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EXTREME LOADS SEISMIC TESTING OF CONDUIT SYSTEMS

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1 SUMMARY

Rigid steel conduit (thin-wall tubes with threaded connections) containing electrical cabling are a common feature in nuclear power plants. Conduit systems are in many cases classified in U.S.A. practice as Seismic Category I structures. This paper summarizes results and other aspects of a dynamic test program conducted to investigate conduit systems seismic performance under three-axis excitation for designs representative at a nuclear power plant sited near Ft. Worth, Texas (a moderate seismic zone), with a Safe Shutdown Earthquake (SSE) of 0.12 g.

Test specimens where subjected to postulated seismic events, including excitation well in excess of Safe Shutdown Earthquake events typical for U.S.A. nuclear power stations. A total of 18 conduit systems of 9-meter nominal lengths were shake table mounted and subjected to a variety of tests.

None of the specimens suffered loss of load capacity when subjected to a site-enveloping Safe Shutdown Earthquake (SSE). Clamp/attachment hardware failures only began to occur when earthquake input motion was scaled upward to minimum values of 2.3-4.6 times site enveloping SSE response spectra. Tensile and/or shear failure of clamp attachment bolts or studs was the failure mode in all case in which failure was induced.

2 OBJECTIVES

This test effort had two principal objectives: 1) to demonstrate the seismic design adequacy of a wide range of conduit systems (including attachment hardware) during postulated seismic events at the site; and 2) to determine the ultimate load capacities of the conduit clamps. System modal properties were also to be determined as well as conduit-to-clamp slip resistance.

A total of 18 conduit runs [diameters up to 127 mm (5 in.)] were suspended from the upper plane of a 12-m x 4.5-m (40-ft x 15-ft) shake table (shake frame); reference Fig. 1. The conduit runs were 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 investigate ultimate load carrying capacity of conduit systems.

The 18 test specimens were assembled, installed, and tested three at a time. All test specimen components were forwarded from the subject nuclear power plant's site. Installation was governed by material control and site installation procedures to insure that the test specimens were representative of site conditions.

3 SPECIMENS AND TEST METHODS

Fig. 2 illustrates a typical test set-up in which three conduit runs at a time were suspended from the shake table. The conduits ranged in diameter from 19 mm (0.75 in.) to 127 mm (5 in.), with nominal 9-m (30-ft) lengths with three supports. Selected specimens had elbow sections (curvature in a horizontal plane) cantilevered beyond an "end" support of a typical two-span specimen to examine clamp-conduit rotational slip behavior. To induce maximum axial loads at the central clamp location and to minimize end effects during fragility level testing, conduit guides permitting axial conduit motion were installed for some specimens (those without cantilevered elbows) in lieu of clamps at the indicated end supports (S1, S3).

For an initial series of tests, conduits are filled to capacity with cables of known mass per unit length pulled through the conduit system after erection on the shake table. That is, specimens were subjected to dynamic testing up to shake table maximums with the maximum achievable internal cable mass. Then external mass was attached in a distributed fashion (spiral wrapped chains or point masses) to increase the dynamic loads induced in specimen clamps during subsequent series of SSE and Fragility level events.

3.1 Test sequence

Each setup was subjected to the following test sequence.

- 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 (to obtain realistic damping estimates). Selected channels of data were recorded on FM tape for later analysis so that the 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, and the one seismic test and two fragility level tests discussed above repeated.

Test specimens were inspected and documented 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.

3.2 Instrumentation

Test instrumentation involved up to 64 channels of piezo-electric accelerometers, displacement transducers, and strain gages. The rugged accelerometers (Dytran 3100) provided flat frequency response from 1 Hz to 5,000 Hz; they were installed to provide conduct support point input motions as well as conduit response.

Two types of displacement transducers were used. Where displacements were expected to be large (> 1 in.), Celesco Model PT-101 linear potentiometers were used. 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).

Strain gages were used to sense load or moment proportional material strains. Bondable strain gauges were placed symmetrically about neutral axes of specially constructed load cells to obtain orthogonal support load histories.

3.3 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 were 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.

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 table maximum amplitudes. Examples of the test response spectra for one of the high-level fragility level tests are compared with the SSE target spectra in Fig. 3.

4 SELECTED TEST RESULTS

4.1 Axial slip

One intent of the test procedure 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.

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 ≥ 1/8 in. to be sensed by the LVDT and often causing damage to the LVDT. Where no failure occurred, slippage ranged from 0.25 mm (0.01 in. to 1.8 mm (0.07 in.).

4.2 Dynamic characterization tests

Random dwell 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 test response spectra (TRS) with SSE required response spectra (RRS) at or near the lowest specimen modes of vibration.

Resonant frequencies from both modal and random dwell tests 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). Critical damping for the lowest modes ranged from as great as approximately 8.4% to as little as 2.4%. 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.

4.3 Clamp ultimate capacities

Strain data acquired at the specially fabricated load cells located at the center support (S2) were reviewed to determine the ultimate (peak) load capacities of the clamps. Table 1 indicates the peak resultant load sensed at the clamp and the components which were combined into a vector sum to determine the resultant. In all cases where failure occurred, the peak resultant was sensed just prior to clamp failure. In the table, the indicated peak resultant force should be reduced by 50 lb to allow for load cell correction due to cell inertia. Where failures were achieved (which required added mass to increase support dynamic loads), these failures typically followed the time of peak resultant load by a few seconds. The loads sustained in the dynamic tests were substantially higher than those reported from previous quasi-static cyclic testing to some 600 or more load cycles.

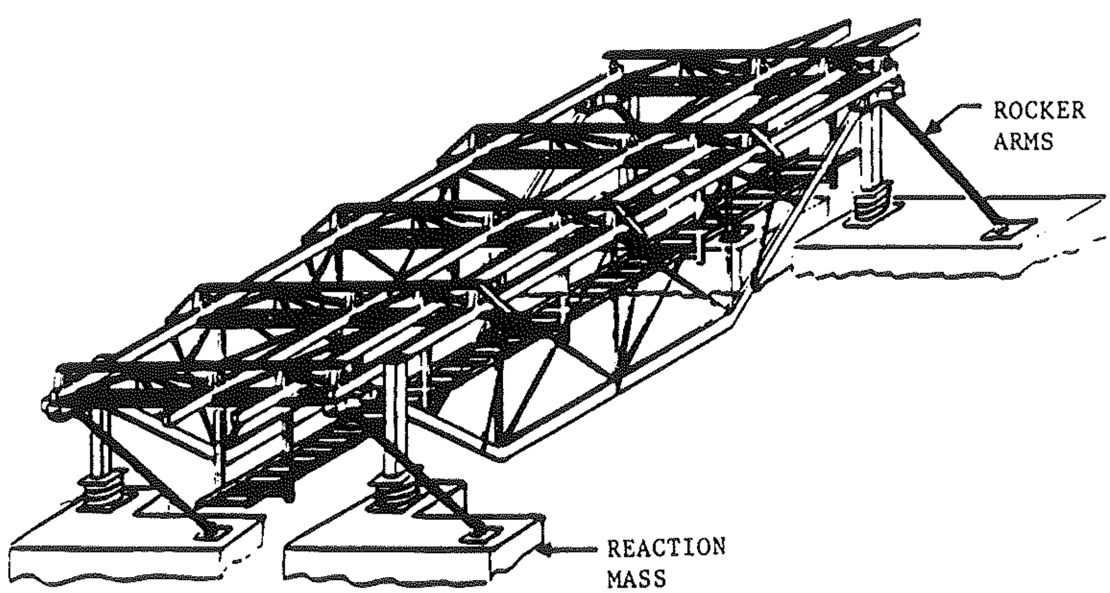
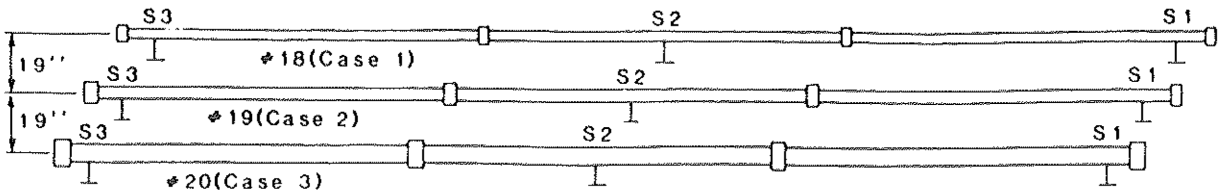


Fig. 1: ISOMETRIC DRAWING OF R-4 FRAME WITH SUSPENDED TRAY TEST SPECIMEN (ACTUATORS NOT SHOWN)



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'

Fig. 2: TYPICAL TEST SPECIMEN (TEST SPECIMENS 18, 19, AND 20)

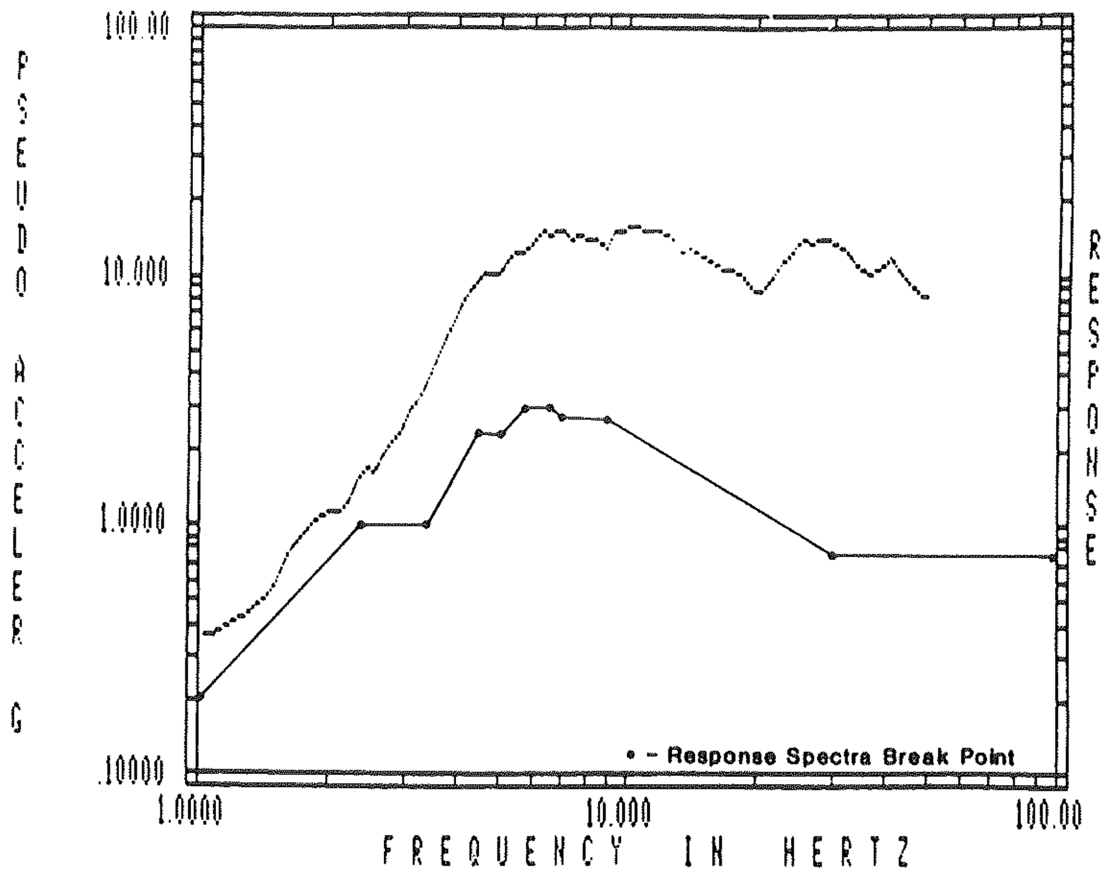


Fig. 3: COMPARISON OF TRANSVERSE TRS AND RRS MAXIMUM FRAGILITY TEST

TABLE 1: PEAK RESULTANT FORCE SUMMARY FOR SELECTED SPECIMENS

SPECIMEN NO.	CONDUIT SIZE (IN.)	CLAMP TYPE	BOLT TYPE	PEAK RESULTANT (LB)	COMMENTS
1-1C1	5	P2558	3/8", NELSON STUD	4460	FAILED AT ~ 7 SEC.
2-1C3	4	P2558	3/8", NELSON STUD	4170	FAILED AT ~ 10 SEC.
3-2C1	3	P2558	3/8", NELSON STUD	3540	FAILED AT ~ 8 SEC.
4-3C3	2	P2558	3/8", NELSON STUD	1590	NO FAILURE.
5-4C1	1-1/2	P2558	1/4", NELSON STUD	1290	FAILED AT ~ 22 SEC.
6-5C1	1	P2558	1/4", NELSON STUD	795	NO FAILURE.
7-5C2	3/4	P2558	1/4", NELSON STUD	440	NO FAILURE.
8-4C2	2	P2558	1/4", NELSON STUD	1570	NO FAILURE.
9-1C2	5	C708S	5/8", NELSON STUD	5470	FAILED AT ~ 7.5 SEC.
10-2C3	4	C708S	3/8", NELSON STUD	4060	FAILED AT ~ 3 SEC.
11-3C1	3	C708S	3/8", NELSON STUD	3090	FAILED AT ~ 20 SEC.
12-3C2	2	C708S	3/8", NELSON STUD	2940	NO FAILURE.
13-4C3	2	C708S	5/8", NELSON STUD	1650	NO FAILURE.
16-5C3	3/4	P2558	1/4", A307 BOLT	840	NO FAILURE.
17-2C2	4	C708S	3/8", A307 BOLT	5460	FAILED AT ~ 4 SEC.