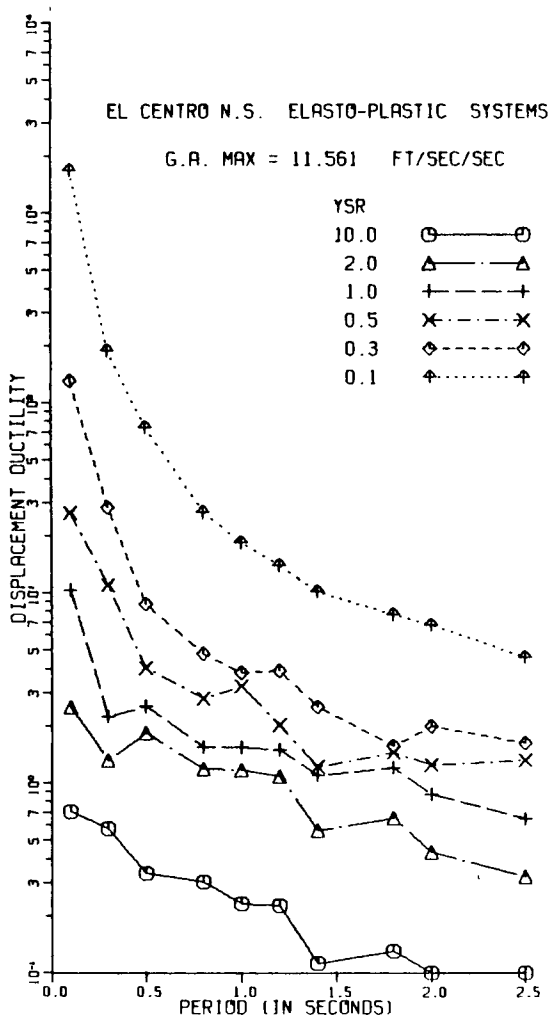
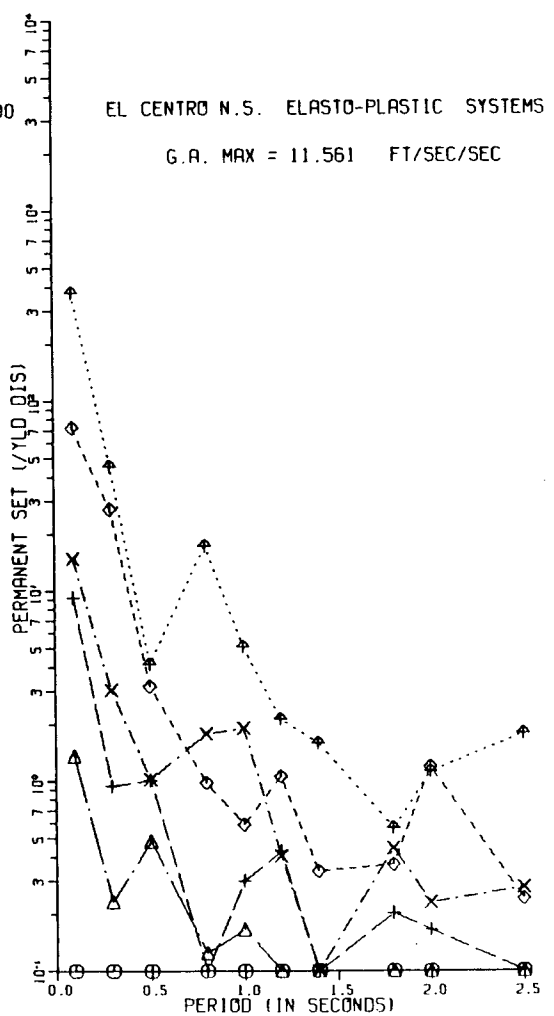


FIG. A.14 CONTINUED





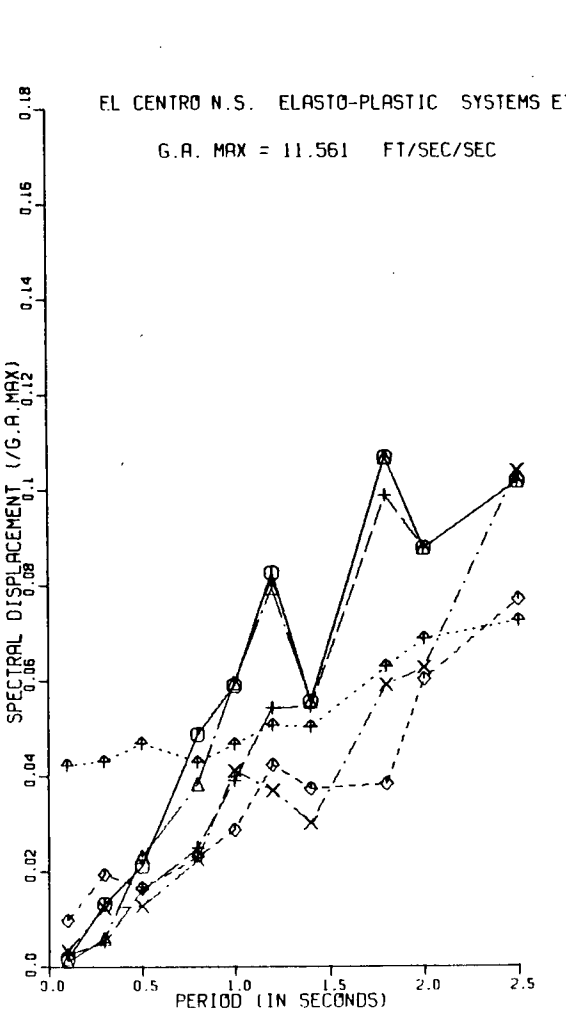


FIG. A.15 RESULTS FOR COMBINATION 15 ELCEP.00

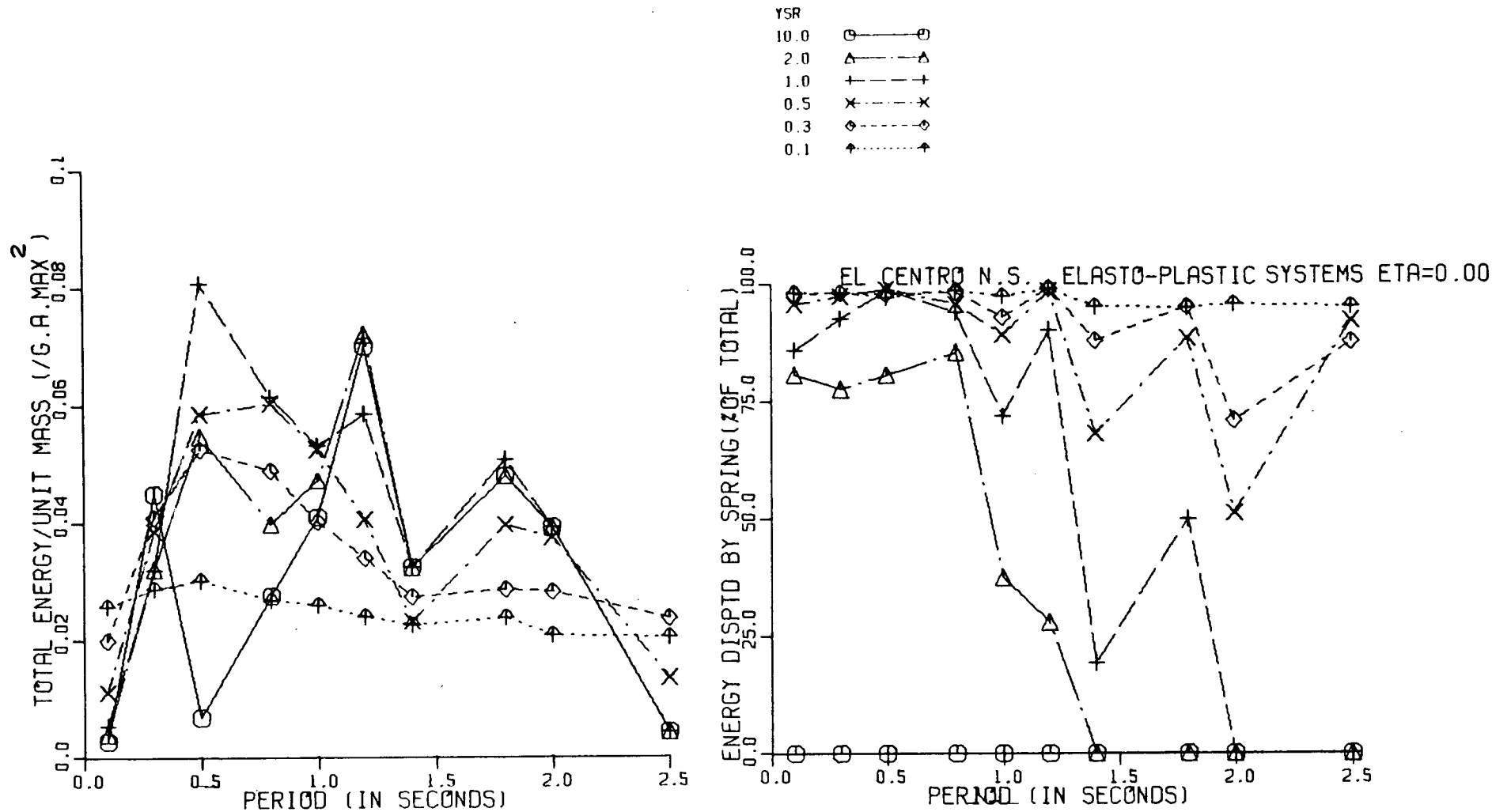
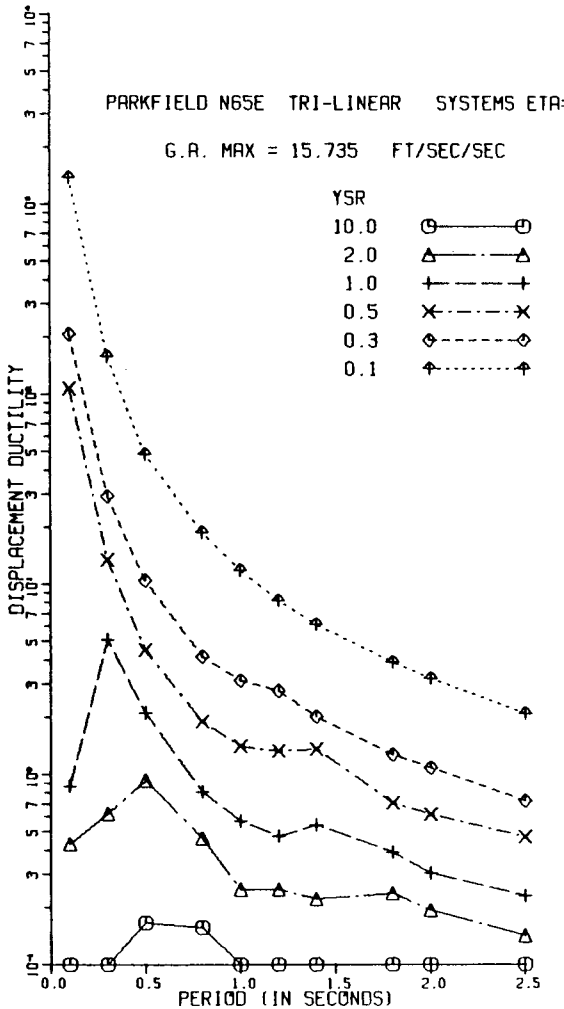
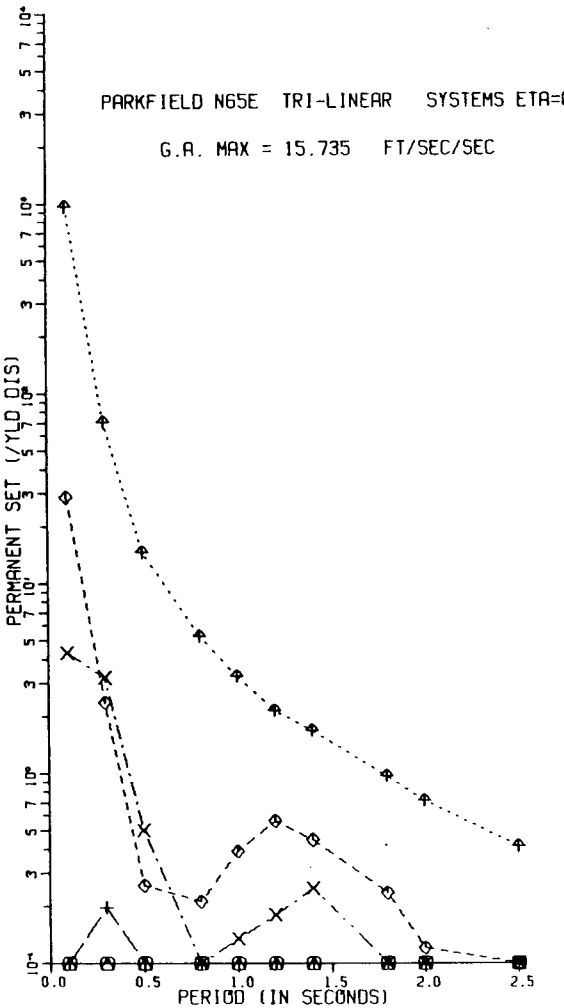


FIG. A.15 CONTINUED





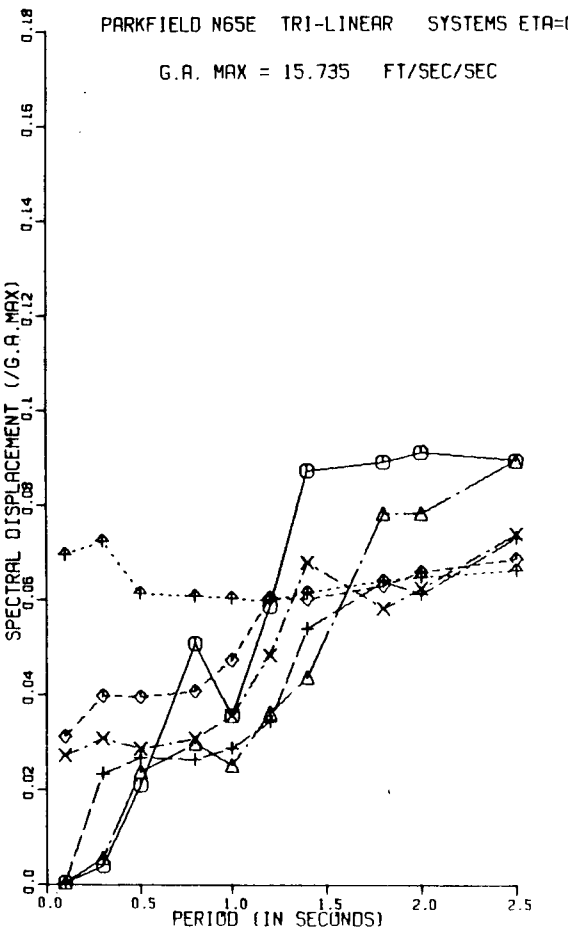


FIG. A.16 RESULTS FOR COMBINATION 16 PKFTL.00

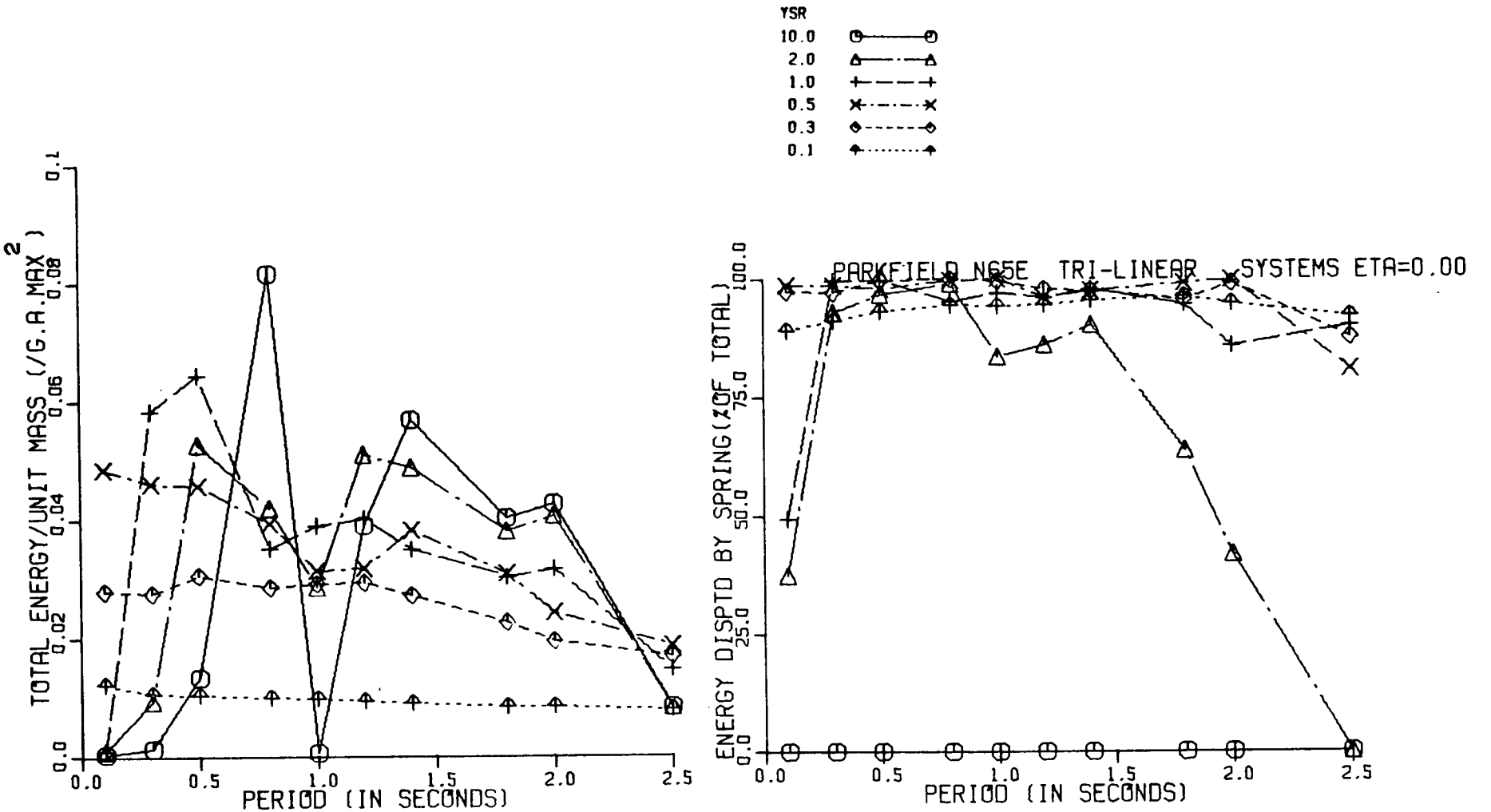


FIG. A.16 CONTINUED

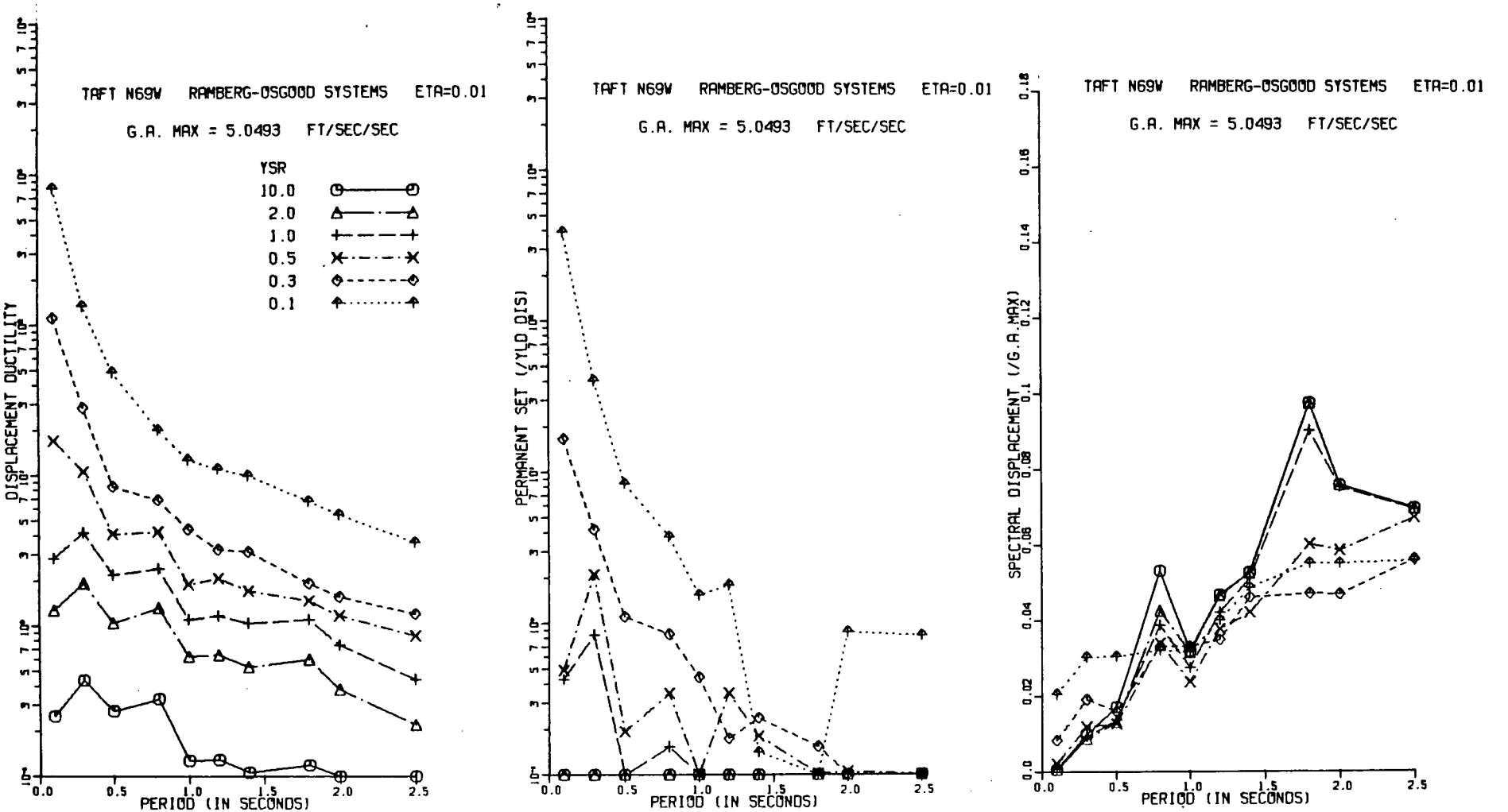


FIG. A.17 RESULTS FOR COMBINATION 17 TAFRO.01

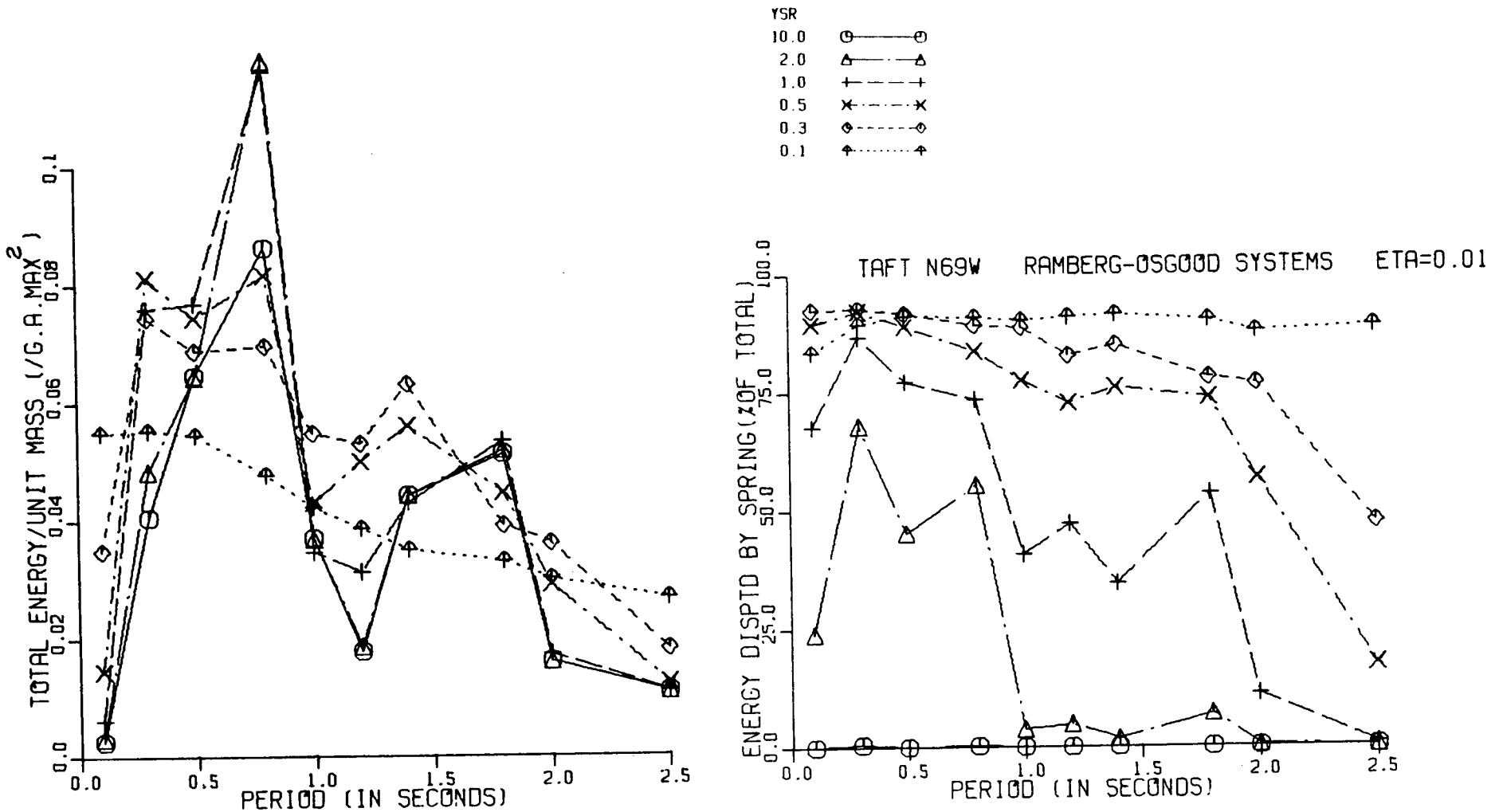
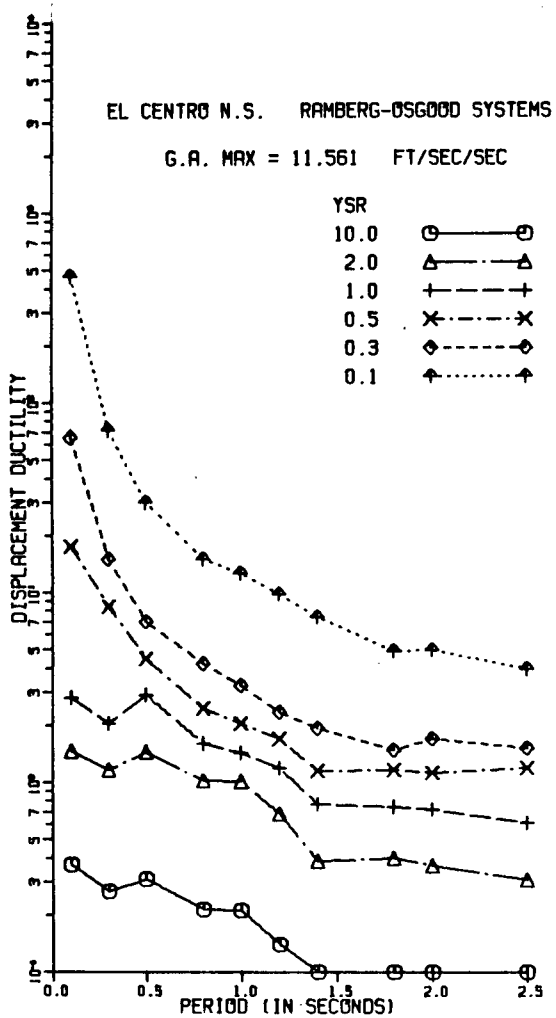
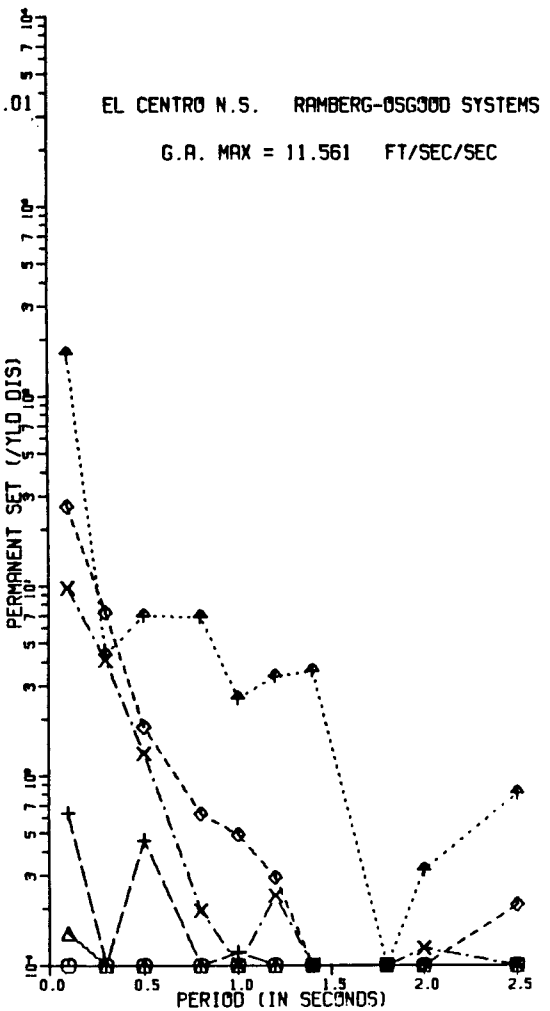


FIG. A.17 CONTINUED





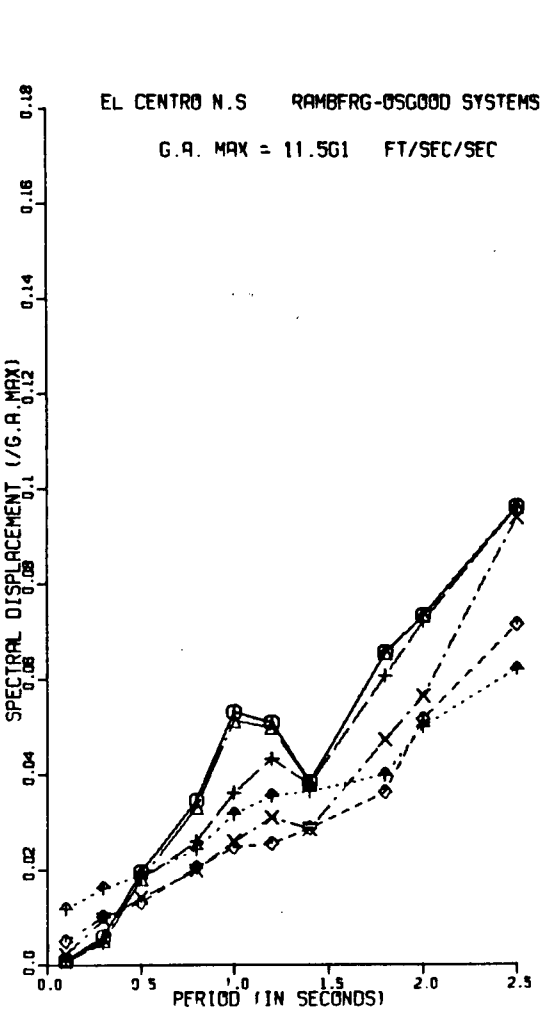


FIG. A.18 RESULTS FOR COMBINATION 18 ELCRO.01

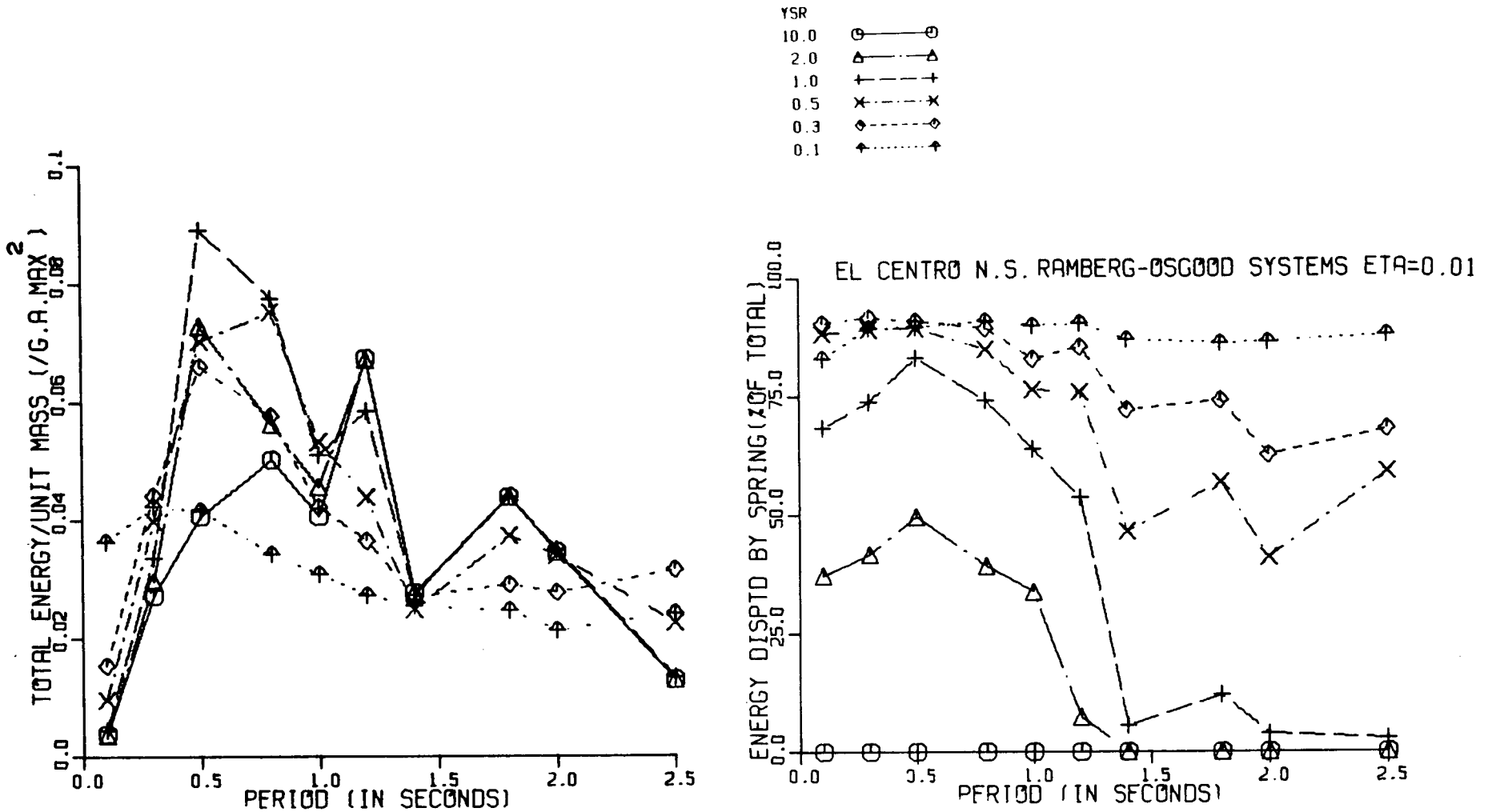


FIG. A.18 CONTINUED

APPENDIX B

LISTINGS OF SUBROUTINES

ENERGY AND SPDIS

In this appendix listings of the two subroutines which perform the energy calculations for this study are presented.

Subroutine ENERGY calculates all energies within the system as given in section 2.4. Subroutine SPDIS is called from ENERGY and calculates the potential energy stored in the spring elements, and the energy dissipated by hysteresis.

```
      SUBROUTINE SPDIS(SPF,SPFO,DISP,DELX,TIM,DISPO)
C
C
C     SUBROUTINE TO CALCULATE ENERGY DISSIPATED
C      AND STORED IN PLASTIC SPRINGS
C       ROUTINE BASED ON ENERGY STORED  =
C                       AVERAGE FORCE*DIST TRAVELLED DURING EACH TIME
STEP
C
C
C  INPUT
C          SPFO     SPRING FORCE AT END OF LAST INCREMENT
C          SPF      SPRING FORCE AT END OF THIS INCREMENT
C          DISP     DISPLACEMENT AT END OF THIS INCREMENT
C          DELX     CHANGE IN DISPLACEMENT DURING THIS INCREMENT
C          TIM      TIME STATION AT END OF THIS INCREMENT
C
C OUTPUT   ENDISS    ENERGY DISSIPATED IN PLASTIC WORK BY SPRING
C          ENSTOR   ENERGY STORED IN SPRING AT END OF THIS INCREMENT
C                   (EITHER DISSIPATED OR RECOVERABLE DONT KNOW YET)
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/PLOTT/TITLE(20),NPLOT,IPRINT,IOUT ,NOUT
      COMMON/STRUCT/DAMP(30),YIELD(30),PERD(30),NDAMP,NYIELD,NPERD
      COMMON/GRND/ACCOP,GRACC(3000),GACC,GACCO,DELGA,GV,GVO,GD,GDO,SCAL
E
     *,CPS,NPTS,NPT2,NEQ,INTYPE
      COMMON/HYST/FYIELD,YLDNEG,STIFYD,STIFKT,ENDISS,ENSTOR,NCROSS
      DIMENSION TIME(200)
C
C     HAVE WE CROSSED ZERO FORCE AXIS?
C
      CHECK=SPF*SPFO
      IF(SPFO.EQ.0.0) GO TO 20
      IF(CHECK.LE.0.0) GO TO 30
   20 DELWK = ((SPF+SPFO)/2.0)*DELX
      ENSTOR=ENSTOR+DELWK
C     WRITE(7,510) SPF,SPFO,DISP,DELX,DELWK,CHECK,ENSTOR
      GO TO 60
   30 CONTINUE
C
C
C     WE HAVE CROSSED ZERO AND THE ENERGY LEFT IN ENSTOR
C     MUST BE CONSIDERED DISSIPATED
C
C
      FORSUM=SPF+SPFO
      IF(FORSUM.EQ.0.0) GO TO 40
      DISPO=DISP-DELX
      ABSPFO=DABS(SPFO)
      ABSPF=DABS(SPF)
      DIST=ABSPFO*DELX/(ABSPF+ABSPFO)
      DELWKD=SPFO*DIST/2.0
      ENSTOR=ENSTOR+DELWKD
      ENDISS=ENDISS+ENSTOR
      DISTC=DABS(DELX)-DABS(DIST)
      ENSTOR=DABS(SPF*DISTC)/2.0
      GO TO 50
   40 DIST=DELX/2.0
      DELWKD=SPFO*DIST/2.0
      ENSTOR=ENSTOR+DELWKD
      ENDISS=ENDISS+ENSTOR
      DISTC=DIST
      ENSTOR=DABS(SPF*DISTC/2.0)
   50 NCROSS=NCROSS+1
C     TIME(NCROSS)=TIM
C     WRITE(7,505) NCROSS
  505 FORMAT('    ZERO CROSSING NUMBER',I4)
C     WRITE(7,510) SPF,SPFO,DISP,DELX,CHECK,
C    *ENSTOR,DIST,DISTC,DELWKD,ENDISS,TIME(NCROSS)
510   FORMAT(10E12.4)
60    CONTINUE
      IF(IOUT.NE.IPRINT) GO TO 149
      ISTEP=IOUT
      I=IOUT
      SPSTOR=0.0
      SPREC=0.0
C     WRITE(7,500) ISTEP,TIM
C     WRITE(7,501)
C     WRITE(7,502) I,SPSTOR,SPREC,ENSTOR,ENDISS,NCROSS
502   FORMAT(I6,7X,E12.5,9X,E12.5,9X,E12.5,5X,E12.5,8X,I2,14X,F6.3)
500   FORMAT('   DETAILS OF ENERGY IN SHEAR BEAMS AT END OF TIME STEP',
I
     *5,'  FOR TIME = ',F10.4,'   SECS')
149   CONTINUE
501   FORMAT(//'   BEAM   TOTAL SHEAR ENERGY   SPF ENGY RECOVERED   SPF
     * ENGY REMAINING   SPF ENERGY   NUMBER OF ZERO    TIME OF LAST',/,
     *10X,'STORED SINCE LAST    SINCE LAST',11X,'IN BEAM SINCE LAST   D
I
     *SSIPATED   CROSSINGS IN      ZERO CROSSING',/,10X,'ZERO CROSSING'
,
     *8X,'ZERO CROSSING',8X,'ZERO CROSSING',21X,'HYSTERESIS LOOP',
     *7X,'(SECS)')
      RETURN
      END
```

```
      SUBROUTINE ENERGY(SPFEND,SPFC,DISP,DELX,TIM,DISPO,DELT,ABACC,
     *ABACCO,VEL,VISFAC,VELO,SUMVIS,ENSUM,SUMIN,EKIN)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/PLOTT/TITLE(20),NPLOT,IPRINT,IOUT ,NOUT
      COMMON/STRUCT/DAMP(30),YIELD(30),PERD(30),NDAMP,NYIELD,NPERD
      COMMON/GRND/ACCOF,GRACC(3000),GACC,GACCO,DELGA,GV,GVO,GD,GDO,SCAL
E
     *,CPS,NPTS,NPT2,NEQ,INTYPE
      COMMON/HYST/FYIELD,YLDNEG,STIFYD,STIFKT,ENDISS,ENSTOR,NCROSS
C
C     ****************************************************************
C
C     SPFEND  = SPRING FORCE AT END OF PRESENT TIME STEP
C     SPFC    = SPRING FORCE AT END OF PREVIOUS TIME STEP
C     DISP    = DISPLACEMENT AT END OF THIS TIME STEP
C     DELX    = CHANGE IN DISPLACEMENT DURING THIS TIME STEP
C     TIM     = TIME STATION AT END OF THIS INTERVAL
C     DISPO   = DISPLACEMENT AT END OF PREVIOUS TIME STEP
C     DELT    = TIME STEP LENGTH (SECS)
C     ABACC   = ABSOLUTE MASS ACCELERATION AT END OF THIS TIME STEP
C     ABACCO  = ABSOLUTE MASS ACCELERATION AT END OF PREVIOUS STEP
C     VEL     = VELOCITY OF MASS AT END OF THIS TIME STEP
C     VELO    = VELOCITY OF MASS AT END OF PREVIOUS TIME STEP
C     VISFAC  = VISCOUS DAMPING FACTOR
C     SUMVIS  = SUM OF ENERGY DISSIPATED IN VISCOUS DAMPING
C     ENSUM   = SUM OF ALL ENERGIES IN SYSTEM
C     SUMIN   = SUM OF ENERGY INPUT TO STRUCTURE
C     EKIN    = KINETIC ENERGY OF MASS AT END OF TIME STEP
C
C     ****************************************************************
C
C
C       CALCULATE ENERGY IN THE SPRING
C
        CALL SPDIS(SPFEND,SPFC,DISP,DELX,TIM,DISPO)
C
C       OBTAIN GROUND ACCEL , VEL , AND DISPLACEMENT
C
        CALL GRN(TIM,DELT)
C
C       CALC. KINETIC ENERGY
C
        ABVEL = VEL + GV
        EKIN = ABVEL*ABVEL/2.0
C       WRITE(7,111)ABVEL,EKIN
C
C       CALC ENERGY IN VISCOUS DAMPERS
C
        VISK = VISFAC*DELX*(VEL+VELO)/2.00
        SUMVIS = SUMVIS + DABS(VISK)
C
C     SUM ENERGIES WITHIN THE SYSTEM
C
        ENSUM = ENDISS + ENSTOR + EKIN + SUMVIS
C       WRITE(7,111) VISK,SUMVIS,ENSUM
C
C       CALC ENERGY INPUT TO STRUCTURE
C
        ENIN = (GD-GDO)*(ABACC+ABACCO)/2.0
        SUMIN = SUMIN + ENIN
        ENBAL = SUMIN - ENSUM
        IF(DABS(SUMIN).LT.0.0001) GO TO 50
        PERCEN = 100.0*ENBAL/SUMIN
        GO TO 55
   50   PERCEN=999.9
   55   CONTINUE
C       WRITE(7,111) ENIN,SUMIN,ENBAL,PERCEN
        IF(IOUT.NE.IPRINT) GO TO 149
C       WRITE(7,101) TIM
  101   FORMAT(//'   ENERGY  BALANCE  AT  TIME  = ',F10.4)
C       WRITE(7,111)ENDISS,ENSTOR,EKIN,SUMVIS,ENSUM,SUMIN,ENBAL,PERCEN
  111   FORMAT(10E12.5)
  149   RETURN
        END
```

APPENDIX C

Result of Multi-Degree of Freedom Study in Original Form

Complete results of the multi-degree of freedom study presented in Chapters 6 and 7 are given here in original form.

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION : 30 Secs. Taft N69W

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1520 INCH KIPS

PERIOD 0.43 SECS. YSR = 1.9 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	147.7 (9.7)	0.0 (0)	9.2 (0.6)	197.4 (13.0)	37.1 (2.4)	392.4 (25.8)
2	255.8 (16.8)	0.0 (0)	10.6 (0.7)	123.4 (8.1)	23.6 (1.6)	413.5 (27.2)
1	631.2 (41.5)	0.0 (0)	8.1 (0.5)	47.3 (3.1)	15.6 (1.0)	702.7 (46.3)
Σ	1034.7	0	27.9	368.1	76.3	1508.6
% Total	(68)	(0)	(1.8)	(24.2)	(5.0)	(99.3)

( ) = % of Total Energy in System.

TABLE C.1 M.D.F. RESULTS SET 1

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Taft N69W

DAMPING: 1% Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1495 INCH KIPS

PERIOD 0.43 SECS. YSR = 1.9 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	86.5 (5.8)	0.2 (0.0)	8.1 (0.5)	0.0 (0.0)	291.7 (19.5)	386.5 (25.8)
2	324.5 (21.7)	0.0 (0)	6.1 (0.4)	0.0 (0)	183.0 (12.2)	513.6 (34.3)
1	495.4 (33.1)	0.0 (0)	5.2 (0.3)	0.0 (0)	80.3 (5.4)	580.9 (38.9)
Σ	906.4	0.0	19.4	0.0	555.0	1481
% Total	(60.6)	(0)	(1.3)	(0)	(37.1)	(99.1)

( ) = % of Total Energy in System.

TABLE C.2 M.D.F. RESULTS SET 2

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Taft N69W

DAMPING: 1% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1517 INCH KIPS

PERIOD 0.43 SECS. YSR 1.9 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	152.9 (10.0)	1.8 (0.1)	5.3 (0.3)	265.8 (17.5)	0.0 (0)	425.8 (28.1)
2	234.0 (15.4)	0.0 (0)	7.8 (0.5)	166.3 (11.0)	0.0 (0)	408.0 (26.9)
1	595.9 (39.3)	0.5 (0)	7.2 (0.5)	67.9 (4.5)	0.0 (0)	671.5 (44.3)
Σ	982.8	2.3	20.3	500.0	0.0	1505
% Total	(64.8)	(0.1)	(1.3)	(33.0)	(0)	(99.3)

( ) = % of Total Energy in System.

TABLE C.3 M.D.F. RESULTS SET 3

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Taft N69W

DAMPING : 10% Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1260 INCH KIPS

PERIOD 0.43 SECS. YSR = 1.9 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.0 (0)	1.2 (0)	0.0 (0)	680 (54)	681.2 (54)
2	0.0 (0)	0.0 (0)	2.2 (0)	0.0 (0)	423.4 (33.8)	425.6 (33.8)
1	3.4 (0)	0.0 (0)	3.5 (0)	0.0 (0)	147.4 (12.2)	154.1 (12.2)
Σ	3.4	0.0	6.9	0.0	1250.8	1260.7
% Total	(0.3)	(0.0)	(0.5)	(0.0)	(99.2)	(100.0)

( ) = % of Total Energy in System.

TABLE C.4 M.D.F. RESULTS SET 4

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. El Centro N.S.

DAMPING: 1% Mass & Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 3715 INCH KIPS

PERIOD 0.43 SECS. YSR = 0.8 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	98.0 (2.6)	1.1 (0)	6.4 (0.1)	229.2 (6.2)	372.7 (10.0)	707.4 (19.0)
2	517.4 (13.9)	1.1 (0)	10.9 (0.3)	150.8 (4.0)	260.4 (7.0)	940.6 (25.3)
1	1816.7 (48.9)	1.3 (0)	17.6 (0.5)	54.9 (1.5)	157.6 (4.2)	2048.4 (55.1)
Σ	2432.1	3.5	34.9	434.9	790.7	3696.4
% Total	(65.5)	(0)	(0.9)	(11.7)	(21.3)	(99.5)

( ) = % of Total Energy in System.

TABLE C.5 M.D.F. RESULTS SET 5

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. El Centro N.S.

DAMPING: 1% Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 3701 INCH KIPS

PERIOD 0.43 SECS. YSR = 0.8 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	111.8 (3.0)	2.2 (0)	9.0 (0.2)	0.0 (0)	406.7 (11.0)	529.7 (14.3)
2	645.8 (17.4)	2.6 (0)	13.8 (0.4)	0.0 (0)	286.9 (7.8)	949.1 (25.6)
1	2007.8 (54.2)	3.2 (0)	19.7 (0.5)	0.0 (0)	171.0 (4.6)	2201.7 (59.5)
Σ	2765.4	8.0	42.5	0.0	864.6	3680.5
% Total	(74.7)	(0)	(1.1)	(0)	(23.4)	(99.5)

( ) = % of Total Energy in System.

TABLE C. 6 M.D.F. RESULTS SET 6

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION : 30 Secs of El Centro N.S.

DAMPING: 10% Stiffness Damping

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 3491 INCH KIPS

PERIOD 0.43 SECS. YSR = 0.8 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.2 (0)	5.9 (0.2)	0.0 (0)	1328.4 (38.0)	1334.6 (38.2)
2	143.2 (4.1)	0.4 (0)	10.2 (0.3)	0.0 (0)	917.6 (26.3)	1071.4 (30.7)
1	626.1 (17.9)	0.5 (0)	15.8 (0.5)	0.0 (0)	436.7 (12.5)	1079.1 (30.9)
Σ	769.3	1.1	31.9	0.0	2682.7	3485.1
% Total	(22.0)	(0)	(0.9)	(0)	(76.9)	(99.8)

( ) = % of Total Energy in System.

TABLE C.7 M.D.F. RESULTS SET 7

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Pacoima S16E

DAMPING: 1% Mass & Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 17,437.0 INCH KIPS

PERIOD 0.43 SECS. YSR= 0.26 WEAK SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	1502.0 (8.6)	0.0 (0)	692.0 (4.0)	259.0 (1.5)	420.0 (2.4)	2874.0 (16.5)
2	2713.0 (15.5)	0.0 (0)	1054.0 (6.0)	190.0 (1.0)	313.0 (1.8)	4270.0 (24.5)
1	8135.0 (46.6)	0.0 (0)	1400.0 (8.0)	104.0 (0.6)	477.0 (2.8)	10,116.0 (58.0)
Σ	12,350	0.0	3146.0	553.0	1210.0	17,260.0
% Total	(70.8)	(0)	(18.0)	(3.0)	(7.0)	(99.1)

( ) = % of Total Energy in System.

TABLE C.8 M.D.F. RESULTS SET 8

STRUCTURE 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Pacoima S16E

DAMPING: 1% Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 17,557.0 INCH KIPS

PERIOD 0.43 SECS. YSR = 0.26 WEAK SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	1540.0 (8.8)	0.0 (0)	696.0 (4.0)	0.0 (0)	439.0 (2.5)	2675.0 (15.2)
2	2886.0 (16.4)	0.0 (0)	1061.0 (6.0)	0.0 (0)	327.0 (2.0)	4274.0 (24.3)
1	8505.0 (48.5)	0.0 (0)	1405.0 (8.0)	0.0 (0)	512.0 (2.9)	10,422.0 (59.4)
Σ	12931.0	0.0	3162.0	0.0	1278.0	17,371.0
% Total	(73.6)	(0)	(18.0)	(0)	(7.3)	(98.9)

( ) = % of Total Energy in System.

TABLE C.9 M.D.F. RESULTS SET 9

STRUCTURE: 1 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Pacoima S16E

DAMPING: 10% Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 16,605.0 INCH KIPS

PERIOD 0.43 SECS. YSR = 0.26 WEAK SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	391.0 (2.3)	0.0 (0)	693.0 (4.2)	0.0 (0)	2724.0 (16.4)	3808.0 (22.9)
2	2107.0 (12.7)	0.0 (0)	1039.0 (6.2)	0.0 (0)	2281.0 (13.7)	5427.0 (32.7)
1	4321.0 (26.0)	0.0 (0)	1388.0 (8.3)	0.0 (0)	1566.0 (9.4)	7276.0 (43.8)
Σ	6819.0	0.0	3120.0	0.0	6571.0	16,510.0
% Total	(41.0)	(0)	(18.8)	(0)	(39.6)	(99.4)

( ) = % of Total Energy in System.

TABLE C.10 M.D.F. RESULTS SET 10

STRUCTURE 2 HYSTERESIS MODEL. E - P

EXCITATION : 30 Secs. Taft N69W

DAMPING : 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 702.8 INCH KIPS

PERIOD 0.33 SECS. YSR = 3.1 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.0 (0)	0.5 (0)	143.7 (20.4)	162.8 (23.2)	307.0 (43.7)
2	0.0 (0)	0.0 (0)	0.6 (0)	92.2 (13.1)	103.5 (14.7)	196.4 (27.9)
1	131.5 (18.7)	0.1 (0)	0.9 (0)	28.9 (4.1)	35.8 (5.1)	197.1 (28.0)
Σ	131.5	0.1	2.0	264.8	302.1	700.5
% Total	(18.7)	(0)	(0)	(37.7)	(43.0)	(99.6)

( ) = % of Total Energy in System.

TABLE C.11 M.D.F. RESULTS SET 11

STRUCTURE 2 HYSTERESIS MODEL. E - P

EXCITATION : 30 Secs. El Centro N.S.

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 681.9 INCH KIPS

PERIOD 0.33 SECS. YSR = 1.4 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.1 (0)	0.2 (0)	110.1 (16.1)	127.0 (18.6)	237.4 (34.8)
2	0.0 (0)	0.4 (0)	0.0 (0)	70.5 (10.3)	79.3 (11.6)	150.2 (22.0)
1	231.8 (34.0)	0.6 (0)	1.3 (0)	22.4 (3.3)	31.3 (4.5)	287.5 (42.2)
Σ	231.8	1.1	1.5	203.0	237.6	675.1
% Total	(34.0)	(0)	(0)	(29.8)	(34.8)	(99.0)

( ) = % of Total Energy in System.

TABLE C.12 M.D.F. RESULTS SET 12

STRUCTURE 2 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. El Centro N.S.

DAMPING: 1% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 622.3 INCH KIPS

PERIOD 0.33 SECS. YSR = 1.4 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.0 (0)	2.6 (0.4)	181.2 (29.1)	0.0 (0)	183.8 (29.5)
2	2.1 (0.3)	0.5 (0)	1.1 (0.2)	115.0 (18.5)	0.0 (0)	118.8 (19.1)
1	265.3 (42.6)	1.5 (0.2)	0.1 (0)	43.8 (7.0)	0.0 (0)	310.8 (49.9)
Σ	267.4	2.0	3.8	340.0	0.0	613.4
% Total	(43.0)	(0.3)	(0.6)	(54.6)	(0)	(98.6)

( ) = % of Total Energy in System.

TABLE C.13 M.D.F. RESULTS SET 13

STRUCTURE 2 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Pacoima S16E

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 8222.6 INCH KIPS

PERIOD 0.33 SECS. YSR = 0.43 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	9.4 (0.1)	0.0 (0)	487.5 (5.9)	200.2 (2.4)	228.1 (2.8)	925.2 (11.3)
2	597.3 (7.3)	0.0 (0)	485.8 (5.9)	138.6 (1.7)	167.5 (2.0)	1389.3 (16.9)
1	5093.1 (61.9)	0.0 (0)	478.5 (5.8)	63.4 (0.8)	225.0 (2.7)	5860.1 (71.3)
Σ	5699.8	0.0	1451.8	402.2	620.6	8174.6
% Total	(69.3)	(0)	(17.6)	(4.9)	(7.5)	(99.4)

( ) = % of Total Energy in System.

TABLE C.14 M.D.F. RESULTS SET 14

STRUCTURE 2 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Pacoima S16E

DAMPING: 1% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 8483.0 INCH KIPS

PERIOD 0.33 SECS. YSR = 0.43 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	43.1 (0.5)	0.0 (0)	513.3 (6.0)	295.7 (3.5)	0.0 (0)	852.1 (10.0)
2	721.2 (8.5)	0.0 (0)	507.5 (6.0)	205.5 (2.4)	0.0 (0)	1434.2 (16.9)
1	5500.7 (64.8)	0.1 (0)	493.5 (5.8)	102.9 (1.2)	0.0 (0)	6097.2 (71.9)
Σ	6265.0	0.1	1514.3	604.1	0.0	8383.5
% Total	(73.8)	(0)	(17.8)	(7.1)	(0)	(98.8)

( ) = % of Total Energy in System.

TABLE C.15 M.D.F. RESULTS SET 15

STRUCTURE: 2 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. Pacoima S16E

DAMPING: 1% Stiffness

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 8297.0 INCH KIPS

PERIOD 0.33 SECS. YSR = 0.43 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	8.6 (0.1)	0.0 (0)	514.0 (6.2)	0.0 (0)	291.5 (3.5)	814.1 (9.8)
2	648.2 (7.8)	0.0 (0)	506.9 (6.1)	0.0 (0)	219.7 (2.6)	1374.8 (16.6)
1	5261.0 (63.4)	0.0 (0)	489.9 (5.9)	0.0 (0)	278.5 (3.3)	6029.5 (72.7)
Σ	5917.8	0.0	1510.8	0.0	789.7	8218.4
% Total	(71.3)	(0)	(18.2)	(0)	(9.5)	(99.0)

( ) = % of Total Energy in System.

TABLE C.16 M.D.F. RESULTS SET 16

STRUCTURE 3 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. El Centro N.S.

DAMPING: 1% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1412.8 INCH KIPS

PERIOD 0.33 SECS. YSR = 0.45 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	2.1 (0.1)	0.0 (0)	0.7 (0)	58.2 (4.1)	0.0 (0)	61.3 (4.3)
2	96.6 (6.8)	0.6 (0)	2.7 (0.1)	41.1 (2.9)	0.0 (0)	141.1 (10.0)
1	1172.2 (83.0)	0.5 (0)	3.2 (0.2)	23.9 (1.6)	0.0 (0)	1199.9 (84.9)
Σ	1270.9	1.1	6.6	123.2	0.0	1402.3
% Total	(89.9)	(0)	(0.5)	(8.7)	(0)	(99.3)

( ) = % of Total Energy in System.

TABLE C.17 M.D.F. RESULTS SET 17

STRUCTURE 4 HYSTERESIS MODEL. E - P

EXCITATION: 30 Secs. El Centro N.S.

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 2356.6 INCH KIPS

PERIOD 0.47 SECS. YSR = 0.68 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	4.9 (0.2)	0.7 (0)	113.6 (4.8)	148.7 (6.3)	267.9 (11.4)
2	0.0 (0)	16.4 (0.7)	1.2 (0)	73.8 (3.1)	86.3 (3.7)	177.7 (7.5)
1	1722.9 (73.0)	26.3 (1.1)	2.8 (0.1)	32.3 (1.4)	112.4 (4.8)	1896.8 (80.5)
Σ	1722.9	47.6	4.7	219.7	347.4	2342.4
% Total	(73)	(2.0)	(0.2)	(9.3)	(14.7)	(99.4)

( ) = % of Total Energy in System.

TABLE C.18 M.D.F. RESULTS SET 18

STRUCTURE 5 HYSTERESIS MODEL. E - P

EXCITATION : 30 Secs. of El Centro N.S.

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 2151.7 INCH KIPS

PERIOD 0.57 SECS. YSR = 0.45 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.9 (0)	27.9 (1.3)	82.1 (3.8)	104.6 (4.9)	215.6 (10.0)
2	0.0 (0)	3.5 (0.2)	22.4 (1.0)	54.0 (2.5)	59.3 (2.7)	139.3 (6.5)
1	1648.5 (76.6)	6.0 (0.3)	14.5 (0.7)	25.2 (1.2)	92.6 (4.3)	1786.9 (83.0)
Σ	1648.5	10.4	64.8	161.3	256.5	2141.5
% Total	(76.6)	(0.5)	(3.0)	(7.5)	(11.9)	(99.5)

( ) = % of Total Energy in System.

TABLE C.19 M.D.F. RESULTS SET 19

STRUCTURE: 6 HYSTERESIS MODEL. E - P

EXCITATION : 30 Secs. El Centro N.S.

DAMPING : 3% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 9005.0 INCH KIPS

PERIOD 0.99 SECS. YSR = 0.37 MODERATE SYSTEM

Storey	Energy Dissipated By Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
10	0.0 (0)	2.3 (0)	114.4 (1.3)	478.5 (5.3)	0.0 (0)	595.3 (6.6)
9	0.0 (0)	3.3 (0)	84.7 (1.0)	439.2 (4.9)	0.0 (0)	527.1 (5.8)
8	0.0 (0)	3.2 (0)	58.6 (0.6)	390.6 (4.3)	0.0 (0)	452.4 (5.0)
7	6.5 (0)	6.7 (0)	37.2 (0.4)	340.7 (3.8)	0.0 (0)	391.1 (4.3)
6	132.5 (1.5)	10.7 (0.1)	26.2 (0.3)	289.8 (3.2)	0.0 (0)	459.2 (5.1)
5	336.6 (3.7)	14.2 (0.1)	21.5 (0.2)	234.2 (2.6)	0.0 (0)	606.4 (6.7)
4	556.7 (6.2)	23.7 (0.3)	17.6 (0.2)	181.0 (2.0)	0.0 (0)	779.0 (8.6)
3	965.9 (10.7)	32.1 (0.3)	17.1 (0.2)	128.8 (1.4)	0.0 (0)	1144.0 (12.7)
2	838.0 (9.3)	36.9 (0.4)	21.9 (0.2)	80.9 (0.9)	0.0 (0)	977.7 (10.8)
1	2977.6 (33.1)	43.0 (0.5)	15.5 (0.2)	38.0 (0.4)	0.0 (0)	3074.1 (34.1)
Σ	5813.8	176.1	414.7	2601.7	0.0	9006.3
% Total	(64.6)	(1.9)	(4.6)	(28.9)	(0)	(100)

( ) = % of Total Energy in System.

TABLE C.20 M.D.F. RESULTS SET 20

STRUCTURE: 6 HYSTERESIS MODEL. E - P

EXCITATION : 30 Secs. of Pacoima S16E

DAMPING : 3% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 35,430.3 INCH KIPS

PERIOD 0.99 SECS. YSR = 0.11 WEAK SYSTEM

Storey	Energy Dissipated By Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
10	0.0 (0)	0.1 (0)	734.8 (2.1)	797.7 (2.3)	0.0 (0)	1532.6 (4.3)
9	55.0 (0.2)	0.2 (0)	730.0 (2.1)	733.9 (2.1)	0.0 (0)	1519.2 (4.3)
8	320.2 (0.9)	0.2 (0)	728.0 (2.1)	675.2 (1.9)	0.0 (0)	1723.6 (4.9)
7	517.7 (1.5)	0.2 (0)	731.9 (2.1)	630.9 (1.8)	0.0 (0)	1880.8 (5.3)
6	1106.3 (3.1)	0.2 (0)	740.1 (2.1)	580.9 (1.6)	0.0 (0)	2427.4 (6.9)
5	1291.8 (3.6)	0.1 (0)	747.7 (2.1)	502.2 (1.4)	0.0 (0)	2541.8 (7.2)
4	922.4 (2.6)	0.1 (0)	749.2 (2.1)	427.1 (1.2)	0.0 (0)	2098.7 (5.9)
3	1098.7 (3.1)	0.2 (0)	746.5 (2.1)	367.8 (1.0)	0.0 (0)	2213.2 (6.2)
2	912.3 (2.6)	0.3 (0)	742.8 (2.1)	304.2 (0.9)	0.0 (0)	1959.6 (5.5)
1	16493.3 (46.6)	0.4 (0)	723.8 (2.0)	238.3 (0.7)	0.0 (0)	17455.7 (49.3)
Σ	22717.6	2.0	7374.7	5258.4	0.0	35352.7
% Total	(64.1)	(0)	(20.8)	(14.8)	(0)	(99.8)

( ) = % of Total Energy in System.

TABLE C.21 M.D.F. RESULTS SET 21

STRUCTURE 1 HYSTERESIS MODEL. Tri-Linear

EXCITATION: 30 Secs. Taft N69W

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1052.3 INCH KIPS

PERIOD 0.43 SECS. YSR = 1.9 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	200.5 (19.1)	1.3 (0.1)	4.6 (0.4)	58.9 (5.6)	7.9 (0.8)	273.1 (25.9)
2	350.0 (33.3)	0.6 (0)	2.9 (0.3)	36.7 (3.5)	5.5 (0.5)	395.8 (37.6)
1	353.5 (33.6)	0.0 (0)	3.2 (0.3)	13.1 (1.2)	3.1 (0.3)	372.9 (35.4)
Σ	904.0	1.9	10.7	108.8	16.5	1041.8
% Total	(85.9)	(0.2)	(1.0)	(10.3)	(1.6)	(99.0)

( ) = % of Total Energy in System.

TABLE C.22 M.D.F. RESULTS SET 22

STRUCTURE 1 HYSTERESIS MODEL. Tri-Linear

EXCITATION: 30 Secs. El Centro N.S.

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 6744.3 INCH KIPS

PERIOD 0.43 SECS. YSR = 0.8 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	419.3 (6.2)	4.0 (0.1)	16.0 (0.2)	270.0 (4.0)	15.3 (0.2)	724.6 (10.7)
2	1984.1 (29.4)	16.8 (0.2)	28.7 (0.4)	282.7 (4.2)	41.7 (0.6)	2354.0 (34.9)
1	3423.3 (50.8)	9.5 (0.1)	25.6 (0.4)	140.5 (2.1)	43.2 (0.6)	3642.1 (54.0)
Σ	5826.7	30.3	70.3	693.2	100.2	6720.7
% Total	(86.4)	(0.4)	(1.0)	(10.3)	(1.5)	(99.6)

( ) = % of Total Energy in System.

TABLE C.23 M.D.F. RESULTS SET 23

STRUCTURE 1 HYSTERESIS MODEL. Tri-Linear

EXCITATION : 30 Secs. Pacoima

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 22367.1 INCH KIPS

PERIOD 0.43 SECS. YSR = 0.26 WEAK SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	279.1 (1.2)	0.0 (0)	607.6 (2.7)	799.6 (3.6)	11.9 (0.1)	1698.1 (7.6)
2	707.8 (3.2)	0.0 (0)	916.5 (4.1)	1097.9 (4.9)	25.5 (0.1)	2747.6 (12.3)
1	14866.4 (66.5)	0.4 (0)	1233.1 (5.5)	1256.3 (5.6)	542.5 (2.4)	17898.7 (80.0)
Σ	15853.2	0.4	2757.1	3153.8	579.9	22344.4
% Total	(70.9)	(0)	(12.3)	(14.1)	(2.6)	(99.9)

( ) = % of Total Energy in System.

TABLE C.24 M.D.F. RESULTS SET 24

STRUCTURE 2 HYSTERESIS MODEL. Tri-Linear

EXCITATION : 30 Secs. Taft N69W

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 553.0 INCH KIPS

PERIOD 0.33 SECS. YSR = 3.1 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.0 (0)	0.7 (0.1)	37.7 (6.8)	45.6 (8.2)	84.0 (15.2)
2	48.5 (8.8)	0.0 (0)	0.8 (0.1)	24.7 (4.5)	29.5 (5.3)	103.4 (18.7)
1	331.1 (59.9)	0.1 (0)	1.0 (0.2)	9.0 (1.6)	20.7 (3.8)	361.8 (65.4)
Σ	379.5	0.1	2.5	71.3	95.8	549.3
% Total	(68.6)	(0)	(0.5)	(12.9)	(17.3)	(99.3)

( ) = % of Total Energy in System.

TABLE C.25 M.D.F. RESULTS SET 25

STRUCTURE 2 — HYSTERESIS MODEL. Tri-Linear

EXCITATION : 30 Secs. El Centro N.S.

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1308.5 INCH KIPS

PERIOD 0.33 SECS. YSR = 1.4 STRONG SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	31.2 (2.4)	0.1 (0)	1.0 (0.1)	64.5 (4.9)	68.8 (5.3)	165.5 (12.7)
2	291.3 (22.3)	0.3 (0)	1.8 (0.1)	44.6 (3.4)	62.7 (4.8)	400.6 (30.6)
1	679.5 (51.9)	0.5 (0)	3.3 (0.3)	15.7 (1.2)	33.0 (2.5)	732.0 (55.9)
Σ	1002.0	0.9	6.1	124.7	164.5	1298.1
% Total	(76.6)	(0.1)	(0.5)	(9.5)	(12.6)	(99.2)

( ) = % of Total Energy in System.

TABLE C.26 M.D.F. RESULTS SET 26

STRUCTURE 2 — HYSTERESIS MODEL. Tri-Linear

EXCITATION: 30 Secs. Pacoima S16E

DAMPING: 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 5,773.3 INCH KIPS

PERIOD 0.33 SECS. YSR = 0.43 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	50.4 (0.9)	0.0 (0)	463.5 (8.0)	173.0 (3.0)	71.4 (1.2)	758.2 (13.1)
2	318.3 (5.5)	0.0 (0)	463.1 (8.0)	150.9 (2.6)	86.7 (1.5)	1019.1 (17.7)
1	2890.6 (50.1)	0.1 (0)	462.9 (8.0)	107.5 (1.9)	516.9 (9.0)	3977.9 (68.9)
Σ	3259.3	0.1	1389.4	431.4	675.0	5755.2
% Total	(56.5)	(0)	(24.1)	(7.5)	(11.7)	(99.7)

( ) = % of Total Energy in System.

TABLE C.27 M.D.F. RESULTS SET 27

STRUCTURE 3 — HYSTERESIS MODEL. Tri-Linear

EXCITATION: 30 Secs. El Centro N.S.

DAMPING: 1% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1946.8 INCH KIPS

PERIOD 0.33 SECS. YSR = 0.45 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	9.2 (0.5)	0.0 (0)	8.9 (0.5)	170.4 (8.8)	0.0 (0)	188.6 (9.7)
2	37.8 (1.9)	0.2 (0)	8.5 (0.4)	163.4 (8.4)	0.0 (0)	209.9 (10.8)
1	1382.1 (71.0)	5.4 (0.3)	8.1 (0.4)	148.8 (7.6)	0.0 (0)	1544.5 (79.3)
Σ	1429.2	5.6	25.5	482.6	0.0	1942.9
% Total	(73.4)	(0.3)	(1.3)	(24.8)	(0)	(99.8)

( ) = % of Total Energy in System.

TABLE C.28 M.D.F. RESULTS SET 28

STRUCTURE 4 — HYSTERESIS MODEL. Tri-Linear

EXCITATION : 30 Secs. El Centro N.S.

DAMPING : 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 2709.6 INCH KIPS

PERIOD 0.47 SECS. YSR = 0.68 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.0 (0)	3.0 (0.1)	115.9 (4.3)	38.1 (1.4)	157.0 (5.8)
2	83.1 (3.1)	0.1 (0)	3.1 (0.1)	104.0 (3.8)	38.6 (1.4)	228.8 (8.4)
1	1814.3 (67.0)	1.0 (0)	3.4 (0.1)	82.4 (3.0)	417.2 (15.4)	2318.2 (85.6)
Σ	1897.3	1.2	9.4	302.3	493.8	2704.0
% Total	(70.0)	(0)	(0.3)	(11.2)	(18.2)	(99.8)

( ) = % of Total Energy in System.

TABLE C.29 M.D.F. RESULTS SET 29

STRUCTURE 5 HYSTERESIS MODEL. Tri-Lin.

EXCITATION : 30 Secs. El Centro N.S.

DAMPING : 1% Stiffness & Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 1908.5 INCH KIPS

PERIOD 0.57 SECS. YSR = 0.45 MODERATE SYSTEM

Storey	Energy Dissipated by Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
3	0.0 (0)	0.1 (0)	4.7 (0.2)	81.6 (4.3)	28.1 (1.5)	114.5 (6.0)
2	7.9 (0.4)	0.4 (0)	5.0 (0.3)	72.8 (3.8)	20.2 (1.1)	106.3 (5.6)
1	1311.4 (68.7)	5.5 (0.3)	5.5 (0.3)	59.8 (3.1)	302.7 (15.9)	1684.9 (88.3)
Σ	1319.3	6.1	15.2	214.1	351.0	1905.7
% Total	(69.1)	(0.3)	(0.8)	(11.2)	(18.4)	(99.9)

( ) = % of Total Energy in System.

TABLE C.30 M.D.F. RESULTS SET 30

STRUCTURE: 6 HYSTERESIS MODEL. Tri-Lin.

EXCITATION : 30 Secs. Pacoima S16E

DAMPING: 3% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 33,493.4 INCH KIPS

PERIOD 0.99 SECS. YSR = 0.11 WEAK SYSTEM

Storey	Energy Dissipated By Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
10	1.2 (0)	0.0 (0)	737.0 (2.2)	1116.3 (3.3)	0.0 (0)	1854.5 (5.5)
9	46.0 (0.1)	0.0 (0)	736.2 (2.2)	1107.0 (3.3)	0.0 (0)	1889.2 (5.6)
8	100.6 (0.3)	0.0 (0)	735.2 (2.2)	1087.7 (3.2)	0.0 (0)	1923.5 (5.7)
7	142.6 (0.4)	0.1 (0)	734.0 (2.2)	1058.7 (3.2)	0.0 (0)	1935.2 (5.8)
6	203.5 (0.6)	0.1 (0)	733.0 (2.2)	1022.5 (3.1)	0.0 (0)	1959.1 (5.8)
5	414.6 (1.2)	0.1 (0)	732.2 (2.2)	980.5 (2.9)	0.0 (0)	2127.4 (6.4)
4	530.7 (1.6)	0.2 (0)	731.5 (2.2)	920.1 (2.7)	0.0 (0)	2182.4 (6.5)
3	520.3 (1.6)	0.2 (0)	730.7 (2.2)	852.7 (2.5)	0.0 (0)	2103.8 (6.3)
2	1282.6 (3.8)	0.5 (0)	729.2 (2.2)	782.4 (2.3)	0.0 (0)	2794.7 (8.3)
1	13,335.6 (39.8)	4.6 (0)	725.7 (2.2)	644.7 (1.9)	0.0 (0)	14,710.6 (43.9)
Total	16,577.9	5.7	7324.6	9572.4	0.0	33,480.6
% Total	(49.5)	(0)	(21.9)	(28.6)	(0)	(100.0)

( ) = % of Total Energy in System.

TABLE C.3.1 M.D.F. RESULTS SET 31

STRUCTURE: 6 HYSTERESIS MODEL. Tri-Lin.

EXCITATION : 30 Secs. of El Centro N.S.

DAMPING : 3% Mass

TOTAL ENERGY IN SYSTEM @ END OF CALCULATIONS = 7356.9 INCH KIPS

PERIOD 0.99 SECS. YSR = 0.37 MODERATE SYSTEM

Storey	Energy Dissipated By Hysteresis In This Storey	Residual Potential Energy In This Storey	Residual Kinetic Energy In This Storey	Energy Dissipated In Mass α Damping In This Storey	Energy Dissipated In Stiffness α Damping In This Storey	Total Energy Dissipated In This Storey
10	0.0 (0)	0.0 (0)	3.7 (0.1)	374.2 (5.1)	0.0 (0)	377.9 (5.1)
9	76.3 (1.0)	0.1 (0)	5.3 (0.1)	355.1 (4.8)	0.0 (0)	436.8 (5.9)
8	175.6 (2.4)	1.7 (0)	6.7 (0.1)	323.6 (4.4)	0.0 (0)	507.6 (6.9)
7	289.6 (3.9)	2.6 (0)	8.1 (0.1)	283.8 (3.9)	0.0 (0)	584.2 (7.9)
6	434.0 (5.9)	1.8 (0)	9.6 (0.1)	238.7 (3.2)	0.0 (0)	684.2 (9.3)
5	529.4 (7.2)	1.3 (0)	10.4 (0.1)	191.3 (2.6)	0.0 (0)	732.3 (10.0)
4	619.6 (8.4)	1.2 (0)	10.7 (0.1)	145.7 (2.0)	0.0 (0)	777.3 (10.6)
3	695.9 (9.5)	2.3 (0)	13.1 (0.2)	102.0 (1.4)	0.0 (0)	813.3 (11.1)
2	1045.2 (14.2)	2.9 (0)	15.4 (0.2)	60.7 (0.8)	0.0 (0)	1124.1 (15.3)
1	1268.3 (17.2)	3.4 (0)	11.4 (0.2)	20.6 (0.3)	0.0 (0)	1303.7 (17.7)
Total	5133.9	17.3	94.4	2095.6	0.0	7341.3
% Total	(69.8)	(0.2)	(1.3)	(28.5)	(0)	(99.8)

( ) = % of Total Energy in System.

TABLE C.32 M.D.F. RESULTS SET 32

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PAPER SUBMITTED FOR PRESENTATION AT 7TH WORLD CONF ON EARTHQUAKE ENG., ISTANBUL TURKEY, SEPT 1980.