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Technical Report NCEER-91-0012

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PREFACE

The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

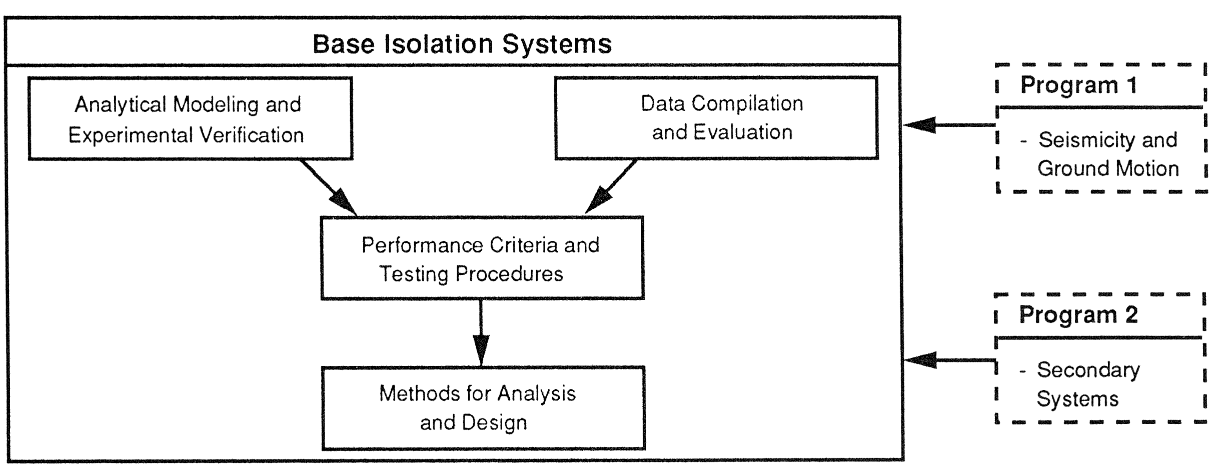
NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 2, Secondary and Protective Systems, and more specifically, to protective systems. Protective Systems are devices or systems which, when incorporated into a structure, help to improve the structure's ability to withstand seismic or other environmental loads. These systems can be passive, such as base isolators or viscoelastic dampers; or active, such as active tendons or active mass dampers; or combined passive-active systems.

Passive protective systems constitute one of the important areas of research. Current research activities, as shown schematically in the figure below, include the following:

1. Compilation and evaluation of available data.
2. Development of comprehensive analytical models.
3. Development of performance criteria and standardized testing procedures.
4. Development of simplified, code-type methods for analysis and design.



The study described in this report concerns seismic response of steel-frame structures with added viscoelastic dampers as energy dissipation devices. The objective is to carry out an experimental investigation on the seismic response of a model structure, which is a 2/5-scaled model of a prototype five-story structure, with added viscoelastic dampers. The results can thus be compared with those from tests to be carried out on the full-scale structure and can be used for a realistic assessment of structural applications of viscoelastic dampers.

A major emphasis is placed on the ambient temperature effect. With ambient temperature taken into account, a procedure is proposed for estimating equivalent damping of a viscoelastically damped structure together with the development of a damper design procedure. These results are verified based on the experimental results.

ABSTRACT

Seismic response characteristics of a 2/5 scale steel frame structure with added viscoelastic dampers are studied experimentally. The major emphasis is placed on the ambient temperature effect. It is shown that, while seismic response of a structure can be significantly improved with added dampers, their degree of effectiveness depends on the surrounding temperature within which they operate. Results also show that, even at very high temperatures, the viscoelastically damped structure can still achieve a significant reduction of structural response as compared to the case with no dampers added.

The design of viscoelastic dampers by taking into account the ambient temperature is addressed. Empirical equations are established based on regression analysis using data obtained from component tests of the dampers. These equations can satisfactorily estimate the dynamic properties of dampers under various ambient temperatures, excitation frequencies and deformations.

Numerical simulations on equivalent structural damping and structural response under various ambient temperatures are also carried out. It is demonstrated that the dynamic behavior of structures with added viscoelastic dampers can be satisfactorily predicted by existing analytical tools.

ACKNOWLEDGEMENT

The authors are grateful to Dr. E.J. Nielsen of the 3M Company for his interest and support to this research program. All the viscoelastic dampers used in this study were designed and donated by the 3M Company, St. Paul, Minnesota.

Thanks are also due Messrs. Mark Pitman and Dan Walch, who are responsible for operating the shaking table at the State University of New York at Buffalo.

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SECTION 1

INTRODUCTION

Earthquake Resistant design and retrofit of moment resisting steel frames using energy absorption devices has received considerable attention in recent years [1-5]. Among the available devices, viscoelastic dampers have shown to be capable of providing structures with added damping to dissipate energy resulting from severe earthquake ground motions.

Viscoelastic dampers are normally made of viscoelastic layers bonded to steel plates under direct shear to dissipate input energy [4,5]. When added to a structure, experimental studies of this type of structures have shown that, while they can be effective in attenuating seismic response of the structure, their proper design for maximum efficiency must take into account important factors such as excitation frequencies and the environmental temperature within which they operate [4-6].

The objectives of this study are to carry out an experimental investigation on the effect of ambient temperature on viscoelastic dampers and on the dynamic response of a viscoelastically damped 2/5 scale five-story steel-frame structure. Based on test results of individual viscoelastic dampers, empirical formulae on the dynamic damper properties as functions of excitation frequency, ambient temperature and strain range are derived. Based on these equations, numerical studies on the prediction of structural damping and on the simulation of dynamic structural response under earthquake excitations are carried out.

The model structure used in this study was constructed as a part of a US-China Cooperative Research program [7]. In that program, Beijing Polytechnic University in China designed and constructed a full-sized five-story steel-frame structure (Fig. 1.1) and the State University of New York at Buffalo constructed

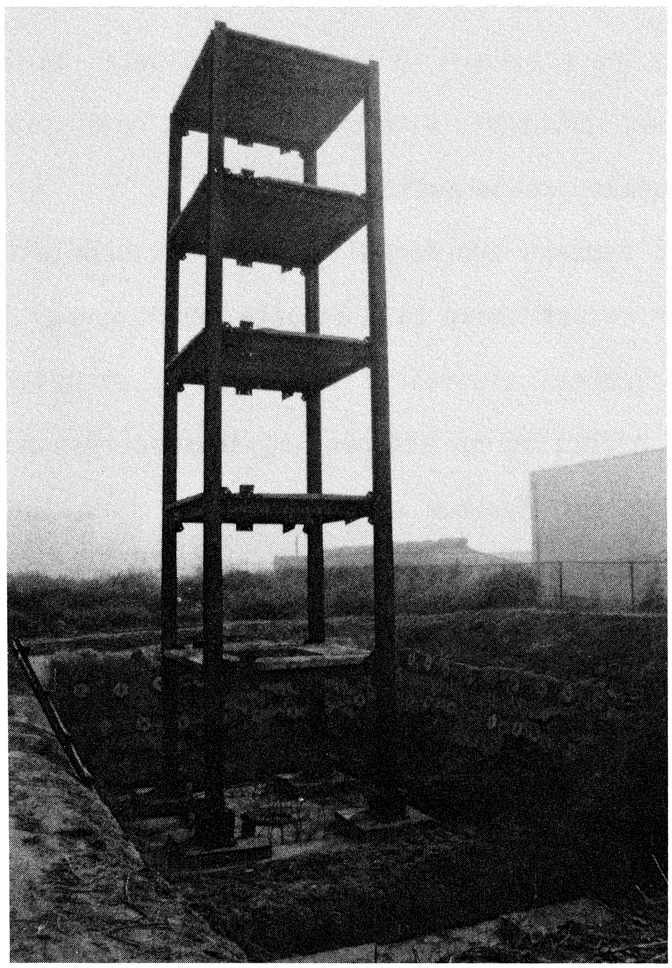


Fig. 1.1 Full-Sized Five-Story Steel Frame

a 2/5 scale steel model to carry out a series of research programs on seismic response of structures. One of the objectives of this research program is the feasibility study of using energy absorption devices to reduce excessive vibration of buildings under severe earthquake ground motions.

This report describes only the test results on the model structure with added viscoelastic dampers. Experimental studies on the dynamic behavior of the prototype structure added with similar viscoelastic dampers will be carried out in the near future.

SECTION 2

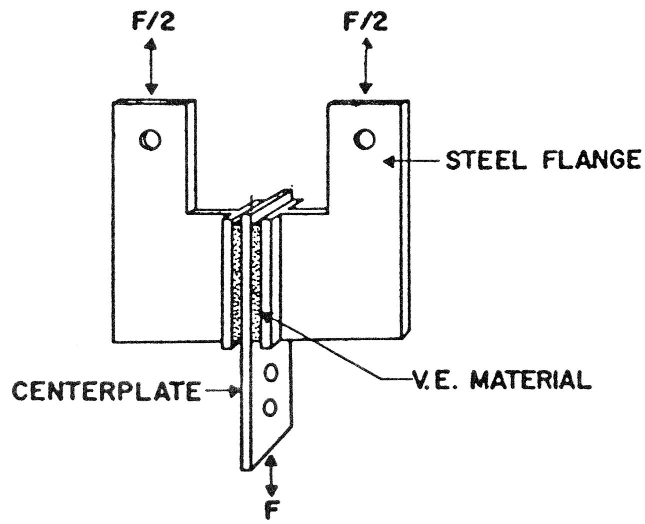
PROPERTIES OF VISCOELASTIC DAMPERS UNDER VARIOUS AMBIENT TEMPERATURES

2.1 Test Set-Up And Experimental Program

Tests of dampers were carried out by using a MTS axial-torsional testing system [8]. The damper (Fig. 2.1), which is identical to those used in the model test, has an area of 1.5 in^2 and a thickness of 0.2 inch of a 3M viscoelastic material. It was rigidly connected to the MTS unit and subjected to sinusoidal excitations of selected magnitudes of strains and frequencies under precise control of selected ambient temperatures. A picture of the test set-up is shown in Fig. 2.2.

Fig. 2.3 shows a special device which was developed to provide accurate control of ambient temperature around the damper. This device consists of a cylindrical cardboard wrapped by a thin layer of teflon tape, an electric heating pad, an electronic thermal couple, and a power controller with a dimmer. When the damper is inserted into the cylinder, the heat generated by the heating pad is transferred to the space between the damper and the cylinder. By properly setting the dimmer in the power controller, different ambient temperatures around the damper can be precisely simulated.

Two types of temperatures were monitored throughout the tests: the temperature rise within the viscoelastic material due to shear deformation and the ambient temperature around the damper. During the test, the damper deformation (strain) and shear force were measured by a LVDT and a load cell within the MTS unit. Using this experimental set-up, it was possible to obtain the load-deformation relationship with corresponding temperature changes in the damper. The basic dynamic properties of dampers under various controlled temperatures were then determined based on the test data.



(A = 1.5 in^2, THICKNESS = 0.2 in)

Fig. 2.1 Damper used in Test

Frequency (Hz)	0.1, 1.0, 2.0, 3.0, 3.5, 4.0	6 cases
Strain (%)	5, 20, 50	3 cases
Temperature (°C)	21, 24, 28, 32, 36, 40	6 cases

Table 2.1 Test Program

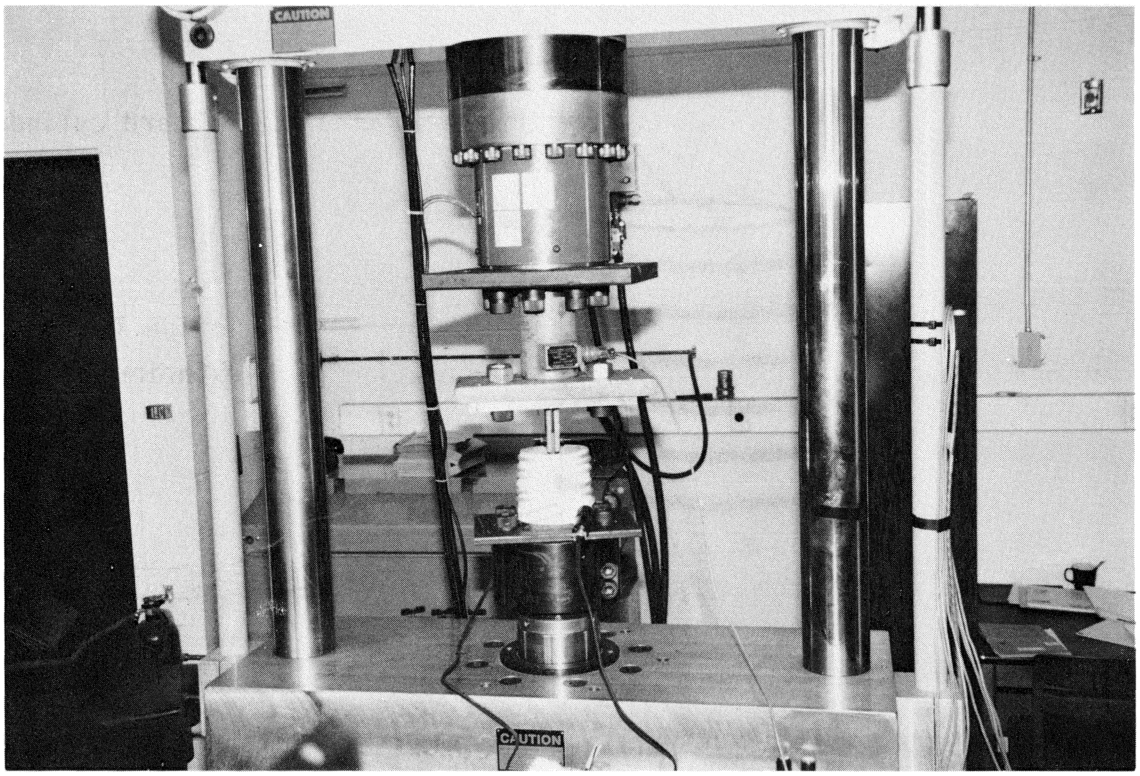


Fig. 2.2 Experimental Set-up

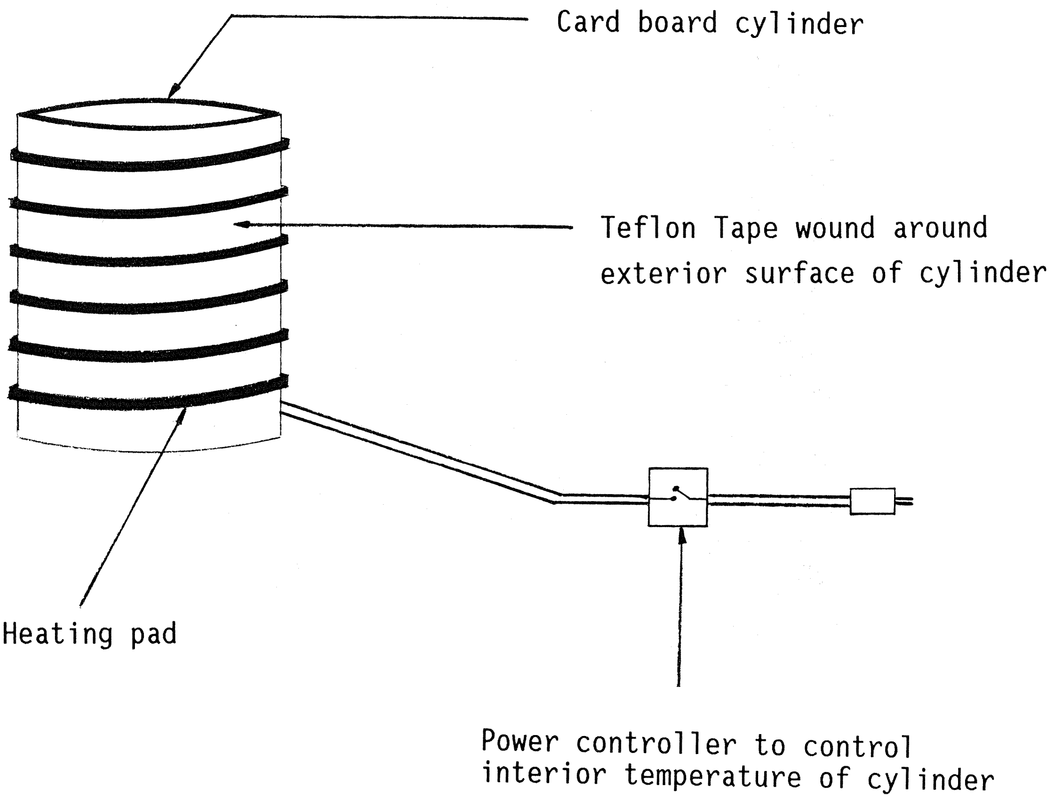


Fig. 2.3 Temperature Control Device

The damper was tested under six different ambient temperatures (21°C, 24°C, 28°C, 32°C, 36°C and 40°C). At each temperature six tests were conducted at frequencies of 0.1, 1.0, 2.0, 3.0, 3.5 and 4.0 Hz, respectively, for up to fifty cycles of deformation in three different strain ranges (5%, 20% and 50%). A list of the test program is summarized in Table 2.1.

2.2 Test Results

Force-deformation hysteresis loops of the damper at two controlled strain ranges (5% and 20%) subjected to excitation frequencies of 1.0 Hz and 3.5Hz under six different ambient temperatures are given in Figs. 2.4-2.7. In each of these figures, the damper experienced up to 20 cycles of excitation. It is clear from these figures that energy dissipation capacity of the damper depends on the excitation frequency and the surrounding ambient temperature. In general, the damper stiffness is a function of deformation, number of loading cycles, excitation frequencies, and the ambient temperature. It is generally stiffer when subjected to a higher excitation frequency, also stiffer when the deformation strain range is smaller and the number of loading cycle is not large. Increasing loading cycles or deformation will cause viscoelastic material softening. This is due to temperature increase within the damper. However, the rate of stiffness softening is stabilized after a number of loading cycles, depending on the surrounding temperature and the strain range.

Based on load-deformation relationships obtained from the damper tests, important dynamic parameters of the viscoelastic dampers such as W (energy dissipation per cycle), K (damper stiffness), G′ (shear storage modulus), G" (shear loss modulus) and Loss Factor, etc., under each ambient temperature and excitation frequency are calculated and listed in Table 2.2a-2.2f. Detailed description of the above parameters can be found in [4,6].

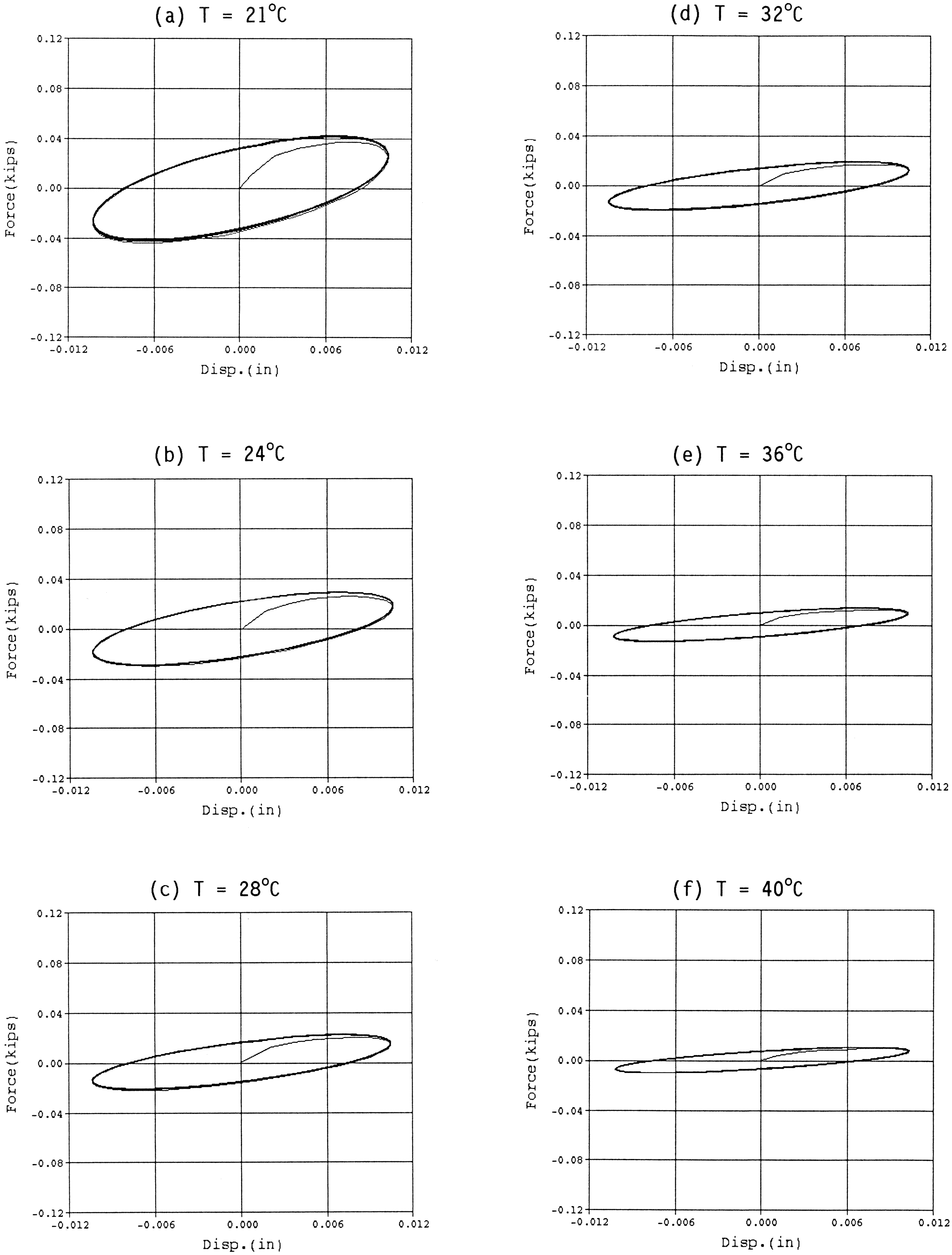


Fig. 2.4 Force-Deformation Hysteresis Loops (5%, 1.0Hz)

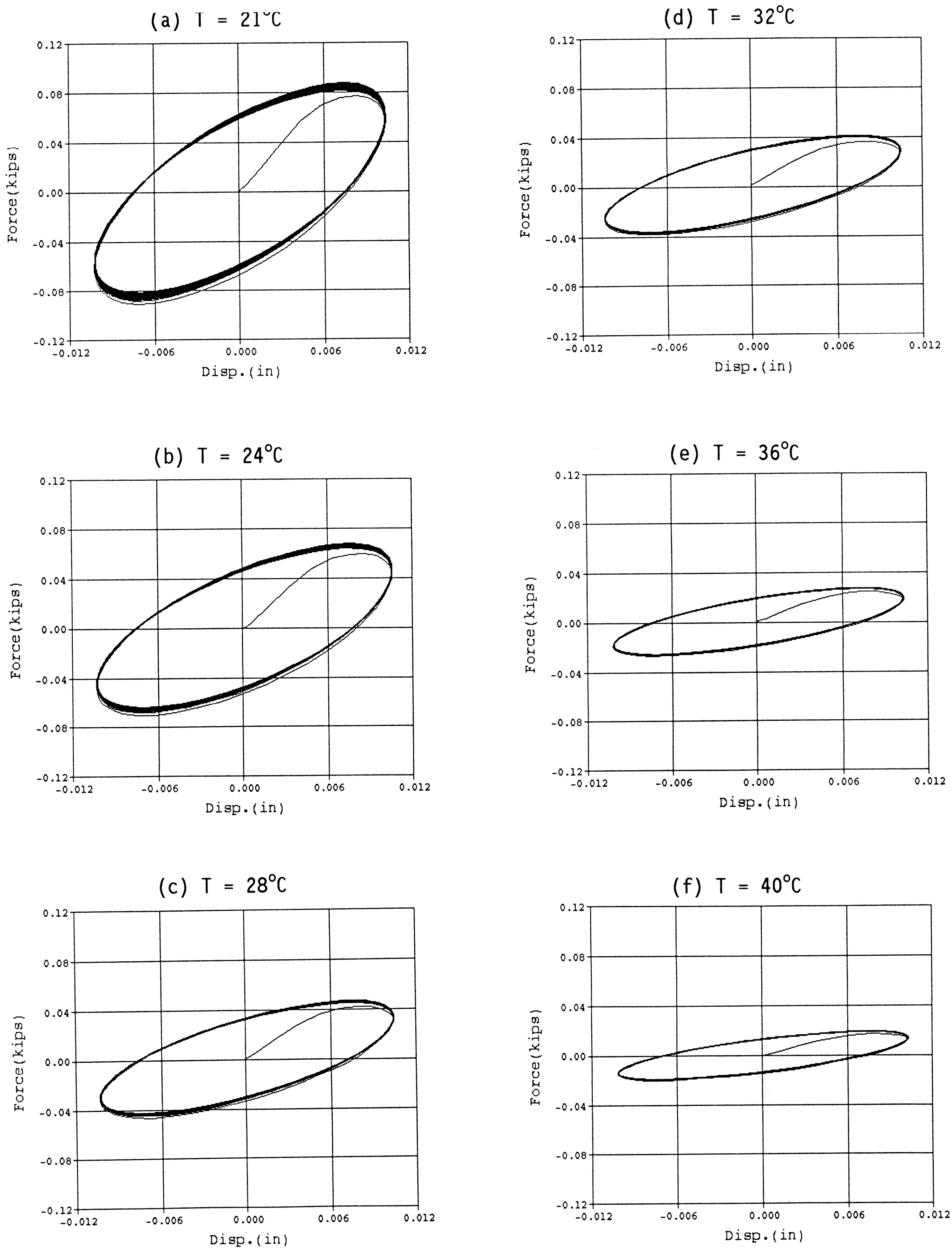


Fig. 2.5 Force-Deformation Hysteresis Loops (5%, 3.5Hz)

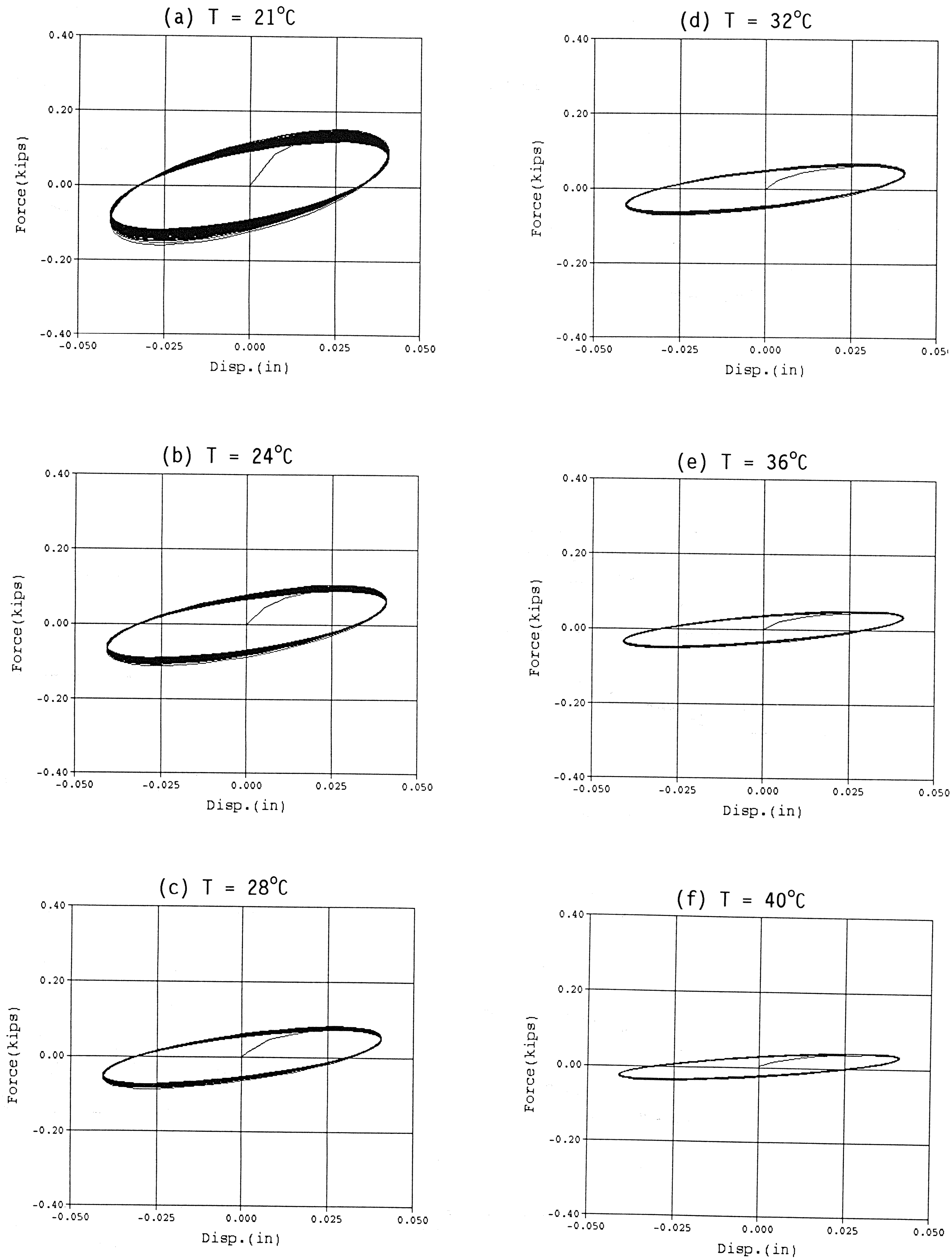


Fig. 2.6 Force-Deformation Hysteresis Loops (20%, 1.0Hz)

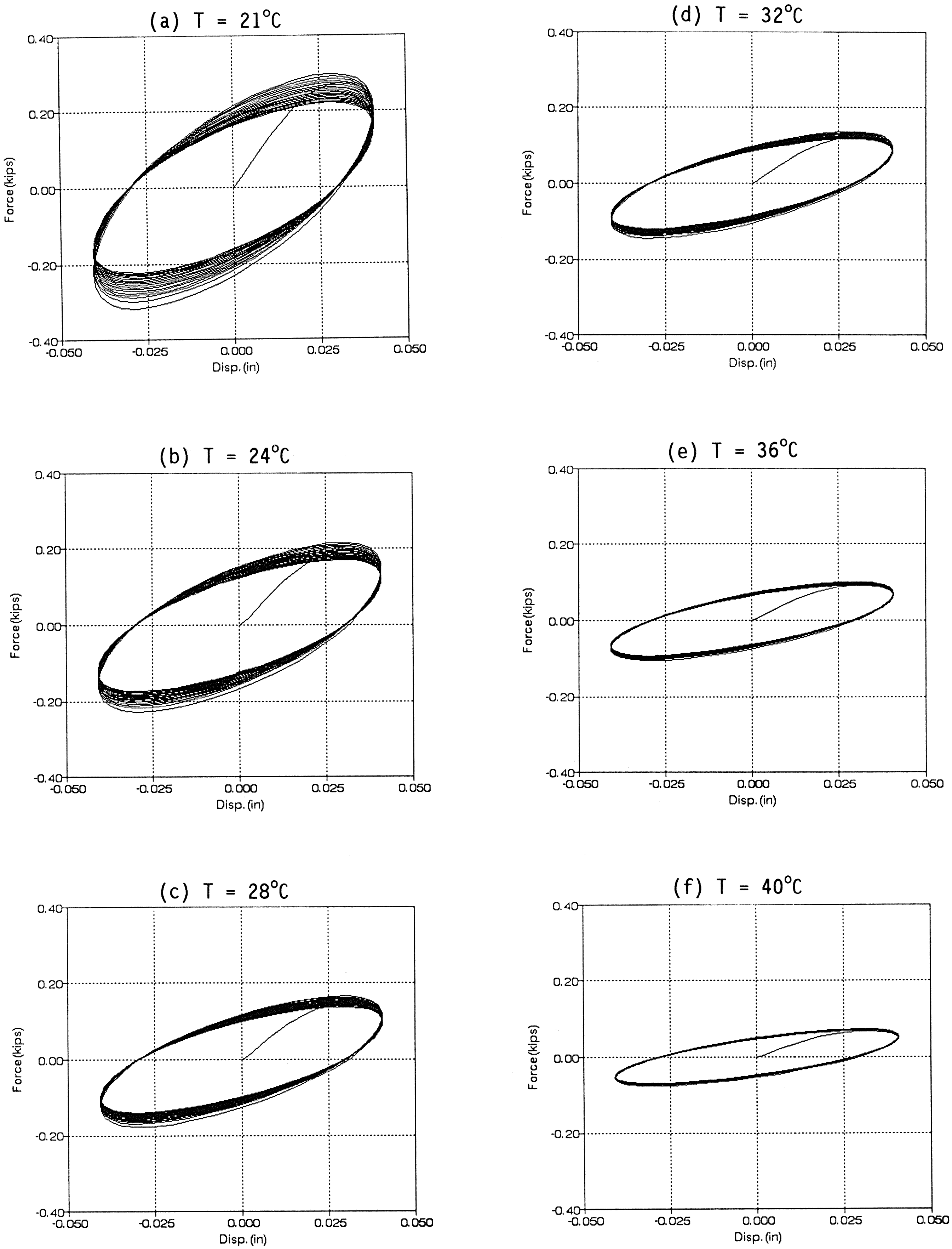


Fig. 2.7 Force-Deformation Hysteresis Loops (20%, 3.5Hz)

(a) T = 21 °C

Freq.(Hz)	Strain(%)	W(lb.in)	K(lb/in)	G'(psi)	G"(psi)	Loss Factor
0.10	5.00	265.00	786.00	51.50	56.16	1.09
	20.00	4503.00	847.00	53.58	59.72	1.11
1.00	5.00	1088.00	2615.00	169.88	230.95	1.36
	20.00	16675.00	2473.00	157.32	221.16	1.40
2.00	5.00	1591.00	3945.00	275.30	337.62	1.23
	20.00	22622.00	3387.00	229.49	300.03	1.31
3.00	5.00	1969.00	5394.00	352.27	417.91	1.18
	20.00	26059.00	4306.00	284.82	345.62	1.21
3.50	5.00	2058.00	6135.00	402.83	436.65	1.08
	20.00	27616.00	5064.00	312.08	366.27	1.18
4.00	5.00	2145.00	6164.00	445.88	455.25	1.02
	20.00	28431.00	5311.00	343.55	377.08	1.10

(b) T = 24 °C

Freq.(Hz)	Strain(%)	W(lb.in)	K(lb/in)	G'(psi)	G"(psi)	Loss Factor
0.10	5.00	213.00	693.00	45.99	45.27	0.99
	20.00	3404.00	663.00	44.04	45.15	1.03
1.00	5.00	873.00	2124.00	136.51	185.18	1.36
	20.00	14580.00	2082.00	140.55	193.37	1.38
2.00	5.00	1256.00	3074.00	211.46	266.46	1.26
	20.00	20013.00	2963.00	206.17	265.43	1.29
3.00	5.00	1528.00	3930.00	272.26	324.25	1.19
	20.00	23132.00	3819.00	256.42	306.79	1.20
3.50	5.00	1623.00	4506.00	304.97	344.48	1.13
	20.00	24122.00	4426.00	279.87	319.93	1.14
4.00	5.00	1767.00	5524.00	345.26	374.97	1.09
	20.00	24984.00	4560.00	312.38	331.36	1.06

Table 2.2 Damper Properties

(c) T = 28 °C

Freq.(Hz)	Strain(%)	W(lb.in)	K(lb/in)	G′(psi)	G"(psi)	Loss Factor
0.10	5.00	168.00	538.00	34.86	35.65	1.02
	20.00	2970.00	593.00	38.49	39.39	1.02
1.00	5.00	659.00	1598.00	100.01	139.84	1.40
	20.00	10419.00	1548.00	104.19	138.19	1.33
2.00	5.00	970.00	2382.00	153.65	205.84	1.34
	20.00	14383.00	2241.00	151.91	190.77	1.25
3.00	5.00	1211.00	3188.00	204.76	256.91	1.26
	20.00	16937.00	3045.00	189.75	224.64	1.19
3.50	5.00	1296.00	3562.00	228.37	275.09	1.20
	20.00	17549.00	3232.00	201.23	232.75	1.16
4.00	5.00	1355.00	4093.00	248.61	287.47	1.15
	20.00	18044.00	3459.00	222.26	239.32	1.07

(d) T = 32 °C

Freq.(Hz)	Strain(%)	W(lb.in)	K(lb/in)	G′(psi)	G"(psi)	Loss Factor
0.10	5.00	136.00	505.00	34.53	28.93	0.84
	20.00	1718.00	415.00	28.15	22.79	0.81
1.00	5.00	478.00	1134.00	77.63	101.43	1.31
	20.00	6451.00	1067.00	71.67	85.56	1.19
2.00	5.00	683.00	1732.00	114.63	144.87	1.27
	20.00	9291.00	1577.00	104.45	123.23	1.18
3.00	5.00	831.00	2420.00	156.54	176.34	1.13
	20.00	11148.00	2051.00	130.41	147.85	1.13
3.50	5.00	934.00	2636.00	168.96	198.20	1.17
	20.00	11807.00	2211.00	143.29	156.60	1.09
4.00	5.00	917.00	2622.00	173.83	194.59	1.12
	20.00	12089.00	2242.00	153.21	160.33	1.05

Table 2.2 (Cont'd.)

(e) T = 36°C

Freq.(Hz)	Strain(%)	W(lb.in)	K(lb/in)	G′(psi)	G″(psi)	Loss Factor
0.10	5.00	88.00	376.00	24.66	18.67	0.76
	20.00	1327.00	353.00	23.16	17.61	0.76
1.00	5.00	317.00	880.00	59.77	67.34	1.13
	20.00	4644.00	873.00	55.23	61.60	1.12
2.00	5.00	462.00	1202.00	84.94	97.97	1.15
	20.00	6764.00	1234.00	80.67	89.71	1.11
3.00	5.00	566.00	1626.00	109.72	120.18	1.10
	20.00	8273.00	1542.00	100.49	109.73	1.09
3.50	5.00	619.00	1871.00	120.72	130.72	1.08
	20.00	8761.00	1614.00	109.47	116.20	1.06
4.00	5.00	651.00	1932.00	133.36	138.22	1.04
	20.00	9121.00	1692.00	119.56	120.97	1.01

(f) T = 40°C

Freq.(Hz)	Strain(%)	W(lb.in)	K(lb/in)	G′(psi)	G″(psi)	Loss Factor
0.10	5.00	69.00	322.00	22.56	14.57	0.65
	20.00	987.00	346.00	23.35	13.08	0.56
1.00	5.00	233.00	709.00	47.86	49.52	1.03
	20.00	3411.00	666.00	44.04	45.24	1.03
2.00	5.00	330.00	1023.00	66.13	69.96	1.06
	20.00	4937.00	957.00	62.46	65.08	1.04
3.00	5.00	404.00	1245.00	81.47	85.73	1.05
	20.00	5938.00	1217.00	77.09	78.76	1.02
3.50	5.00	434.00	1353.00	91.38	92.03	1.01
	20.00	6317.00	1232.00	84.35	83.78	0.99
4.00	5.00	455.00	1547.00	99.43	96.55	0.97
	20.00	6370.00	1249.00	88.76	84.48	0.95

Table 2.2 (Cont'd.)

2.3 Empirical Formulae for Viscoelastic Dampers

From the above description, it is clear that one has to take into account the effect of ambient temperature, excitation frequency, maximum expected strain range, and maximum expected number of loading cycles for an effective design of viscoelastic dampers. However, these factors are inter-related. For example, Figs. 2.8 - 2.9 show the dependence of G" on ambient temperature and on the number of loading cycles, respectively, under six different vibration frequencies. It is seen that the shear loss modulus decreases as the ambient temperature increases. The number of loading cycles also affects G", especially under large strain ranges. The change in G" can be as much as 30% from cycle one to twenty at 4 Hz and 20% strain. It is expected that for typical earthquake excitations, the number of significant loading cycles will generally be less than twenty.

In order to consider all the factors which affect the properties of viscoelastic dampers in the design, empirical formulae for the damper stiffness and the loss factor based on regression analysis using the data obtained from damper tests are proposed as follows:

$$K_d=e^{14.78}(\omega)^{0.69}(T)^{-2.26} \qquad (2.1)$$

$$\eta_v=e^{0.85}(\omega)^{-0.27}(T)^{-0.12} \qquad (2.2)$$

where K_d = stiffness of the damper (kip/in)

ω = vibration frequency (Hz)

T = ambient temperature ($^{\circ}$C)

η_v = loss factor of the damper

The above formulae were derived based on average of the first twenty cycles

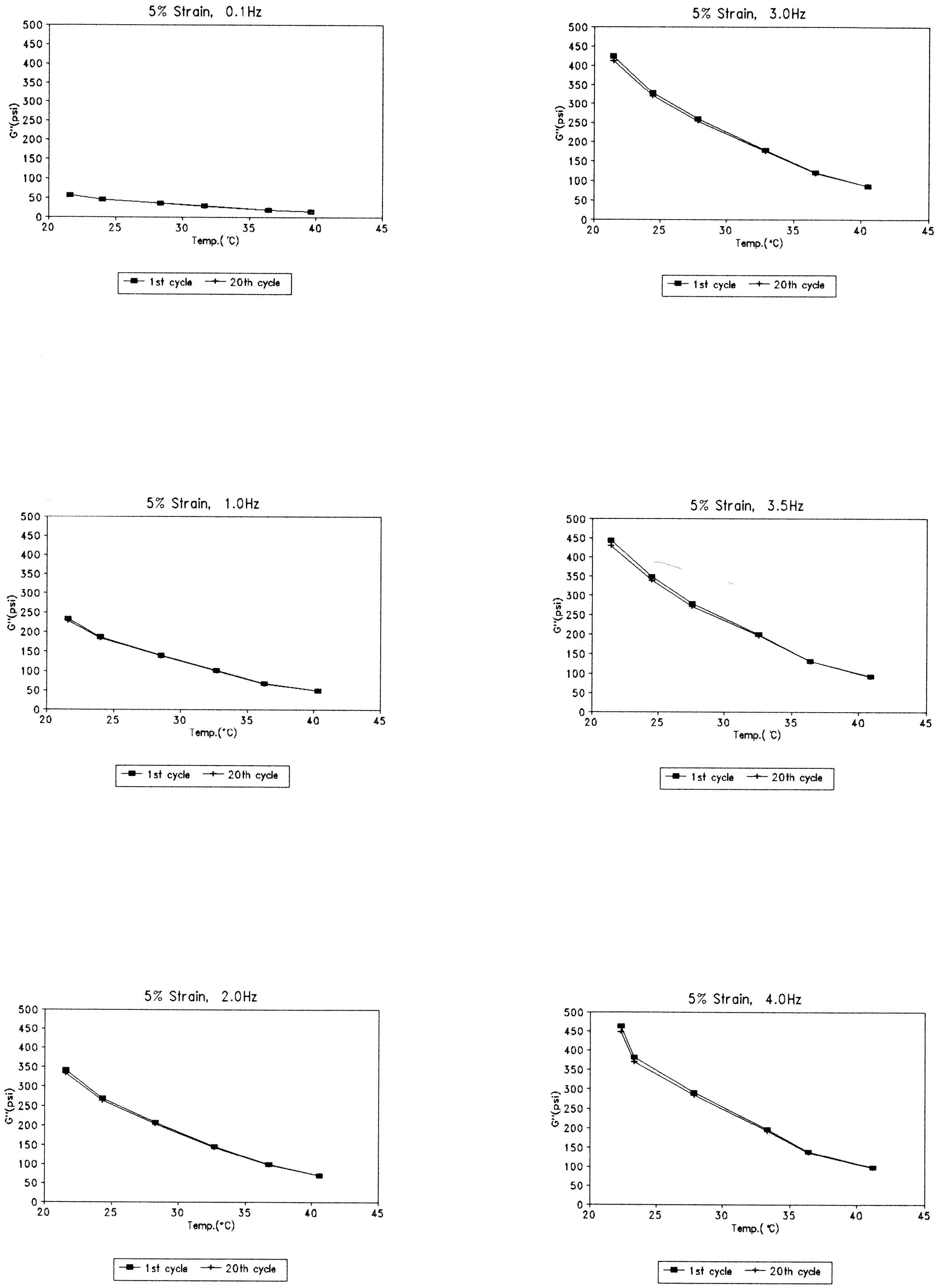


Fig. 2.8 Shear Loss Modulus (G") as a function of Temperature, 5% Strain

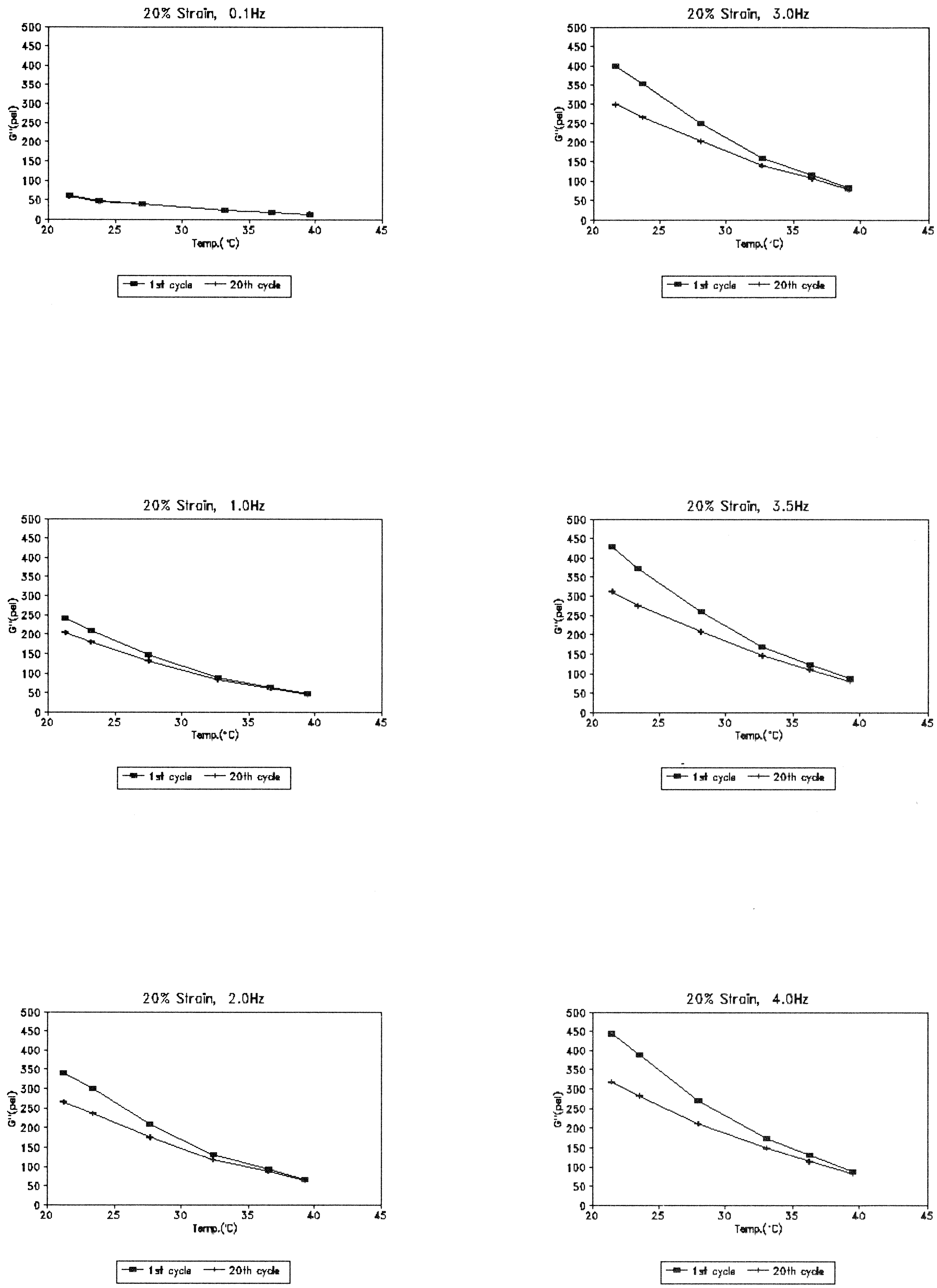


Fig 2.9 Shear Loss Modulus (G") as a Function of Temperature (20% Strain)

of damper deformation with an average strain of 5%, which is considered to be reasonable during a typical earthquake excitation. The relationships between the values obtained from the above formulae and the test results are shown in Figs. 2.10a and 2.10b, showing good agreements in general. These formulae will be used in Section 4 for computer simulation of equivalent structural damping.

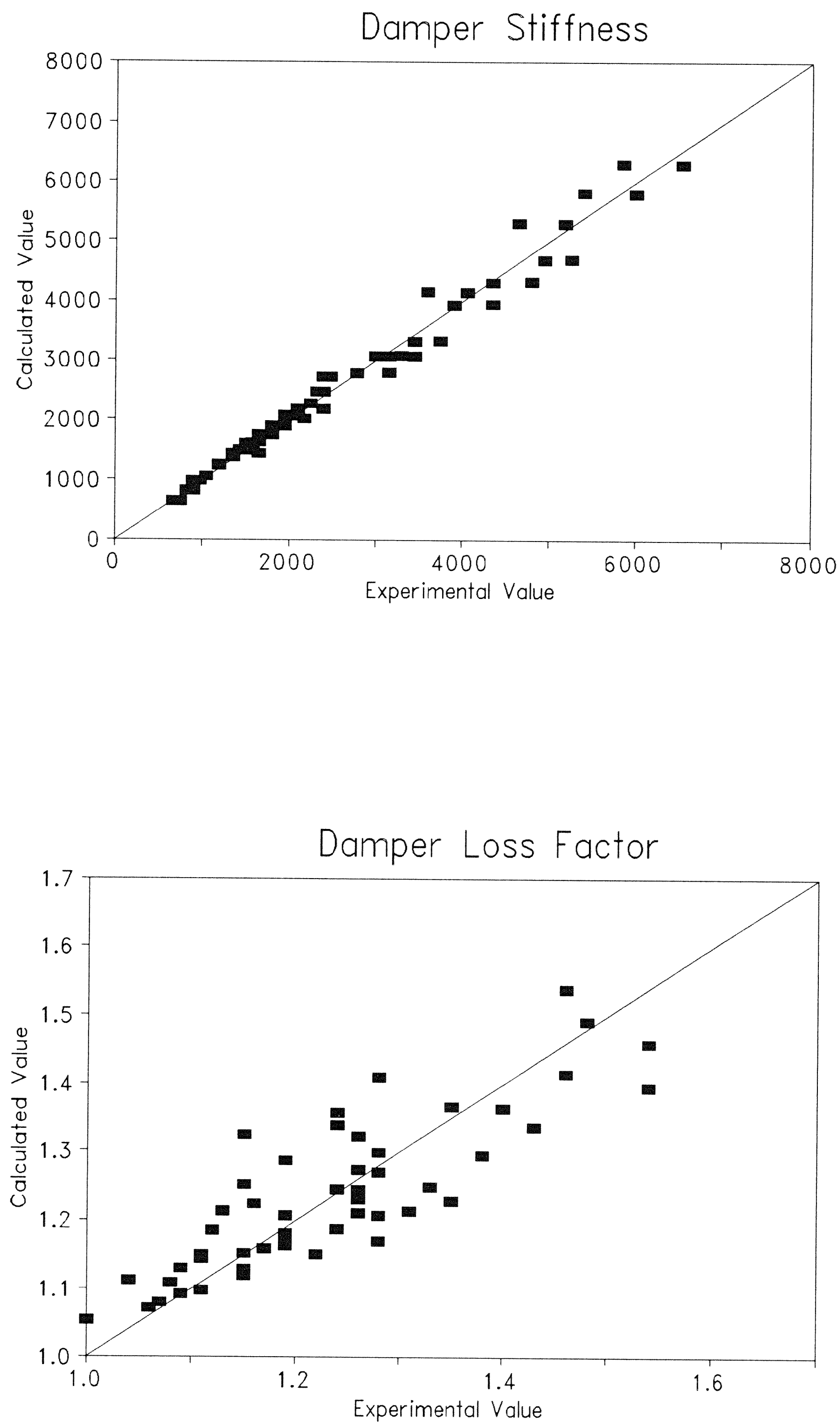


Fig. 2.10 Comparison Between Experimental and Calculated Results

SECTION 3

MODEL STRUCTURE TEST ON EARTHQUAKE SIMULATOR UNDER VARIOUS AMBIENT TEMPERATURES

3.1 Description of the Test Structure

The test structure is a 2/5 scale five-story steel frame constructed under the U.S-China Cooperative Research Program on dynamic Testing and Analysis [7]. Overall dimensions of the test frame are 52.0" x 52.0" in plan and 224.0" in height, as shown in Fig. 3.1. A lumped mass system simulating the dynamic properties of the prototype structure was accomplished by adding steel plates at each floor level. The weight at each floor is 1.27 kips for the first four floors and 1.31 kips for the fifth one. All the girder-to-column joints are fully welded as rigid connections. This type of design produces a frame behaving as a lumped mass five-degree-of-freedom system when subjected to lateral loads. The ends of the first floor columns were welded to base plates which were bolted to a large concrete boat-type foundation secured to the shake table [9]. The use of this large foundation effectively minimizes table-structural interaction. The diagonal bracing members with added viscoelastic dampers were connected by bolts to the gusset plates welded to the girders (Fig. 3.2). Each set of bracing is composed of two double angles (L 1-1/2 x 1-1/2 x 1/8) with a viscoelastic damper connected at the upper 1/3 part of the bracing.

3.2 Test Set-Up and Experimental Program

The test set-up was designed to monitor the global structural response, local damper response, and temperature rise in the viscoelastic dampers under precisely controlled ambient temperatures. Typical instrumentations used are Endevco type accelerometers, Temposonics displacement transducers and thermal

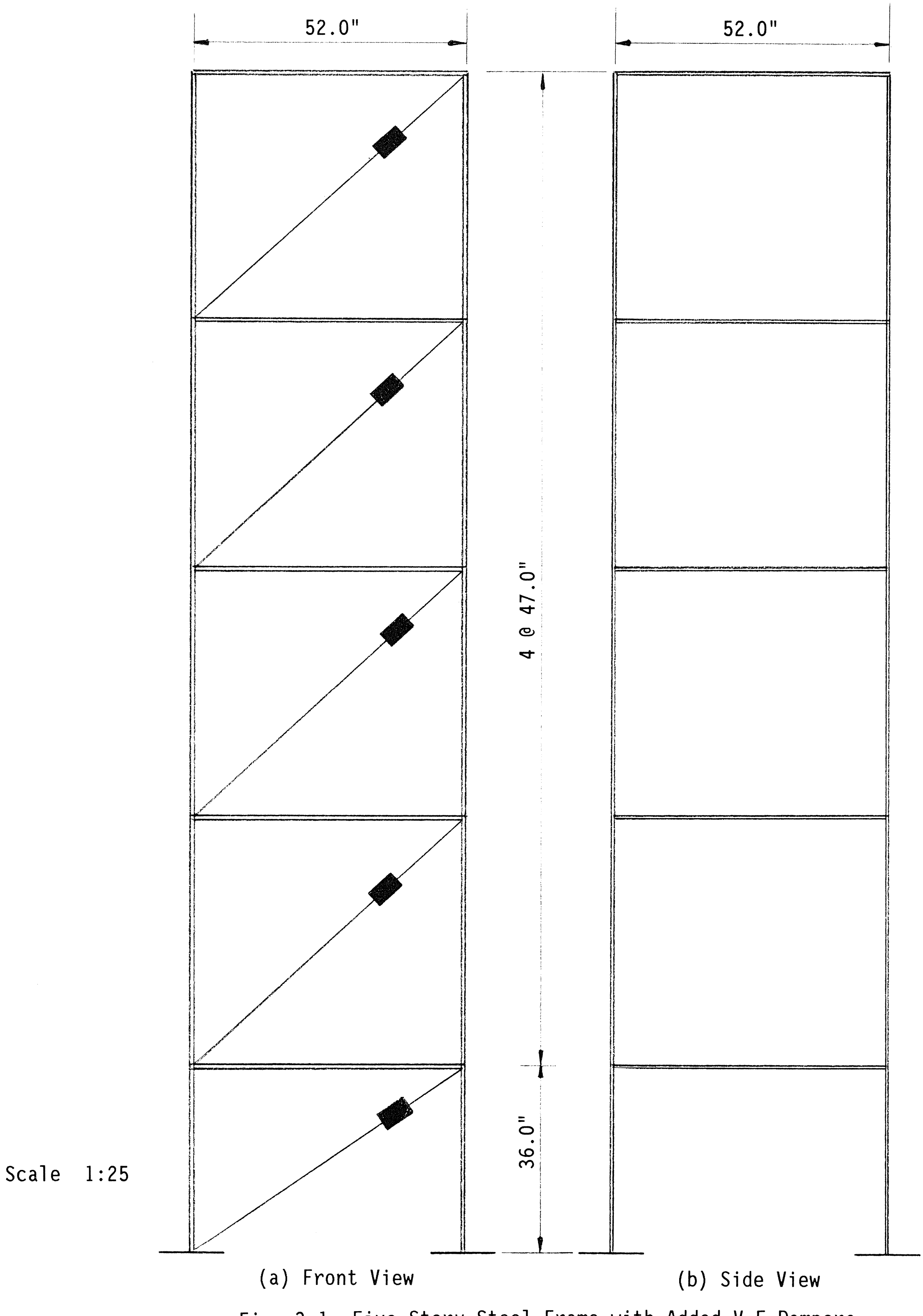


Fig. 3.1 Five-Story Steel Frame with Added V E Dampers

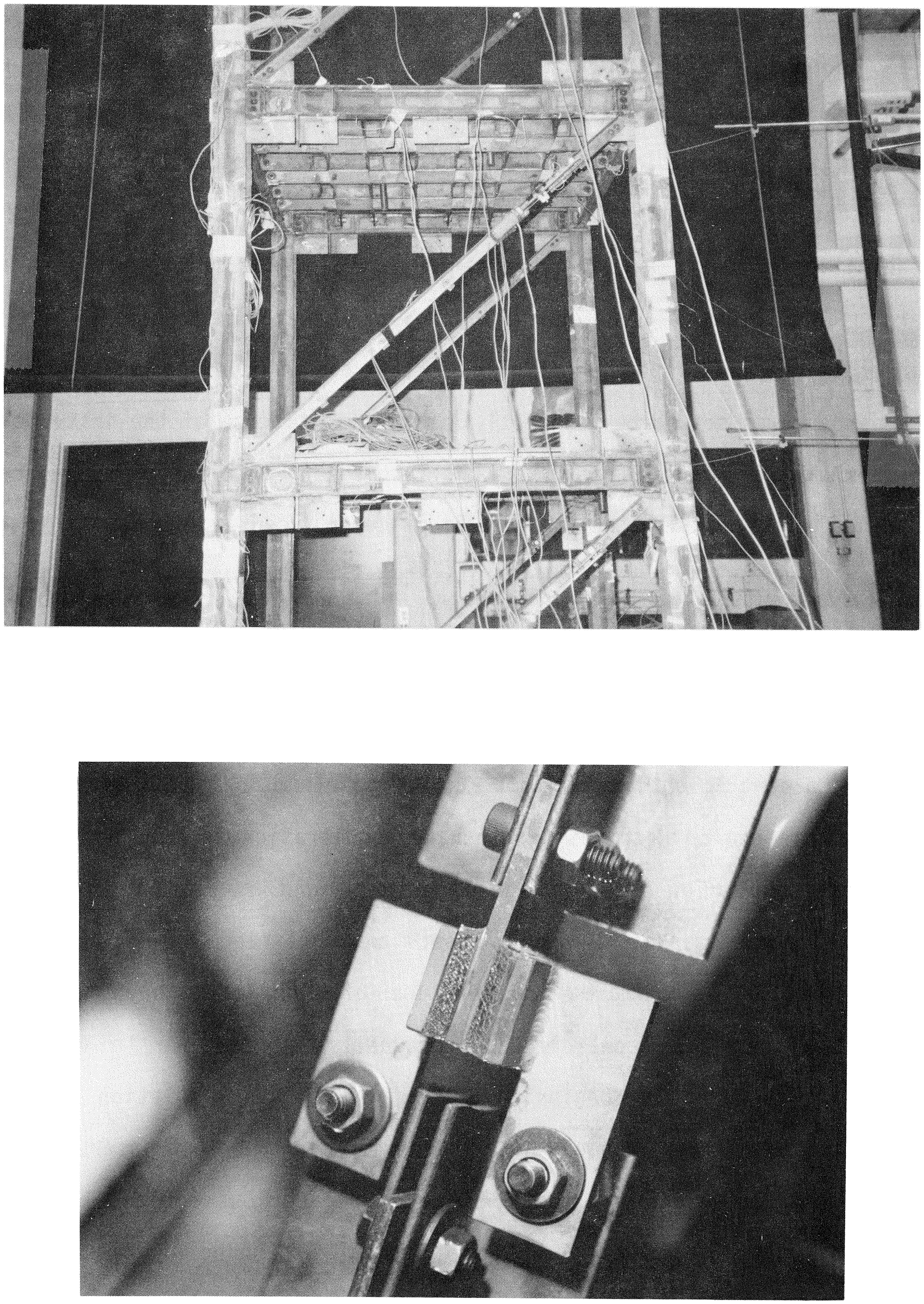


Fig. 3.2 V E Damper Incorporated with Diagonal Bracing

couples within the damper material. Ten temperature control devices identical to that used in the damper tests were utilized for the control of the ambient temperature during the model structure tests. Thermocouples were connected between the thermometers mounted on the second floor and each damper's surface to detect the ambient temperature around the dampers. A total of 20 data acquisition channels and 10 temperature control devices, one for each damper, were used in the test set-up. All the ten temperature control devices were connected to a common power controller so that the surrounding temperature around the dampers was set to be identical. A schematic diagram of the instrumentation is shown in Fig. 3.3. The relative displacement at each floor of the frame was obtained by subtracting the absolute displacement recorded during the tests from the table motion. A summary of the instrumentation is listed in Table 3.1.

Signals obtained from accelerometers, temposonics and thermocouples were processed through the data acquisition system equipped in the laboratory. In addition, response time histories and their transfer functions were monitored on the screen of a Scientific Atlanta Fourier Spectrum Analyzer during the tests.

A time-scaled Hachinohe Earthquake acceleration record, normalized to a peak acceleration of 0.12g, was used as the input excitation to the shaking table. The earthquake simulation tests were carried out starting at the temperature of 25°C (normal temperature of the laboratory). The ambient temperature was then controlled to gradually increase up to 42°C in each subsequent test. At the beginning of each earthquake simulation test, system identification using a banded white noise was carried out to observe changes in dynamic characteristics of the structure under various ambient temperatures. Tests on the structure without any added viscoelastic dampers were also performed under both earthquake and white noise excitations to generate bench marks for comparisons.

Channel No.	Channel File Identification	Signal
01	Temposonic	Foundation Displacement
02	Temposonic	1st. Floor Displacement
03	Temposonic	2nd. Floor Displacement
04	Temposonic	3rd. Floor Displacement
05	Temposonic	4th. Floor Displacement
06	Temposonic	5th. Floor Displacement
07	Endevco	Foundation Acceleration
08	Endevco	1st. Floor Acceleration
09	Endevco	2nd. Floor Acceleration
10	Endevco	3rd. Floor Acceleration
11	Endevco	4th. Floor Acceleration
12	Endevco	5th. Floor Acceleration
13	Temposonic	Table Lateral Displacement
14	Endevco	Table Lateral Acceleration
15	Temposonic	1st. Floor Damper Deformation
16	Temposonic	2nd. Floor Damper Deformation
17	Temposonic	3rd. Floor Damper Deformation
18	Temposonic	4th. Floor Damper Deformation
19	Temposonic	5th. Floor Damper Deformation
20	Thermocouple	Internal Temperature of 2nd. Floor Dampers's V.E Material

Table 3.1 Instrumentation Scheme

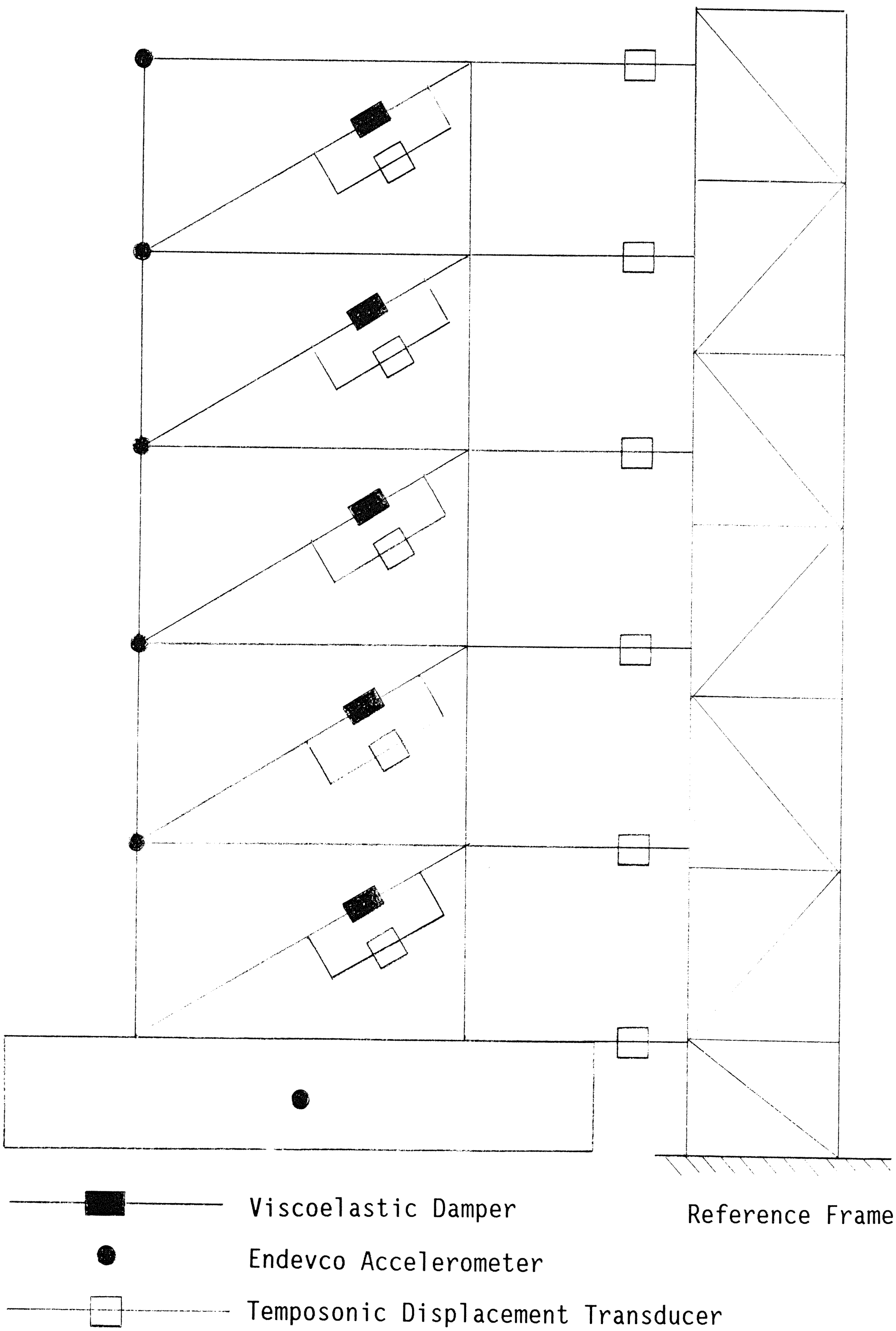


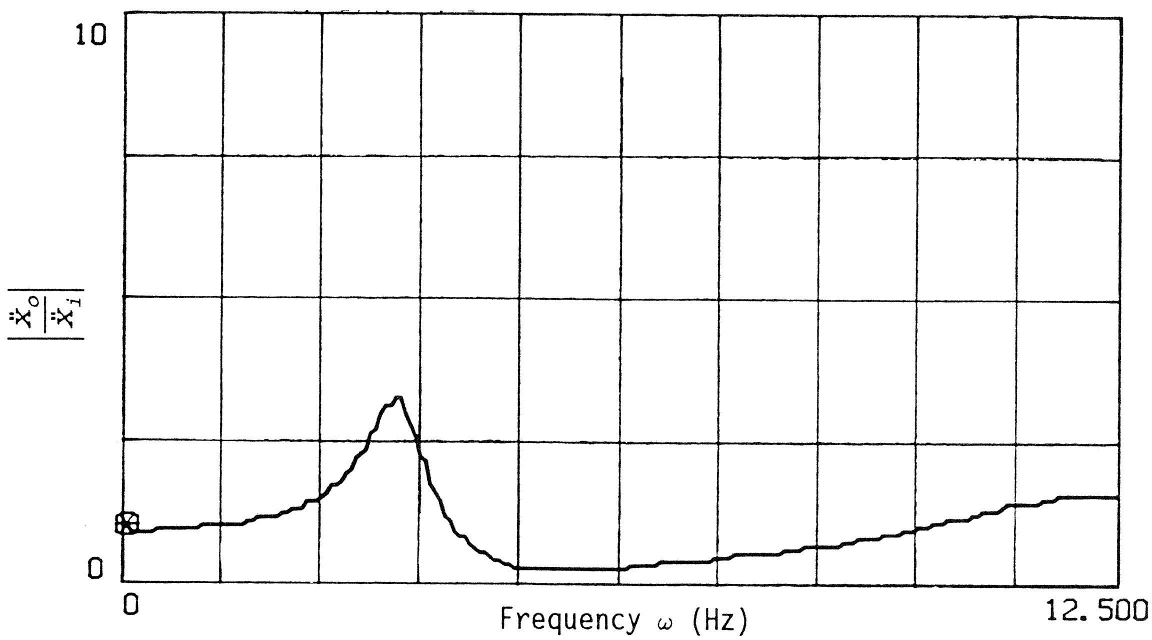
Fig. 3.3 Instrumentation of Model Structure

3.3 Dynamic Characteristics of The Test Structure

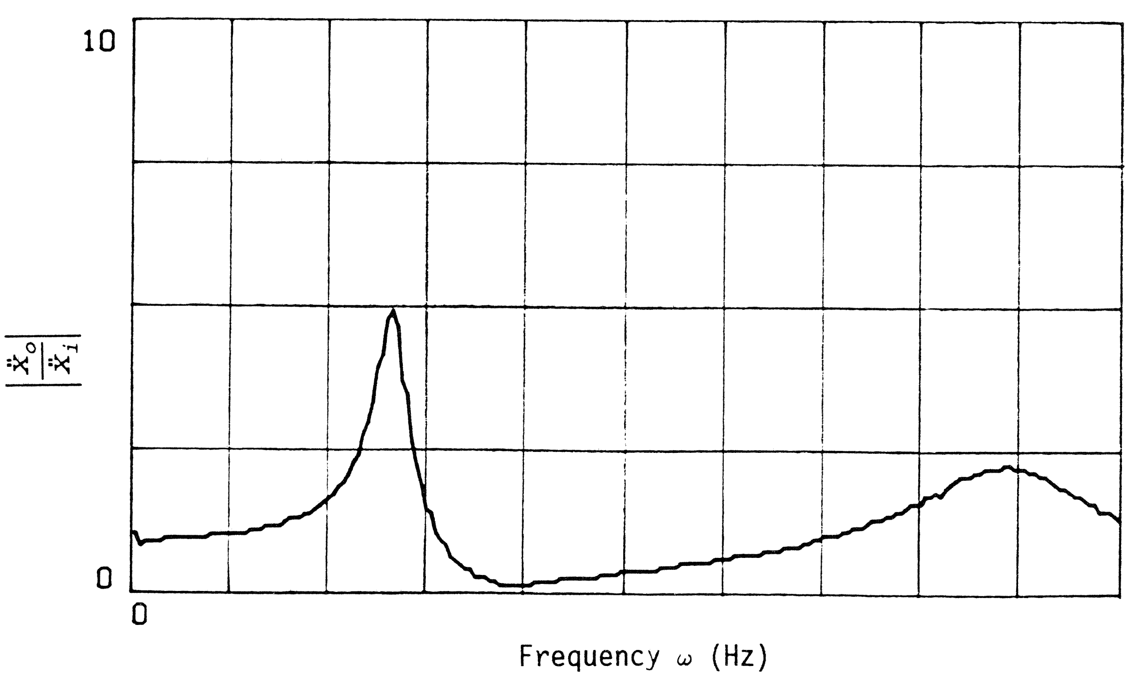
Based on the acceleration transfer function between signals of the structural response output and the white noise input, important dynamic characteristics of the structure such as natural frequencies and damping ratios can be obtained [10]. Figs. 3.4a and 3.4b show two typical transfer functions at the third floor at ambient temperatures of 25°C and 30°C, respectively. It is clear from these two figures that, due to the added viscoelastic dampers, higher modes of vibration become insignificant as compared to the first mode. Therefore, only the damping ratios associated with the first vibration mode under various ambient temperatures are calculated using the Half-Power Method.

Figs. 3.5a and 3.5b show the temperature dependence of the dynamic characteristics of the test structure under five controlled ambient temperatures. Also shown in the figures are the first natural frequency and damping ratio of the structure without added viscoelastic dampers. These two figures indicate that, while structural damping increases significantly with the addition of viscoelastic dampers, both the natural frequency and damping ratio of the structure become lower under increasing ambient temperature. When the ambient temperature is as high as 42°C, the natural frequency reduces to almost the same as that without dampers, and the structural damping decreases to less than a half of that at normal temperature (25°C). This can be realized from the results of damper tests described in the previous section that the stiffness and energy dissipation capacity of viscoelastic dampers decrease as a result of rising ambient temperature.

It should be noted that the damping ratios evaluated in this report using the Half-Power Method is considered to be reliable because they are generally less than 15% of critical damping [11].



T=25°C



T=30°C

Fig. 3.4 Absolute Acceleration Frequency Transfer Function, Third Floor

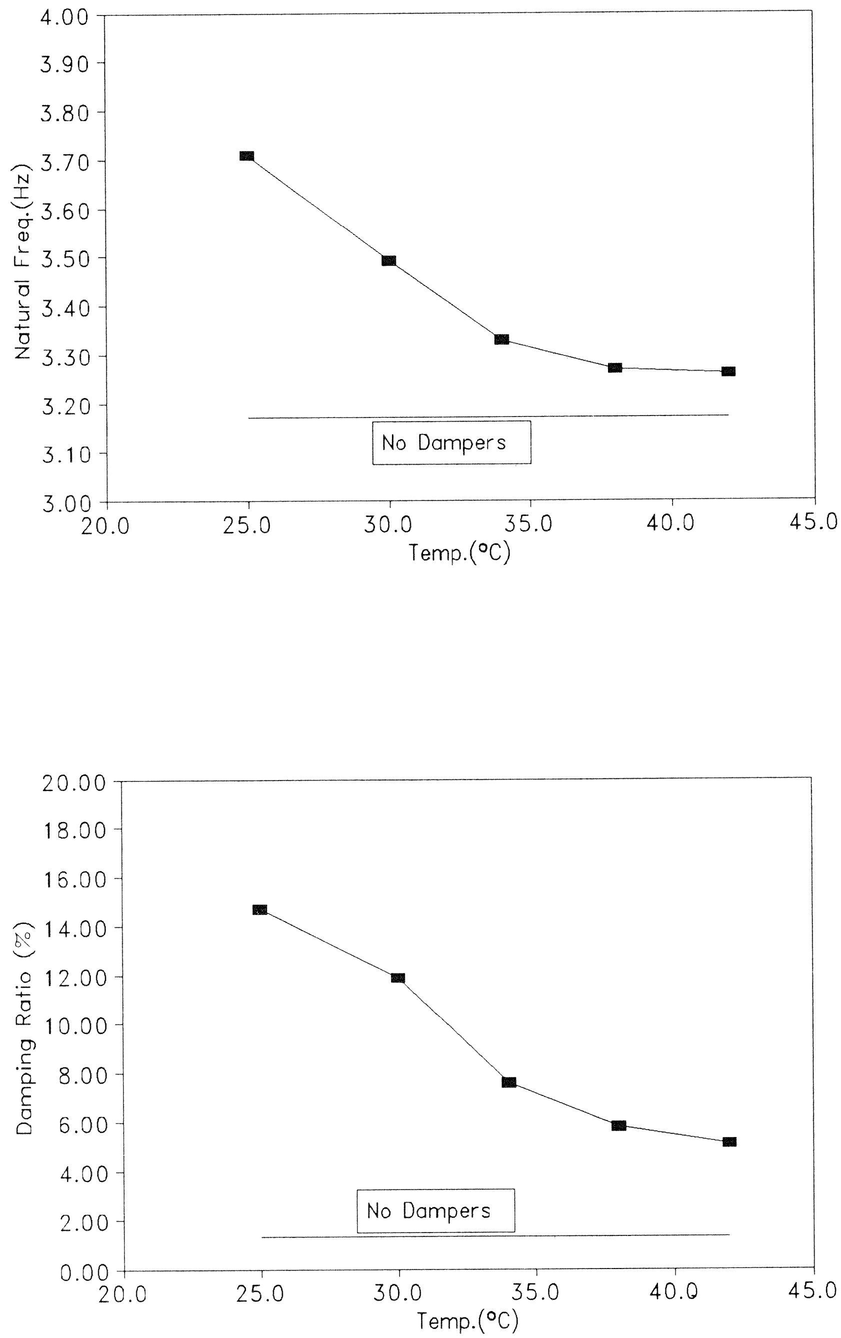


Fig. 3.5 Temperature Dependence of Structural Dynamic Characteristics

3.4 Dynamic Response of The Test Structure

Two criteria were considered in order to determine an appropriate earthquake record in this test program:

(1) The structure without added dampers will behave elastically without being damaged.

(2) The maximum effective damper strain will be less than 75% to prevent possible damage to the dampers.

Preliminary dynamic analyses using "DRAIN-2D" [14] were first carried out for the test structure with and without added viscoelastic dampers by assuming different damping ratios for the structure. A number of earthquake acceleration records scaled to different peak accelerations were used in the preliminary analyses. Numerical results showed that the Hachinohe earthquake with a peak acceleration of 0.12g could conservatively satisfy the above two criteria over the range of ambient temperature values selected for these tests.

Figs. 3.6a-3.6c show the dynamic response envelopes of the test structure without added dampers and with dampers at five different ambient temperatures. The influence of ambient temperature in seismic responses can be easily visualized by comparing the response envelope values at each floor level. Figs. 3.7a-3.7f, 3.8a-3.8f, 3.9a-3.9f show the effect of ambient temperature on time histories of the relative displacements at the roof, the inter-story drift in the second story, and the acceleration at the roof, rspectively. Also shown in these figures are the response of the structure without added dampers.

3.5 Discussion of Test Results

Figs.3.10a-3.10d show the temperature dependence of structural response on the maximum displacement, maximum floor acceleration, maximum inter-story drift and maximum damper deformation, respectively. It can be seen that the

Fig.3.6a Max. Floor Displacement (in)
(0.12g Hachenoe Earthquake)

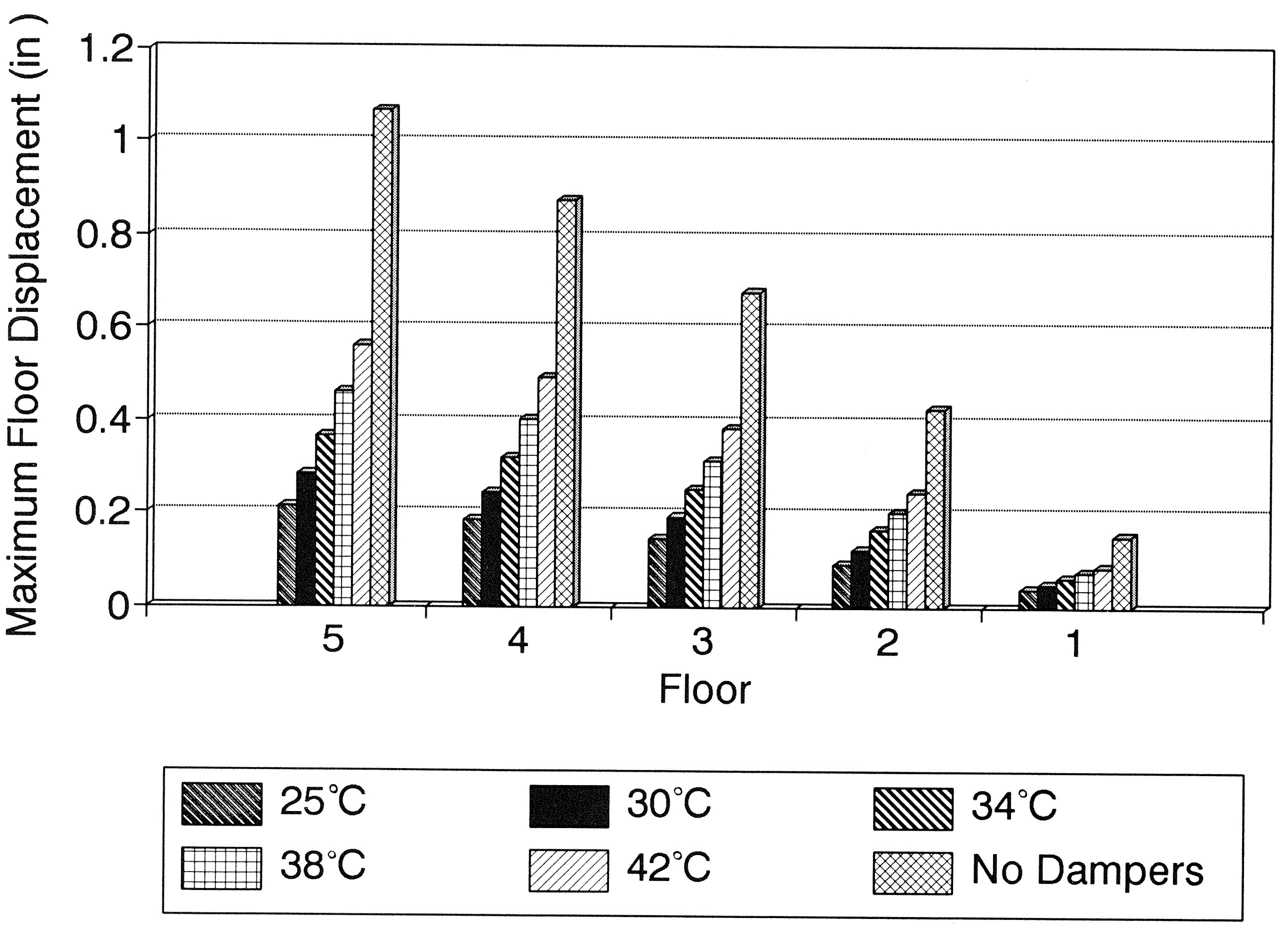
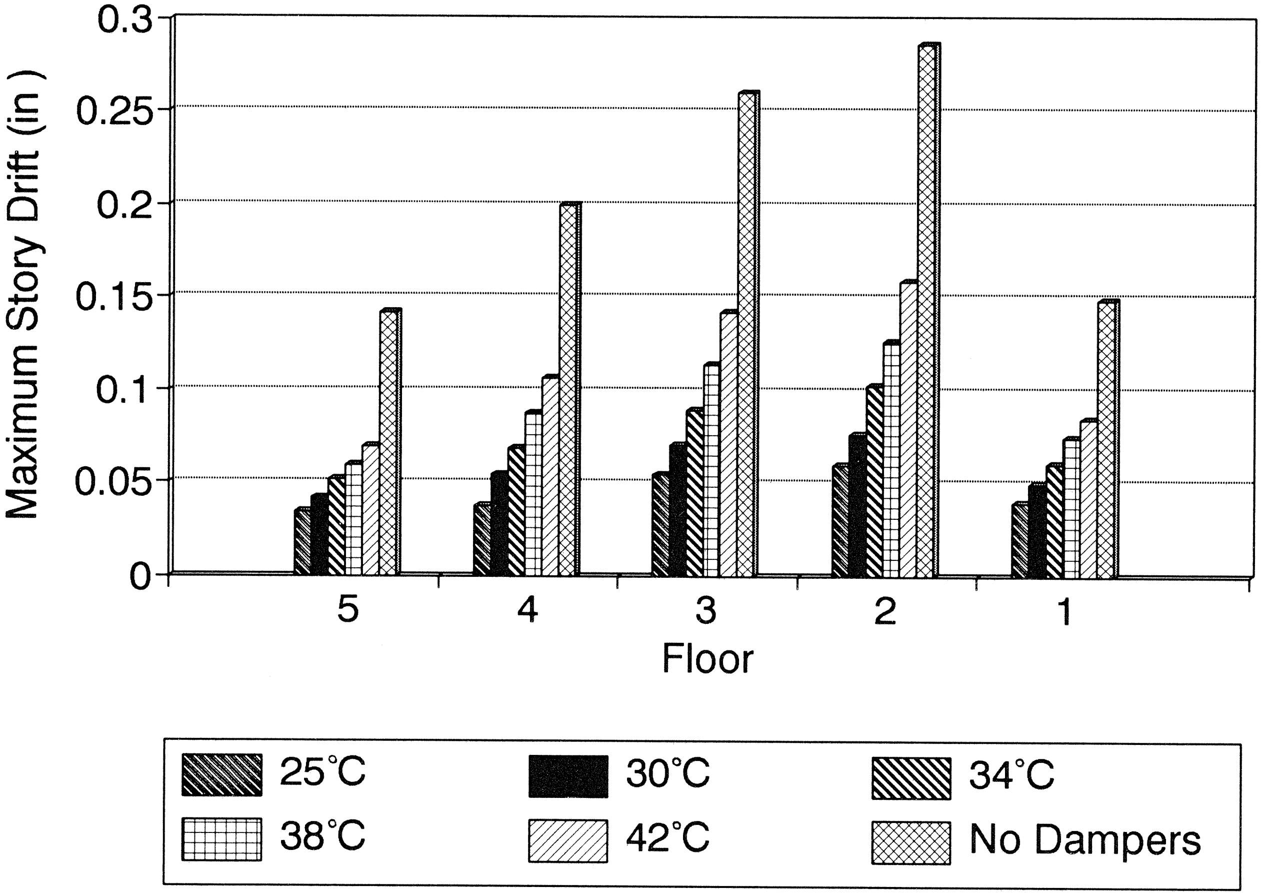


Fig.3.6b Maximum Story Drift (in)
(0.12g Hachenoe Earthquake)



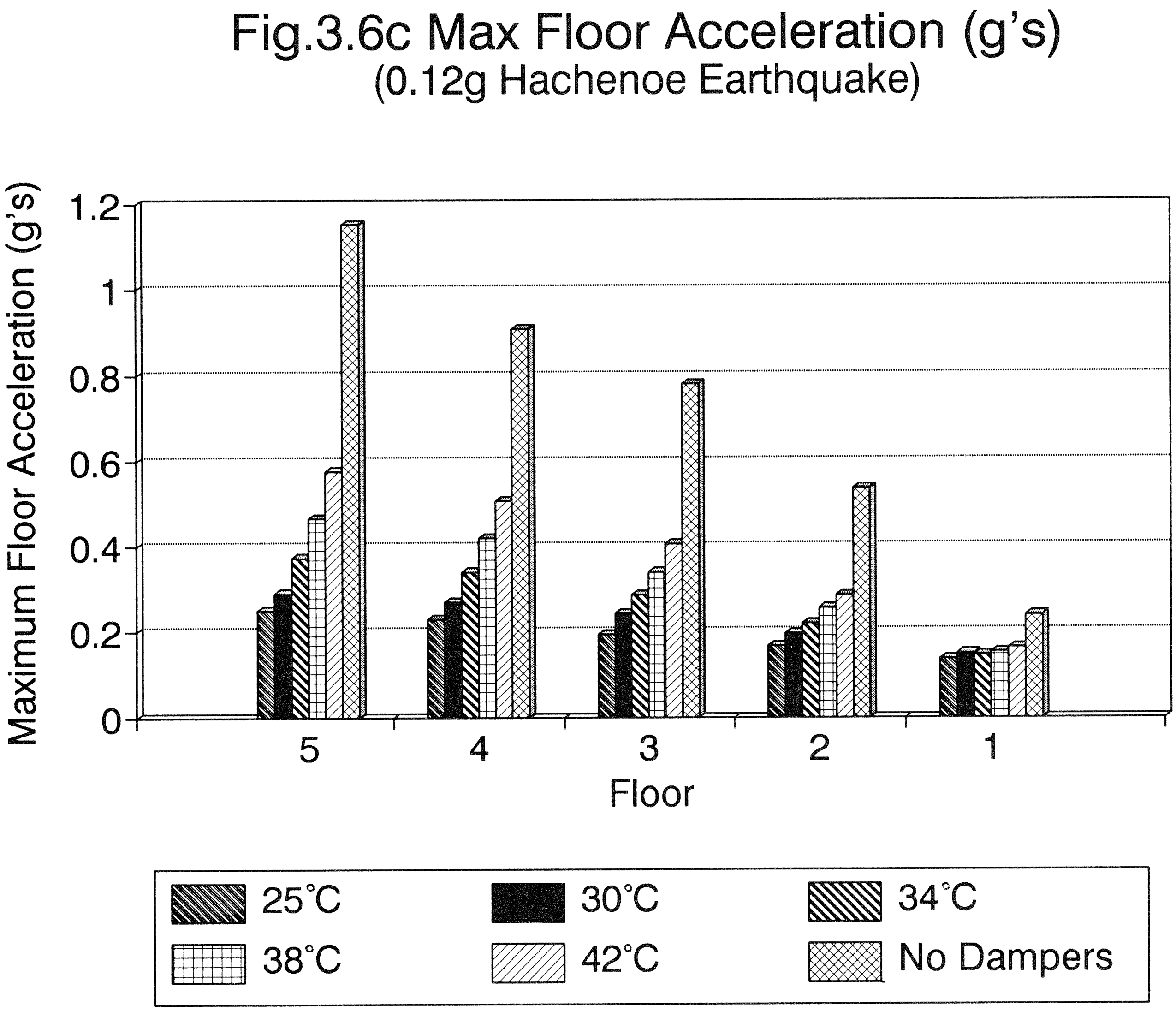


Fig.3.6c Max Floor Acceleration (g's)
(0.12g Hachenoe Earthquake)
Maximum Floor Acceleration (g's)
1.2
1
0.8
0.6
0.4
0.2
0
5
4
3
2
1
Floor
25˚C
30˚C
34˚C
38˚C
42˚C
No Dampers

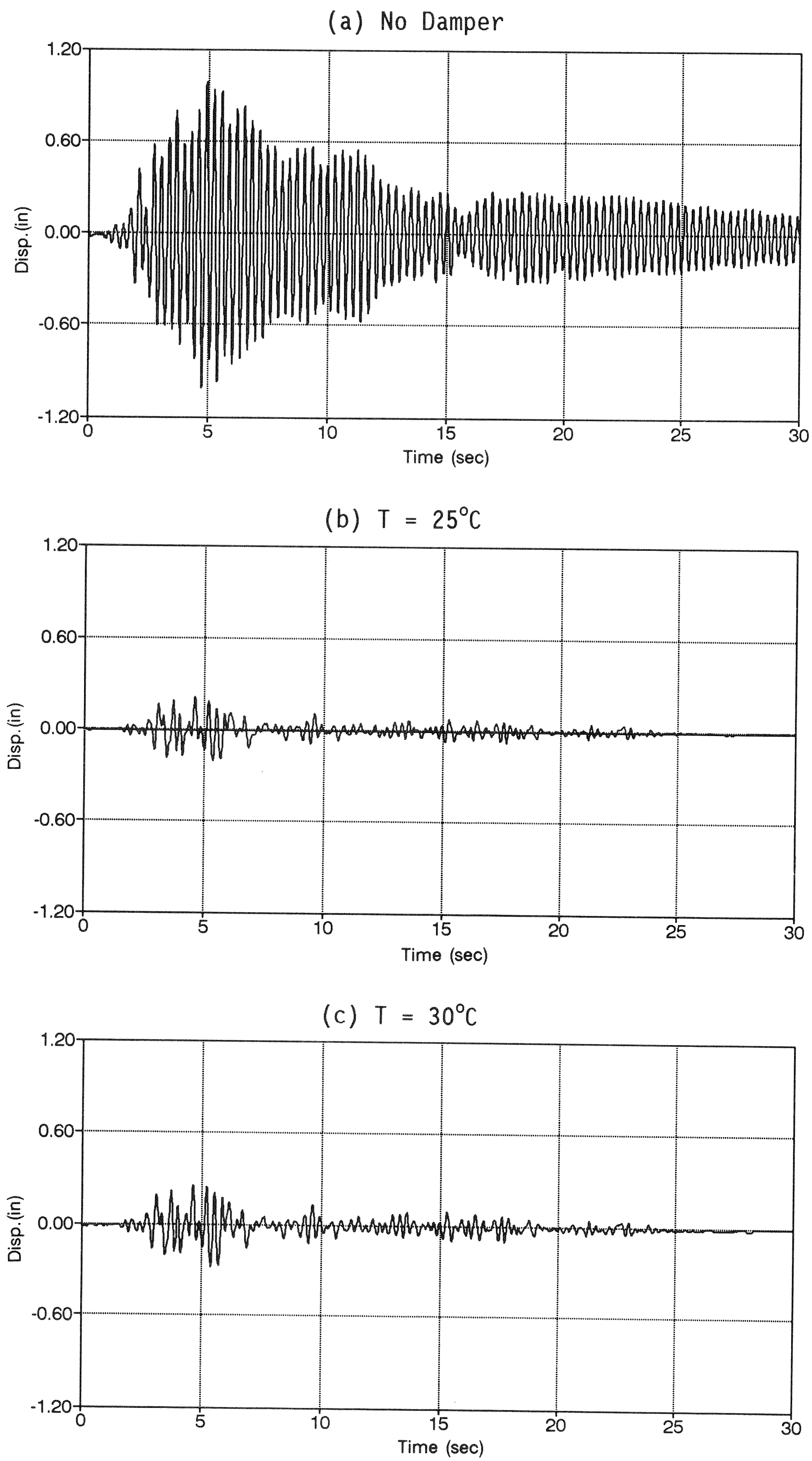
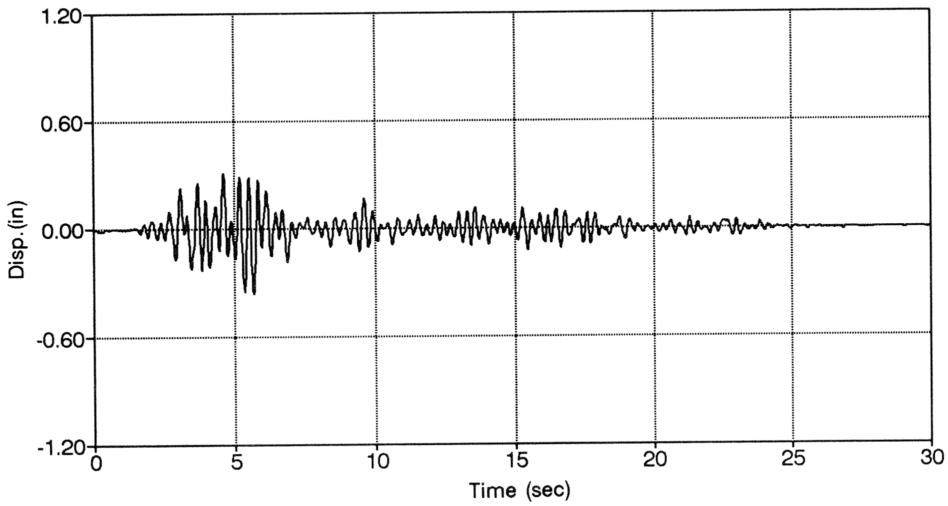
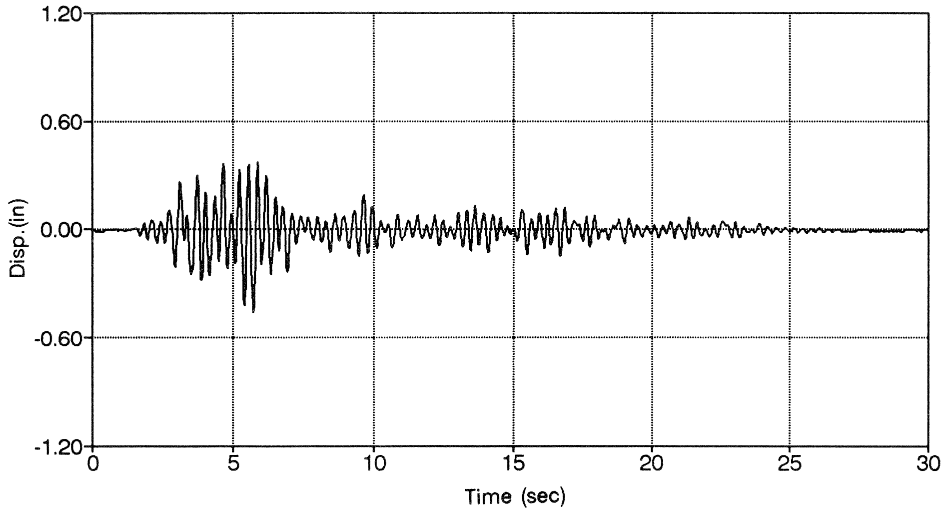


Fig. 3.7 Damper Effectiveness on Relative Displacement (5th. Fl.)

(d) T = 34°C



(e) T = 38°C



(f) T = 42°C

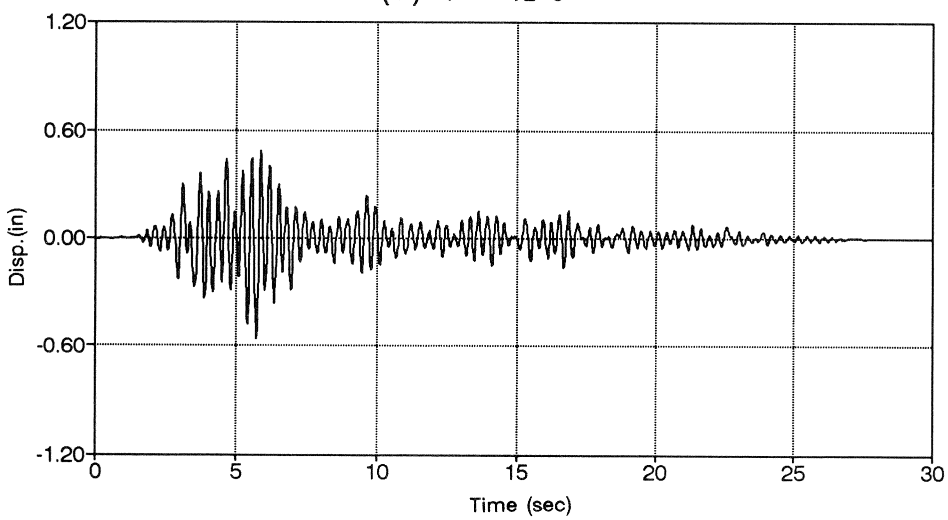


Fig. 3.7 (Cont'd.)

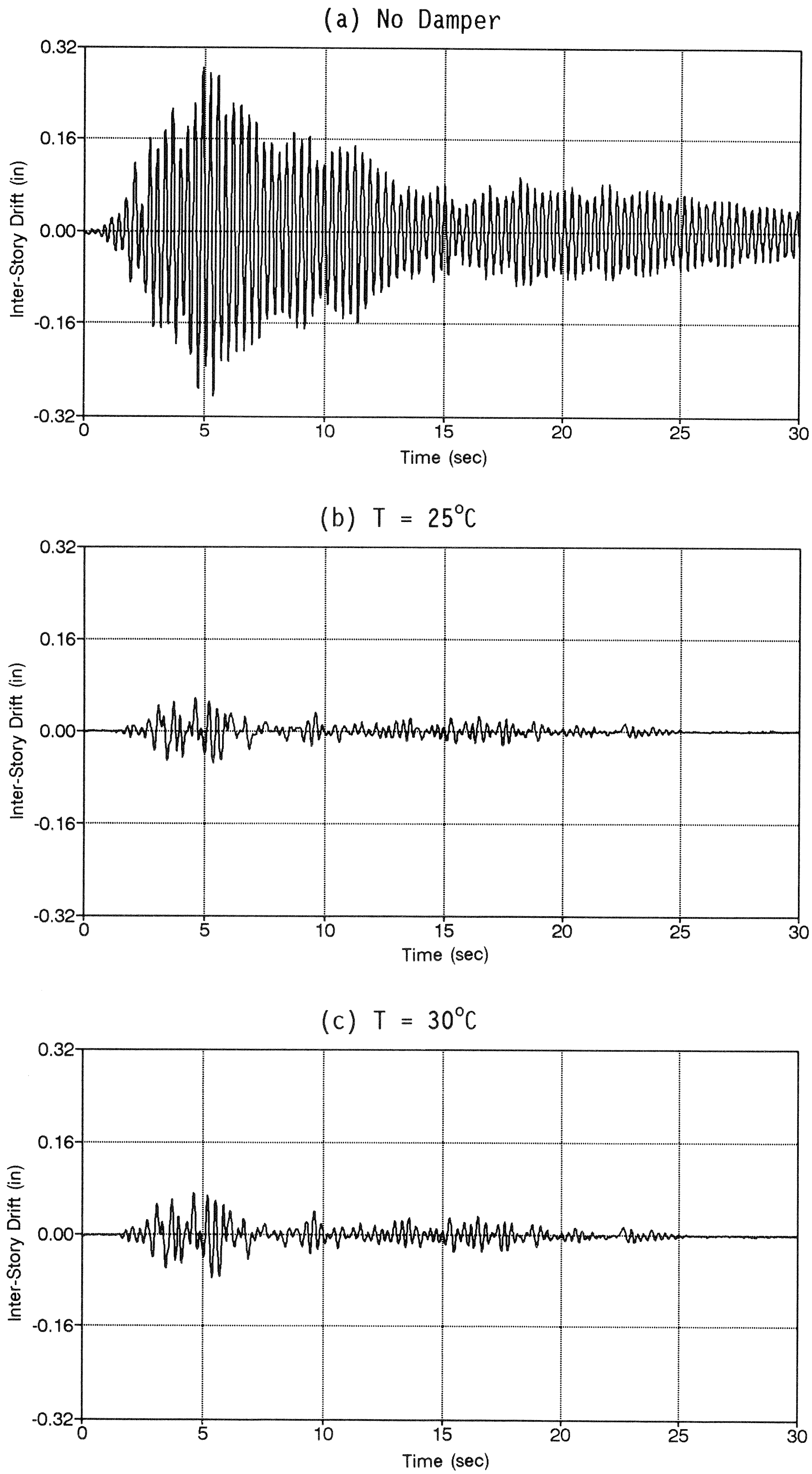
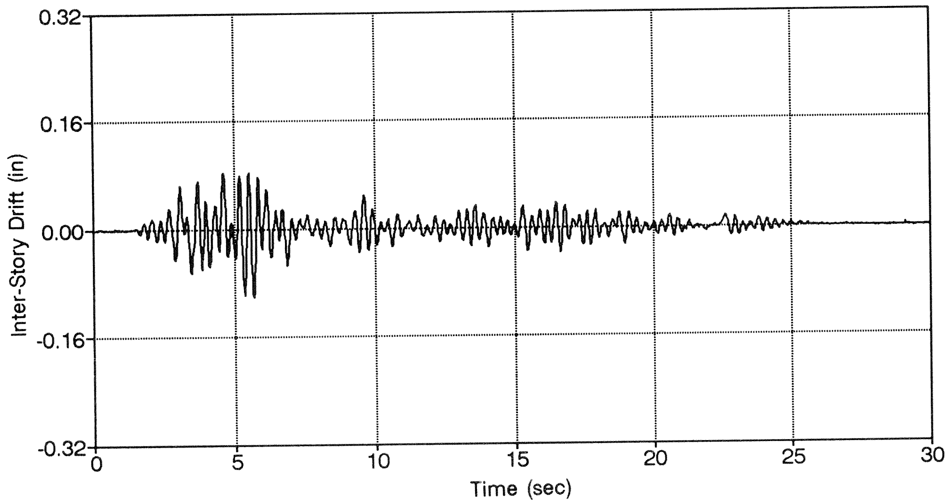
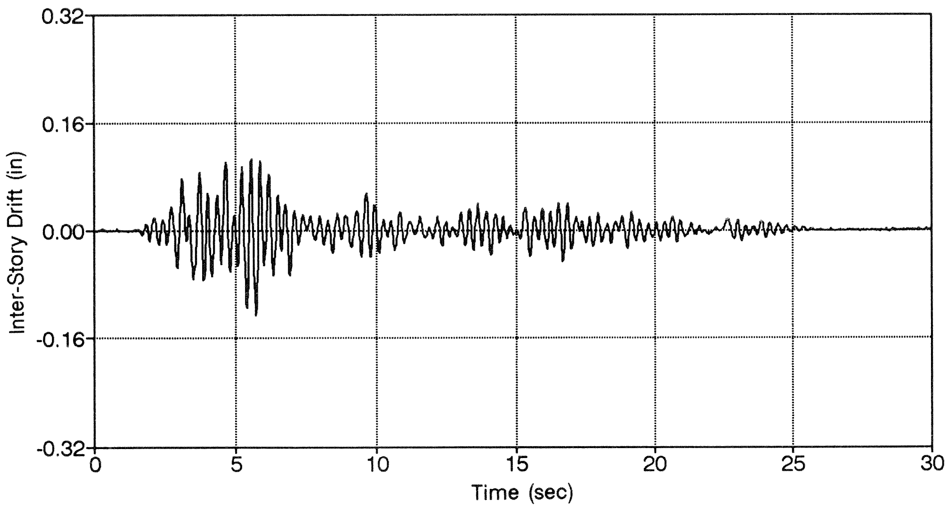


Fig. 3.8 Damper Effectiveness on Inter-Story Drift (1st.-2nd. Fl.)

(d) T = 34°C



(e) T = 38°C



(f) T = 42°C

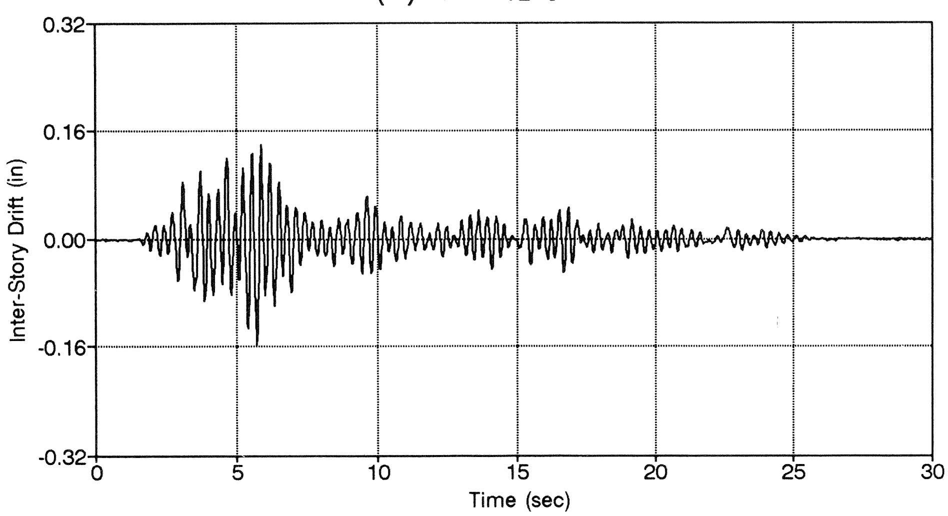


Fig. 3.8 (Cont'd.)

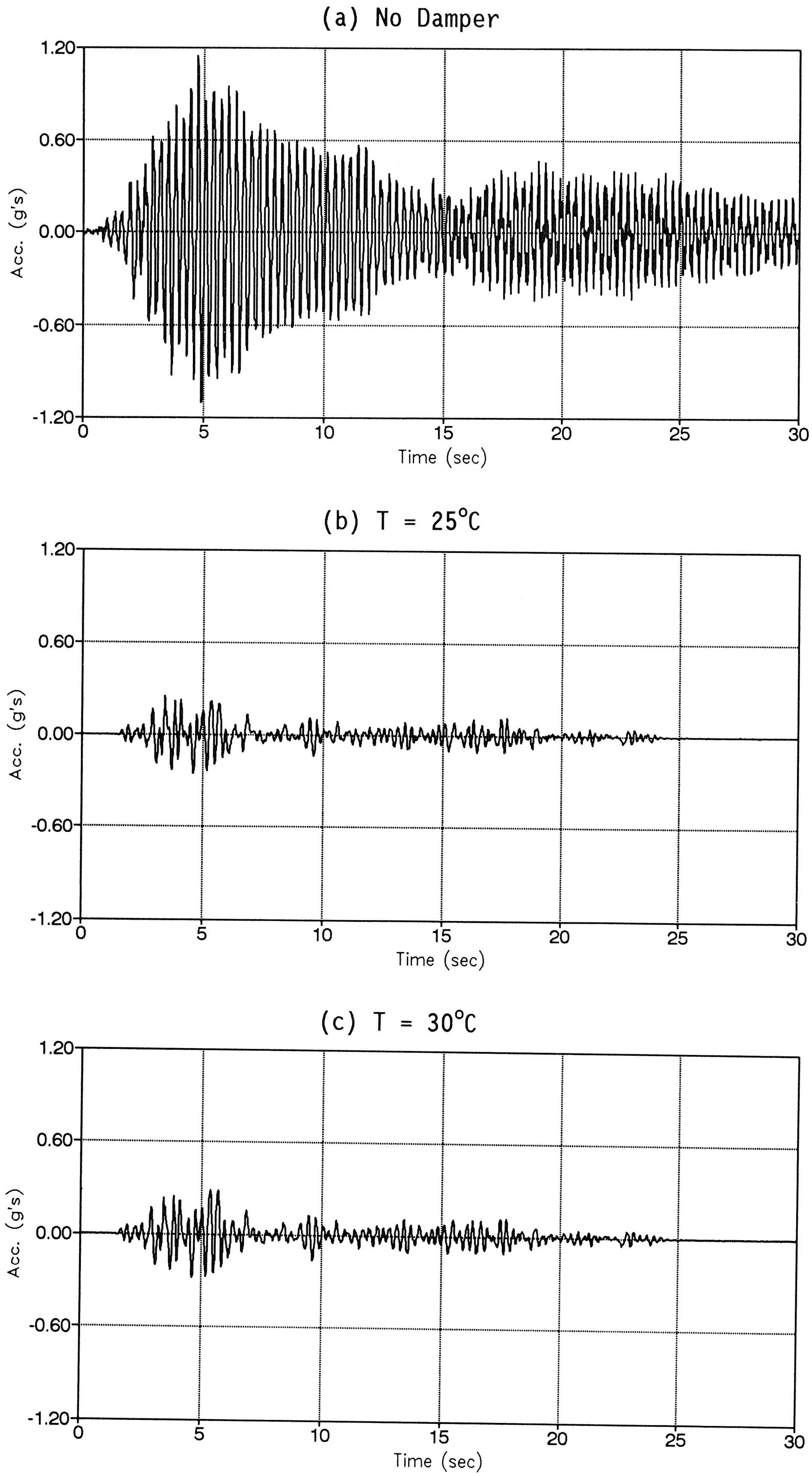


Fig. 3.9 Damper Effectiveness on Absolute Acceleration (5th. Fl.)

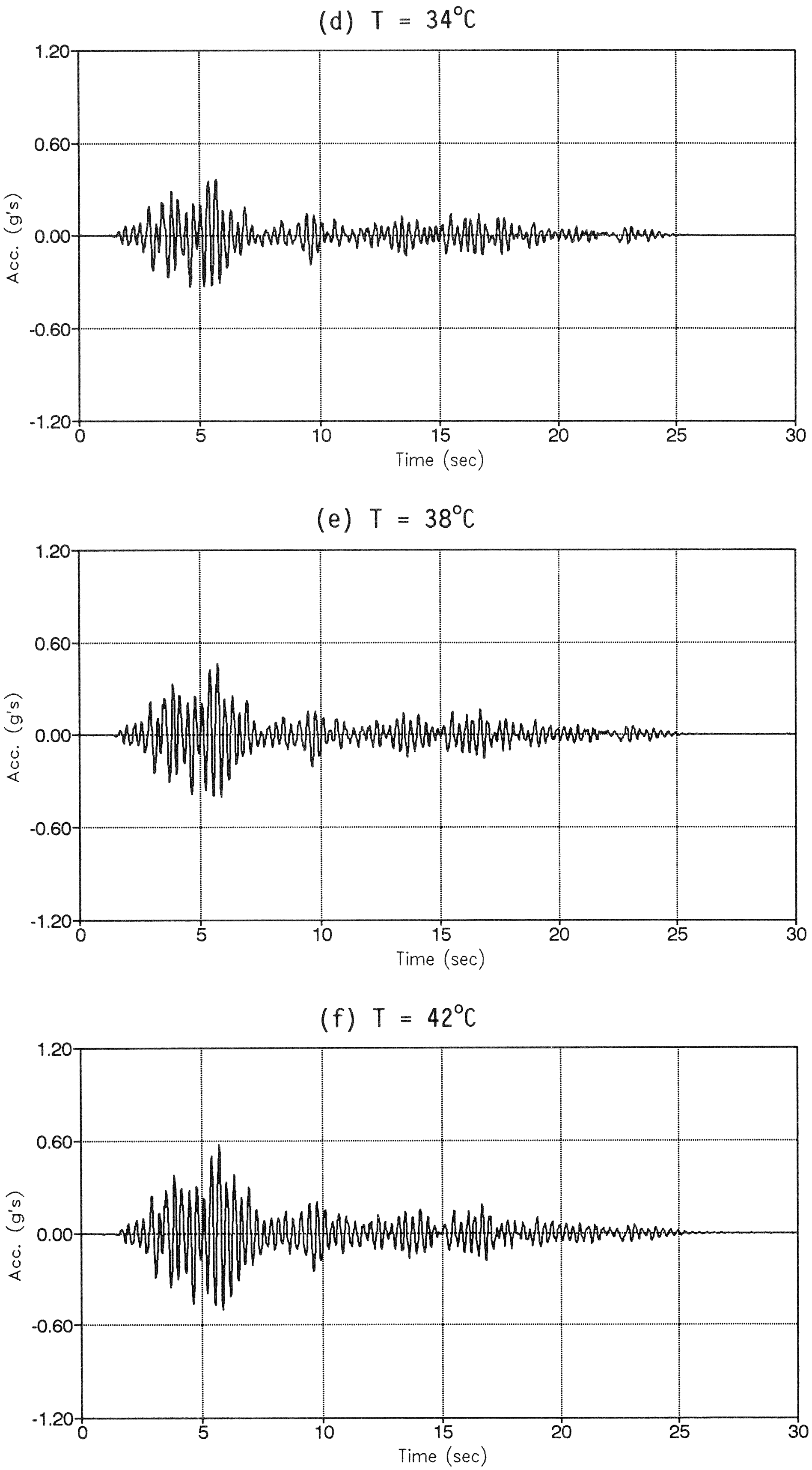

(d) T = 34°C
1.20
0.60
0.00
-0.60
-1.20
Acc. (g's)
0
5
10
15
20
25
30
Time (sec)
(e) T = 38°C
1.20
0.60
0.00
-0.60
-1.20
Acc. (g's)
0
5
10
15
20
25
30
Time (sec)
(f) T = 42°C
1.20
0.60
0.00
-0.60
-1.20
Acc. (g's)
0
5
10
15
20
25
30
Time (sec)

Fig. 3.9 (Cont'd.)

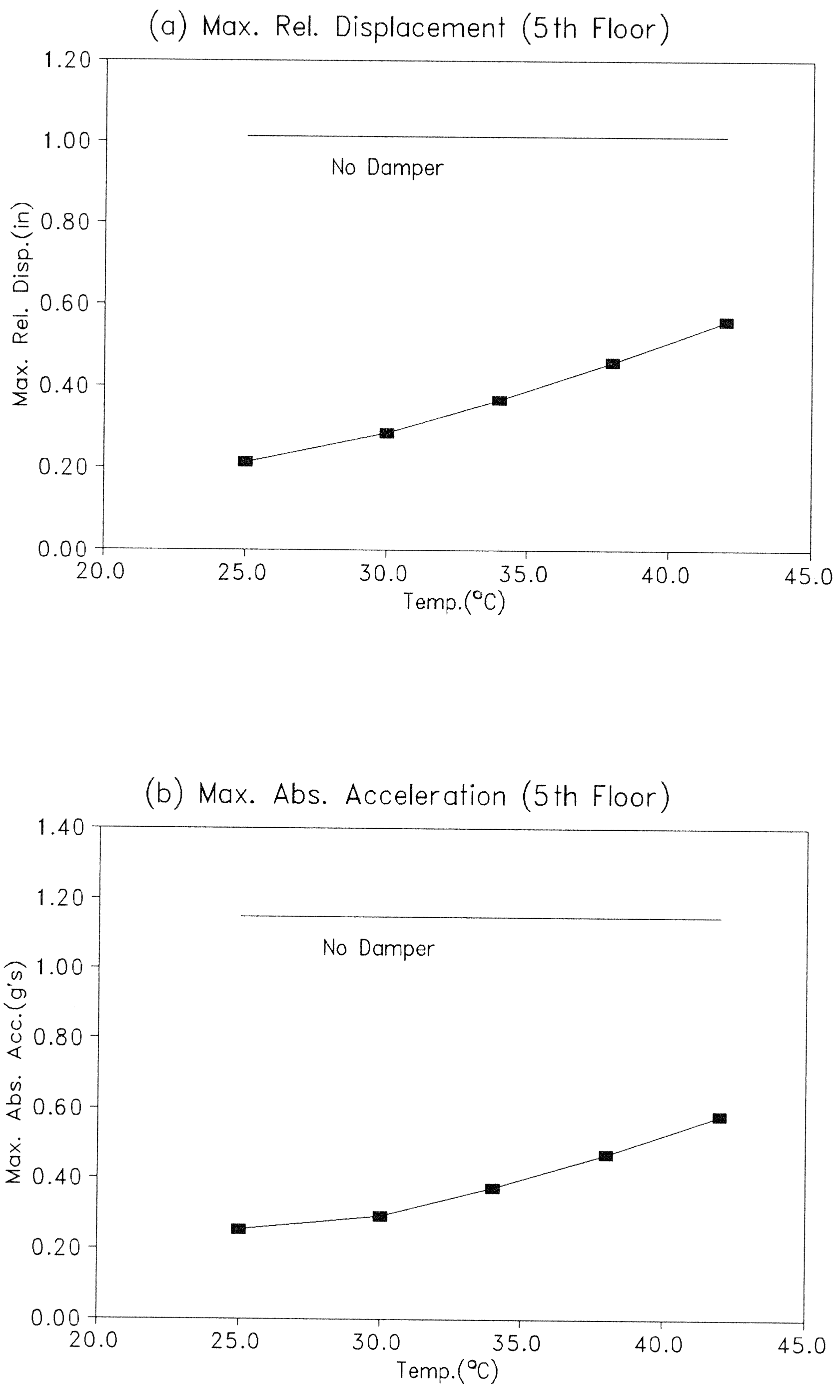
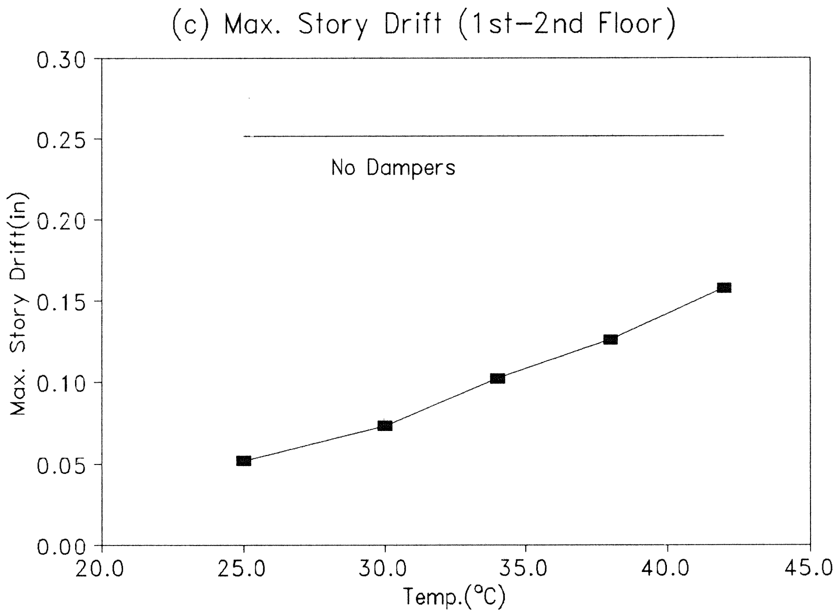


Fig. 3.10 Temperature Dependence of Structural Response



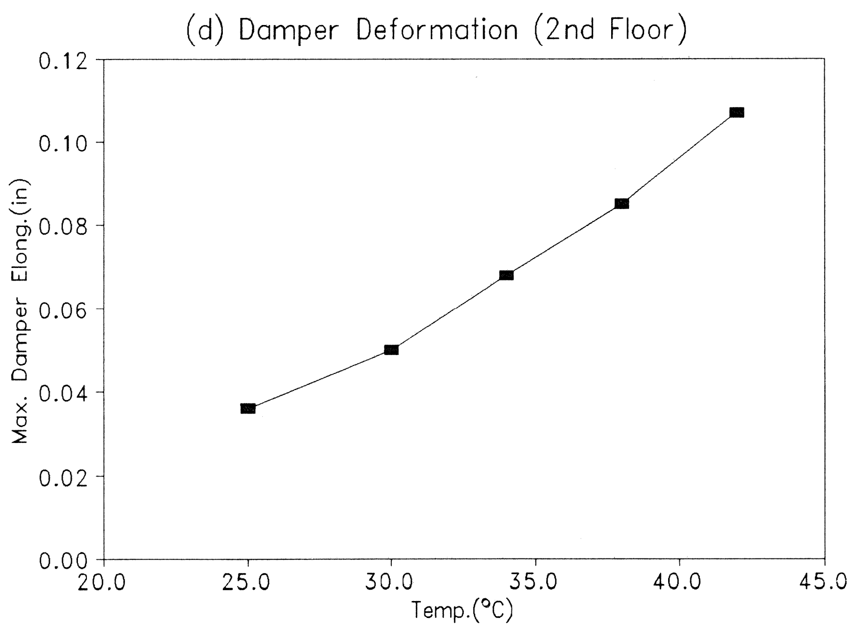


Fig. 3.10 Temperature Dependence of Structural Response (Cond.)

effectiveness of added viscoelastic dampers reduces almost linearly with increasing temperature. The damper deformation also increased with temperature, due to the softening effect in the viscoelastic material. However, even at the highest temperature, the viscoelastically damped structure can still achieve a reduction of more than 40% of the structural response without added dampers.

Figs. 3.11a-3.11c show maximum response of the test structure as a function of the structural damping ratio. It is seen that the dampers increasingly reduce maximum relative displacement, maximum story drift and maximum absolute acceleration with increased damping ratio. The range of most effective damping ratios appears to be 0 to 8%.

Tables 3.2a and 3.2b summarize comparisons of the dynamic response at each floor of the structure with added viscoelastic dampers subjected to the 0.12g Hachinohe earthquake and 0.12g white noise input excitation, respectively, under five different ambient temperatures. The values are given in percent reduction of the dynamic response in the no-damper case. It can be seen that the added viscoelastic dampers effectively reduce the maximum dynamic response of the structure. The effect of temperature on dampers' effectiveness is also shown by the reduced percentage effectiveness. At 42°c (108°F), the efficiency reduces to about 40%.

Fig. 3.12 shows the maximum temperature rise within the viscoelastic material during the earthquake excitation, which is less than 1.5°C for all five ambient temperatures tested. It can thus be concluded that earthquake excitations have minimal effect on the temperature rise in the viscoelastic material of the damper. This is a similar conclusion to the results obtained previously [5].

Based upon the observations made above, it is important to design viscoelastic dampers for the expected maximum ambient temperature to ensure adequate damping for the building. However, the temperature rise in the damper

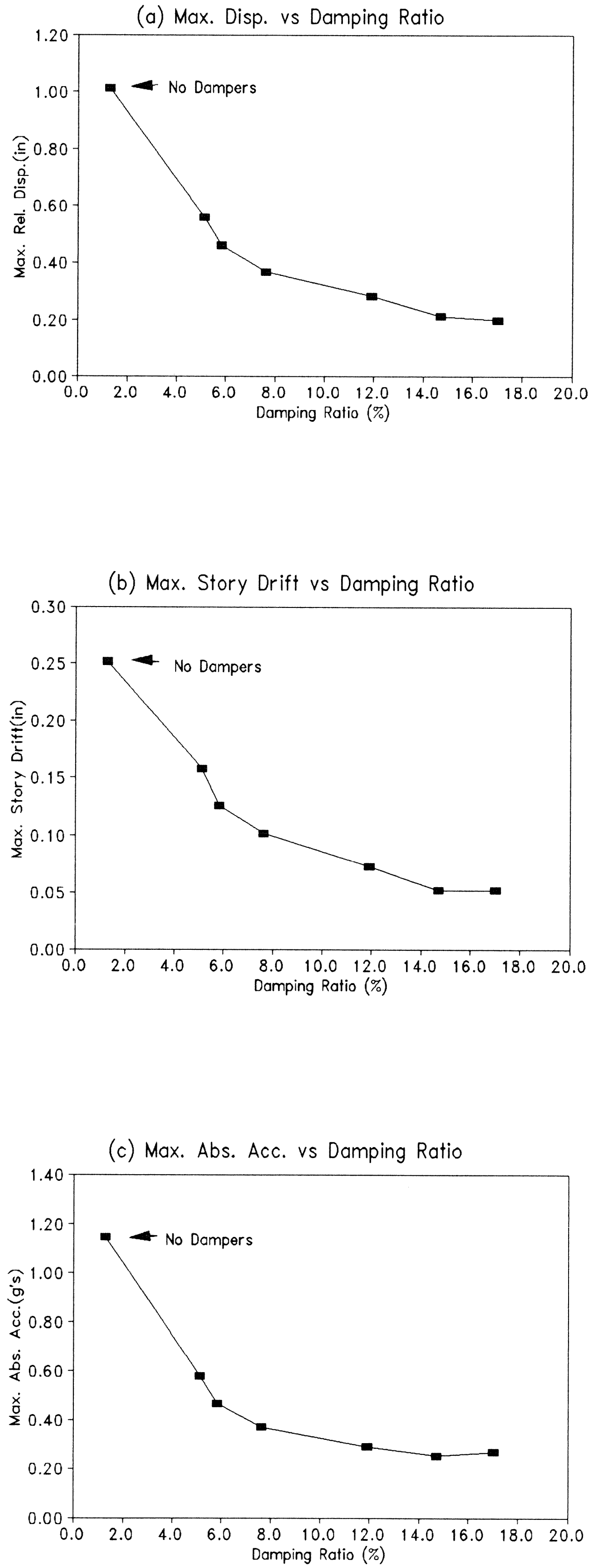


Fig.3.11 Maximum Structural Response as A Function of Damping Ratio

Maximum Response	Floor Level	No Dampers Reference	With Dampers (% reduction of No-Damper Case)				
			T=25°C	T=30°C	T=34°C	T=38°C	T=42°C
Relative Floor Disp. (inch)	5	1.066	80.1	73.5	65.7	56.8	47.6
	4	0.874	79.1	72.3	63.6	54.1	43.9
	3	0.677	78.6	71.9	63.1	53.6	43.4
	2	0.426	78.6	71.4	62.0	53.1	43.2
	1	0.149	73.8	67.1	59.7	50.3	43.6
Inter-story drift (inch)	5	0.142	76.1	70.4	63.4	58.5	51.4
	4	0.200	81.0	73.0	66.0	56.5	47.0
	3	0.260	79.2	73.1	65.8	56.2	45.4
	2	0.286	79.4	73.4	64.3	55.9	44.8
	1	0.148	73.6	66.9	59.5	50.0	43.2
Maximum Floor Acc. (g's)	5	1.151	78.2	74.8	67.8	59.5	49.9
	4	0.909	74.8	70.2	62.8	54.0	44.1
	3	0.777	74.9	68.7	63.2	56.2	48.0
	2	0.538	69.1	63.4	58.9	52.6	46.8
	1	0.241	43.6	38.2	38.6	36.5	32.0

Table 3.2a Summary of Dynamic Response under 0.12g Hachenoe Earthquake Motion

Maximum Response	Floor Level	No Damper Reference	With Dampers (% reduction of No-Damper Case)				
			T=25°C	T=30°C	T=34°C	T=38°C	T=42°C
Relative Floor Disp. (inch)	5	0.696	81.9	81.3	76.4	70.7	66.7
	4	0.588	83.3	80.1	75.0	69.9	66.7
	3	0.484	84.3	80.8	75.6	71.1	68.6
	2	0.328	83.5	79.6	75.6	71.6	69.5
	1	0.116	76.7	73.3	70.7	65.5	63.8
Inter-Story Drift (inch)	5	0.152	78.3	82.2	78.3	75.0	73.0
	4	0.164	86.0	84.1	78.7	73.2	70.1
	3	0.178	82.0	82.0	74.2	68.5	65.2
	2	0.214	85.0	82.7	77.1	72.4	68.2
	1	0.116	76.7	73.3	70.7	65.5	63.8
Max. Floor Accel. (g's)	5	1.222	85.7	85.1	81.1	77.0	73.9
	4	0.856	82.5	80.5	76.8	72.5	69.4
	3	0.988	86.5	85.2	81.5	78.7	77.8
	2	0.948	84.6	84.7	84.7	80.1	78.4
	1	0.658	74.6	75.2	77.4	75.2	76.4

Table 3.2b Summary of Dynamic response under 0.12g White Noise Motion

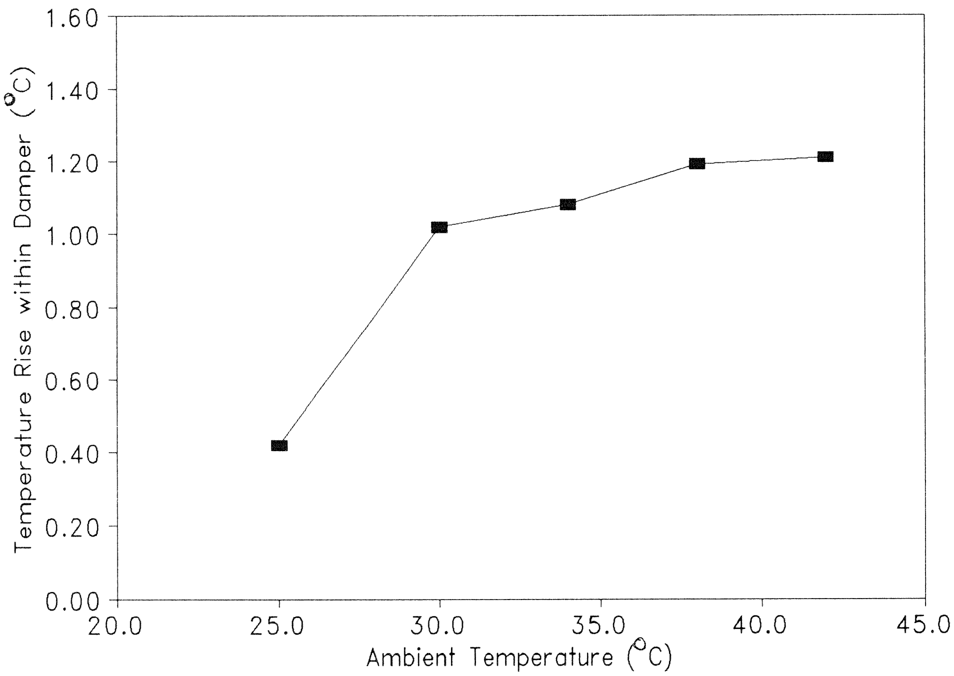


Fig. 3.12 temperature Rise within Damper Material under 0.12g Hachinohe Earthquake

during operation is relatively insignificant compared to the effect of the ambient temperature.

SECTION 4

NUMERICAL SIMULATIONS

In the previous section, we have once again shown the effectiveness of applying viscoelastic dampers to improve the seismic behavior of structures. We have also demonstrated the effect of temperature on the seismic response of viscoelastically damped structure. In this section, numerical simulations are carried out to predict the equivalent structural damping and seismic structural response of the test structure under various ambient temperatures.

4.1 Estimation of Structural Damping

Viscoelastically damped structures dissipate seismic input energy through added damping provided by the added viscoelastic dampers. In order to insure the effectiveness of these dampers, it is very important that we first be able to predict the amount of equivalent structural damping due to the added dampers. In a recent study [13], by assuming a proportionally damped system, the resultant damping ratio for the i^{th} mode of the structure with added dampers can be expressed as

$$\xi_i = \frac{E_d{}^i}{4\pi E^i} \tag{4.1}$$

where

ξ_i = structural damping ratio for the ith vibration mode

$E_d{}^i$ = Energy dissipated in one cycle by the dampers for the ith vibration mode

E^i = strain energy of the structure of the ith vibration mode

The above equation can also be expressed in terms of modal strain energy as [12,15]:

$$\xi_i = \frac{\eta_v}{2} \frac{\Phi_i^T K_d \Phi_i}{\Phi_i^T K_s \Phi_i} \tag{4.2}$$

where

Φ_i = ith modal shape vector

K_d = Structural stiffness matrix due to the contribution of dampers alone

K_s = Structural stiffness matrix including the contribution of dampers.

η_v = loss factor of the viscoelastic damper

In this section, we only calculate the structural dynamic properties associated with the first mode of vibration since the higher mode response of the test structure with added dampers are relatively insignificant, as reported in the previous section.

Table 4.1 shows the damper properties used in the numerical study. These values are obtained from the empirical formulae derived in Section 2 by assuming an average 5% strain of dampers. Figs. 4.1a and 4.1b show both the experimental and the predicted first natural frequency and structural damping using Equation 4.2. As can be seen, the natural frequency and equivalent structural damping of the viscoelastically damped structure under various ambient temperatures can be satisfactorily predicted using the modal strain energy method.

4.2 Simulation of Dynamic Structural Response

Numerical simulations on dynamic response of the test structure under various ambient temperatures were carried out using the general purpose program DRAN-2D [14]. The damping ratios obtained from the experiments were used in the

Table 4.1 Damper Properties used in Numerical Simulation

T(°C)	ω (Hz)	γ (%)	K_d(lb/in)	η
25	3.71	5	4421	1.11
30	3.49	5	2840	1.11
34	3.33	5	2044	1.11
38	3.27	5	1569	1.09
42	3.26	5	1248	1.08

analysis. Figs. 4.2a-4.4b show the experimental results and the numerical simulations on the dynamic response of the viscoelastically damped structure at ambient temperature of 25°C, 34°C and 42°C, respectively, and Figs. 4.5a,b show the dynamic response of the structure without added dampers. It can be seen that they generally agree very well with each other. It is also interesting to observe that numerical simulations of the structure with added dampers agree better with the experimental results than those of the structure without added dampers. One reasonable explanation to this may be due to modeling of the equivalent structural damping. For the viscoelastically damped structure the added damping provided by the dampers which can be reliably modeled dominates the dynamic response of the structure. For the structure without added dampers the effect of inherent structural damping which normally varies during the vibration significantly affects the accuracy of the numerical simulation.

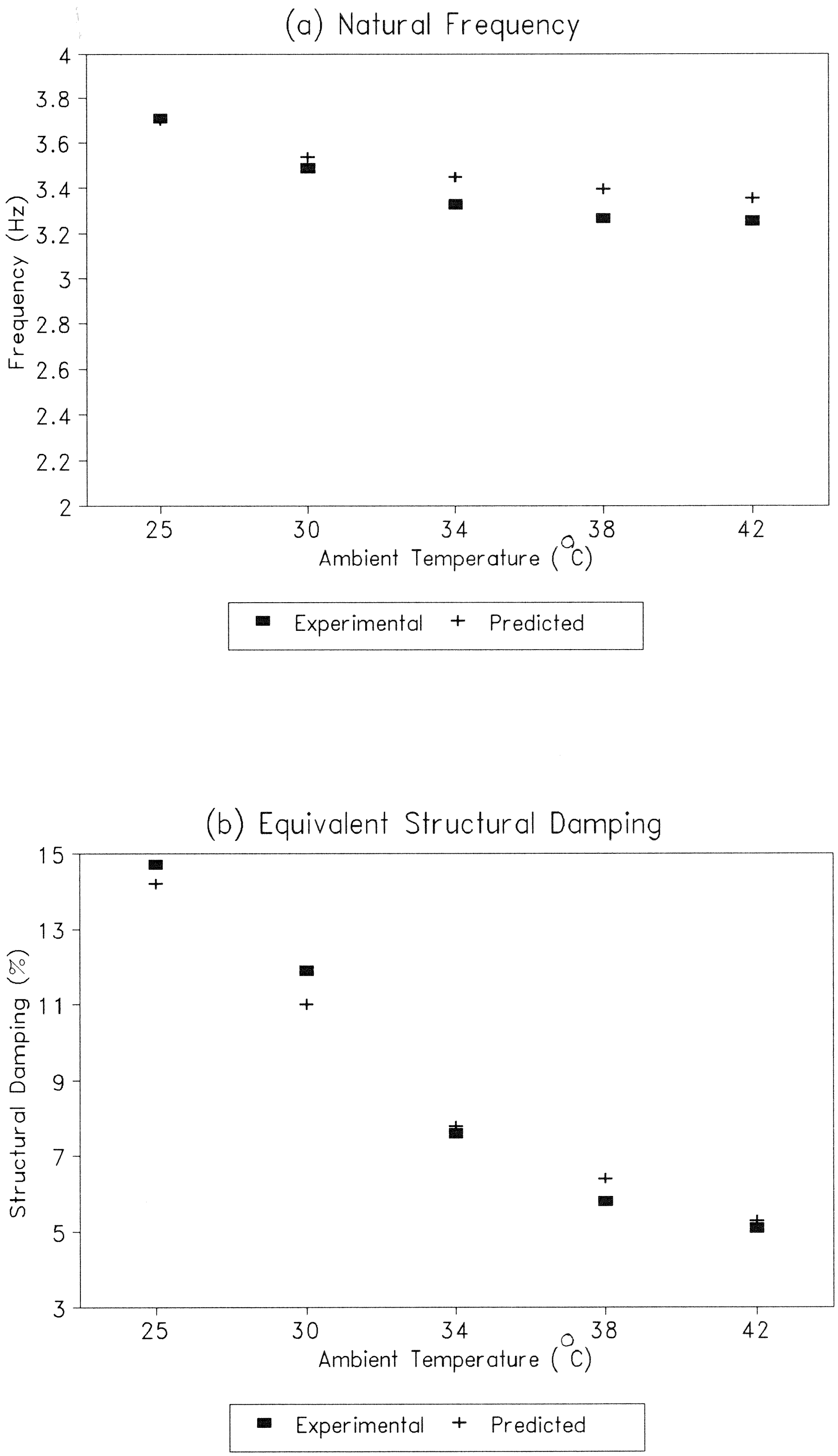


Fig. 4.1 Prediction of Dynamic Structural Properties

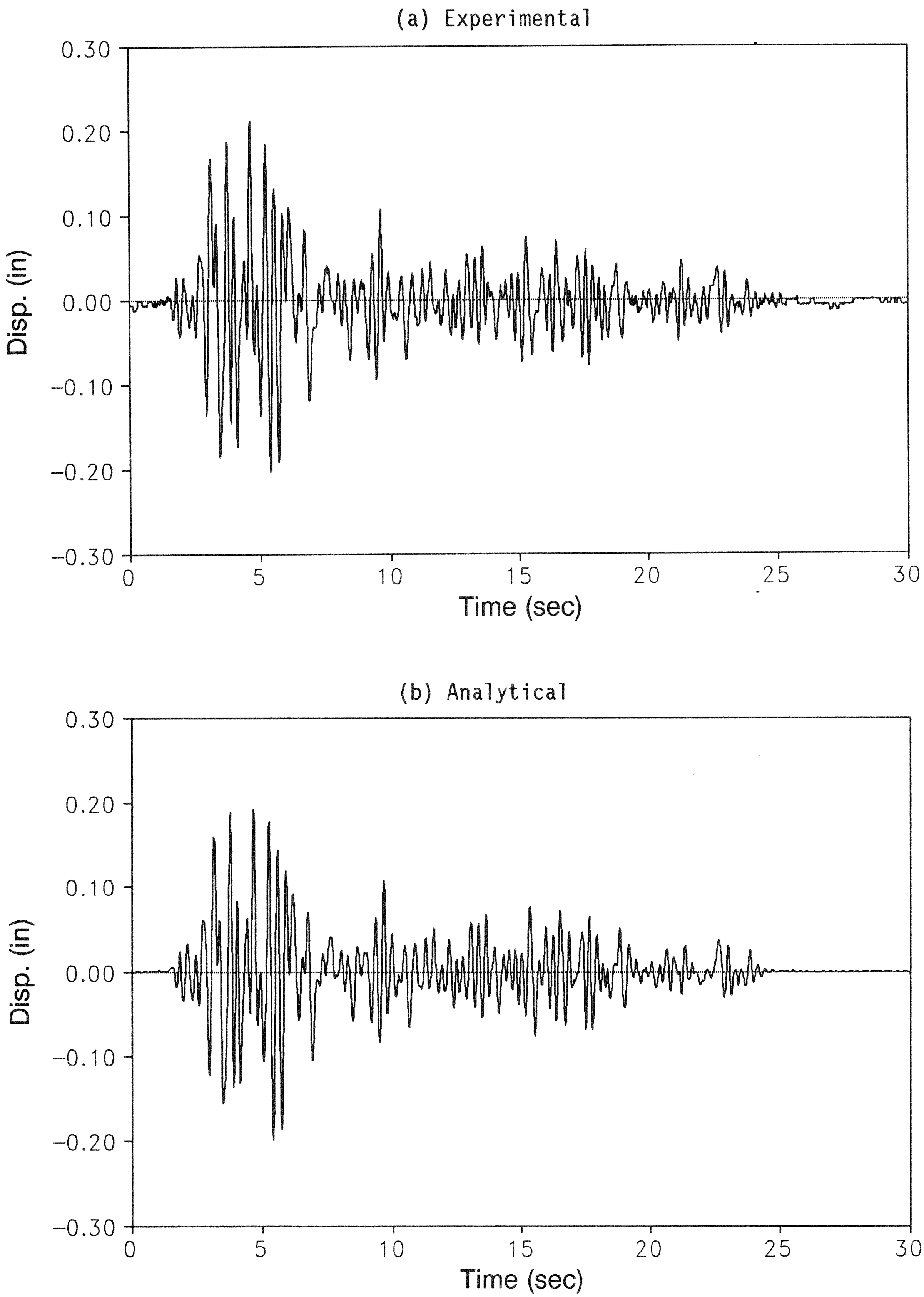
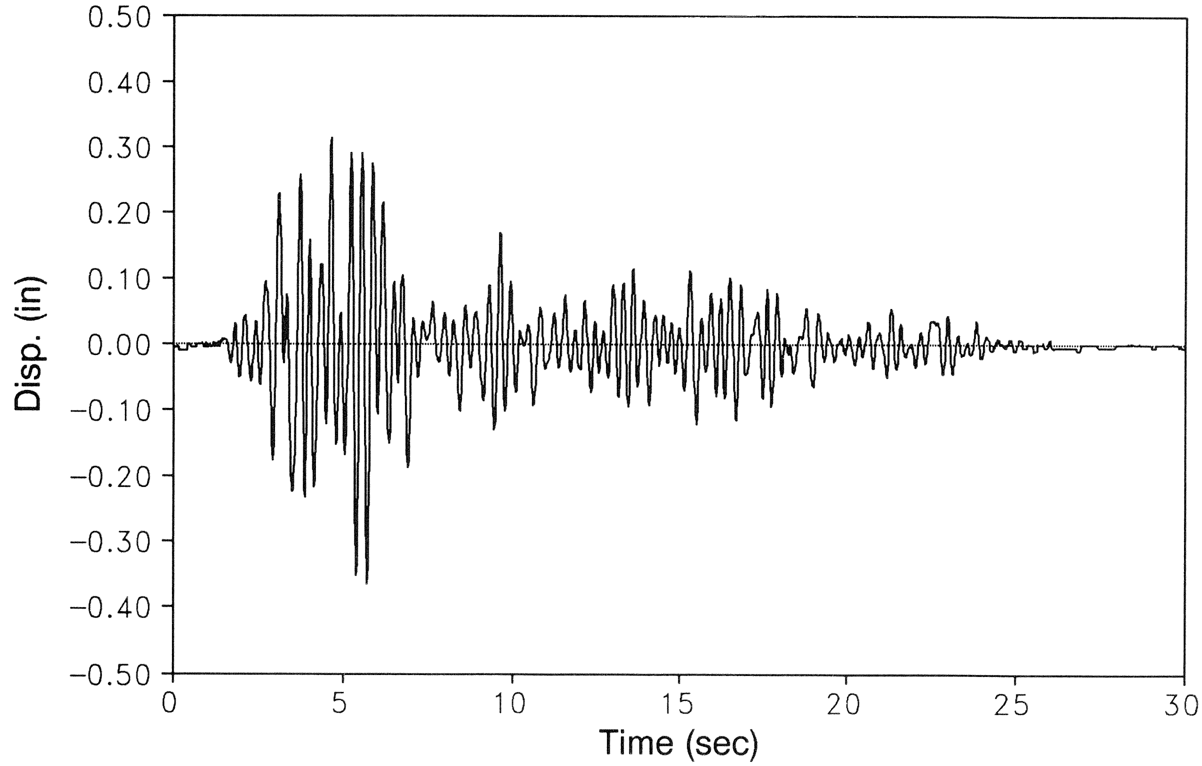


Fig. 4.2 Fifth Floor Relative Displacement, T=25°C

(a) Experimental



(b) Analytical

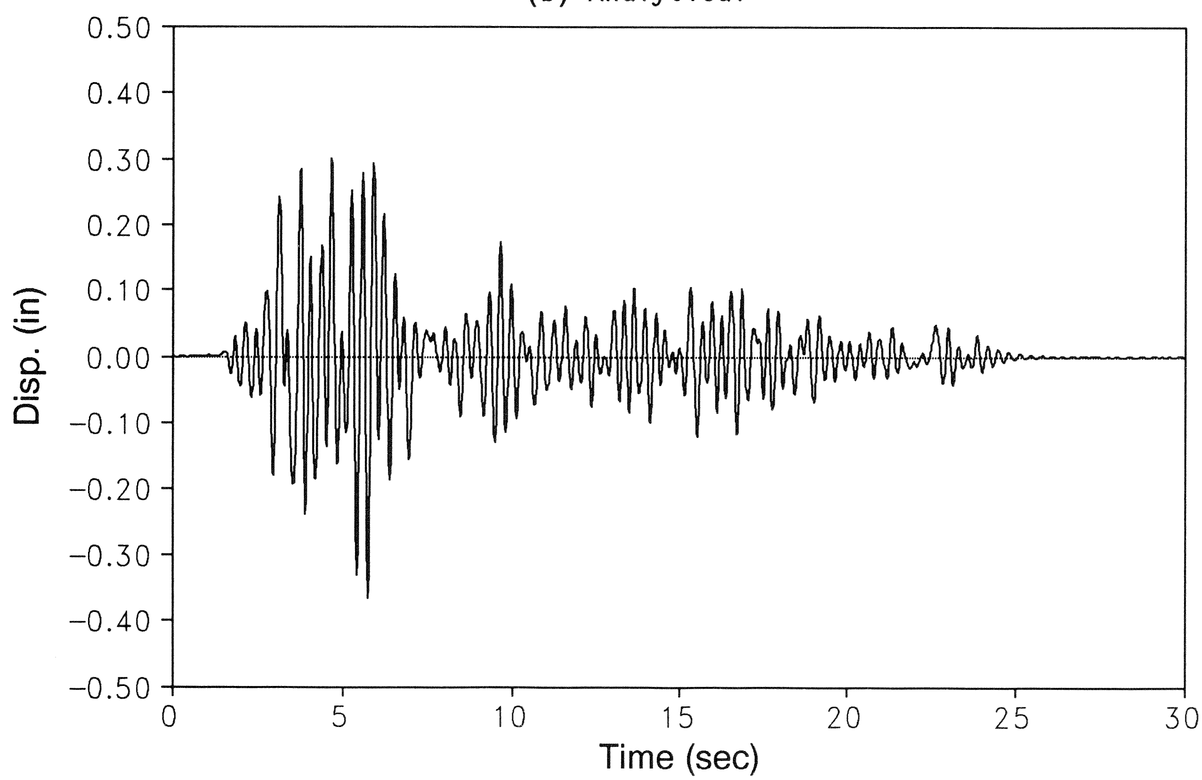
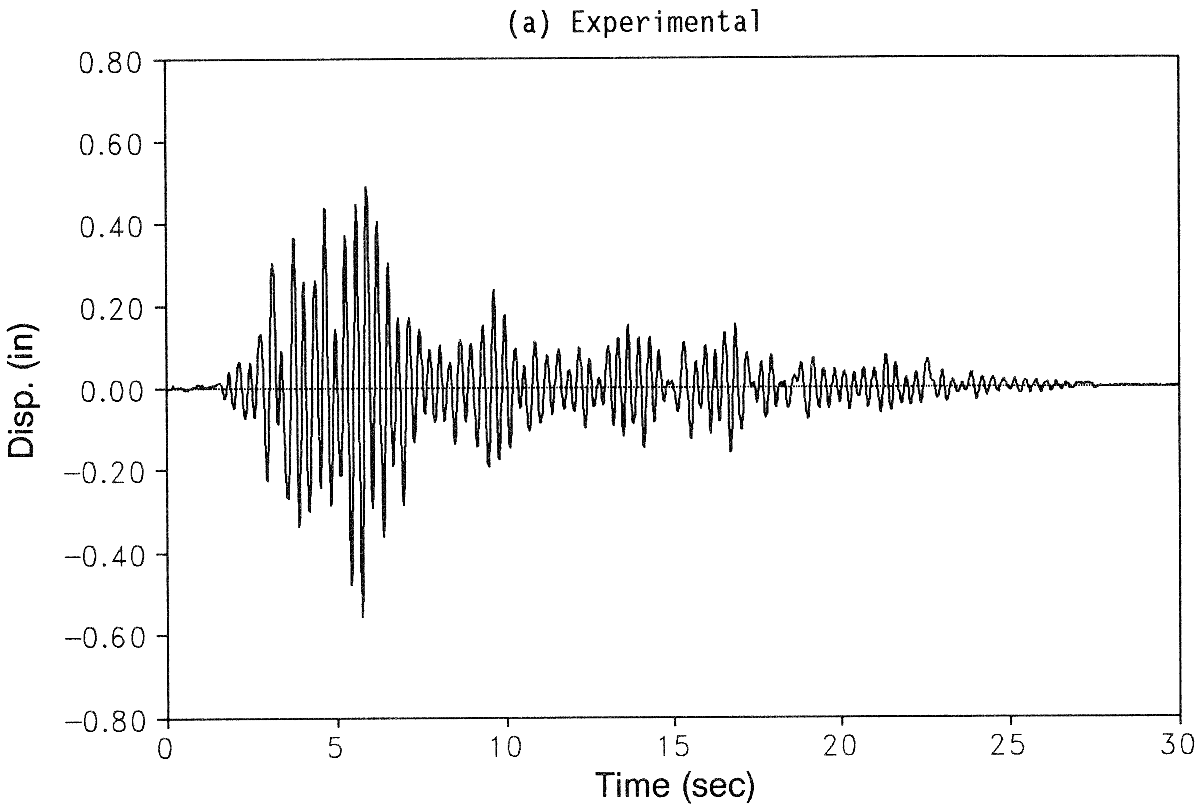


Fig. 4.3 Fifth Floor Relative Displacement, T=34°C



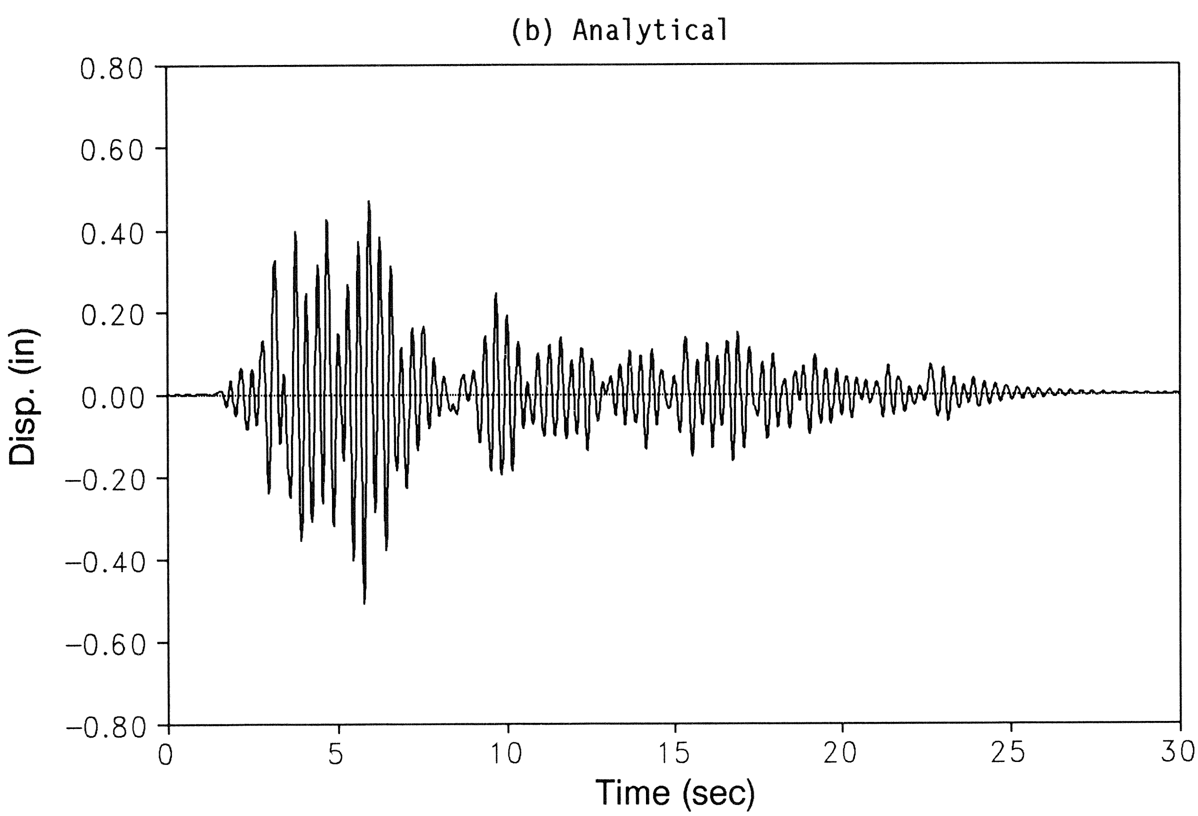
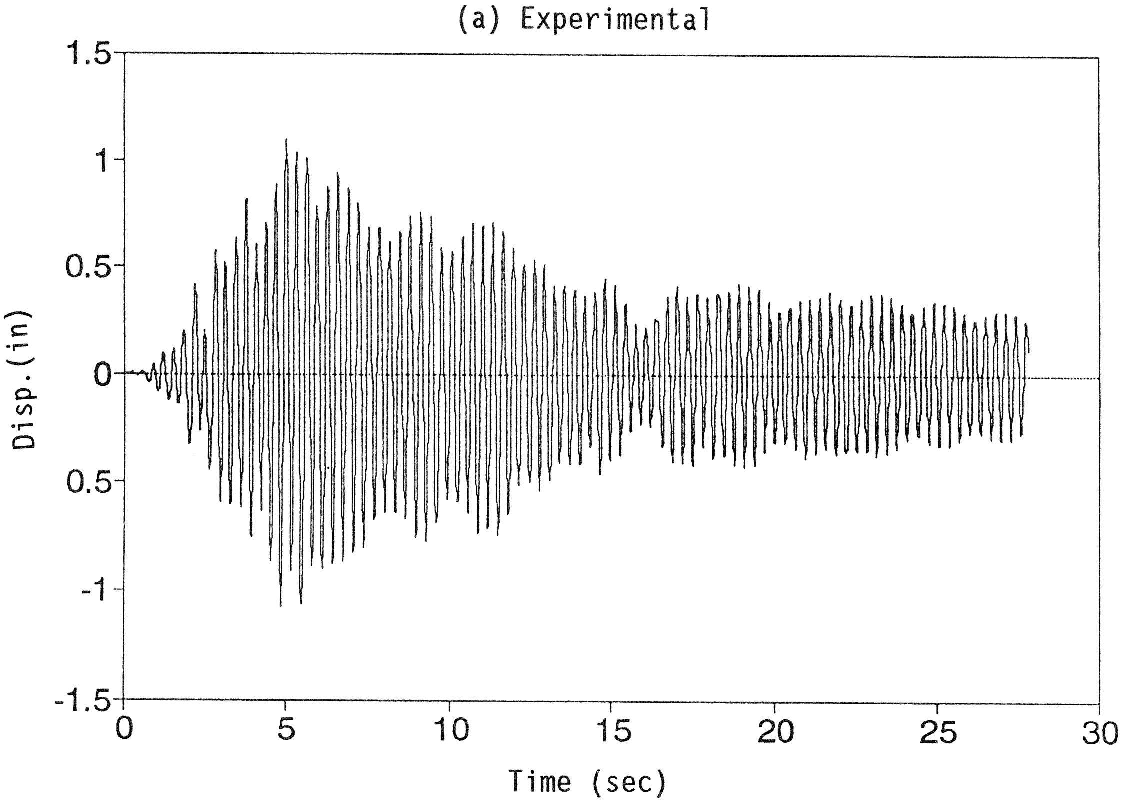


Fig. 4.4 Fifth Floor Relative Displacement, T=42°C



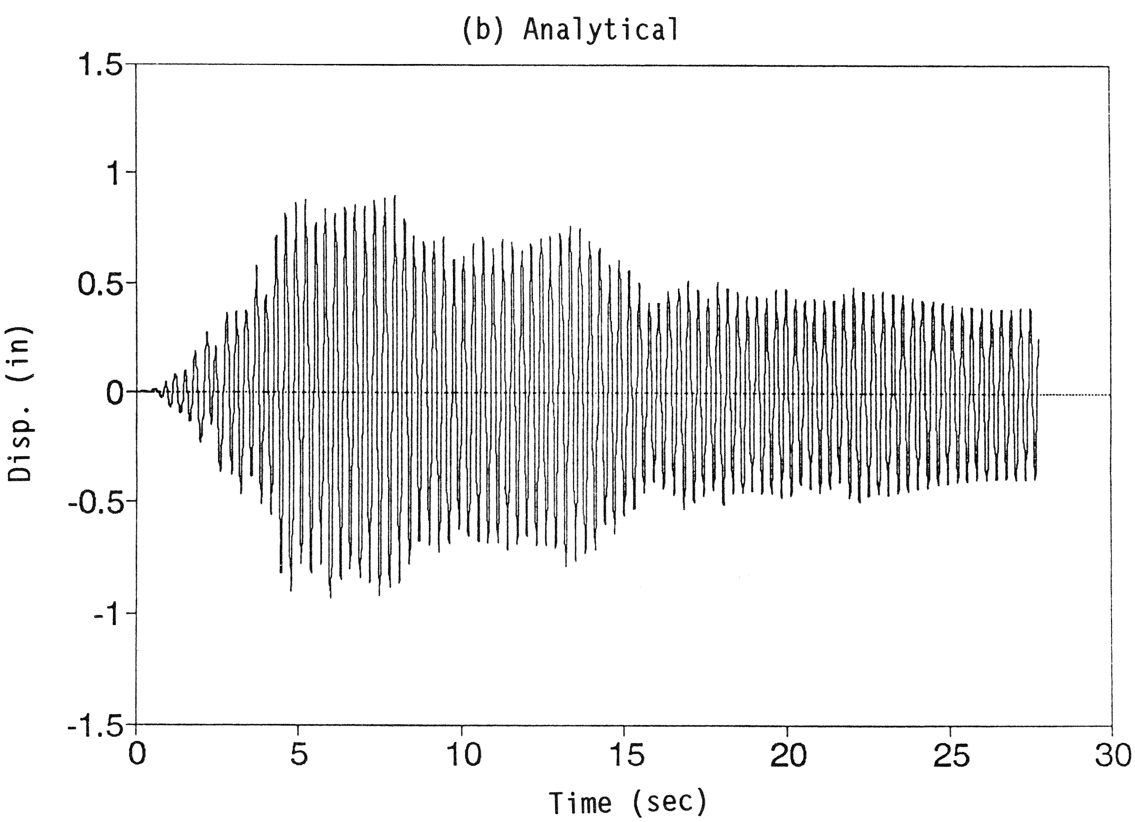


Fig. 4.5 Fifth Floor Relative Displacement, No Damper Case

SECTION 5

SUMMARY AND CONCLUSION

Experimental studies on the dynamic properties of viscoelastic dampers and on the seismic behavior of a viscoelastically damped steel-frame model structure have been carried out under precisely controlled ambient temperatures between 25°C and 42°C. The test structure is a 2/5 scale model of a prototype which was constructed in China as part of a US-China cooperative research program. Only results from tests on the model structure are discussed in this report.

Test results show that, in general, viscoelastic dampers are very effective in reducing excessive vibration of the test structure due to seismic excitations. At 25°C, the dampers can achieve a reduction of about 80% of the maximum floor acceleration, maximum story drifts and maximum lateral displacements of the test structure without added dampers. With increasing ambient temperature, however, the viscoelastic material softens and the effectiveness of the dampers is decreased. However, at the temperature of 42°C, the dampers can still reduce the structural response by more than 40%. Of course, the viscoelastic dampers can be designed for higher efficiency with temperature depending on the specific temperature requirements of the application. For example, the viscoelastic dampers should be designed for the expected maximum ambient temperature to ensure adequate damping for the building.

It should be noted that, in the simulated Hachinohe earthquake tests, the temperature rise in the damper material was insignificant (approximately 1°C). The result is similar to that obtained from tests conducted elsewhere [5]. Only one set of dampers was used for this series of tests; the mechanical properties of the viscoelastic damper material were recoverable after each test under different temperatures, strains and load cycles.

Empirical equations for estimating the stiffness and loss factor of the viscoelastic dampers used in this study were established based on regression analysis using data obtained from component tests of dampers. These equations can adequately estimate the dynamic properties of the dampers under various ambient temperatures, excitation frequencies and deformations.

Numerical predictions on structural damping under various ambient temperatures were carried out using the modal strain energy method and the aforementioned empirical formulae. Numerical results show that structural damping with added dampers can be satisfactorily estimated by the modal strain energy method used in this report.

Numerical simulations were also carried out on the dynamic response of viscoelastically damped structures under seismic excitations. Comparison between numerical simulation and test results shows very good agreements for the viscoelastically damped structure. Numerical simulation deviates from experimental results for the structure without added dampers. This is believed due to the difficulty in simulating the inherent structural damping.

SECTION 6

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