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ANCO

FINAL SUMMARY REPORT
COMANCHE PEAK CONDUIT TESTS

Volume I - (TECHNICAL REPORT)

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1.0 SUMMARY

The experimental effort discussed herein was performed to: 1) demonstrate the adequacy of a wide range of conduit clamp sizes (and their attachment hardware) during postulated seismic events at the Comanche Peak site, and 2) to determine the ultimate capacities of the clamps and their related hardware in terms of ultimate load components at the attachment locations so that design margins could be established. Other objectives were to determine test specimen (conduit) resonant frequencies, damping ratios and response shapes and to determine the axial and rotational slip resistance of the conduit within its clamps.

In order to meet test objectives, a total of 18 conduit raceways were constructed on a large shake table (using site-specific materials, construction details and procedures). These raceways were subjected to: modal testing to identify resonant frequencies and response shapes; random dwell moving support testing to identify resonant frequencies and modal damping ratios; and earthquake testing at Safe Shutdown Earthquake amplitudes and higher input levels to demonstrate design adequacy and to determine ultimate loads.

A comparison of achieved peak loads with design values is beyond the scope of this report. However, it was determined that none of the clamps or their attachment hardware suffered loss of load capacity when subjected to site enveloping Safe Shutdown Earthquakes (SSE), based on comparison of test response spectra with the SSE response spectra. Clamp/attachment hardware failures began to occur when shake table input amplitudes were scaled upwards to minimum values corresponding to 2.3 - 4.6 times site enveloping SSE response spectra.

Tensile and/or shear failure of the clamp attachment studs or bolts established the ultimate capacities of supports in all cases where failure occurred. Testing was performed to the limits of the shake table's capacity.

2.0 INTRODUCTION

Conduit clamps, which are used to secure electrical conduits to supports, at the Comanche Peak Site, in many cases are classified as seismic category one structures. A thorough understanding of the clamps' behavior during postulated seismic events was sought, hence the experimental effort discussed herein was performed.

This test effort had two principal objectives: 1) to demonstrate the adequacy of a wide range of conduit clamp sizes (including attachment hardware) during postulated seismic events at the site; and 2) to determine the ultimate load capacities of the conduit clamps (including attachment hardware) in terms of ultimate load components at the attachment locations, so that design margins could be established.

Other objectives included:

- determination of conduit resonant frequencies, damping ratios and in some cases mode shapes, and
- determination of the axial and rotational slip resistance of the conduit within the clamps during dynamic loading.

All test results are summarized in Section 5.0. No comparison with design values are made.

To achieve those goals, a total of 18 conduit runs were installed on ANCO's R-4 Shake Table and subjected to (in some cases) modal testing to identify resonant frequencies and mode shapes for the lowest few modes of vibration, random dwell testing (in some cases) to identify resonant frequencies and modal dampings of the lowest few modes of vibration at meaningful levels of support point input motion amplitude, earthquake testing at safe shutdown levels to demonstrate design adequacy, and fragility level testing to acquire data to meet the remaining objectives.

The 18 test specimens were assembled and installed on the shake table and tested three at a time, hence a total of six test setups were made. The test specimens are discussed in Section 3.0. All test specimen components were forwarded from the Comanche Peak Site. Installation was governed by ANCO material control and site installation procedures to insure that the test specimens were representative of site conditions.

A total of 64 transducers consisting of accelerometers, displacement transducers and strain gauges were used to sense support point input and conduit response parameters. ANCO's Computerized Vibration Testing and Analysis System (CVTAS) was used to acquire and store the test data. Subsequent data analysis presented the data in meaningful formats of transfer function moduli, summaries of peak measured variables, test response spectra, and time histories of the measured variables.

Subsequent sections of this report discuss the test specimens (Section 3.0), the test methods and tests performed (Section 4.0), the test results in summary form (Section 5.0), and the references (Section 6.0). Unattached appendices include Quality Assurance records (Volume II, Appendix A), pertinent project documents and memoranda (Volume III, Appendix B), the test procedure (Volume IV, Appendix C), the test data (Volume V, Appendix D), and a detailed discussion of the load measurement method used (Volume VI, Appendix E).

All work discussed herein was performed in compliance with the test procedure contained in Volume IV, Appendix C, and under control of ANCO's Quality Assurance Program which has been designed to meet the requirements of 10CFR50, Appendix B.

3.0 TEST SPECIMENS AND TESTS PERFORMED

This section is intended to provide the reader with an overview of the test specimens and the tests performed. Additional details on the test specimens and construction details are contained in Volume II, Appendix A and Volume IV, Appendix C. Additional details on the tests performed are contained in Volume IV, Appendix C.

3.1 Test Specimens

Table 3.1 summarizes the key features of the test specimens. Test Specimens 1 through 17 (Test Specimens 14 and 15 were deleted) consisted of 3-support, 2-span straight runs of conduit with a 90° cantilevered bend at one end. Attachment of the clamps to a horizontal steel surface was provided above the conduits. Conduits of two-inch diameter and less were tested with 10-ft, 0-in. nominal support spacing. Conduits of three-inch and greater diameter were tested with 14-ft, 0-in. nominal support spacing. The clamps at each of the three supports on a given test specimen were the same, i.e., either all No. P2558 or all No. C708S, as specified in the table. Figures 3.1, 3.2 and 3.3 illustrate typical specimens with 10-ft and 14-ft support spacings and a typical conduit clamp assembly.

Figure 3.4 is typical of Test Specimens 18, 19 and 20. These specimens consisted of 3-support, 2-span straight run sections with 14-ft, 0-in. nominal support spacing. Guides were installed in lieu of clamps at the end supports (Supports 1 and 3), so that higher axial shears would result at the clamp assembly located at the center support (Support 2). The cantilevered elbows used previously were not installed.

Table 3.2 summarizes the approximate weight of each test system. Empty rigid steel (RS) conduit was filled with cable (from ANCO stock) to the maximum extent possible, resulting in the total test specimen weights shown in the column headed by Footnote 3. Specimen weights remained as in that column during all modal, random, SSE and fragility level testing. Next, weight was added to the test specimens in the forms of wrapped chain (Specimens 1 through 13, 16 and 17) and welded steel plate (Specimens 18 through 20) to increase the inertial loads input to the specimens' clamps during a subsequent series of SSE and fragility level events. The added weight was evenly distributed between supports and resulted in total specimen weights as shown in the column of Table 3.2 headed by Footnote 5.

Table 3.3 serves to document the cabling used as fill in each of the test specimens. This cabling was from ANCO's stock initially supplied by Public Service of New Hampshire from their Seabrook site. The code number stamped on each cable permitted easy identification of the cable's weight and other properties through ANCO Report A-000161. The total fill weights given in the table are in excess of minimum values specified for the project (see Table 3.3, Footnote 1).

Specimen assembly and installation was governed by pertinent sections of the test procedure (Volume IV, Appendix C), and appropriate sections of the test specification and memoranda (Volume III, Appendix B). All materials, less cabling, were received from the Comanche Peak Site (CPSES). Installation was reviewed as part of ANCO's Quality Assurance Program. As-built documentation for each of the test specimens is provided in Volume II, Appendix A.

3.2 Tests Performed

Table 3.4 summarizes the tests performed. Conduit specimens were assembled, installed on the R-4 Shake Table and tested three at a time. Review of the second column of the table indicates that Setup 1 included Test Specimens 1, 2 and 9, Setup 2 included Test Specimens 3, 10 and 17, etc. Specimens were tested in order of priority (established in the test specification) and in that order to minimize setup time.

Each setup was subjected to the following test sequence which is detailed in the test procedure contained in Volume IV, Appendix C after verification that the test specimens complied with appropriate construction details.

- Random dwell testing was performed (selected specimens). Random dwell testing consisted of random transverse and vertical support point input motion at an amplitude corresponding to SSE levels. Selected channels of data were recorded on FM tape for later analysis so that he lowest few modes of vibration could be identified. Input acceleration data were acquired using the CVTAS system and Test Response Spectra (TRS) computed to assure that test amplitudes approached SSE requirements.
- Modal testing was performed (selected specimens). Modal testing consisted of multiple light impacts from a calibrated force measuring hammer while transfer functions were recorded at many locations on the specimen. Subsequent data analysis yielded

detailed information on the resonant frequencies of the lowest few modes of vibration of the test specimen and their corresponding mode shapes.

- Seismic testing was performed (all test specimens). SSE level earthquake-like support point input motion was input to the tests specimens to determine specimen response, loads at the center support (clamp at Support 2) and rotational loads at the clamp nearest the elbow (clamp at Support 1).

- Fragility testing was performed (all test specimens). Shake table gains were adjusted to approximately one-half table capacity and earthquake-like support point input motion input as in the seismic test. Fragility testing was performed with the shake table input gains set to yield the highest attainable input values.

Finally, weight was added to the test specimens as discussed in Section 3.1, and the one seismic test and two fragility level tests discussed above repeated.

Test specimens were inspected between each test and post-test conditions of the clamps/clamp hardware, nut torques, etc., recorded. Nuts were retorqued to specified values and hardware replaced as required. Inspection data are included in Volume V, Appendix D.

TABLE 3.1: SUMMARY OF TEST SPECIMENS

Specimen No.	(1) Setup/ Conduit No.	(2) Conduit Size (in.)	(3) Anchor Type	(4) Clamp P/N	Bolt Diameter (in.)	Bolt Spacing (in.)	Nut Torque (ft-lb)	Span Length (ft)	Elbow (?)
1	1/C1	5	NS	P2558	3/8	7-7/32	19	14	Yes
2	1/C3	4	NS	P2558	3/8	6-5/32	19	14	Yes
3	2/C1	3	NS	P2558	3/8	5-5/32	19	14	Yes
4	3/C3	2	NS	P2558	3/8	4-1/32	19	10	Yes
5	4/C1	1-1/2	NS	P2558	1/4	3-1/32	6	10	Yes
6	5/C1	1	NS	P2558	1/4	2-15/16	6	10	Yes
7	5/C2	3/4	NS	P2558	1/4	2-3/16	6	10	Yes
8	4/C2	2	NS	P2558	5/8*	4-1/32	70	10	Yes
9	1/C2	5	NS	C708S	3/8	8-1/8	19	14	Yes
10	2/C3	4	NS	C708S	3/8	7	19	14	Yes
11	3/C1	3	NS	C708S	3/8	5-7/8	19	14	Yes
12	3/C2	2	NS	C708S	3/8	4-3/4	19	10	Yes
13	4/C3	2	NS	C708S	5/8*	4-3/4	70	10	Yes
14	deleted								
15	deleted								
16	5/C3	3/4	A307	P2558	1/4	2-3/16	6	10	Yes
17	2/C2	4	A307	C708S	3/8	7	19	14	Yes

TABLE 3.1 (concluded)

Specimen No.	(1) Setup/ Conduit No.	(2) Conduit Size (in.)	(3) Anchor Type	(4) Clamp P/N	Bolt Diameter (in.)	Bolt Spacing (in.)	Nut Torque (ft-lb)	Span Length (ft)	Elbow (?)
18**	6/C1	3	NS	P2558	3/8	5-5/32	19	14	No
19**	6/C2	4	NS	P2558	3/8	6-5/32	19	14	No
20**	6/C3	5	NS	P2558	3/8	7-7/32	19	14	No

(1) Conduits setup and tested three at a time, designated C1, C2 and C3 per location on shake table.

(2) Nominal pipe size.

(3) NS designates Nelson Studs, A307 designates A307 Bolts with appropriate nuts used through drilled hole.

(4) All 2-hole conduit straps with appropriate 1/4-in. spacer plates between conduit/clamp and support.

* Oversized bolt, clamp drilled to bolt size + 1/16 in.

** Additional tests to increase axial shears at Support 2, reference GEH memo of 29 June 1987. See Test Procedure (Volume IV, Appendix C).

TABLE 3.2: SUMMARY OF APPROXIMATE TEST SPECIMEN WEIGHTS

Test Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	Total Length (ft)	(1) Conduit Weight (lb/ft)	(2) Cable Weight (lb/ft)	Conduit + Cable Weight (lb/ft)	(3) Specimen Weight (lb)	(4) Total Added Weight (lb)	(5) Specimen Weight (lb)
1	1/C1	5	37.08	14.81	8.04	22.85	847.27	720	1,567
2	1/C3	4	35.75	10.89	7.26	18.15	648.86	540	1,189
3	2/C1	3	36.33	7.62	5.25	12.87	467.57	360	828
4	3/C3	2	28.28	3.68	1.21	4.89	138.29	180	318
5	4/C1	1-1/2	24.79	2.73	1.06	3.79	93.96	90	184
6	5/C1	1	25.25	1.68	0.42	2.10	53.03	45	98
7	5/C2	3/4	25.38	1.13	0.21	1.34	34.01	45	79
8	4/C2	2	28.28	3.68	1.21	4.89	138.29	180	318
9	1/C2	5	37.08	14.81	8.03	22.84	846.98	720	1,567
10	2/C3	4	35.75	10.89	7.27	18.16	649.22	540	1,189
11	3/C1	3	36.33	7.62	4.93	12.55	459.00	360	819
12	3/C2	2	28.28	3.68	1.23	4.91	138.85	180	319
13	4/C3	2	28.28	3.68	1.23	4.91	138.85	180	319
16	5/C3	3/4	25.38	1.13	0.21	1.34	34.01	45	79
17	2/C2	4	35.75	10.89	7.26	18.15	648.86	540	1,189

TABLE 3.2 (concluded)

Test Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	Total Length (ft)	(1) Conduit Weight (lb/ft)	(2) Cable Weight (lb/ft)	Conduit + Cable Weight (lb/ft)	(3) Specimen Weight (lb)	(4) Total Added Weight (lb)	(5) Specimen Weight (lb)
18	6/C1	3	30.00	7.62	4.49	12.11	363.30	390	753
19	6/C2	4	30.00	10.89	7.26	18.15	544.50	525	1,070
20	6/C3	5	30.00	14.81	8.04	22.85	682.50	0	683

(1) Reference Unistrut General Catalog No. 9, page 122, Rigid Steel (RS) Conduit.

(2) Reference Table 3.3.

(3) SSE and Fragility Level Tests.

(4) Wrapped chain for Specimens 1 through 17, steel plates for Specimens 18 through 20. Added between supports only.

(5) Special Tests (ST_.__), refer to Section 4.0.

TABLE 3.3: SUMMARY OF CABLE FILLS

Test Specimen No.	Setup/ Conduit No.	Cables Used (1) Quantity	Code	Unit Weight (lb/ft)	Weight (lb/ft)
1	1/C1	1	BB1H	0.76	0.76
		2	BC1L	0.57	1.14
		2	BC6F	2.41	4.82
		1	BC6H	1.32	1.32
	Total:	6			8.04
2	1/C3	1	BB1H	0.76	0.76
		2	BC1L	0.57	1.14
		2	BC6G	2.02	4.04
		1	BC6H	1.32	1.32
	Total:	6			7.26
3	2/C1	2	BB1H	0.76	1.52
		1	BC6F	2.41	2.41
		1	BC6H	1.32	1.32
	Total:	4			5.25
4	3/C3	1	AG6P	0.20	0.20
		1	BB1H	0.76	0.76
		1	BC6N	0.25	0.25
	Total:	3			1.21
5	4/C1	2	AD6M	0.28	0.56
		2	BC6H	0.25	0.50
	Total:	4			1.06
6	5/C1	1	AB6M	0.15	0.15
		1	AB6P	0.07	0.07
		1	AG6P	0.20	0.20
	Total:	3			0.42
7	5/C2	1	AB1P	0.07	0.07
		1	AB6P	0.07	0.07
		1	AB7P	0.07	0.07
	Total:	3			0.21
8	4/C2	1	AG6P	0.20	0.20
		1	BB1H	0.76	0.76
		1	BC6N	0.25	0.25
	Total:	3			1.21

TABLE 3.3 (continued)

Test Specimen No.	Setup/ Conduit No.	Cables Used (1)			
		Quantity	Code	Unit Weight (lb/ft)	Weight (lb/ft)
9	1/C2	3	BB1H	0.76	2.28
		1	BC2H	1.32	1.32
		1	BC6F	2.41	2.41
		1	BC6G	2.02	2.02
	Total:	6			8.03
10	2/C3	2	BB1H	0.76	1.52
		1	BC2H	1.32	1.32
		1	BC6F	2.41	2.41
		1	BC6G	2.02	2.02
	Total:	5			7.27
11	3/C1	4	BB1H	0.76	3.04
		1	BB1L	0.57	0.57
		1	BC2H	1.32	1.32
	Total:	6			4.93
12	3/C2	1	AB6D	0.07	0.07
		1	AB6M	0.15	0.15
		1	BB1H	0.76	0.76
		1	BC6N	0.25	0.25
	Total:	4			1.23
13	4/C3	1	AB6D	0.07	0.07
		1	AB6M	0.15	0.15
		1	BB1H	0.76	0.76
		1	BC6N	0.25	0.25
	Total:	4			1.23
16	5/C3	1	AB1P	0.07	0.07
		2	AB6P	0.07	0.14
	Total:	3			0.21
17	2/C2	1	BB1H	0.76	0.76
		2	BC1L	0.57	1.14
		2	BC6G	2.02	4.04
		1	BC6H	1.32	1.32
	Total:	6			7.26

TABLE 3.3 (concluded)

Test Specimen No.	Setup/ Conduit No.	Cables Used (1)			
		Quantity	Code	Unit Weight (lb/ft)	Weight (lb/ft)
18	6/C1	1	BB1H	0.76	0.76
		1	BC6F	2.41	2.41
		1	BC6H	1.32	1.32
	Total:	3			4.49
19	6/C2	1	BB1H	0.76	0.76
		2	BC1L	0.57	1.14
		2	BC6G	2.02	4.04
		1	BC6H	1.32	1.32
	Total:	6			7.26
20	6/C3	1	BB1H	0.76	0.76
		2	BC1L	0.57	1.14
		2	BC6F	2.41	4.82
		1	BC6H	1.32	1.32
	Total:	6			8.04

(1) Reference Memo from GEH to RSK, et al., dated 30 April 1987.

TABLE 3.4: SUMMARY OF TESTS PERFORMED

Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	(1) Anchor Type	Clamp P/N	Bolt Diameter (in.)	Type of Test Performed: Random Dwell	Model Survey	Seismic and Fragility	Seismic and Fragility With Added Weight
1	1/C1	5	NS	P2558	3/8			✓	✓
2	1/C3	4	NS	P2558	3/8			✓	✓
3	2/C1	3	NS	P2558	3/8	✓	✓	✓	✓
4	3/C3	2	NS	P2558	3/8	✓		✓	✓
5	4/C1	1-1/2	NS	P2558	1/4	✓		✓	✓
6	5/C1	1	NS	P2558	1/4	✓	✓	✓	✓
7	5/C2	3/4	NS	P2558	1/4	✓		✓	✓
8	4/C2	2	NS	P2558	5/8	✓		✓	✓
9	1/C2	5	NS	C708S	3/8			✓	✓
10	2/C3	4	NS	C708S	3/8	✓		✓	✓
11	3/C1	3	NS	C708S	3/8	✓		✓	✓
12	3/C2	2	NS	C708S	3/8	✓		✓	✓
13	4/C3	2	NS	C708S	5/8	✓		✓	✓
16	5/C3	3/4	A307	P2558	1/4	✓		✓	✓
17	2/C2	4	A307	C706S	3/8	✓		✓	✓

TABLE 3.4 (concluded)

Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	(1) Anchor Type	Clamp P/N	Bolt Diameter (in.)	Type of Test Performed: Random Dwell	Model Survey	Seismic and Fragility	Seismic and Fragility With Added Weight
18	6/C1	3	NS	P2558	3/8			✓	✓
19	6/C2	4	NS	P2558	3/8			✓	✓
20	6/C3	5	NS	P2558	3/8			✓	✓ (2)

(1) NS denotes Nelson Stud, A307 denotes A307 bolt and appropriate nut and washer.

(2) Performed without added mass.

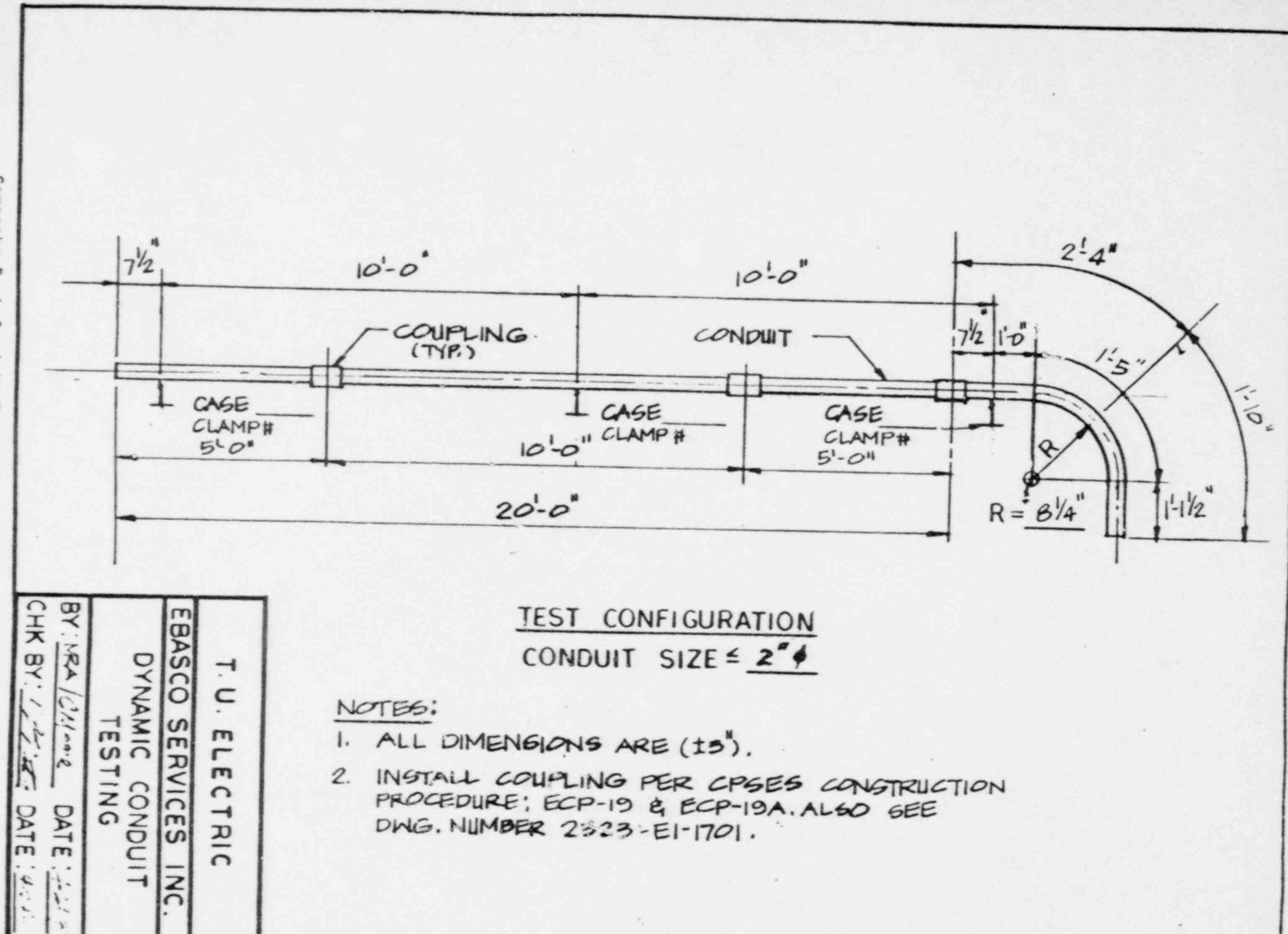


Figure 3.1: Typical Test Specimen (10-ft, 0-in. nominal support spacing)

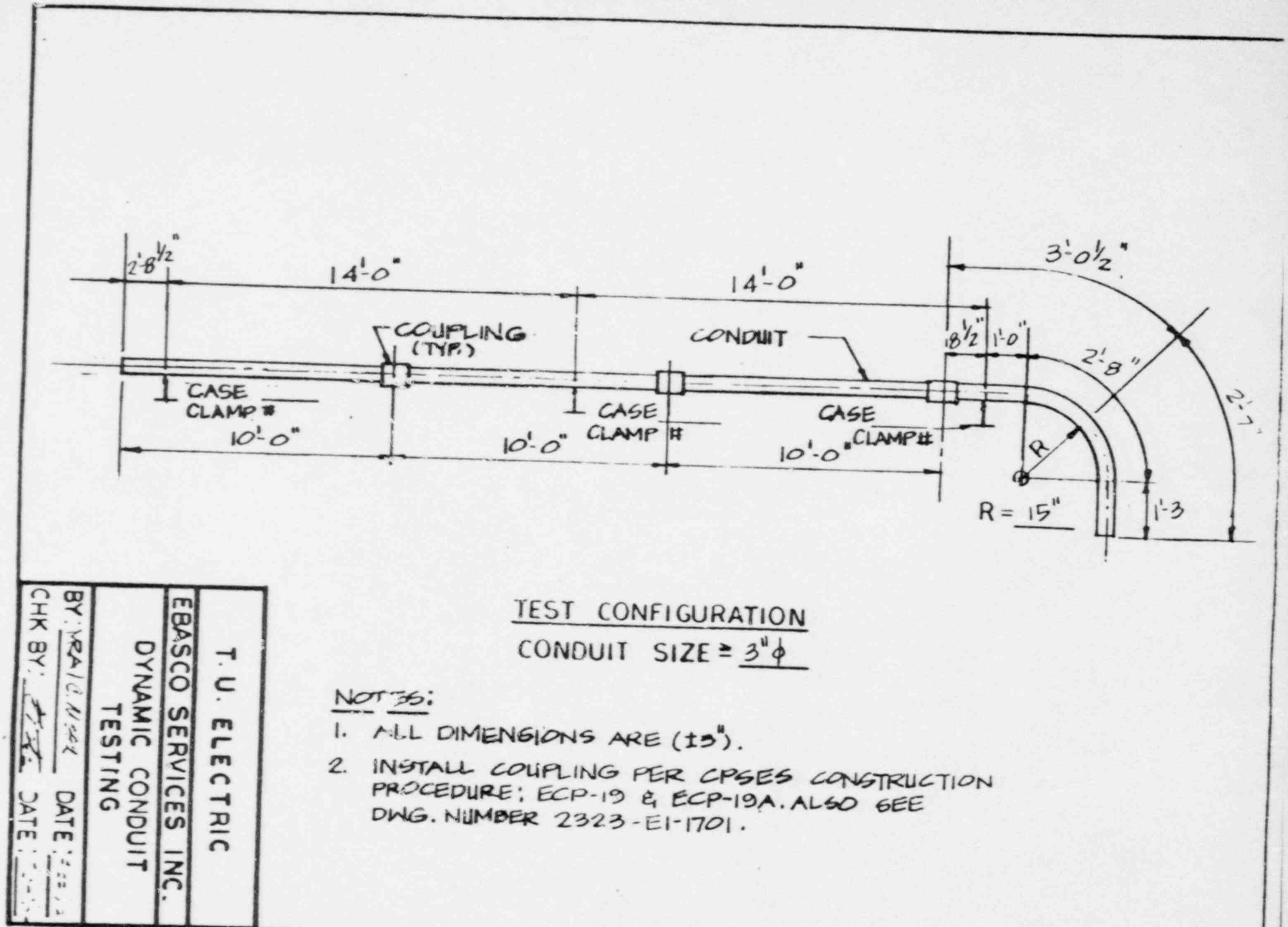


Figure 3.2: Typical Test Specimen (14-ft, 0-in. nominal support spacing)

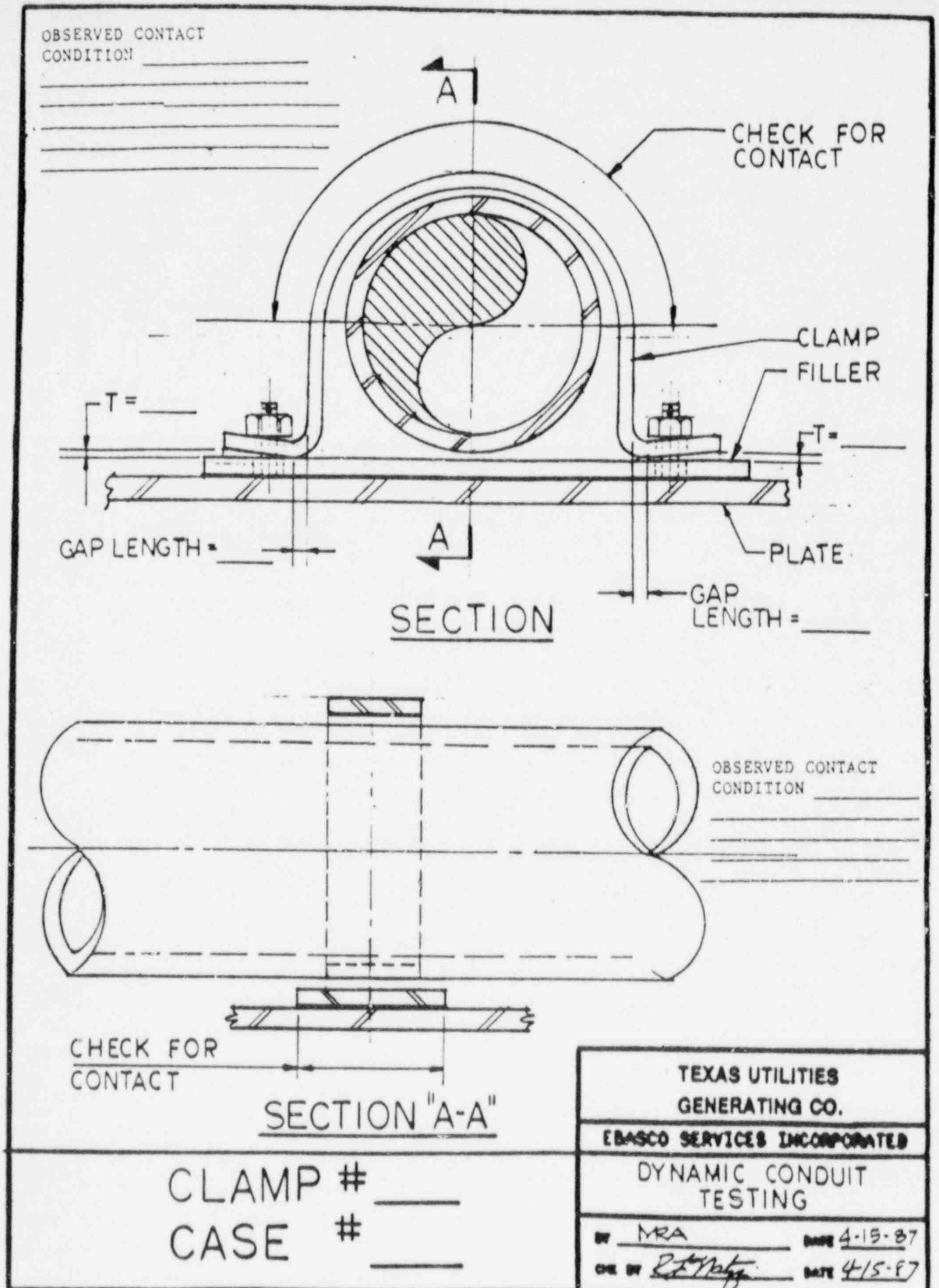
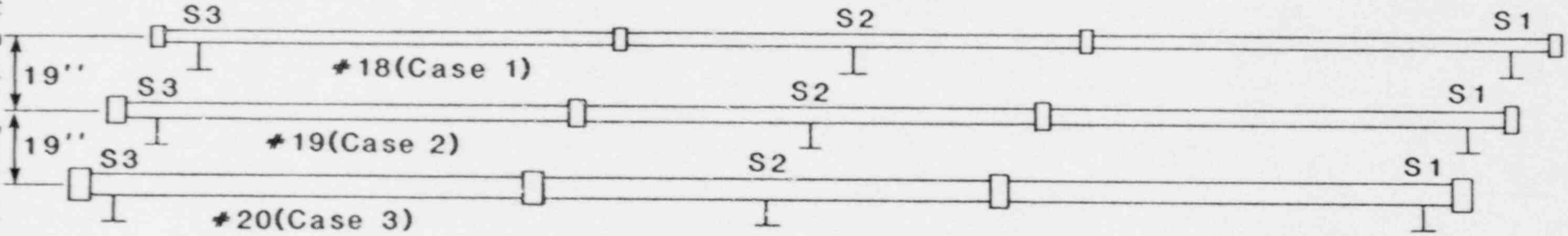


Figure 3.3: Typical Conduit Clamp Assembly

SYSTEM #6 CONFIGURATION



Specimen#	Conduit Diameter	Conduit Length (Coupling to Coupling)	Conduit Span (Support to Support)
#18	3''	10'	14'
#19	4''	10'	14'
#20	5''	10'	14'

Figure 3.4: Typical Test Specimen (Test Specimens 18, 19 and 20)

4.0 TEST METHODS, INSTRUMENTATION AND DATA ANALYSIS

This section reviews the methods used to test the test specimens, the instrumentation used to sense input and response parameters and the data analysis methods used to convert the sensed input and response parameters to more usable formats.

4.1 Test Methods

Test methods included modal testing to identify the lowest few modes of vibration and their corresponding mode shapes (selected test specimens), random dwell support point input motion (selected specimens) to identify the lowest few modes of vibration and to estimate their damping ratios and earthquake testing to demonstrate clamp design adequacy and establish clamp ultimate loads.

4.1.1 Modal Testing

Modal testing was performed by attaching a uniaxial reference accelerometer to a selected point on the test conduit. A rubber hammer containing a calibrated force transducer was used to strike the test conduit at a large number of points/directions. For each new reference accelerometer location, the test conduit was repeatedly struck by the hammer. Subsequent data analysis developed the mode shapes associated with identified resonant frequencies. A curve fitting was used to develop the mode shapes of interest.

The curve fitting (parameter estimation) method of hammer testing, to determine structural modes, consists basically of the following:

- determine elements of transfer function matrix, for multi-degree-of-freedom (MDOF) system, by performing hammer testing; and
- establish an analytical MDOF linear modal model and perform curve fitting and sorting to obtain the structural modes.

There are numerous other steps required to produce and display the final modes in global coordinates (see Table 4.1).

The transfer function matrix is defined by the following equation:

$$\{X(\omega)\} = [H(\omega)]\{F(\omega)\} \tag{4-1}$$

where $\{X(\omega)\}$ = the vector of system responses (outputs), Fourier transform of;

$[H(\omega)]$ = transfer function matrix; and

$\{F(\omega)\}$ - the vector of system applied forces (inputs), Fourier transform of.

A particular element of the transfer function matrix, say H_{ij}, was found by applying only force F_j and measuring X_i. This is seen from the following:

$$X_i = \sum_{k=1}^{n} H_{ik}F_k = H_{i1}F_1 + \cdots + H_{ij}F_j + \cdots + H_{in}F_n = H_{ij}F_j$$

$$H_{ij}(\omega) = X_i(\omega)/F_j(\omega)$$

The basic procedure used was to select an accelerometer as a fixed (fixed location) reference and move the force location and direction. Sometimes the reference accelerometer was moved. By using a fixed reference and moving the force, the element for a single row of the transfer function matrix was developed. Once the needed parts of the transfer function had been developed, curve fitting was performed. After the curve fitting had been completed, the orthogonal modes were "backed-out" using a sorting method.

4.1.2 Random Dwell Testing

Random dwell testing was performed by driving (moving) the shake table in the coupled transverse and vertical (T/V) directions with band-limited random (white) noise. Drive signal gains were adjusted so that TRS computed from sensed input motions would closely match SSE required response spectra. Selected transducers (accelerometers and load cell) signals were recorded on FM tape during the two-minute event. Subsequent playback of recorded input and response acceleration signals (two at a time) into a Hewlett-Packard dual-channel real-time analyzer (set to compute the transfer function between input and response signals) permitted identification of test specimen resonant frequencies by peaks noted in the transfer function moduli. Damping was estimated by the half-power bandwidth method.

The formula used to estimate damping was

$$\beta_i = \frac{\Delta f_i}{2 f_i} .$$

where Δf_i is the bandwidth of i<u>th</u> the resonant peak (peak of the transfer function modulus curve) at 0.707 of the maximum peak height and f_i is the i<u>th</u> test specimen resonant frequency. Examples of this calculation are contained in the data of Volume V, Appendix D. In some cases, the presence of closely spaced modes of vibration prevented the estimation of modal damping.

4.1.3 Earthquake and Fragility Testing

Earthquake and fragility level earthquake testing was performed by driving the shake table in the coupled transverse and vertical plus independent longitudinal directions (T/V + L) with statistically independent signals. These drive signals, illustrated in Figure 4.1, are the displacement time histories whose resulting acceleration input motions when converted to test response spectra (TRS) were expected to conservatively match the shape of site enveloping required response spectra (RRS) over the frequency range of interest, 5 Hz and greater. Drive signal gains were adjusted to meet amplitude requirements. The 30-second plus event was a collection of three 10-second time histories representing a range of soil conditions at the site.

Figure 4.2 illustrates the resulting shake table input motion (measured at the test specimen attachment elevation) acceleration time histories for the longitudinal (x-direction), transverse (y-direction) and vertical (z-direction), respectively.

Figures 4.3 through 4.5 illustrate comparisons of typical SSE test TRS and RRS for the longitudinal, transverse and vertical directions, respectively. During this test (and all earthquake tests), it was desired to have as close a match between TRS and RRS as practical over the frequency range of 5 to 25 Hz. It should be noted that the lowest specimen frequency was about 10 Hz, hence the range of at least one-half the lowest specimen frequency and above was considered in assigning a test amplitude.

Fragility level testing was performed using the same input motion time histories with input gains scaled upward to achieve approximately one-half shake table maximum amplitudes (based on zero period acceleration values) then scaled to achieve shake table maximum amplitudes. Examples of TRS for one of the high-level fragility level tests are compared with RRS in Figures 4.6 through 4.8.

4.2 Instrumentation and Data Acquisition

Three different types of transducers were used to sense shake table input and test system response parameters. A total of 64 transducers were comprised of accelerometers, displacement transducers and load cells comprised of strain gauged elements. Data were acquired and stored in analog form (random and modal testing) and in digital form (earthquake and fragility testing) with some overlap of the two forms between test types.

4.2.1 Transducers

Figures 4.9 and 4.10 illustrate typical instrumentation layouts used during testing of Specimens 1 through 13, 16 and 17, and used during testing of Specimens 18 through 20, respectively. Tables 4.2 and 4.3 summarize the measurement locations, type of transducers, their orientation, and their data channel numbers during testing of Specimens 1 through 13, 16 and 17, and during testing of Specimens 18 through 20, respectively. The location identifiers shown in the tables correspond to measurement locations/directions and transducer type, in general, by the following:

$$\text{Location Identifier} = C_i \begin{Bmatrix} S_i \\ \text{or} \\ M_i \end{Bmatrix} \begin{Bmatrix} A \\ D \\ F \\ \text{or} \\ M \end{Bmatrix} \begin{Bmatrix} Y \\ X \\ \text{or} \\ Z \end{Bmatrix}$$

where: C_i = Conduit Nos. 1, 2 or 3 (see Figures 4.9 and 4.10),

S_i and M_i = Support or mid-span locations,

A = accelerometer,

D = displacement transducer,

F = strain gauges configured to sense load,

M = strain gauges configured to sense moment, and

X,Y,Z = the sensed direction or principal axis about which a moment was sensed.

4.2.1.1 Accelerometers

Dytran Model 3100 piezo-electric accelerometers were used to sense both shake table (support point) input and conduit response accelerations. These are rugged, reliable accelerometers with essentially flat frequency response (volts per g) over the frequency range of 1 to 5,000 Hz. Additional details on these accelerometers are contained in Volume IV, Appendix C.

4.2.1.2 Displacement Transducers

Two types of displacement transducers were used. Where displacements were expected to be large (> 1 in.), Celesco Model PT-101 linear potentiometers were used. These transducers formed one leg of a Wheatstone Bridge. A change in resistance across the bridge was converted to a voltage proportional to a positive or negative displacement through a signal conditioner/amplifier. Amplifier gains were set to yield the highest possible resolution given the anticipated or actual displacement resulting from testing.

The second type, used where displacements were expected to be small, was Shevitz Model HCD Linear Variable Differential Transformers (LVDTs). The LVDTs were supplied with a DC voltage from a signal conditioner and responded with a DC voltage in proportion to displacement.

4.2.1.3 Strain Gauges

Strain gauges were used to sense load or moment proportional material strains. Bondable strain gauges were placed symmetrically about neutral axes of specially constructed load cells (see Figure 4.11) and wired so that strains due to bending and axial forces would either add (moment measurement) or cancel (load measurement). For each measured moment or force, the appropriate gauges formed one leg of a Wheatstone Bridge, as with the displacement transducers; however, a change in resistance across the bridge (proportional to a change in length) was converted to a voltage proportional to a moment or load as appropriate.

Strain gauges were also used to determine the moments at the clamps near Support 1 due to the eccentric cantilevers of the 90° bends. Gauges mounted on either side of the clamp were oriented to sense tangential strains in the conduit itself. The difference in sensed tangential strains was converted to a moment. Volume VI, Appendix E contains an indepth discussion of the load cells and moment sensing gauges used.

4.2.2 Data Acquisition and Analysis

Data acquisition and analysis during modal testing was accomplished by using a Hewlett Packard Model 3682A Real-Time Analyzer (RTA) and special purpose computer. See Section 4.1.1 for the data analysis methods used.

Analog data resulting from random dwell testing were acquired and stored on FM tape. See Section 4.1.2 for the data analysis methods used.

ANCO's CVTAS was used to acquire, store and convert all data resulting from seismic and fragility testing to usable formats. The CVTAS system is represented symbolically in Figure 4.12. The acquisition/analysis process started with the measuring of responses by transducers. The analog signals were then filtered (to prevent aliasing of the data) and amplified (to achieve better resolution). Finally, they were digitized and then stored as computer files on hard disk (with tape backup) for subsequent analysis. The basic features of the CVTAS system are given in Table 4.4.

The data contained in Volume V, Appendix D of this report represent the data acquired during performance of all testing. The seismic and fragility test data are organized by test number as specified in the test procedure contained in Volume IV, Appendix C. Each seismic or fragility test data set consists of the following:

- a test setup sheet indicating pertinent information about the performance of the test (date, time, purpose, test specimen(s), etc.),
- a post-test inspection sheet indicating what test specimen/instrumentation/test specimen support damage (if any) occurred as a result of the test,
- a print out of the current transducer calibration file. The calibration file lists transducer serial numbers, their location identifiers, their calibration factors (g per volt, etc.) and additional data relative to the transducers,

- a print out indicating the status (operability) of the transducers,

- a summary of the peak positive and peak negative value of the measured input or response parameter in engineering units and the times that the peak values were sensed within the data set by data channel number. During some of the test, erroneous values are reported in this data set, due to transducer failure/malfunction. A review of the time traces was often necessary to determine peak value validity,

- plots of the calculated TRS at 7% damping for the control accelerometers (Accelerometers 1, 2 and 3 sensed shake table input accelerations in the longitudinal (x), transverse (y), and vertical (z) directions, respectively, near the C2S2 location), and

- plotted time histories of the measured input or response parameter in engineering units by data channel number.

Post-test analyses of strain time history data, as discussed in Volume VI, Appendix E, was performed to determine the ultimate capacity of the conduit clamps and/or their related hardware.

TABLE 4.1: MODAL HAMMER TESTING USING CURVE FITTING
(MODAL TEST - START TO FINISH)

1. SETUP THE TEST

Layout test points on the structure.
Mount the structure as required.
Attach transducer(s).
Setup analyzer; make trial measurements.

2. CHARACTERIZE THE STRUCTURE

Define components, enter coordinates.
Define constraint equations.
Define display sequence.

3. MAKE MEASUREMENTS

Make measurements, transfer them to Modal 3.0.
Save measurements on disc.

4. ESTIMATE MODAL PARAMETERS

Identify resonance peaks.
Curve fit a measurement with SDOF or MDOF methods.*
Autofit remaining measurements.

5. SORT THE MODAL DATA

Sort residues, generate mode shapes.
Transform mode shapes to global coordinates.

6. DISPLAY MODE SHAPES

Display undeformed/deformed structure.
Display mode shapes in animation.

7. PRINT AND PLOT RESULTS

Print modal data and associated data tables.
Plot measurements and mode shapes.

* SDOF and MDOF refer to single-degree-of-freedom and multi-degree-of-freedom, respectively.

TABLE 4.2: INSTRUMENTATION FOR SYSTEMS 1 THROUGH 13, 16 AND 17

Data Channel No.	(1) Location	(2) Measured Variable	(3) Direction
1	C2S2	A	X
2	C2S2	A	Y
3	C2S2	A	Z
4	C2S1	A	X
5	C2S1	A	Y
6	C2S1	A	Z
7	C2S3	A	X
8	C2S3	A	Y
9	C2S3	A	Z
10	C1S1	A	Y
11	C1S1	A	Z
12	C1S3	A	Y
13	C1S3	A	Z
14	C3S1	A	Y
15	C3S1	A	Z
16	C3S3	A	X
17	C3S3	A	Y
18	C3S3	A	Z
19	C1M1	A	Y
20	C2M1	A	Y
21	C2M1	A	Z
22	C3M1	A	Y
23	C3M1	A	Z
24	C1S2	S	X
27	C1S1	R	Z
28	C1S1	R	Z
29	C2M2	D	Y
30	C2M2	D	Z
31	C2S2	S	X
32	C2S2	S	Y
33	C2M1	D	Y
34	C2M1	D	Z
35	C2S1	R	Z
36	C2S1	R	Z
38	C3S2	S	X
39	C3S2	S	Y
40	C3M1	D	Y
41	C3M1	D	Z
42	C3S1	R	Z
43	C3S1	R	Z
44	C1S2-Upper	MS-B	X
45	C1S2-Upper	MS-B	Y
46	C1S2-Lower	MS-B	X
47	C1S2-Lower	MS-B	Y
48	C1S2-Axial	MS-A	Z
49	C1S1-Inside	MS-T	X

TABLE 4.2 (concluded)

Data Channel No.	(1) Location	(2) Measured Variable	(3) Direction
50	C1S1-Outside	MS-T	X
51	C2S2-Upper	MS-B	X
52	C2S2-Upper	MS-B	Y
53	C2S2-Lower	MS-B	X
54	C2S2-Lower	MS-B	Y
55	C2S2-Axial	MS-A	Z
56	C2S1-Inside	MS-T	X
57	C2S1-Outside	MS-T	X
58	C3S2-Upper	MS-B	X
59	C3S2-Upper	MS-B	Y
60	C3S2-Lower	MS-B	X
61	C3S2-Lower	MS-B	Y
62	C3S2-Axial	MS-A	Z
63	C3S1-Inside	MS-T	X
64	C3S1-Outside	MS-T	X

(1) C = conduit number, M = mid-span number, S = support number, Upper = upper location on load cell, Lower = lower location on load cell, Axial = mid-point on load cell, Inside = on S2 side of Support S1, Outside = on elbow side of S1.

(2) A = acceleration, D = displacement, S = slip, R = rotation, MS-B = microstrain-bending, MS-A = microstrain-axial, MS-T = microstrain-torsion.

(3) X = longitudinal, Y = transverse, Z = vertical.

TABLE 4.3: INSTRUMENTATION FOR SYSTEMS 18 THROUGH 20

Data Channel No.	(1) Location	(2) Measured Variable	(3) Direction
1	C2S2	A	X
2	C2S2	A	Y
3	C2S2	A	Z
4	C2S1	A	X
5	C2S1	A	Y
6	C2S1	A	Z
7	C2S3	A	X
8	C2S3	A	Y
9	C2S3	A	Z
10	C1S1	A	Y
11	C1S1	A	Z
12	C1S3	A	Y
13	C1S3	A	Z
14	C3S1	A	Y
15	C3S1	A	Z
16	C3S3	A	X
17	C3S3	A	Y
18	C3S3	A	Z
19	C1M1	A	Y
20	C2M1	A	Y
21	C2M1	A	Z
22	C3M1	A	Y
23	C3M1	A	Z
24	C1S2	S	X
27	C2M2	D	Y
28	C2M2	D	Z
29	C2S2	S	X
30	C2S2	S	Y
31	C2M1	D	Y
32	C2M1	D	Z
33	C3S2	S	X
34	C3S2	S	Y
35	C3M1	D	Y
36	C3M1	D	Z
37	C1S2-Upper	MS-B	X
38	C1S2-Upper	MS-B	Y
39	C1S2-Lower	MS-B	X
40	C1S2-Lower	MS-B	Y
41	C1S2-Axial	MS-A	Z
42	C2S2-Upper	MS-B	X
43	C2S2-Upper	MS-B	Y
44	C2S2-Lower	MS-B	X
45	C2S2-Lower	MS-B	Y
46	C2S2-Axial	MS-A	Z
47	C3S2-Upper	MS-B	X
48	C3S2-Upper	MS-A	Y
49	C3S2-Lower	MS-B	X

TABLE 4.3 (concluded)

Data Channel No.	(1) Location	(2) Measured Variable	(3) Direction
50	C3S2-Lower	MS-B	Y
51	C3S2-Axial	MS-A	Z

(1) C = conduit number, M = mid-span number, S = support number, Upper = upper location on load cell, Lower = lower location on load cell, Axial = mid-point on load cell, Inside = on S2 side of Support S1.

(2) A = acceleration, D = displacement, S = slip, MS-B = microstrain-bending, MS-A = microstrain-axial.

(3) X = longitudinal, Y = transverse. Z = vertical.

TABLE 4.4: BASIC FEATURES OF THE CVTAS SYSTEM

1. ECLIPSE S-130 Chassis
2. 256 k-byte Memory and CPU
3. 96-Mbyte Disk Drive With Adapter
4. 9-Track Digital Tape System
5. Data General G300 Graphics Terminal
6. DEC Writer II Printing Terminal
7. G300 Graphics Printer
8. Computer Products Real Time Peripheral (RTP) System with 128 channels of A/D converters and 4 channels of D/A converters. The maximum sample rate with a full compliment of channels is 625 points/sec.
9. 64 channels of STI different amplifier/anti-aliasing filters and 64 channels of frequency devices (FD).

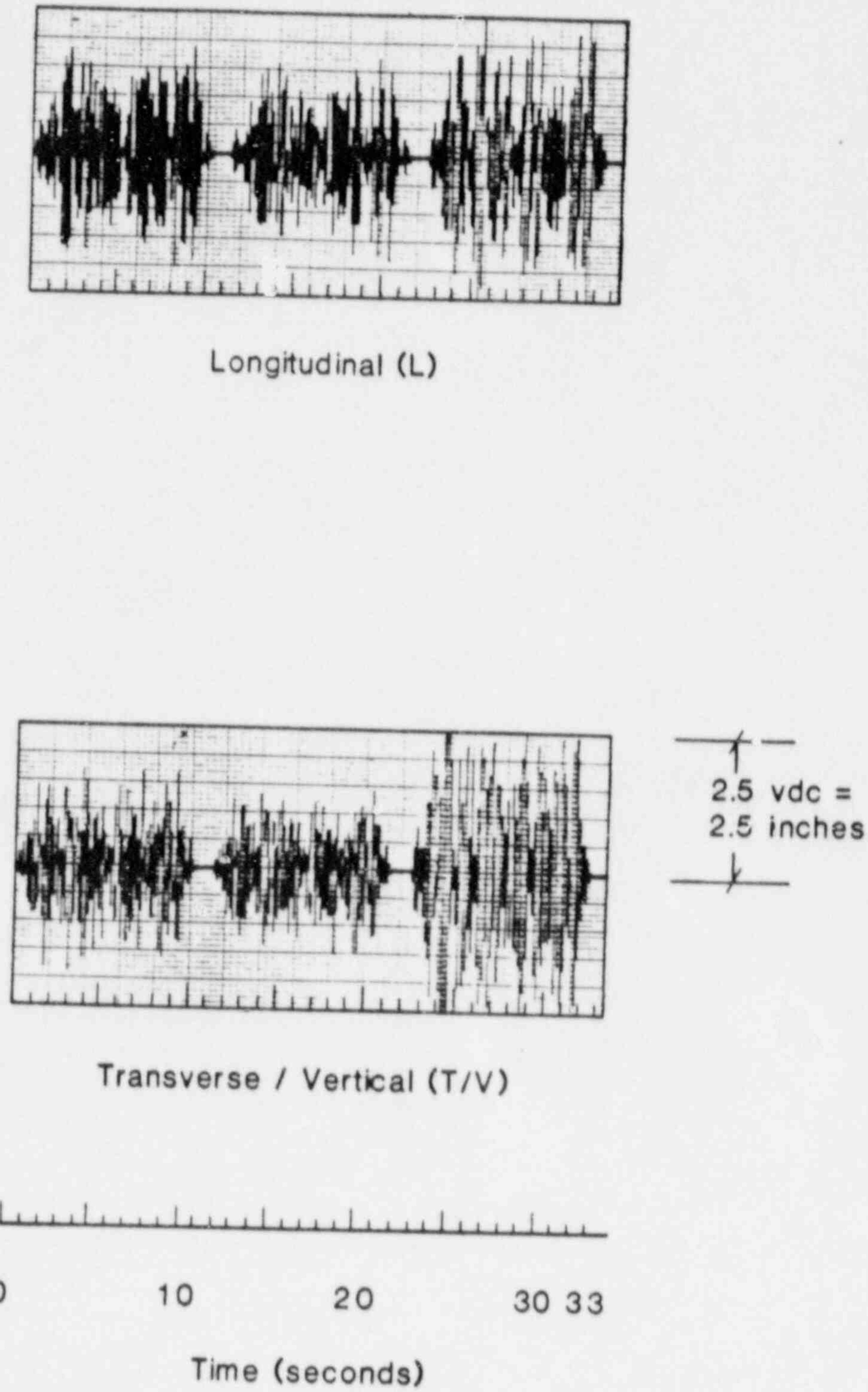


Figure 4.1: Typical Shake Table Actuator Drive Signals (T/V and L)

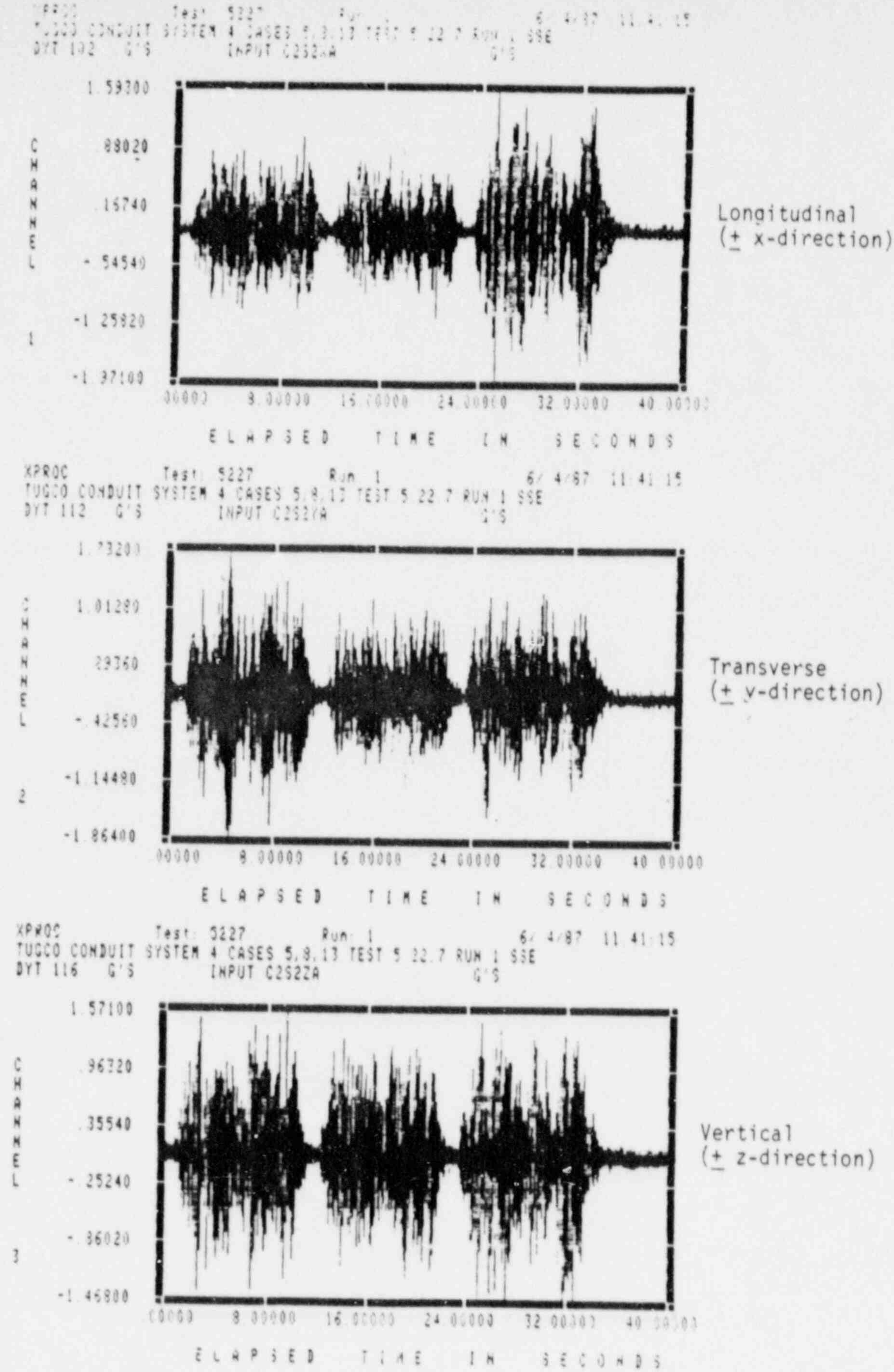


Figure 4.2: Typical Acceleration Time Histories

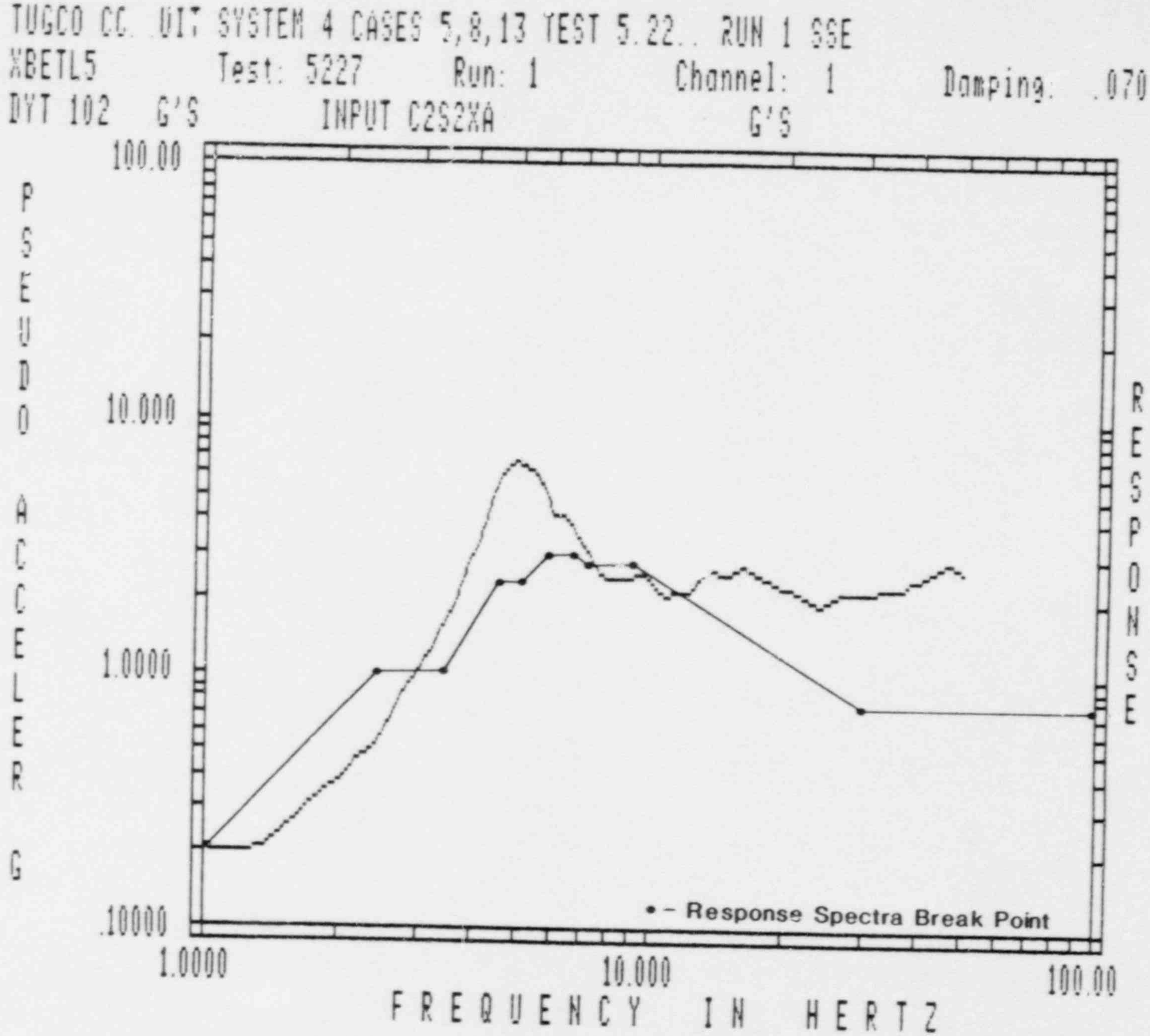


Figure 4.3: Comparison of Longitudinal TRS and RRS SSE Test

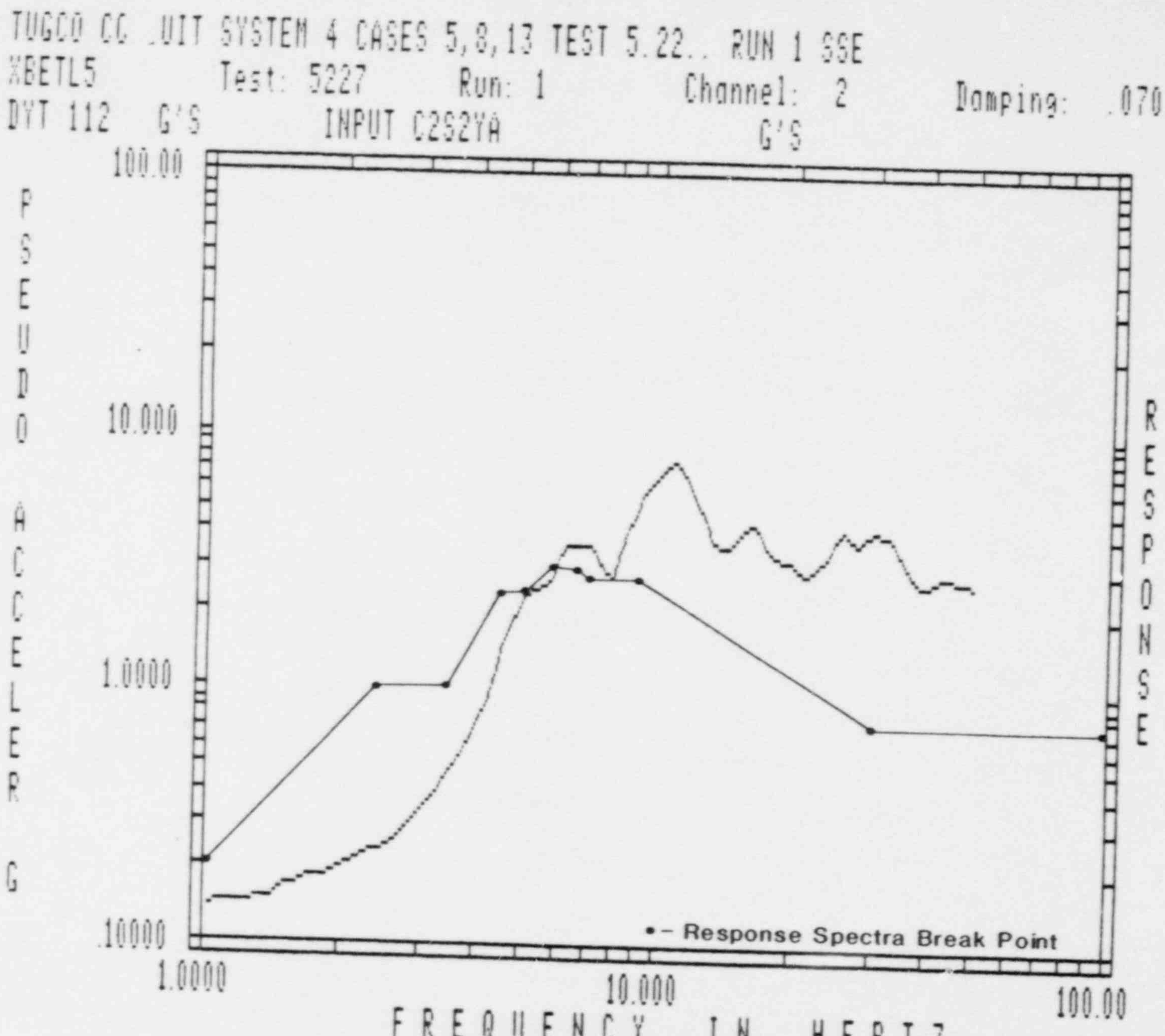


Figure 4.4: Compar:son of Transverse TRS and RRS SSE Test

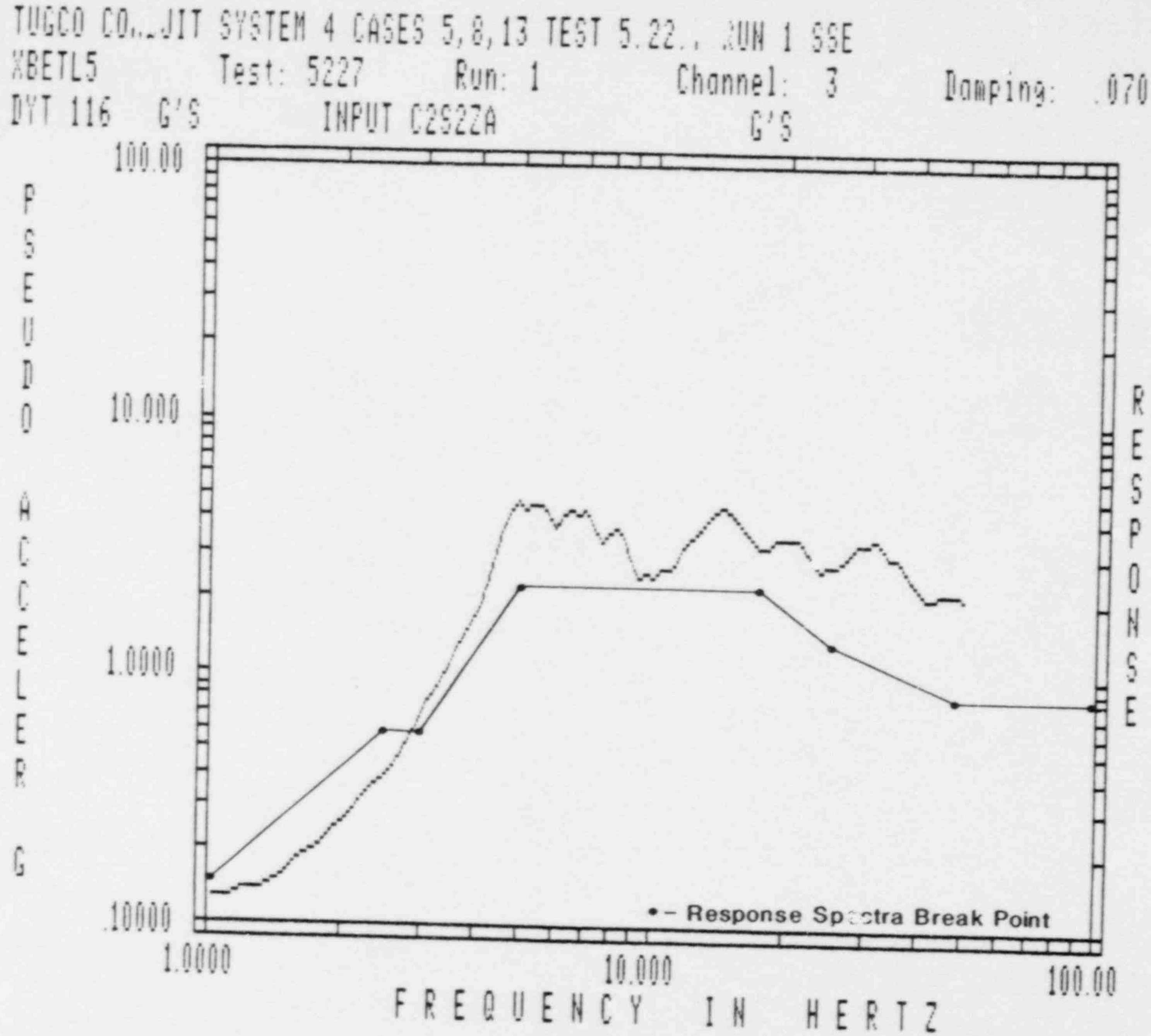


Figure 4.5: Comparison of Vertical TRS and RRS SSE Test

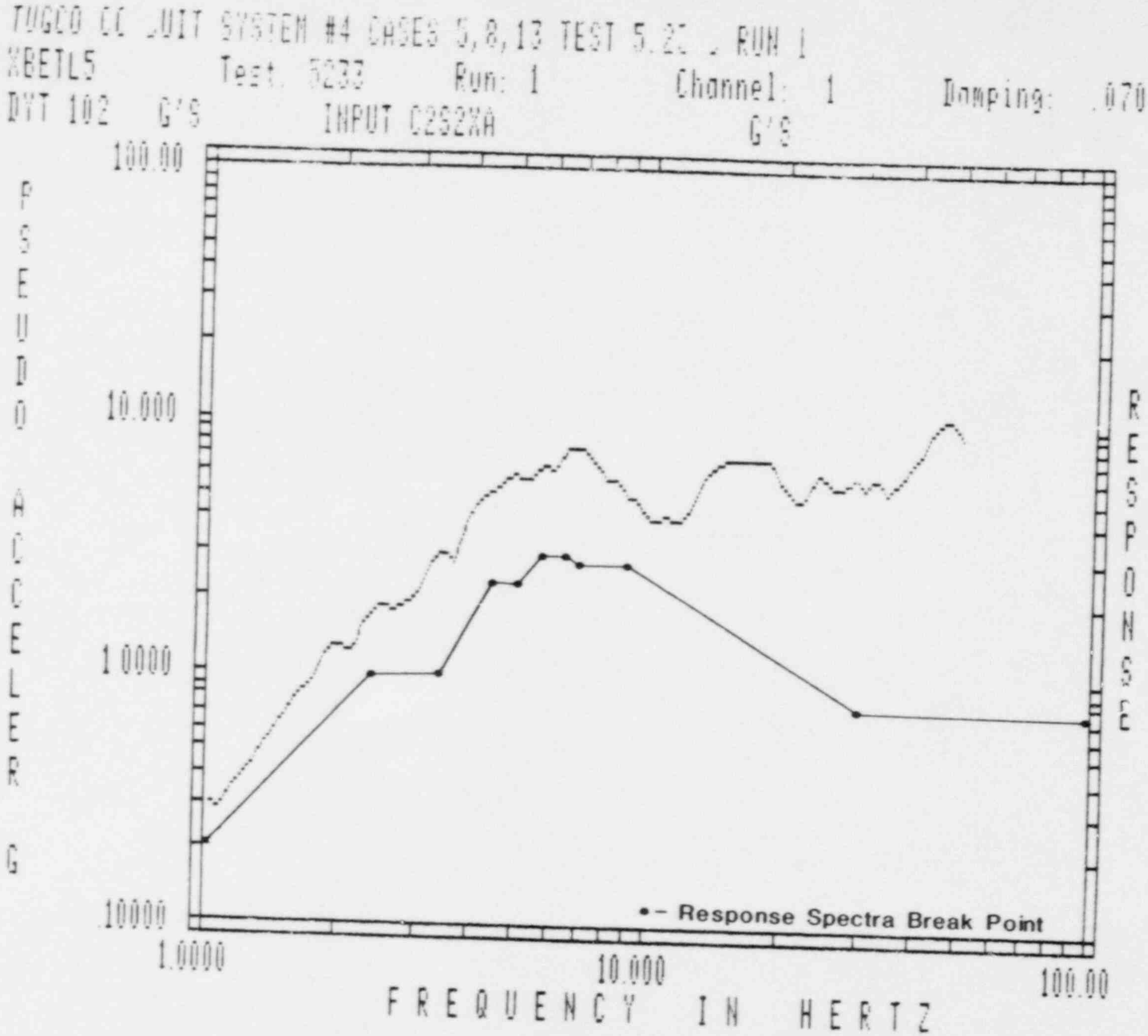


Figure 4.6: Comparison of Longitudinal TRS and RRS Maximum Fragility Test

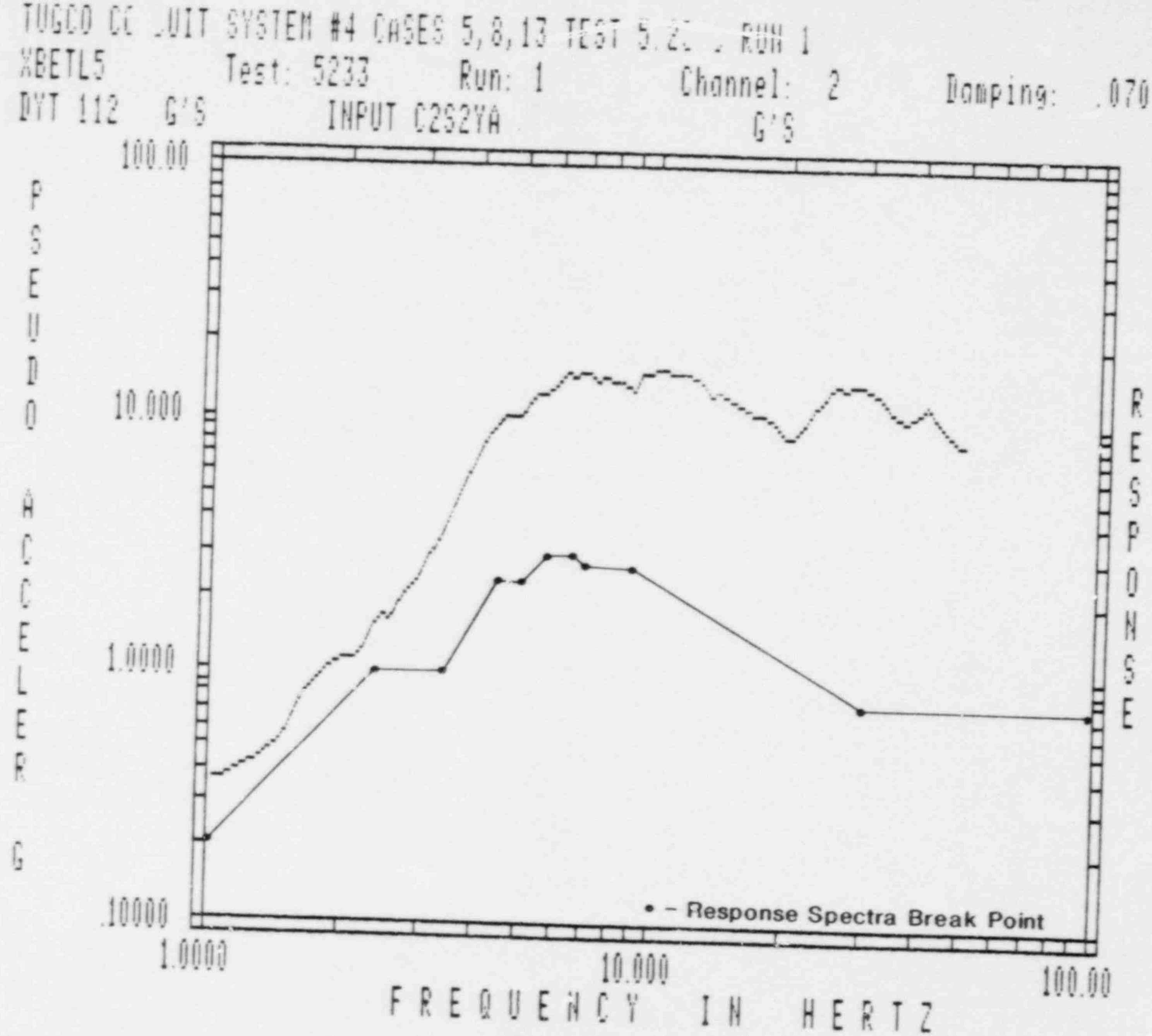


Figure 4.7: Comparison of Transverse TRS and RRS Maximum Fragility Test

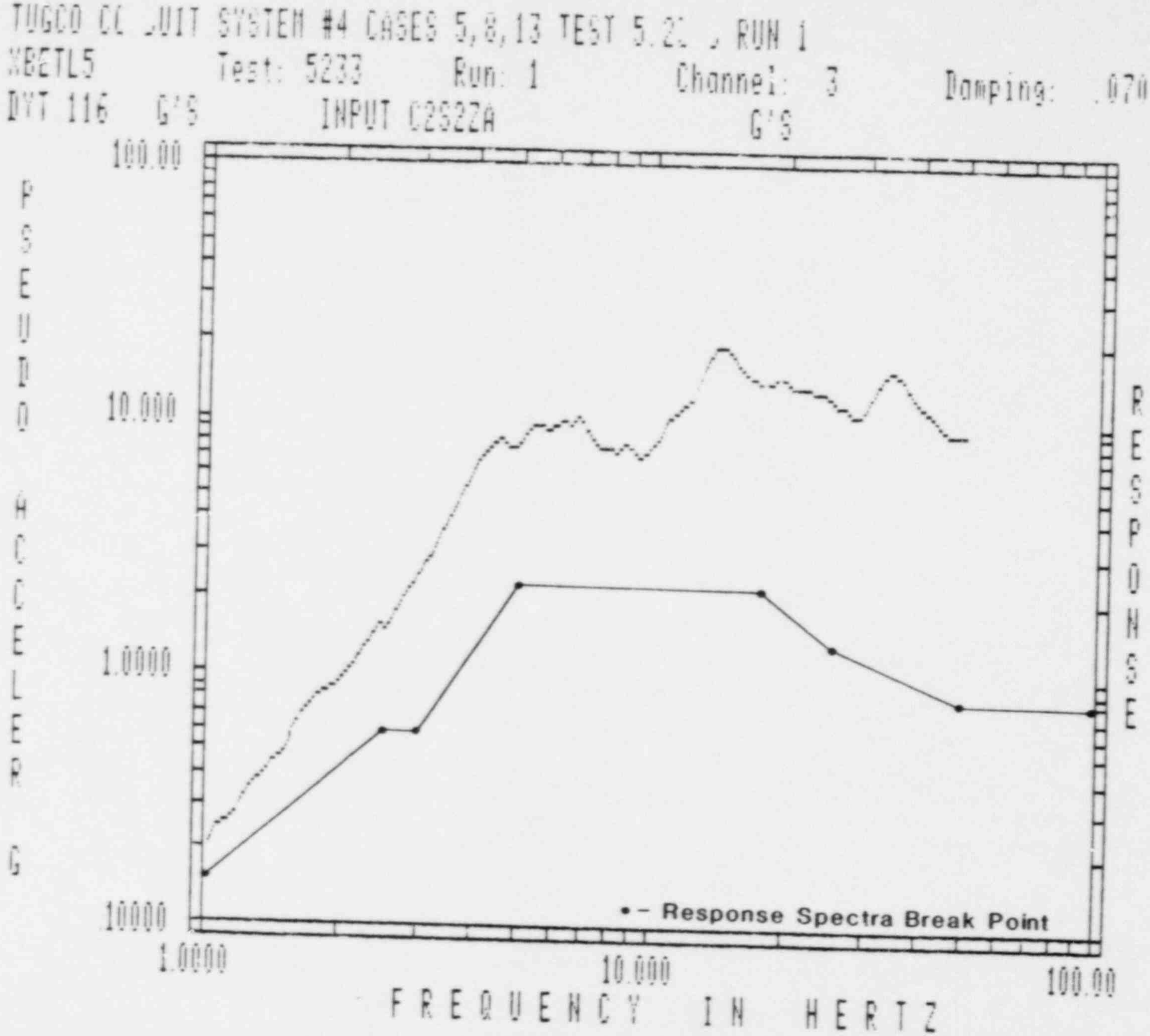


Figure 4.8: Comparison of Vertical TRS and RRS Maximum Fragility Test

A - Accelerometer	●	(I) - Designates input placement
		(CN) - Designates conduit placement
		x,y,z - Designates direction
D - Displacement Transducer	◇	Designates LVDT
	◆	Designates Celesco
		x,y,z - Designates direction
M - Moment Sensing Guage	▼	Superscript 1 - Designates upper pairs of strain gauges at S2 (load cell)
		Subscript 2 - Designates lower pairs of strain gauges at S2 (load cell)
		Subscript x,y,z - Designates direction
F - Force Sensing Gauge	▽	x,y,z - Designates direction

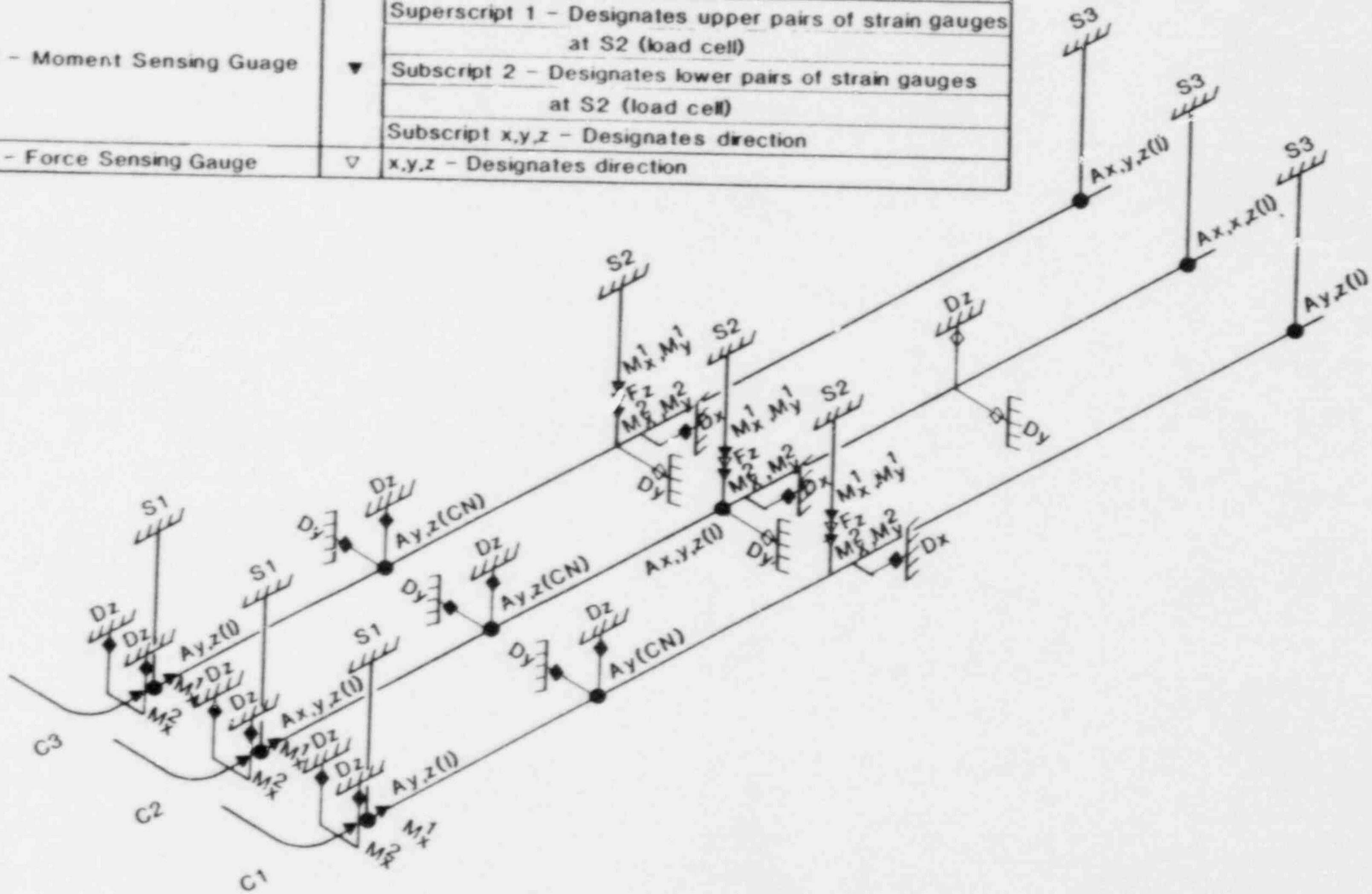


Figure 4.9: Instrumentation Layout, Test Specimens 1 Through 13, 16 and 17

A - Accelerometer	●	(I) - Designates input placement
		(CN) - Designates conduit placement
		x,y,z - Designates direction
D - Displacement Transducer	◇	Designates LVDT
	◆	Designates Celesco
		x,y,z - Designates direction
M - Moment Sensing Guage	▼	Superscript 1 - Designates upper pairs of strain gauges at S2 (load cell)
		Subscript 2 - Designates lower pairs of strain gauges at S2 (load cell)
		Subscript x,y,z - Designates direction
F - Force Sensing Gauge	▽	x,y,z - Designates direction

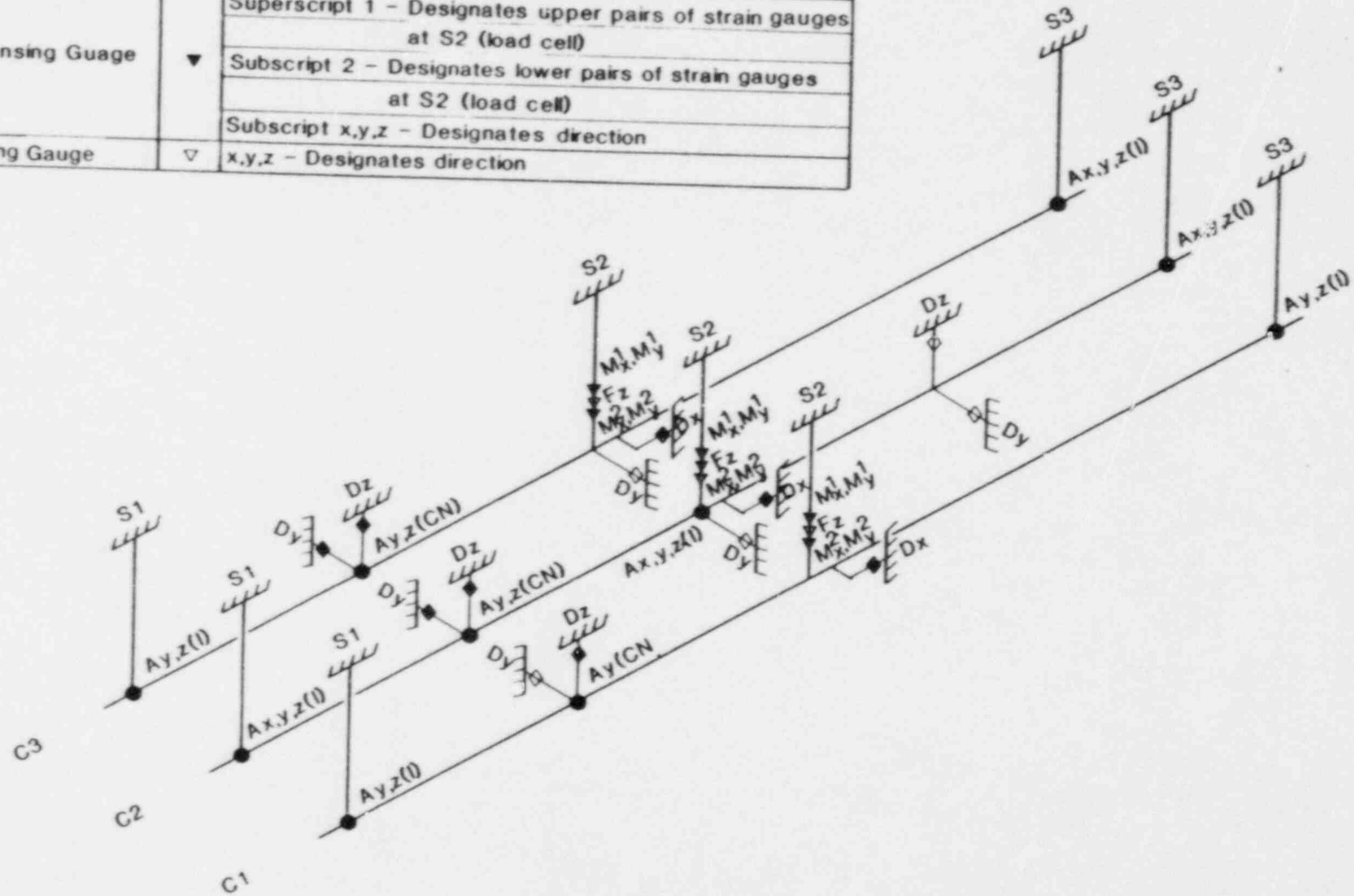


Figure 4.10: Instrumentation Layout, Test Specimens 18 through 20

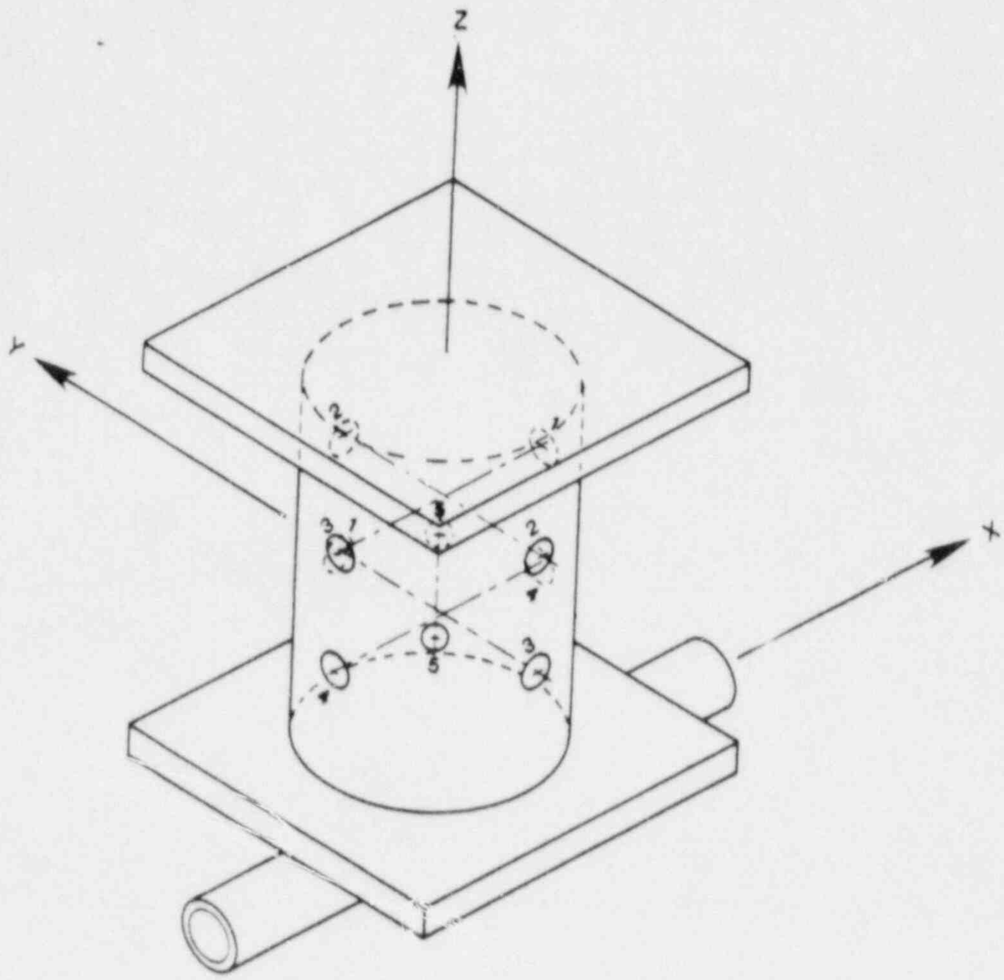


Figure 4.11: Load Cell

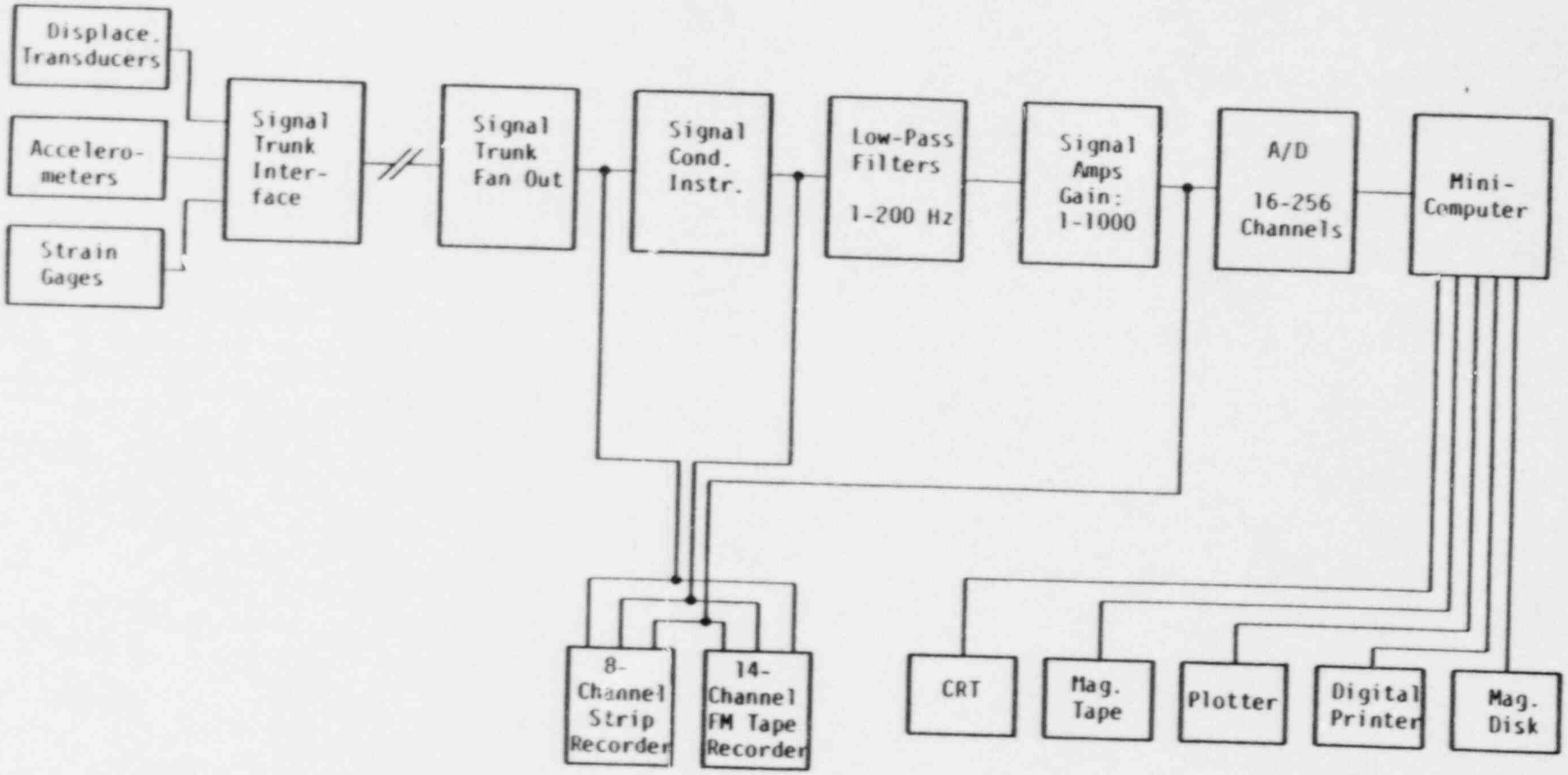


Figure 4.12: Data Acquisition/Instrumentation Flow Chart

5.0 TEST RESULTS

Test results are in the form of resonant frequencies and their corresponding damping ratios from random dwell testing, resonant frequencies and their corresponding mode shapes from modal testing, and achieved clamp loads prior to failure, clamp rotational capacities and clamp slip capacities from earthquake, and fragility testing. The data which are summarized in this section are contained in Volume V, Appendix D and Volume VI, Appendix E. Clamp/attachment hardware failure modes were discussed briefly in Section 1.0 and will not be discussed here.

5.1 Random Dwell Test Results

Table 5.1 summarizes the resonant frequencies and their corresponding modal damping ratios identified during random dwell testing. Recall that testing was performed using band-limited (5 - 33 Hz) white-noise support-point input motion at amplitudes approximately equal to SSE levels based on comparisons of calculated TRS with SSE RRS at or near the lowest specimen modes of vibration. Random dwell testing was not performed on Test Setups 1 and 6 (Test Specimens 1, 2, 9, 18, 19 and 20). Further, Test Specimens 14 and 15 were deleted from the program.

Resonant frequencies of the lowest modes of vibration were closely spaced (lowest vertical and lowest transverse modes) but separable in the data. These were found to range from 9.6 Hz (4-in. conduit on 14-ft support spacing) to 31.6 Hz (2-in. conduit on 10-ft support spacing). Dampings for the lowest modes ranged from as great as approximately 8.4% to as little as 2.4% of critical. The table indicates that (generally) the lower the first mode frequency the higher the modal damping ratio. Second and higher order modes were (generally) found to be somewhat less damped than the lowest modes of vibration. Application of least-mean-square curve fitting techniques to the data contained in Table 5.1 suggests that damping could be expressed in terms of frequency by the relation, $\beta \approx 7.81 - 0.18f_i$ (%), where f_i is the frequency of interest and $9.6 \leq f \leq 31.6$ Hz.

5.2 Modal Test Results

Table 5.2 summarizes mode shape, natural frequency and damping ratios obtained from modal tests performed on Test Specimens 3 and 6. For Specimen

3, three modes were identified below 33 Hz, two horizontal (X-Y) modes and one vertical mode. For Specimen 6, two modes were identified, one horizontal (X-Y) mode and one vertical mode. Table 5.2 describes the modes obtained and compares the frequencies with those obtained from the Random Dwell test results. The mode shapes are shown in Figure 5.1.

5.3 Earthquake and Fragility Level Test Results

Recall that the intent of this effort was to determine axial and rotational slip characteristics of the conduit within the clamps and to establish the ultimate capacities of the clamps and their related hardware. This section summarizes the results which are discussed in greater depth in Volume V, Appendix D and Volume VI, Appendix E. The relative magnitude of the fragility level tests remained the same for Systems 2 through 6. The relative level for the three seismic tests performed, using SSE RRS as 1.0, were as follows: 1

1. SSE Level - longitudinal amplitude = 1.2
   transverse amplitude = 1.0
   vertical amplitude = 1.0
2. 1st Fragility - longitudinal amplitude = 1.5
   transverse amplitude = 3.0
   vertical amplitude = 2.0
3. 2nd Fragility - longitudinal amplitude = 1.8
   transverse amplitude = 4.0
   vertical amplitude = 2.7

For System 1, several tests were performed to allow iteration on the gain and equalization settings to achieve the desired response. The relative amplitudes of these tests are documented in Table 5.4, Footnote 6.

5.3.1 Axial Slip

Axial slip was sensed at the center support location (S2) on all test specimens by axially-oriented displacement transducers. During the majority of the test effort, these were LVDTs with a maximum range of ± 1/8 in. to yield the highest possible data resolution, hence data on slip > 1/8 in. is not available. The LVDTs were incapable of withstanding significant off-axis displacements. When clamp/attachment hardware failure occurred at the S2 location, the conduit sagged downward causing slip measurements $\geq$ 1/8 in. to be sensed by the LVDT and often causing damage to the LVDT.

Table 5.3 summarizes the available data (from Volume V, Appendix D) on axial slip characteristics. The table indicates the test number and test description where the maximum axial slippage at the S2 location was sensed and whether or not conduit clamp/attachment hardware failure occurred during that test. Data were not available on Test Specimen 11. Clamp/attachment hardware failure occurred on eight of the remaining 17 test specimens. On the eight specimens where failure occurred, there was no evidence of slippage during the prior tests. Where no failure occurred, slippage ranging from 10 to 70 mils, was noted in Table 5.3.

5.3.2 Clamp Torsional Capacities

Rotational displacements and strains measured on either side of the clamp closest to the cantilevered elbows (Support S1) were reviewed to determine the clamps' rotational restraint capacities. These data are discussed in Volume VI, Appendix E and summarized here in Table 5.4. The table gives two torque values (T1 and T2) for each test specimen for all earthquake and fragility tests performed. The value, labeled T1 in Table 5.4, represents the peak torsional moment restrained by the clamp prior to rotation of the conduit (if rotation occurred). The value, labeled T2, represents the peak torsional moment restrained by the clamp during rotation of the conduit, if rotation occurred. No rotation occurred if the values of T1 and T2 are reported as equal. If rotation commenced at the onset of the test, a zerorotation torsional capacity could not be determined. Occasions when this happened are noted by Footnote 5 in Table 5.4. Clamp failures or instrumentation failures are conspicuous in the table by the absence of values for T1 and T2.

Data scatter in Table 5.4 is large. A discussion of the rotation phenomenon is warranted. Data presented for Test Specimens 1, 2 and 9 are extreme examples and in our opinion should not be used. During the testing of these specimens, several clamp/hardware change outs were made. The rotational phenomenon was found to be largely unpredictable and dependent on the following:

- The mechanical state of the other two specimen clamps.

- Previous rotational history.
- Flexibility of the test specimen (prying action).

If one of the other two clamps (at S2 or S3) or both had loosened significantly or failed during a test, additional axial and vertical demand was placed on the clamp where torsional strains were sensed (at S1). Further, failure or loosening of the remaining clamps increased test specimen flexibility, hence increased prying action on the clamp of S1. It is believed that increased prying action often loosened the attachment hardware at S1 permitting rotation to occur at a lower applied moment.

Clamps and their related attachment hardware were not replaced if rotation occurred without clamp/attachment hardware failure. When this occurred, the conduit was put back to its initial (pre-rotation) position and the attachment hardware retorqued to its initial value. Once rotation had occurred, it seemed more likely to do so again at a lesser value.

Adding weight to the test specimen not only increased the downward inertial loads (not sensed) at S1 which increased the tendancy to loosen attachment hardware, but, more importantly, increased the prying action (again not sensed) at the S1 location. It is believed that the increased prying action due to increased test specimen flexibility lead to lower peak torque values during testing with added weight.

5.3.3 <u>Clamp Ultimate Capacities</u>

Strain data acquired at the load cells located at the center support (S2) were reviewed and combined to determine the ultimate (peak) load capacities of the clamps. These data are summarized in two ways on Tables 5.5 and 5.6. The numerical methods used to generate the values given here are contained in Volume VI, Appendix E.

Table 5.5 indicates the peak resultant load sensed at the clamp and the components which were combined by the square root of the sum of the squares method to determine the resultant. Also noted in Table 5.5 is the time in the data set when the peak resultant occurred and the estimated time when clamp failure occurred. In all cases where failure occurred, the peak resultant was sensed just prior to clamp failure.

In Tables 5.5 and 5.6, the indicated peak resultant force, the components making up the resultant, and the peak component forces have been corrected for inertial loading effects due to additional weight of bottom plate(s) on the load cells. Specifically, Specimens 5 through 7, 16 and 17 have these corrected values. Appendix E contains the calculations used to arrive at the inertial loading contribution. The method used assumes that the peak inertial loading occurs at the peak input acceleration; hence, conservative numbers are generated for the inertial effects. All other specimens tabulated have not been corrected for inertial effects, due to the insignificance of these effects. (Worst case error less than 5%.)

Table 5.6 indicates the peak x-direction shear, the peak y-direction shear and the peak z-direction loads that the clamps experienced during the highest level tests prior to clamp failure. The times that these peak load components were sensed within the data sets is also indicated along with the remaining two components sensed at that instance in time. None of the peak components were sensed at the same instance in time for a given test specimen.

It is interesting to note that the resultants, which can be computed from the peak values at given instances in time from Table 5.6, are all less than or equal to the peak resultants presented in Table 5.5.

Test Specimen 16 appears to have its ultimate load capacity established by x-direction (longitudinal) shear since the SRSS load case including the peak x-shear was the largest of the three possible SRSS load combinations. The majority of the test specimens' clamp failures or ultimate load capacities (Test Specimens 1, 3 through 6, 9 through 13 and 18 through 20) appear to be established by the peak y-shear component for the same reasons. Finally, Test Specimens 2, 7, 8 and 17 appear to have had their ultimate capacities established by the z-direction (vertical) load component.

TABLE 5.1: SUMMARY OF RESONANT FREQUENCIES AND DAMPING RATIOS IDENTIFIED DURING RANDOM DWELL TESTING

Test Specimen No.	Setup/ Conduit No.	Diameter (in.)	Span Length (ft)	(1) Location	(2) Direction	f_1 (Hz)	β_1 (%)	f_2 (Hz)	β_2 (%)	f_3 (Hz)	β_3 (%)
3	2/C1	3	14	C1M1YA	T	14.8	7.1	21.6	2.1		
4	3/C3	2	10	C3M1YA	T	31.6	~2.4	33.2	*		
				C3M1ZA	V	29.2	~2.9				
5	4/C1	1-1/2	10	C1M1YA	T	16.4	~8.4				
6	5/C1	1	10	C1M1YA	T	14.4	7.3	16.4	4.1	18.0	3.3
7	5/C2	3/4	10	C2M1YA	T	13.2	6.7	18.4	4.8		
				C2M1ZA	V	12.4	3.7				
10	2/C3	4	14	C1M1YA	T	15.6	*	18.4	*	20.8	*
11	3/C1	3	14	C1M1YA	T			21.2	2.4	24.0	2.3
12	3/C2	2	10	C2M1YA	T	31.6	*				
				C2M1ZA	V	27.2	*	28.8	*		
13	4/C3	2	10	C3M1YA	T	31.6	*				
				C3M1ZA	V	28.8	3.3				
16	5/C3	3/4	10	C3M1YA	T	13.2	4.4	18.4	*		
				C3M1ZA	V	12.8	4.9	14.4	3.5		
17	2/C2	4	14	C2M1YA	T	15.6	*	20.4	4.7	24.8	*
				C2M1ZA	V	9.6	6.1	17.6	*		

(1) Refer to Section 4.2.1.

(2) T = transverse (y-direction), V = vertical (z-direction).

* Could not be estimated from data.

TABLE 5.2: MODAL TEST RESULTS

Specimen No.	Frequency (Hz)	Damping[1] (%)	Description
3	12.89	1.[illegible]	Y spans out-of-phase. Compares with 14.8 Hz mode from random.
	16.30	0.93	Y spans in-phase.
	21.84	1.02	Z spans in-phase. Compares with 21.6 Hz mode from random.
6	15.28	0.85	Y spans out-of-phase.
	13.44	0.88	Z spans out-of-phase.

(1) Damping estimated at very low response amplitudes.

TABLE 5.3: PEAK AXIAL SLIP AT SUPPORT 2

Specimen No.	Test No.	Test Description	Peak Axial Slip (in.)	Comment
1-1C1	ST1.10, Run 1	1st Fragility With Added Mass	0.125	Failed.
2-[illegible]	[illegible]T1.10, Run 1	1st Fragility With Added Mass	0.125	Failed.
[illegible]	[illegible]10, Run 1	1st Fragility With Added Mass	0.04	No failure.
4-3C[illegible]	[illegible]18.3, Run 1	2nd Fragility	0.01[illegible]	No failure.
5-4C1	5.23.3, Run 1	2nd Fragility	0.025	No failure.
6-5C1	ST5.21, Run 2	2nd Fragility With Added Mass	0.045	No failure.
7-5C2	ST5.21, Run 2	2nd Fragility With Added Mass	0.070	No failure.
8-4C2	ST4.21, Run 1	2nd Fragility With Added Mass	0.035	No failure.
9	ST1.10, Run 1	1st Fragility With Added Mass	0.125	Failed.
10-2C3	ST2.10, Run 1	1st Fragility With Added Mass	0.125	Failed.
11-3C1				
12-3C2	5.18.3, Run 1	2nd Fragility	0.03	No failure.
13-4C3	ST4.21, Run 1	2nd Fragility With Added Mass	0.018	No failure.
16-5C3	ST5.21, Run 2	2nd Fragility With Added Mass	0.10	No failure.
17-2C2	ST2.10, Run 1	1st Fragility With Added Mass	0.125	Failed.
18-6C1	ST7.21, Run 1	2nd Fragility With Added Mass	0.125	Failed.
19-6C2	ST7.21, Run 1	2nd Fragility With Added Mass	0.500(1)	Failed.
20-6C3	ST7.21, Run 1	2nd Fragility With Added Mass	0.500(1)	Failed.

(1) LVDT with a range of ±1/2 in. used.

TABLE 5.4: SUMMARY OF CLAMP TORSIONAL CAPACITIES

△1

Test Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	Clamp P/N	Bolt Diameter (in.)	(1) Bolt Type	(2) Test No., Run No.	Test Description	(3) T1 (in.-lb)	(4) T2 (in.-lb)
1	1/C1	5	P2558	3/8	NS	5.2.7, R1	SSE (6)	*	*
						5.3.2, R1	1st Fragility	*	*
						5.3.3, R1	2nd Fragility	*	*
						5.3.3, R2	3rd Fragility	*	*
						5.3.3, R3	4th Fragility	*	*
						5.3.3, R4	5th Fragility	1200	10180
						ST1.5, R1	SSE With Added Weight	6400	6400
						ST1.10, R1	1st Fragility With Added Weight	*	*
						ST1.19, R1	2nd Fragility With Added Weight	*	*
2	1/C3	4	P2558	3/8	NS	5.2.7, R1	SSE	5840	5840
						5.3.2, R1	1st Fragility	4740	4740
						5.3.3, R1	2nd Fragility	3200	3200
						5.3.3, R2	3rd Fragility	7900	7900
						5.3.3, R3	4th Fragility	9680	9680
						5.3.3, R4	5th Fragility	2440	2440
						ST1.5, R1	SSE With Added Weight	6020	6020
						ST1.10, R1	1st Fragility With Added Weight	(5)	14100
						ST1.19, R1	2nd Fragility With Added Weight	*	*
3	2/C1	3	P2558	3/8	NS	5.12.7, R1	SSE	3940	3940
						5.13.2, R1	1st Fragility	6120	6120
						5.13.3, R2	2nd Fragility	(5)	6720
						ST2.5, R1	SSE With Added Weight	3560	3560
						ST2.12, R1	1st Fragility With Added Weight	(5)	6120
						ST2.21, R1	2nd Fragility With Added Weight		
4	3/C3	2	P2558	3/8	NS	5.17.7, R1	SSE	1400	1400
						5.18.2, R1	1st Fragility	2000	2840
						5.18.3, R1	2nd Fragility	3400	3400
						ST3.5, R1	SSE With Added Weight	3400	3600
						ST3.12, R1	1st Fragility With Added Weight	3380	3380
						ST3.21, R1	2nd Fragility With Added Weight	3460	4610

TABLE 5.4 (continued)

Test Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	Clamp P/N	Bolt Diameter (in.)	(1) Bolt Type	(2) Test No., Run No.	Test Description	(3) T1 (in.-lb)	(4) T2 (in.-lb)
5	4/C1	1-1/2	P2558	1/4	NS	5.22.7, R1	SSE	500	500
						5.23.2, R1	1st Fragility	1000	1380
						5.23.3, R1	2nd Fragility	1300	1300
						ST4.5, R1	SSE With Added Weight	800	900
						ST4.12, R1	1st Fragility With Added Weight	1000	1000
						ST4.21, R1	2nd Fragility With Added Weight	*	*
6	5/C1	1	P2558	1/4	NS	5.27.7, R1	SSE	267	267
						5.28.2, R1	1st Fragility	300	1370
						5.28.3, R1	2nd Fragility	*	*
						ST5.5, R1	SSE With Added Weight	*	*
						ST5.12, R1	1st Fragility With Added Weight	575	575
						ST5.21, R1	2nd Fragility With Added Weight	300	800
7	5/C2	3/4	P2558	1/4	NS	5.27.7, R1	SSE	257	157
						5.28.2, R1	1st Fragility	475	475
						5.28.3, R1	2nd Fragility	620	620
						ST5.5, R1	SSE With Added Weight	340	340
						ST5.12, R1	1st Fragility With Added Weight	230	230
						ST5.21, R1	2nd Fragility With Added Weight	300	350
8	4/C2	2	P2558	5/8	NS	5.22.7, R1	SSE	1630	1630
						5.23.2, R1	1st Fragility	2000	2000
						5.23.3, R1	2nd Fragility	5100	5100
						ST4.5, R1	SSE With Added Weight	4380	4380
						ST4.12, R1	1st Fragility With Added Weight	3000	7120
						ST4.21, R1	2nd Fragility With Added Weight	5000	5640

TABLE 5.4 (continued)

Test Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	Clamp P/N	Bolt Diameter (in.)	(1) Bolt Type	(2) Test No., Run No.	Test Description	(3) T1 (in.-lb)	(4) T2 (in.-lb)
9	1/C2	5	C708S	3/8	NS	5.2.7, R1	SSE (6)	(5)	13600
						5.3.2, R1	1st Fragility	11340	11340
						5.3.3, R1	2nd Fragility	7280	7280
						5.3.3, R2	3rd Fragility	(5)	27800
						5.3.3, R3	4th Fragility	1400	23400
						5.3.3, R4	5th Fragility	6740	6740
						ST1.5, R1	SSE With Added Weight	(5)	8840
						ST1.10, R1	1st Fragility With Added Weight	(5)	*
						ST1.19, R1	2nd Fragility With Added Weight	*	*
10	2/C3	4	C708S	3/8	NS	5.12.7, R1	SSE	2280	2280
						5.13.2, R1	1st Fragility	5500	5500
						5.13.3, R2	2nd Fragility	5660	6400
						ST2.5, R1	SSE With Added Weight	2500	3900
						ST2.12, R1	1st Fragility With Added Weight	(5)	5420
						ST2.21, R1	2nd Fragility With Added Weight	(5)	5880
11	3/C1	3	C708S	3/8	NS	5.17.7, R1	SSE	4240	4240
						5.18.2, R1	1st Fragility	5060	6020
						5.18.3, R2	2nd Fragility	*	*
						ST3.5, R1	SSE With Added Weight	(5)	2900
						ST3.12, R1	1st Fragility With Added Weight	*	*
						ST3.21, R1	2nd Fragility With Added Weight		
12	3/C2	2	C708S	3/8	NS	5.17.7, R1	SSE	1500	1500
						5.18.2, R1	1st Fragility	3040	3040
						5.18.3, R1	2nd Fragility	3800	3800
						ST3.5, R1	SSE With Added Weight	3540	3540
						ST3.12, R1	1st Fragility With Added Weight	3000	3480
						ST3.21, R1	2nd Fragility With Added Weight	(5)	4860

TABLE 5.4 (concluded)

Test Specimen No.	Setup/ Conduit No.	Conduit Diameter (in.)	Clamp P/N	Bolt Diameter (in.)	(1) Bolt Type	(2) Test No., Run No.	Test Description	(3) T1 (in.-lb)	(4) T2 (in.-lb)
13	4/C3	2	C708S	5/8	NS	5.22.7, R1	SSE	1288	1288
						5.23.2, R1	1st Fragility	3440	3440
						5.23.3, R1	2nd Fragility	3000	4620
						ST4.5, R1	SSE With Added Weight	2500	2500
						ST4.12, R1	1st Fragility With Added Weight	4900	4900
						ST4.21, R1	2nd Fragility With Added Weight	4000	4320
16	5/C3	3/4	P2558	1/4	A307	5.27.7, R1	SSE	193	193
						5.28.2, R1	1st Fragility	447	447
						5.28.3, R1	2nd Fragility	720	720
						ST5.5, R1	SSE With Added Weight	200	200
						ST5.12, R1	1st Fragility With Added Weight	500	760
						ST5.21, R1	2nd Fragility With Added Weight		
17	2/C2	4	C708S	3/8	A307	5.12.7, R1	SSE	2040	2040
						5.13.2, R1	1st Fragility	4040	4040
						5.13.3, R1	2nd Fragility	5640	5640
						ST2.5, R1	SSE With Added Weight	3560	3560
						ST2.12, R1	1st Fragility With Added Weight	5660	9180
						ST2.21, R1	2nd Fragility With Added Weight	(5)	6500

* Gage failure.

(1) NS = Nelson Stud, A307 = A307 Bolt and appropriate nut.

(2) See Test Procedure, Volume IV, Appendix C.

(3) Peak torque recorded prior to rotation.

(4) Peak torque recorded during rotation.

(5) Rotation commenced at beginning of test.

(6) For System 1, Specimens 1, 2 and 9, the tests can be ordered from lowest level input to highest level input as follows: 5.3.3, R4 - L = 0.7, T = 1.2, V = 1.2; 5.3.3, R1 - L = 1.0, T = 1.8, V = 1.3; 5.3.2, R1 - L = 1.2, T = 3.5, V = 2.0; 5.2.7, R1 - L = 1.8, T = 4.0, V = 2.8; 5.3.3, R2 - L = 1.8, T = 4.0, V= 2.8; 5.3.3, R3 - L = 1.8, T = 4.0, V = 2.8; ST1.5, R1 - L = 1.2, T = 1.0, V = 1.0; ST1.10, R1 - L = 1.5, T = 3.0, V = 2.0; ST1.19, R1 - L = 1.8, T = 4.0, V = 2.7.

TABLE 5.5: PEAK RESULTANT FORCE SUMMARY △1

Specimen No.	Conduit Size (in.)	Clamp Type	Bolt Type	(1,2) Peak Resultant (lb)	Time of Occurrence (sec.)	Components X-Shear (lb)	Y-Shear (lb)	Z-Tension (lb)	Comments
1-1C1	5	P2558	3/8", Nelson Stud	4460	6.68	1100	4050	1520	Failed at ~ 7 sec.
2-1C3	4	P2558	3/8", Nelson Stud	4170	7.01	538	3060	2780	Failed at ~ 10 sec.
3-2C1	3	P2558	3/8", Nelson Stud	3540	5.95	150	3490	585	Failed at ~ 8 sec.
4-3C3	2	P2558	3/8", Nelson Stud	1590	20.80	379	1450	527	No failure.
5-4C1(2)	1-1/2	P2558	1/4", Nelson Stud	1237	3.55	52	1216	222	Failed at ~ 22 sec.
6-5C1(2)	1	P2558	1/4", Nelson Stud	718	32.80	472	527	121	No failure.
7-5C2(2)	3/4	P2558	1/4", Nelson Stud	370	34.70	227	169	238	No failure.
△2 8-4C2	2	P2558	5/8", Nelson Stud	1317	22.10	45	1270	347	No failure.
9-1C2	5	C708S	5/8", Nelson Stud	5470	5.94	273	5240	1550	Failed at ~ 7.5 sec.
10-2C3	4	C708S	3/8", Nelson Stud	4060	0.94	101	3960	906	Failed at ~ 3 sec.
11-3C1	3	C708S	3/8", Nelson Stud	3090	3.23	68	3080	263	Failed at ~ 20 sec.
12-3C2	2	C708S	3/8", Nelson Stud	1470	16.50	5	153	1460	No failure.
13-4C3	2	C708S	5/8", Nelson Stud	1650	6.49	41	1450	780	No failure.
16-5C3(2)	3/4	P2558	1/4", A307 Bolt	831	22.60	774	151	263	No failure.
17-2C2(2)	4	C708S	3/8", A307 Bolt	5465	1.88	353	3434	4237	Failed at ~ 4 sec.

TABLE 5.5 (concluded)

Specimen No.	Conduit Size (in.)	Clamp Type	Bolt Type	Peak Resultant (lb) (1,2)	Time of Occurrence (sec.)	Components X-Shear (lb)	Components Y-Shear (lb)	Components Z-Tension (lb)	Comments
18-6C1	3	P2558	3/8", Nelson Stud	3690	4.31	218	3530	1050	Failed at ~ 5 sec.
19-6C2	4	P2558	3/8", Nelson Stud	4000	4.23	1030	3370	1900	Failed at ~ 6 sec.
20-6C3	5	P2558	3/8", Nelson Stud	2910	20.70	1130	2670	281	Failed at ~ 28 sec.

(1) Peak Resultant = max $[Vx(t)^2 + Vy(t)^2 + Fz(t)^2]^{1/2}$.

(2) Values corrected for mass added below load cell. All other specimen loads were not corrected, due to insignificant effects on the tabulated values.

TABLE 5.6: INDIVIDUAL PEAK FORCE SUMMARY

Specimen No.	Peak X-Shear (lb)	Time of Occurrence (sec.)	Y-Shear (lb)	Z-Tension (lb)	Peak Y-Shear (lb)	Time of Occurrence (sec.)	X-Shear (lb)	Z-Tension (lb)	Peak Z-Tension (lb)	Time of Occurrence (sec.)	X-Shear (lb)	Y-Shear (lb)
1-1C1	1300	4.88	2900	1110	4050	6.68	1100	1520	2900	5.16	836	2180
2-1C3	1410	7.69	1320	1440	3910	9.69	13	94	3380	7.90	0	1010
3-2C1	1250	2.34	137	1080	3490	5.95	150	585	1960	4.50	694	904
4-3C3	627	6.25	602	946	1540	3.09	146	479	1210	21.80	105	21
5-4C1[1]	487	3.32	43	121	1216	3.55	52	220	685	21.10	216	124
6-5C1[1]	469	29.50	406	101	527	32.80	472	121	304	32.70	217	293
7-5C2[1]	296	30.50	87	20	286	35.00	67	108	278	34.60	106	188
8-4C2	379	21.50	45	190	1270	21.20	45	347	1071	22.10	187	130
9-1C2	1080	5.77	1970	230	5330	5.33	520	834	3650	7.19	237	1320
10-2C3	1040	1.14	3010	2160	3960	0.94	101	906	3280	1.32	982	1290
11-3C1	1240	11.30	1650	556	3080	3.23	68	263	2140	6.66	381	1030
12-3C2	424	26.10	60	35	1280	5.43	148	450	1460	16.50	5	153
13-4C3	733	5.95	807	527	1620	6.68	3	20	1450	22.20	269	108

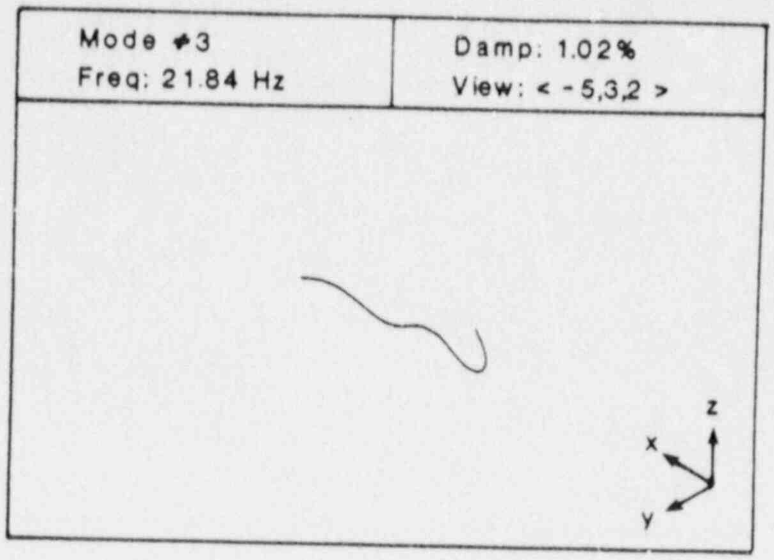
TABLE 5.6 (concluded)

△1

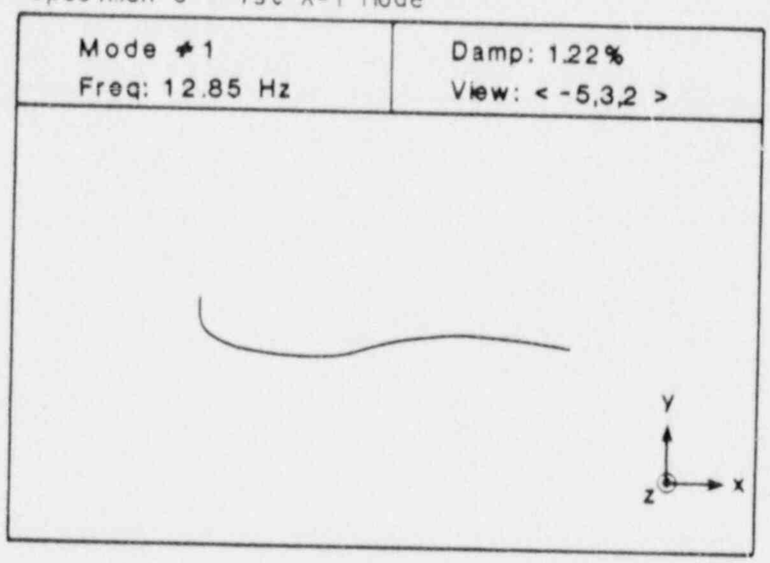
Specimen No.	Peak X-Shear (lb)	Time of Occurrence (sec.)	Y-Shear (lb)	Z-Tension (lb)	Peak Y-Shear (lb)	Time of Occurrence (sec.)	X-Shear (lb)	Z-Tension (lb)	Peak Z-Tension (lb)	Time of Occurrence (sec.)	X-Shear (lb)	Y-Shea (lb)
16-5C3(1)	774	22.60	151	263	554	32.60	205	263	409	27.20	441	8
17-2C2(1)	957	3.49	3112	2411	4147	3.72	219	1572	4237	1.88	353	3434
18-6C1	1330	5.35	1380	702	3530	4.31	218	1050	1640	5.25	639	2080
19-6C2	2650	4.46	2640	604	3750	4.24	1760	3710	4510	4.39	1850	2550
20-6C3	1810	13.00	1010	281	2670	20.70	1130	281	1970	23.00	484	205

(1) Values corrected for mass added below load cell.

Specimen 3 - 1st Z Mode



Specimen 3 - 1st X-Y Mode



Specimen 3 - 2nd X-Y Mode

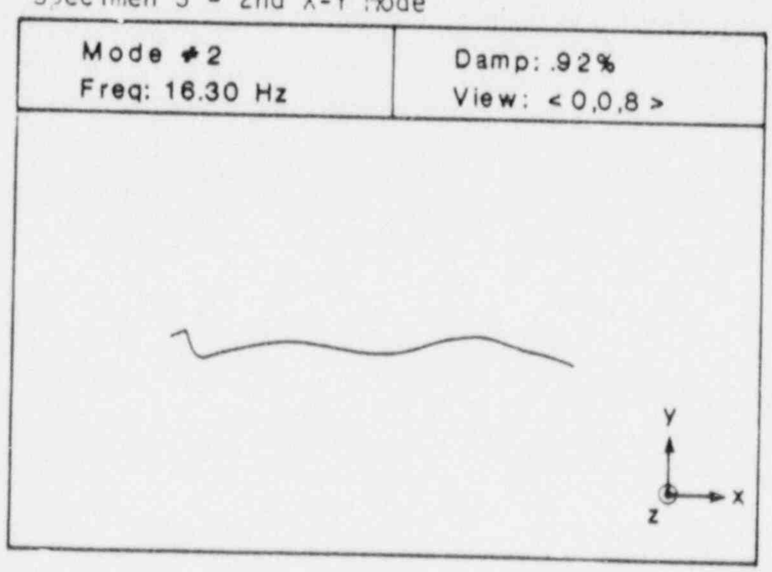
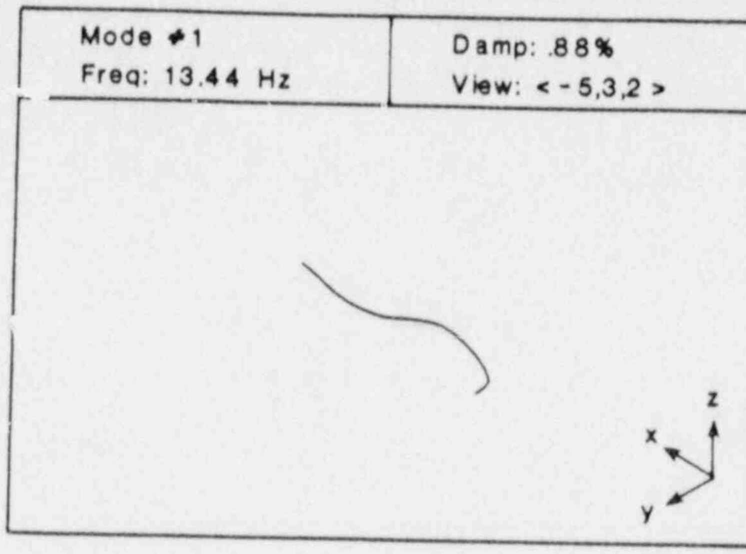


Figure 5.1: Experimentally Obtained Mode Shapes

Specimen 6 - 1st Z Mode



Specimen 6 - 1st X-Y Mode

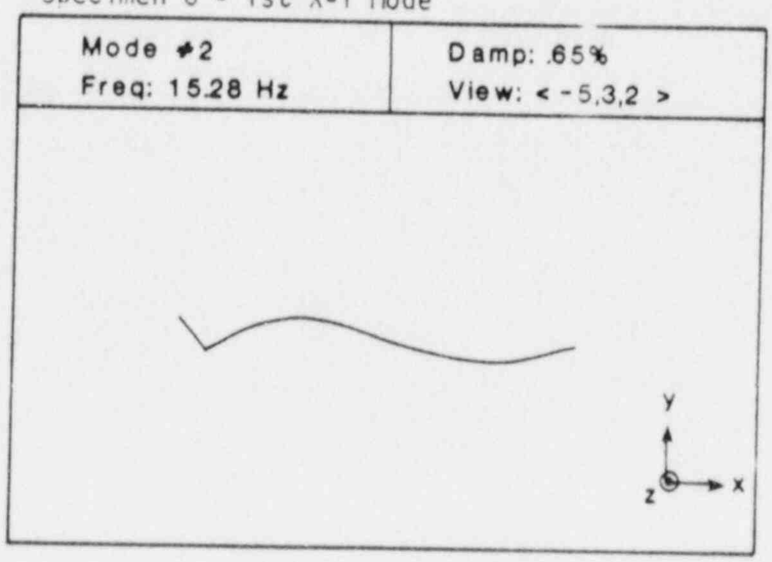


Figure 5.1 (concluded)

6.0 REFERENCES

References are Ebasco Services' test specifications and memoranda which are contained in Volume III (Appendix B) of this report and the test procedure which is contained in Volume IV (Appendix C).