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DYNAMIC RESERVE MARGINS
IN A MULTI-DEGREE-OF-FREEDOM SYSTEM

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1.0 INTRODUCTION

This report describes in detail the analysis method, assumptions and results of Task 2 of EWA: EAG01-49 in connection with justifying the use of SRSS for combining responses from two or more dynamic loads such as those from earthquake, SRV discharge and LOCA events. This task specifically deals with evaluating the actual dynamic reserve margin of a multi-degree-of-freedom (MDOF) system (such as a beam) when it is subjected to a combination of loads from an earthquake and SRV discharge event.

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2.0 DYNAMIC RESERVE MARGINS

The peak amplitudes of multiple dynamic responses of structures and components of nuclear power plants are calculated elastically and are combined using the SRSS rule. This report demonstrates that the design of a multi-degree-of-freedom (MDOF) system based on this method and limiting the combined stresses to ASME Code (or equivalent) allowable stress levels is very conservative. In fact, there is significant additional reserve margin to failure in a component based on the design approach described above than in a design based on combined equivalent static loads and the same allowable stresses.

For static loads, limiting calculated stresses to code allowable limit results in a static reserve margin (SRM) which is equal to the ratio of the static load to cause failure (elastic-plastic analysis) to the static load resulting in code stress limits calculated by linear elastic analysis. For dynamic loads, the dynamic reserve margin (DRM) is the ratio of the peak dynamic load to cause failure (dynamic elastic-plastic analysis) to the peak dynamic load resulting in code stress limits calculated by linear elastic analysis.

The DRM is related to the ratio of energy absorption capability of the structure at failure to its energy absorption capability at code allowable stress. For structures exhibiting even moderately ductile behavior, the DRM is generally many times greater than the SRM both for vibratory forcing functions and for impulsive forcing functions. The additional dynamic design margin, given by the ratio of DRM to SRM, is inherent in structures associated with transient dynamic responses such as those from earthquake, LOCA, and SRV discharge. Such additional dynamic design margin is more than adequate to compensate for peak combined responses which could probabilistically exceed the SRSS value.

Examples of the dynamic reserve margin are quantified in this report through the study of MDOF system subjected to random oscillatory loadings.

3.0 BEAM ANALYSIS

A cantilever beam, 100 inches long with the following properties was chosen for the analysis.

Cross Section - Pipe section (14 in.O.D.; t = 0.25 in)

$E = 30 \times 10^6$ psi

Mass density (ρ) = 0.00073 $\frac{\text{lb-sec}^2}{\text{in}^4}$

Lumped mass (M) = 0.792 $\frac{\text{lb-sec}^2}{\text{in}}$

A sketch of the beam is shown in Figure 1.

The beam property was chosen such that its fundamental frequency was 25 Hz. The material properties used for the beam are shown in Figure 2. The frequency and the material properties are representative of some BWR components. The beam was subjected to a combination of normal or static loads (N), vertical earthquake (EQ) and SRV discharge loads. The EQ and SRV acceleration time histories are at the top of the basemat of a typical BWR plant and are shown in Figures 3 and 4. The EQ and SRV acceleration time histories have significantly different peak accelerations. For the purposes of this study these two loading functions were scaled upward to result in equal elastic responses such that when these elastic responses were combined by SRSS and added absolutely to the normal load (N), the code limit for ASME Service Level C was reached, i.e.

$$N + \sqrt{(K_1\ EQ)^2 + (K_2\ SRV)^2} = S_c$$

Where N is chosen such that it produced a stress equal to $0.4S_c$.

$K_1 EQ = K_2 SRV$

S_c = ASME Code allowable stress for Service Level C

= greater of $1.8S_m$ or $1.5S_y$ (for $P_L + P_b$)

K_1, K_2 = scale factors to make stresses from SRV & EQ equal.

The value of N chosen is typical in the design of nuclear plant components. It may also be noted that a larger value of N will make the DRM smaller and a smaller value of N will make the DRM larger.

From Figure 2, S_u = 90ksi: S_y = 30ksi

S_m = 18.1ksi (from ASME III, Div 1, B&PV Code)

From this data, it was found that,

S_c = 45ski

N = 18ksi

Using this data and the elastic dynamic analysis responses due to EQ and SRV, it was found that

K_1(EQ) = K_2(SRV) = 19ksi

and the scale factors K_1 and K_2 were equal to 227.4 and 11.37 respectively. The EQ and SRV time histories were scaled up using these scale factors. From the elastic dynamic analysis for EQ and SRV, it was found that in order to get the worst possible combined response which is equivalent to the Absolute Sum Rule, the SRV time history needed sign reversal and phase shift by 0.42 seconds such that the peak responses combined. A new combined acceleration time history based on this worst phase elastic response was synthesized accordingly. From this combined time history, a portion having a duration of 1.0 second (see Table I), which included the worst combined peaks was chosen for the elastic-plastic dynamic analysis of the cantilever beam.

To account for normal loads N in the stresses from the elastic-plastic analysis, a static load P (-6910 lbs) which would produce a stress of 0.4 S_c at the support was applied at the free end.

The beam was subjected to the following three load combination cases:

(1) $[N + K_1(EQ) + K_2(SRV)] \times SRM$

(2) $\left[N + 1.25\left[K_1(EQ) + K_2(SRV)\right]\right] \times SRM$

(3) $\left[N + 1.5\left[K_1(EQ) + K_2(SRV)\right]\right] \times SRM$

where SRM is the static reserve margin which has a value of 2.0 for Level C limits.

The ANSYS computer program was used to perform elastic and elastic-plastic transient dynamics calculations.

The plastic beam element was used to model the cantilever. Other options used include third order cubic direct integration, kinematic hardening rule and small deflection solution. No damping was used in either the elastic or the elastic-plastic analysis.

An integration time step size (ΔT) of 0.002 seconds was used in the analyses. Decreasing the time step size in half to 0.001 second did not change the results significantly. Hence, it is concluded that the time step size used is small enough for accurate results. The results of these anslyses with ΔT equal to 0.002 seconds is tabulated below.

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Loading Case No.	FCT4*	Max. σ (ksi)	ϵ_{max} (%)	$\epsilon_{max}/\epsilon_{ult}$
1	1.0	70	3.51	0.23
2	1.25	77	4.75	0.32
3	1.5	82	6.6	0.44

*Multiplication factor for dynamic loads.

4. RESULTS AND CONCLUSIONS

For the first case, all the loads were multiplied by the static reserve margins (SRM) for Level C and the peaks of the dynamic loads were added based on worst case elastic response phasing. These amplified loads would cause failure of the beam if applied statically. However, the elastic-plastic analysis shows the maximum strain is only 23 percent of the ultimate strain. Even when the dynamic loads were multiplied by a factor of 1.5, (this case is equal to increasing the SRSS dynamic response combination by a factor equal to 2.12 times SRM), the maximum strain was less than half the ultimate strain.

Hence, it may be concluded that for the MDOF system considered, the dynamic reserve margin (DRM) is significantly larger than the SRM and as such the consequence of the actual peak combined response exceeding the SRSS combined response is negligible.

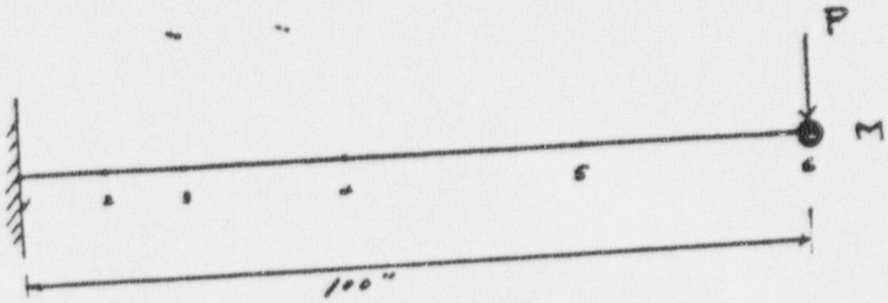


FIGURE 1: BEAM MODEL

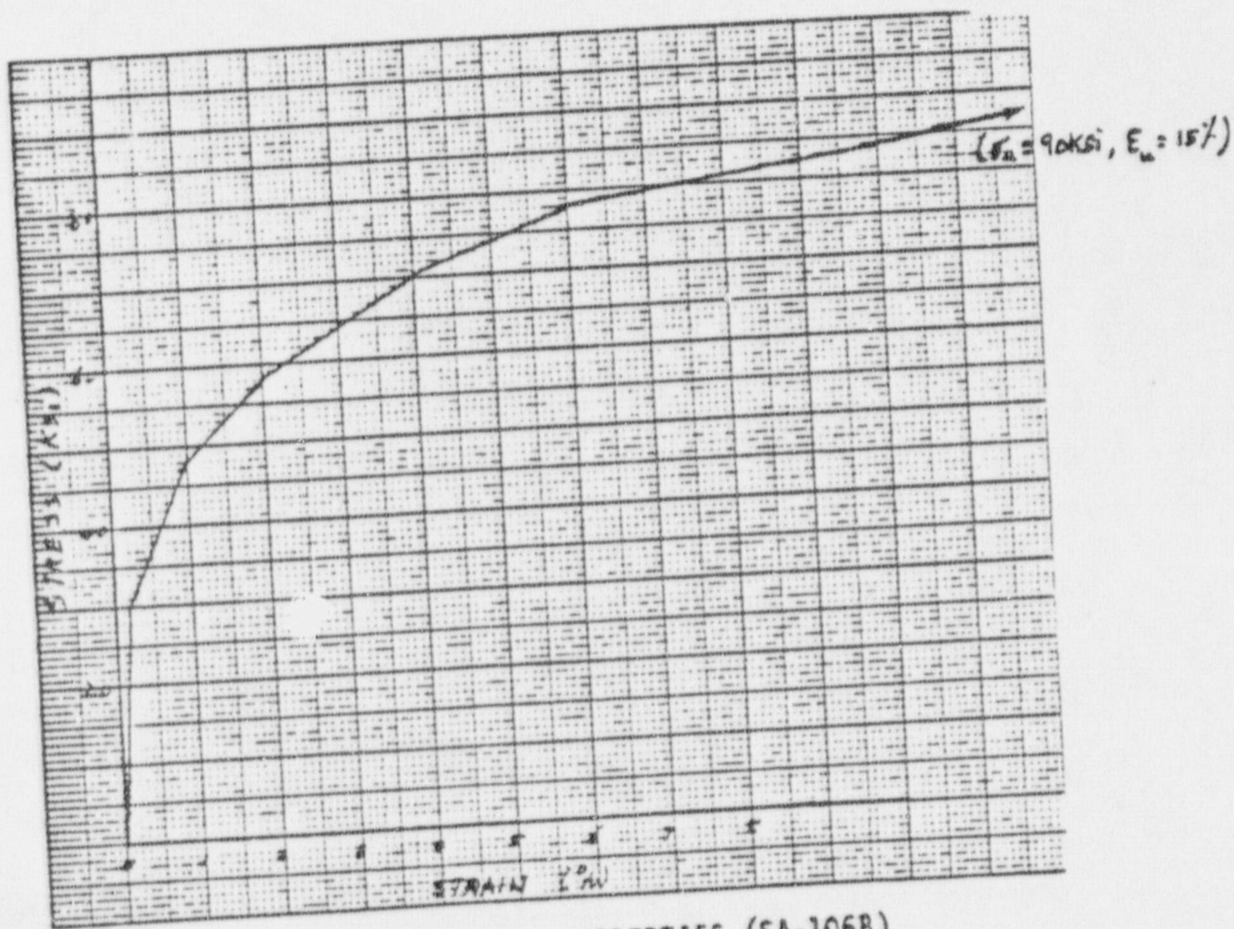
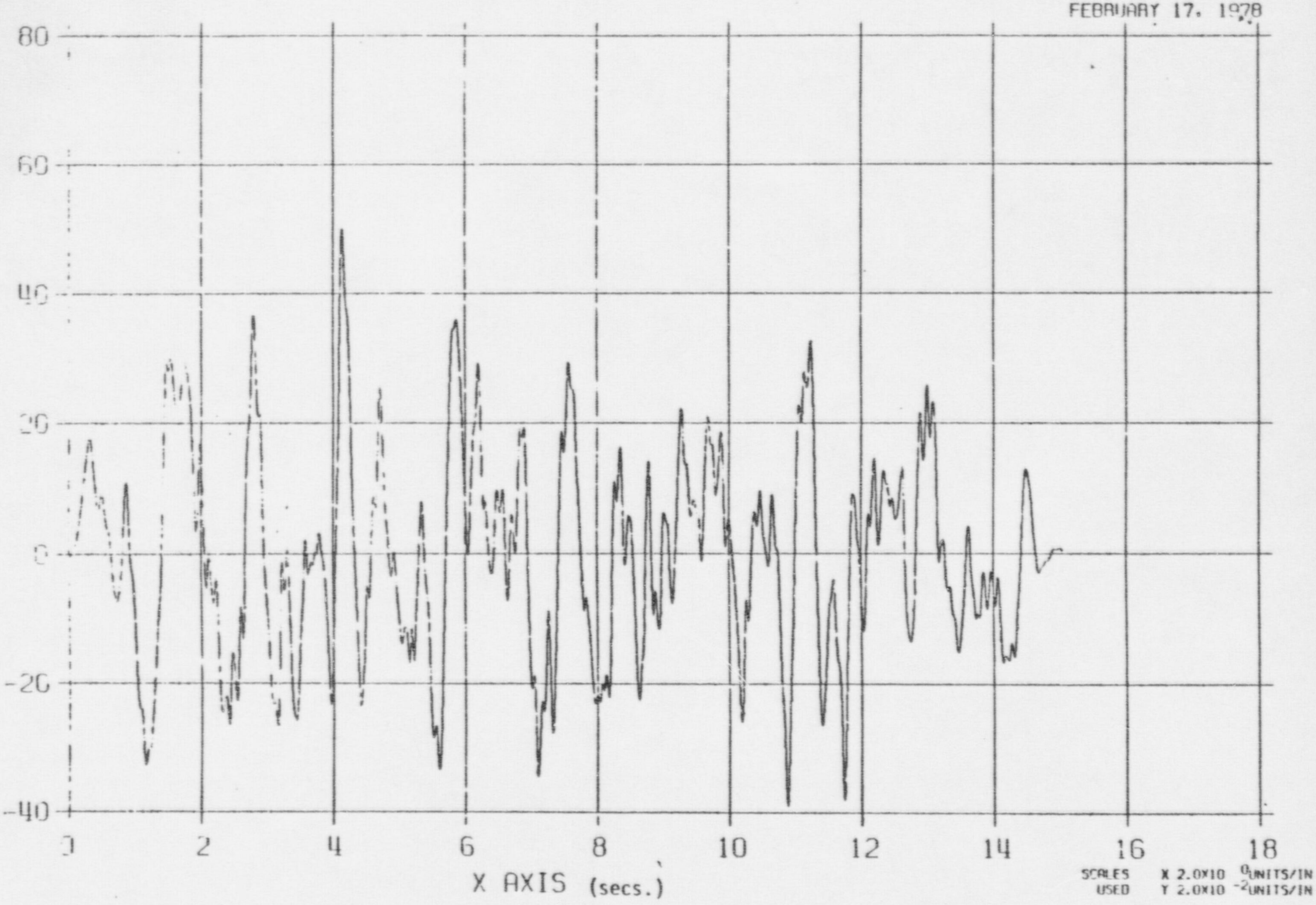


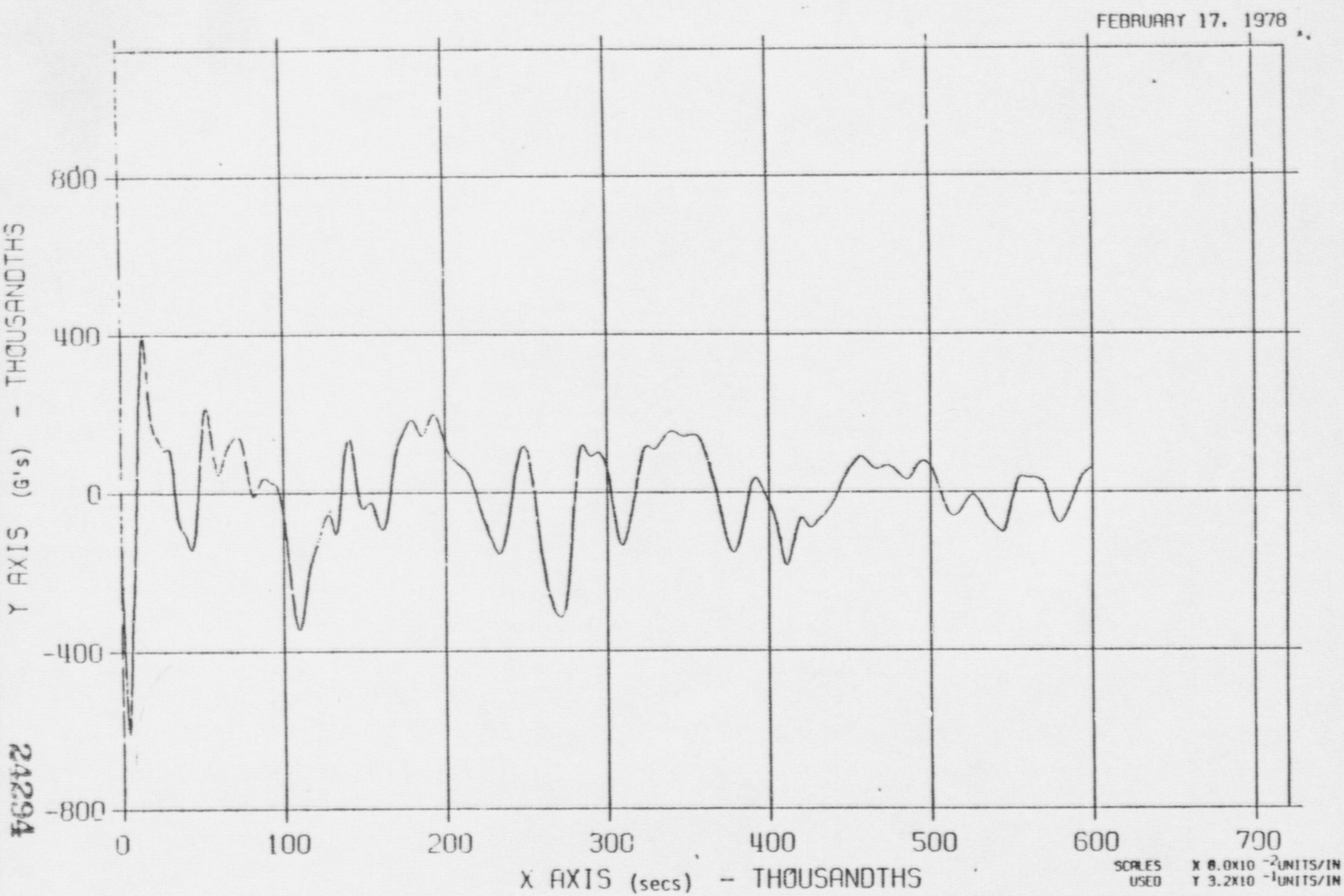
FIGURE 2: MATERIAL PROPERTIES (SA-106B)
MIL. CERT.

FIGURE 3: VERTICAL OBE AT BASEMAT



FL 1

FIGURE 4: VERTICAL SRV AT BASEMAT



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PL 1

TIME SEC.					
0.01400	0.01600	0.01800	0.02000	0.02200	0.02400
0.02600	0.02800	0.03000	0.03200	0.03400	0.03600
0.03800	0.04000	0.04200	0.04400	0.04600	0.04800
0.05000	0.05200	0.05400	0.05600	0.05800	0.06000
0.06200	0.06400	0.06600	0.06800	0.07000	0.07200
0.07400	0.07600	0.07800	0.08000	0.08200	0.08400
0.08600	0.08800	0.09000	0.09200	0.09400	0.09600
0.09800	0.10000	0.10200	0.10400	0.10600	0.10800
0.11000	0.11200	0.11400	0.11600	0.11800	0.12000
0.12200	0.12400	0.12600	0.12800	0.13000	0.13200
0.13400	0.13600	0.13800	0.14000	0.14200	0.14400
0.14600	0.14800	0.15000	0.15200	0.15400	0.15600
0.15800	0.16000	0.16200	0.16400	0.16600	0.16800
0.17000	0.17200	0.17400	0.17600	0.17800	0.18000
0.18200	0.18400	0.18600	0.18800	0.19000	0.19200
0.19400	0.19600	0.19800	0.20000	0.20200	0.20400
0.20600	0.20800	0.21000	0.21200	0.21400	0.21600
0.21800	0.22000	0.22200	0.22400	0.22600	0.22800
0.23000	0.23200	0.23400	0.23600	0.23800	0.24000
0.24200	0.24400	0.24600	0.24800	0.25000	0.25200
0.25400	0.25600	0.25800	0.26000	0.26200	0.26400
0.26600	0.26800	0.27000	0.27200	0.27400	0.27600
0.27800	0.28000	0.28200	0.28400	0.28600	0.28800
0.29000	0.29200	0.29400	0.29600	0.29800	0.30000
0.30200	0.30400	0.30600	0.30800	0.31000	0.31200
0.31400	0.31600	0.31800	0.32000	0.32200	0.32400
0.32600	0.32800	0.33000	0.33200	0.33400	0.33600
0.33800	0.34000	0.34200	0.34400	0.34600	0.34800
0.35000	0.35200	0.35400	0.35600	0.35800	0.36000
0.36200	0.36400	0.36600	0.36800	0.37000	0.37200
0.37400	0.37600	0.37800	0.38000	0.38200	0.38400
0.38600	0.38800	0.39000	0.39200	0.39400	0.39600
0.39800	0.40000	0.40200	0.40400	0.40600	0.40800
0.41000	0.41200	0.41400	0.41600	0.41800	0.42000
0.42200	0.42400	0.42600	0.42800	0.43000	0.43200
0.43400	0.43600	0.43800	0.44000	0.44200	0.44400
0.44600	0.44800	0.45000	0.45200	0.45400	0.45600
0.45800	0.46000	0.46200	0.46400	0.46600	0.46800
0.47000	0.47200	0.47400	0.47600	0.47800	0.48000
0.48200	0.48400	0.48600	0.48800	0.49000	0.49200
0.49400	0.49600	0.49800	0.50000	0.50200	0.50400
0.50600	0.50800	0.51000	0.51200	0.51400	0.51600
0.51800	0.52000	0.52200	0.52400	0.52600	0.52900

TABLE 1: COMBINED TIME HISTORY

0.53000	0.53200	0.53400	0.53600	0.53800	0.54000
0.54200	0.54400	0.54600	0.54800	0.55000	0.55200
0.55400	0.55600	0.55800	0.56000	0.56200	0.56400
0.56600	0.56800	0.57000	0.57200	0.57400	0.57600
0.57800	0.58000	0.58200	0.58400	0.58600	0.58800
0.59000	0.59200	0.59400	0.59600	0.59800	0.60000
0.60200	0.60400	0.60600	0.60800	0.61000	0.61200
0.61400	0.61600	0.61800	0.62000	0.62200	0.62400
0.62600	0.62800	0.63000	0.63200	0.63400	0.63600
0.63800	0.64000	0.64200	0.64400	0.64600	0.64800
0.65000	0.65200	0.65400	0.65600	0.65800	0.66000
0.66200	0.66400	0.66600	0.66800	0.67000	0.67200
0.67400	0.67600	0.67800	0.68000	0.68200	0.68400
0.68600	0.68800	0.69000	0.69200	0.69400	0.69600
0.69800	0.70000	0.70200	0.70400	0.70600	0.70800
0.71000	0.71200	0.71400	0.71600	0.71800	0.72000
0.72200	0.72400	0.72600	0.72800	0.73000	0.73200
0.73400	0.73600	0.73800	0.74000	0.74200	0.74400
0.74600	0.74800	0.75000	0.75200	0.75400	0.75600
0.75800	0.76000	0.76200	0.76400	0.76600	0.76800
0.77000	0.77200	0.77400	0.77600	0.77800	0.78000
0.78200	0.78400	0.78600	0.78800	0.79000	0.79200
0.79400	0.79600	0.79800	0.80000	0.80200	0.80400
0.80600	0.80800	0.81000	0.81200	0.81400	0.81600
0.81800	0.82000	0.82200	0.82400	0.82600	0.82800
0.83000	0.83200	0.83400	0.83600	0.83800	0.84000
0.84200	0.84400	0.84600	0.84800	0.85000	0.85200
0.85400	0.85600	0.85800	0.86000	0.86200	0.86400
0.86600	0.86800	0.87000	0.87200	0.87400	0.87600
0.87800	0.88000	0.88200	0.88400	0.88600	0.88800
0.89000	0.89200	0.89400	0.89600	0.89800	0.90000
0.90200	0.90400	0.90600	0.90800	0.91000	0.91200
0.91400	0.91600	0.91800	0.92000	0.92200	0.92400
0.92600	0.92800	0.93000	0.93200	0.93400	0.93600
0.93800	0.94000	0.94200	0.94400	0.94600	0.94800
0.95000	0.95200	0.95400	0.95600	0.95800	0.96000
0.96200	0.96400	0.96600	0.96800	0.97000	0.97200
0.97400	0.97600	0.97800	0.98000	0.98200	0.98400
0.98600	0.98800	0.99000	0.99200	0.99400	0.99600
0.99800	1.00000				

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-117.71588	-131.74646	-145.77704	-159.80762	-176.59702	-193.38642	
-210.17581	-226.96521	-243.75461	-267.82262	-291.89064	-315.95866	
-340.02667	-364.09469	-399.01969	-433.94469	-468.86969	-503.79470	
-538.71970	-589.36623	-640.01276	-690.65928	-741.30581	-791.95234	
-860.69172	-929.43109	-998.17048	-1066.90985	-1135.64925	-1217.52780	
-1299.40634	-1381.28491	-1463.16345	-1545.04201	-1632.85298	-1720.66394	
-1808.47490	-1896.28586	-1984.09563	-2079.91409	-2175.73135	-2271.54865	
-2367.36591	-2463.18317	-2565.07385	-2666.96451	-2768.85513	-6660.77612	
-8349.73425	-6837.55237	-5364.71710	-2952.68350	-493.44163	-67.31950	
-951.09779	-1884.51289	-2368.35825	-2608.03055	-2815.61218	-2999.75711	
-3048.82639	-3089.83606	-3572.90332	-4367.52091	-4806.44739	-4910.67206	
-4996.28638	-5177.84521	-5241.51996	-4784.49054	-3737.53000	-2516.40109	
-1797.37958	-1842.20377	-2291.42792	-2712.32715	-2816.35809	-2587.61188	
-2209.62759	-1863.53845	-1607.06308	-1387.69940	-1213.25175	-1168.44942	
-1321.56376	-1634.59575	-1887.33267	-1884.00719	-1631.98158	-1300.57155	
-1060.77007	-948.04060	-874.71502	-766.58086	-699.12858	-787.01049	
-1076.03770	-1550.49232	-2129.95120	-2656.96982	-2974.36200	-2966.20831	
-2585.84637	-1913.44821	-1289.18155	-872.30367	-527.24781	-168.22052	
173.12417	530.59698	740.44169	711.10709	564.16330	955.82587	
1928.93506	2848.49973	3339.60458	3431.62247	3086.48657	2727.60663	
2645.69986	2847.58832	3155.51520	3417.50546	3545.49710	3553.59616	
3641.37622	3911.68567	4407.96704	5179.68811	6022.16144	6706.91290	
7204.82336	7635.76910	8028.22510	8389.90027	8662.15259	8795.97290	
8661.81885	8963.88879	9235.06238	9601.22559	9930.74084	10115.30237	Max.
10042.04858	9372.57739	9701.87830	9586.00061	9543.93701	9469.14063	
9399.58362	9333.24646	9270.62048	9176.77710	8948.71936	8651.81409	
8323.30664	8013.93347	7749.66467	7461.45514	7154.96277	6864.97949	
6637.89520	6524.16516	6588.91772	6831.77911	7192.16998	7580.17346	
7904.84698	8131.71033	8214.11096	8107.84241	7743.07458	7183.51416	
6573.23077	5911.03467	5303.63293	4830.48810	4406.00409	4200.52826	
4002.78122	3869.02664	3380.60373	4017.54404	4578.78271	5531.44043	
6469.77197	7141.14496	7517.61659	7498.06018	7318.73254	7213.87390	
7214.72888	7222.73340	7118.14575	6933.00397	6637.40033	6154.71021	
5557.00110	4993.52118	4606.89478	4468.42548	4548.31470	4738.55664	
4943.84790	5183.55756	5423.91656	5587.06976	5604.77783	5447.91815	
5223.84827	5051.68005	4953.62610	4886.35297	4842.39478	4770.63007	
4647.09998	4473.16272	4284.09320	4109.82660	3959.95541	3840.42853	
3725.56787	3595.01663	3442.34845	3214.25623	2921.38232	2593.25232	
2238.51651	1867.32239	1460.43011	1019.98177	565.89491	158.98899	
-128.53831	-286.09286	-299.15743	-176.10948	43.18326	314.47510	
581.34082	750.11437	719.24892	535.35781	307.85867	49.68781	
-200.51223	-447.74606	-760.51202	-1178.45865	-1606.48090	-2050.31754	
-2091.58063	-1895.95660	-1728.48560	-1572.12080	-1555.19769	-1733.22006	

-1956.43135	-2113.99225	-2179.97467	-2210.42807	-2265.68628	-2325.03766
-2343.12961	-2357.21021	-2359.27866	-2322.65268	-2268.77252	-2229.54602
-2211.00656	-2205.40161	-2223.81009	-2251.38736	-2282.33923	-2384.34903
-2553.70566	-2745.05640	-2923.22702	-3042.60382	-3121.07596	-3177.55392
-3237.06085	-3315.12363	-3391.50549	-3496.93901	-3610.57901	-3728.35672
-3835.65588	-3835.89600	-3761.42157	-3638.51099	-3515.73682	-3438.09698
-3385.91867	-3387.93436	-3437.84048	-3546.41580	-3698.15253	-3845.37311
-3996.54501	-4112.25610	-4153.14545	-4132.26733	-4053.54691	-3926.49945
-3769.29871	-3602.51721	-3450.07007	-3368.43527	-3370.10529	-3423.21594
-3507.15381	-3606.75500	-3665.43787	-3690.17444	-3697.85599	-3705.23740
-3706.34256	-3521.68558	-3157.58270	-2755.73508	-2391.37842	-2075.34335
-1875.66341	-1771.62793	-1675.77582	-1558.97255	-1439.05542	-1344.92183
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-1690.43346	-1545.59050	-1348.98228	-1185.56081	-997.86940	-797.08794
-618.58440	-493.86277	-455.68413	-427.95679	-971.36730	-1006.10220
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-1202.73134	-1198.22336	-1193.71538	-1189.20740	-1184.69943	-1126.70059
-1068.70178	-1010.70294	-952.70412	-894.70530	-790.42330	-686.14130
-581.85930	-477.57729	-373.29529	-246.01952	-118.74373	8.53205
135.80783	263.08361	384.09952	505.11544	626.13135	747.14725
868.16317	957.73329	1047.30344	1136.87357	1226.44370	1316.01382
1359.55093	1403.08801	1446.62511	1490.16220	1533.69930	1530.66942
1527.63954	1524.60966	1521.57979	1518.54991	1485.89709	1453.24426
1420.59145	1387.93863	1355.28581	1324.03740	1292.78900	1261.54062
1230.29222	1199.04382	1204.59511	1210.14641	1215.69769	1221.24898
1226.80026	1294.68916	1362.57808	1430.46698	1498.35588	1566.24478
1700.72551	1835.20622	1969.68695	2104.16766	2238.64841	2408.37338
2578.09839	2747.82339	2917.54837	3087.27338	3243.33981	3399.40625
3555.47269	3711.53915	3867.60556	3967.28409	4066.96259	4166.64111
4266.31964	4365.99817	4380.81464	4395.63110	4410.44757	4425.26404
4440.08051	4390.43457	4340.78657	4291.14264	4241.49664	4191.85065
4106.14539	4020.44022	3934.73495	3849.02972	3763.32446	3670.45706
3577.58960	3484.72217	3391.85474	3298.98730	3210.47412	3121.96097
3033.44778	2944.93463	2856.42145	2765.90625	2675.39102	2584.87579
2494.36060	2403.84540	2307.36139	2210.87741	2114.39340	2017.90939
1921.42540	1834.00739	1746.58937	1659.17134	1571.75333	1484.33531
1417.17863	1350.02196	1282.86528	1215.70860	1148.55193	1105.35957
1062.16721	1018.97486	975.78249	932.59015	900.23567	867.88120
835.52673	803.17226	770.81778	730.96002	691.10226	651.24449
611.38673	571.52897				

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