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**Hydraulic Pressure Pulses
with Elastic and Plastic
Structural Flexibility:
Test and Analysis
(LWBR Development Program)**

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March 1978

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Pressure pulse tests were conducted with a flexible test section in a test vessel filled with room temperature water. The pressure pulses were generated with a drop hammer and piston pulse generator and were of a sufficient magnitude to cause plastic deformation of the test section. Because of the strong pressure relief effect of the deforming test section, pressure pulse magnitudes were below 265 psig in magnitude and had durations of 50-55 msec.

Calculations performed with the FLASH-35 bi-linear hysteresis model of structural deformation show good agreement with experiment. In particular, FLASH35 adequately predicts the decrease in peak pressure and the increase in pulse duration due to elastic and plastic deformation of the test section. Predictions of flexible member motion are good, but are less satisfactory than the pressure pulse results due to uncertainties in the values of yield point and beyond yield stiffness used to model the various flexible members. Coupled with this is a strong sensitivity of the FLASH35 predictions to the values of yield point and beyond yield stiffness chosen for the various flexible members.

The test data versus calculation comparisons presented here provide preliminary qualification for FLASH35 calculations of transient hydraulic pressures and pressure differentials in the presence of flexible structural members which deform both elastically and plastically.

I. INTRODUCTION

During the course of a postulated Loss-of-Coolant Accident (LOCA), reactor structural members are subjected to transient loadings as a result of rapid temporal and spatial pressure variations in the coolant. The most severe loadings are calculated to occur during the subcooled blowdown when strong decompression waves propagate from the break through the various flow passages. The FLASH-35* computer program is used to calculate coolant pressures during the subcooled and saturated blowdown. A unique feature of the FLASH-35 program is its ability to account for the coupled effects of structural deflection and coolant hydrodynamics. That is, FLASH-35 has a coupled hydro-elastic capability.

Earlier versions of the FLASH program have been used to calculate transient pressures resulting from blowdown and check valve slam (References 3-6). Generally, good agreement was obtained with experimental data. In these experiments the test vessels were very stiff and hence a rigid structure was assumed.

Basic data for the qualification of the flexible structural member option in FLASH-35 were reported in References 7 and 8. In the test series reported therein pressure pulse tests were run on flexible test sections with room temperature water in a 2 inch diameter vessel. Pressure pulses were generated by rapidly displacing a piston into the test vessel. Although these tests were not prototypical, the basic mechanism of pressure relief due to structural deflection clearly existed. Comparisons of the test data with FLASH-34 calculations demonstrated that the FLASH-34 program with the flexible structural member option correctly modeled the effect of elastic structural deflection on hydraulic pressure.

The present test series is an extension of the work reported in References 7 and 8. In this series the test geometry, is that depicted in Figure 1 and used in the tests of References 7 and 8. The primary difference between the present test series and previous tests is that the wall thickness of the flexible test sections is nominally 1/16 inch rather than 1/8 inch, thus permitting wall deflections in the beyond yield range. The purpose of this testing is to qualify FLASH-35 for cases in which structural members are strained beyond their yield points by pressure pulse loadings. The motivation for this testing and for a beyond-yield flexible member model is that FLASH-35-calculated "transient loading" performed with an elastic flexible member model often indicate beyond-yield loads. A flexible member model with only elastic flexibility cannot correctly treat either the structural deformation or the concomitant pressure relief associated with yielding. Both elastic and plastic flexibility are needed in this case.

Because the present tests caused permanent deformation of the test section, only a limited number of tests could be performed. In all, five dynamic runs were made with a single test section at drop heights of 2, 4, 6, 8 and 10 inches. The pressure pulses were provided by a drop hammer (with no weights attached) which impacted a one inch piston at the top of the test vessel (see Figure 1). The measured pressure pulses were below

* FLASH-35 is an advanced version of FLASH-34, which is a combination of FLASH-3 (Reference 1) and FLASH-4 (Reference 2).

265 psig in magnitude and had durations of 50-55 msec. Pulses in excess of 265 psig could not be produced because the pressure relief effect was so strong after the load at yield ($\approx$ 200 psig) was reached. For a given reactor application, the load at yield-and thus the expected pressure differential-might be smaller or larger than those characteristic of the present tests.

II. PRESSURE PULSE TESTS WITH 1/16 INCH TEST SECTION

The pressure pulse test vessel consisted of a 2 inch diameter, 45-1/4 inch long test vessel with a one inch piston at one end (see Figures 1, 2 and 3). An aluminum test section was mounted inside as in Figure 1. A drop hammer displaced the piston into the water-filled vessel, thus compressing the water and producing a hydraulic pressure pulse. Piezoelectric pressure transducers were located near the top of the test vessel, at an elevation corresponding to the midpoint of the aluminum test section, and at a point 4.5 inches above the bottom of the vessel. The aluminum test section was 1 1/4 inch square extruded aluminum tubing (6063-T5), 34 3/8 inches long with a nominal wall thickness of 1/16 inch. Aluminum was selected because its modulus of elasticity at room temperature is approximately the same as that of Zircaloy at reactor operating temperature. Schematics of the test section are shown in Figures 1 and 4. An "O-ring" at the test section base provided the pressure boundary for the test vessel.

The inside of each test section was open to the atmosphere and provided the access necessary for measurements of wall displacement. Both a proximeter and strain gages were used to measure wall displacement, as shown in Figures 1 and 4. The different faces of the test section are labeled A, B, C and D. Strain gages were placed in the axial center of the test section on faces A and B. At the bottom, approximately 1.25 inches from the lower end, strain gages were located on faces C and D. It was not possible to place strain gages on the upper end of the test section because the cap (i.e., the top) would have had to be welded on after the strain gages were installed, a process which most probably would have damaged the strain gages. All strain gages were placed on the inside (i.e., the dry side) of the test section. A proximeter was also placed at the approximate axial location of the strain gages on walls C and D, to measure the deflection of wall A at this point directly.

Test section wall deflection was measured by the strain gages and proximeter and converted to test section volumetric diaplacement in much the same way as in Appendix A of Reference 7, with some differences. The differences result primarily from the necessity to determine the load-displacement characteristics in the beyond-yield range. This meant that a different test section ("static" test section) had to be used to determine the load-displacement characteristics than was used in the subsequent pressure pulse tests ("dynamic" test section). Variations in wall thicknesses between the test sections and between the walls of a given test section made it necessary to use scaling laws to determine the "dynamic" test section stiffnesses and yield points from measurements of the same quantities on the "static" test section.

The measured load-displacement characteristics of the static test section are shown in Figure 5. In essence, the static test section was taken through a series of hysteresis cycles of increasing magnitude to determine a) the load-displacement characteristics of the static test section and b) whether the FLASH-35 bi-linear hysteresis model is a reasonable representation of the behavior of the static test section in the beyond-yield range. The load on the test section was provided by piling lead bricks on the piston at the top of the test vessel (Figure 1) and was measured with a static pressure gage. The net displacement of the piston was used to determine the volume displacement of the test assembly. By subtracting out the amount of displacement due to fluid compressibility and test vessel displacement the "true" load displacement curve of the static test section curve (shown in Figure 5) was obtained. The details of this procedure together with the means of relating the static test results to the yield points and stiffnesses (elastic and plastic) required as input to the FLASH-35 program are discussed in Appendix A.

In the dynamic tests, pressure pulse magnitudes on the "dynamic" test section were controlled by varying the drop hammer height. Because the test section was stressed beyond-yield, only a limited number of runs were made. Initially, seven runs were planned using a single test section with drop heights of 2, 4, 6, 8, 10, 12 and 14 inches. Unlike some of the tests of References 7 and 8, only the one inch piston was used and no additional weights were attached to the drop hammer. The run sequence was such that the drop height increased by two inches in successive runs, so that each run increased the permanent set in the walls beyond that of the previous run. In fact only five of the runs planned were made because of the disengagement of the strain gage from wall C during run 5Y.

The tests were initiated with the water in the test vessel at approximately 68°F and 23 psig. Static pressure readings were taken before and after each run using the dial gage indicator shown in Figure 1. During the tests the dial gage was valved out of the system.

Because of the permanent deformation of the test section, check runs of the sort made in References 7 and 8 could not be made. However, a run was made at a drop height of 6 inches after run 4Y at a drop height of 8 inches had already been completed. In this run, no additional permanent set occurred, giving some confidence that the test apparatus was yielding valid results.

III. FLASH-35 SIMULATION OF PRESSURE PULSE TESTS

Schematics of the FLASH-35 model of the dynamic test section are shown in Figures 4 and 6. In each case a total of 11 nodes represents the compressed water volume in the test vessel. Of the eleven nodes in the test vessel, the first two represent that portion of the test vessel volume above the test section, while the remaining nine nodes represent the annular region around the test section.

Ten flow paths connecting the eleven test vessel nodes in series were given friction factors of 0.06. Sensitivity studies reported in

Reference 7 indicated that FLASH-34 (and hence, FLASH-35) calculations were not affected by rather large (factor of 3) changes in the in-vessel flow path friction factors. It is reasonable to assume, and was assumed, that the same holds for the present series of tests. The initial flow in all flow paths was set equal to zero.

In general, the in-vessel modeling of the present tests was the same as that of Reference 7*. The piston mass and damping coefficients reported in Reference 7 for the one inch piston were used - 3.11 lbs and 9 lbf-sec/ft. The test vessel flexible member model was identical to that of Reference 7.

The initial node pressures were calculated as 37.7 psia plus the elevation head from the top of the test vessel. An initial enthalpy of 36 Btu/lb was used for all of the eleven test vessel nodes. Node 12 was the constant pressure atmosphere node.

The FLASH-35 flexible member model of the dynamic test section is shown in Figures 4 and 6 and reflects the results of the tests on the static test section discussed in Appendix A. There were several problems with beyond-yield tests and analysis which did not exist in previous tests (References 7 and 8):

1. A different test section had to be used in static tests than was used in the pressure pulse tests. These are referred to as the "static" and "dynamic" test sections, respectively.
2. Slight differences in the various wall thicknesses of a given test section are much more important if yield occurs than if it does not.
3. Slight differences in assembly of the static and dynamic test sections may lead to differences in the beyond-yield characteristics which are difficult to account for.

As discussed in Appendix A, there were significant differences in the wall thicknesses between the two test sections as well as significant differences in the wall thicknesses of a given test section. Because the stiffness of a wall after yield is considerably smaller than its stiffness before yield, a slight increase in pressure beyond its yield point can cause extensive deformation of that wall. If this wall happens to be the weakest wall - that is, if it is less stiff and has a lower yield point than the other walls - it may deform considerably in the beyond-yield range while the other walls deform only slightly in the elastic range. There is also an additional complication in dynamic testing in that the beyond-yield deformation of the weak wall provides significant pressure relief (i.e., attenuates the pressure pulse). This pressure attenuation enhances the possibility that the other walls will not reach yield and thus not deform extensively or permanently.

* In this reference, a study was made to determine the optimum number of nodes in the test vessel. The in-vessel modeling in the present study uses this optimum nodalization.

To account for this effect, the walls at each end of the dynamic test section were modeled differently than those in the middle of the test section. Statically measured strain gage readings on the dynamic test section indicated that wall C was the weakest (i.e., had the most deformation for a given load) with wall B following close behind. These walls were therefore modeled as independent flexible members (see Figure 4). Walls A and D were found to be stronger than walls B and C and to have approximately the same load-strain behavior. They were therefore modeled as a single flexible member. These differences in strength were confirmed by post-test measurements of wall thickness (Appendix A).

The flexible members adjacent to the seven middle nodes (see Figures 4 and 6) were modeled so that each represented all four walls. There were two reasons why such an approximation will work in the middle nodes but not necessarily the end nodes: 1) dynamic pressure loads were expected to be highest in the end regions because of the effects of the abrupt area change at the top and wave reflection at the bottom and 2) the static tests gave some indication that welding of the cap and the base to the test section ends had generated sufficiently high temperatures to reduce the yield point of the metal in the end regions. The test section was therefore characterized by two yield points as discussed in Appendix A: a "normal" yield point which characterized the seven middle flexible members and a "low" yield point which characterized the flexible members at the ends. Although the yield point of aluminum can be affected by high temperatures, its elastic modulus usually is not. Therefore, only one modulus of elasticity was used for the entire test section. This is not to say that the stiffness (psi/ft^3), which is an input parameter to the FLASH-35 model, is a constant; the different areas and thicknesses of the various flexible members make this quantity different for each, even though the modulus of elasticity may be the same.

To relate stiffnesses and yield points of the static test section to those of the dynamic test section, it is, unfortunately, necessary to assume a mode of deformation. Two modes of deformation which are important in the present tests are bending and membrane stretching or tension. Measurements of the load-displacement characteristics of both test sections were made in the elastic range via the strain gages illustrated schematically in Figure 4. With this information the stiffnesses of the dynamic test section can be computed from those of the static test section, but only if the mode of deformation is known. Likewise, the yield points of the various flexible members in the dynamic test section model can be obtained through certain scaling laws (Reference 9), but again only if the mode of deformation is known. If bending is assumed to be the dominant mode, the dynamic test section stiffnesses (psi/ft^3) are lower and the yield points (ft^3) higher than if tension is assumed to be the dominant mode. Unfortunately, it is probable that both bending and tension are important in the deformation process, and the extent of each is uncertain. It is also not possible to select one mode as 'most conservative', since a bending mode assumption gives the lowest stiffnesses, whereas a tension mode assumption gives the lowest yield point.

One way to avoid this uncertainty is to abandon the technique of measuring stiffnesses and calculate the load-deformation characteristics of the various members based on the measured thicknesses of each member. However, this introduces as many uncertainties as it removes. There is still the uncertainty of the yield point at the ends. In addition, it is not clear how the corners of the test section are to be treated; they do not remain 90° angles after a beyond-yield load is applied.

Rather than attempt calculations of this sort at this time it was decided to a) perform two sets of FLASH-35 calculations, with 'most conservative' and 'least conservative' combinations of input stiffnesses and yield points, and b) do a parametric study on the FLASH-35 input stiffnesses and yield points to determine the sensitivity of the calculations to the values of these quantities. This parameter study and the results obtained from it are discussed in Appendix B.

The 'most conservative' and 'least conservative' cases alluded to above result from scaling the stiffnesses and yield points from the static to the dynamic test section with the 'most conservative' or 'least conservative' assumed mode of deformation. Details of these calculations are given in Appendix A. The 'least conservative' case scales the stiffnesses according to a tension mode of deformation and the yield points according to a bending mode of deformation. By doing this, maximum estimates of stiffnesses and yield points are obtained and predicted wall deflections are minimized. The 'most conservative' case reverses this, using bending mode stiffnesses and tension mode yield points. Table I summarizes the stiffnesses and yield points used in each of these models. The 'least conservative' case was also used as the base case for the parameter study in Appendix B. Included in this parameter study are predictions of pressure pulse magnitudes and wall deflections using consistent assumptions for the mode of deformation (i.e., both yield points and stiffnesses are computed assuming the same mode of deformation). Predictably, these results fall between those of the 'least' and 'most' conservative cases.

V. COMPARISON OF FLASH-35 SIMULATIONS WITH TEST DATA

Tables I and II summarize the input parameters and show the results of comparisons between the test data and the two sets (bending and tension) of FLASH-35 calculations. Generally speaking, pressure pulse prediction is good, with the 'least-conservative' case averaging about 8% high and the 'most-conservative' case averaging about 3% low in the bottom node. Prediction of wall displacement is somewhat less accurate, however, and shows a strong sensitivity to the values of the yield points and beyond yield stiffnesses used to describe the various walls. For wall C - which is the weakest wall and reaches yield first - both the peak and final values of deflection are, on the average, underestimated in the 'least conservative' case (5% and 28% low, respectively). In contrast, the 'most conservative' case averages 20% high on peak deflection and 26% high on final deflection. The differences in the wall C yield point and beyond yield stiffness for these two cases are only 6% and 10%, respectively. Nevertheless, the comparisons of predictions with experimental results give strong indications that the bi-linear hysteresis model is a sufficiently accurate representation of reality that flexible member motion in the elastic and beyond-yield ranges can be adequately treated by FLASH-35.

Aside from the uncertainty concerning the mode of deformation, it appears that the estimates of yield points and/or beyond-yield stiffnesses used in the calculations are somewhat high. Given the uncertainties associated with the computation of these quantities, it is not surprising that the estimates of their magnitudes might be somewhat in error. In fact, it is probably safe to say that the major part of the disagreement between predicted and experimental results is caused by the uncertainties in these input quantities, rather than by FLASH-35 inadequacies.

Table II compares experimental results with calculations based on the two yield point/stiffness models for drop heights of 2, 4, 6, 8 and 10 inches. The results for the 10 inch drop height are not complete because the wall C strain gage failed during that test. The table lists experimental and calculated peak pressures at the top, middle and bottom of the test section, the peak and final deflections of walls A-D and C at the bottom of the test section, and the peak deflection of the wall at the axial middle of the test section (which experiences no permanent deformation). In comparing the deflection results, it should be remembered that wall A-D represents two faces of the test section, wall C one face, and the middle wall four faces.

An examination of the results given in Table II indicates in most cases that when pressure pulse magnitudes in the bottom node are high, wall C deflections are low, and vice versa. The deflections of the middle wall are generally overpredicted and those of wall A-D generally underpredicted for both 'least conservative' and 'most conservative' cases. Although a strain gage was not attached to wall B at the bottom of the test section, post-test inspection revealed that it behaved more like wall C than either wall A or wall D. If it is assumed that wall B behaves exactly like wall C, then the total predicted volume displacement of walls A, B, C and D and the predicted pressures in the bottom node agree quite well with the test results for the 'most conservative' case. The predicted peak and final displacements average 6% higher and 6% lower, respectively, than the test values. The predicted pressures average 3% lower than the measured bottom node pressures. This does not mean that the flexible member model used in the 'most conservative' case is the best approximation of reality. The wall C displacements are too high and the wall A-D displacements too low for that. It does show, however, that if the total amount of pressure relief - in the form of flexible member motion - is predicted correctly, then the predicted pressures are also reasonably accurate.

Figures 7-9 are comparisons of the wall deflection - time responses predicted in run 304 with those measured experimentally. As can be seen, the deflections for the two walls which undergo permanent deformation (A-D and C) are underpredicted, whereas the deflection of the middle wall is only slightly underpredicted. The middle wall did not undergo permanent deformation. The FLASH-35 input listing for run 304 is given in Appendix C. A description of the FLASH-35 flexible structural member model is given in Appendix D.

Figures 10-12 are comparisons of the pressure-time responses of nodes 1, 7 and 10 at the top, middle and bottom of the test vessel for run 305. This run is shown rather than run 304 because of difficulties experienced in reproducing the pressure pulse traces from the recorded signals in run 304. In run 305, the FLASH-35 model was identical to that of run 304 except that the drop height was 10 inches rather than 8 inches. The runs are much the same in the relationship of calculated to experimental results. At least in the bottom two nodes, the FLASH-35 model slightly overpredicts the magnitude of the pressure pulses in both runs 304 and 305. This can be seen for run 305 in Figures 11 and 12.

It was mentioned earlier that the 'least conservative' case (series 300) underpredicts wall deflections and overpredicts pressure pulse magnitudes in the bottom node. This suggests that either yield point or beyond-yield stiffness estimates of the various walls - or both - are too high. While the 'most conservative' case yields results which are closer to reality, it is of interest to at least examine such a possibility. The beyond-yield stiffness estimates obtained in Appendix A may be somewhat high because in the static tests which were used to determine the beyond-yield stiffness, only the top of the test section deformed plastically (see Figures 13 and 14). The estimates of beyond-yield stiffness, however, assumed that the entire test section deformed uniformly. Therefore, the actual beyond-yield stiffnesses at the ends of the test section are most probably somewhat lower than the values used in the calculations. However, since there are no sharp dividing lines between the ends of the test section and the middle, it is impossible to tell how much lower these stiffness values should actually be.

Figures 13 and 14 also show the need to model the ends of the dynamic test section differently than the middle. It is evident that the ends not only behave differently from the middle of the test section; they behave differently from one another. A further complexity is that the walls behave differently from one another, even at a given axial position, as can be seen in Figure 14. These experimental observations led to the flexible member model shown in Figures 4 and 6.

V. CONCLUSIONS

Beyond-yield pressure pulse tests were conducted with a flexible test section in a test vessel filled with room temperature water. A drop hammer and piston pulse generator were used to generate pulses which strained the test section beyond its yield point at the top and bottom. The results of these tests lead to the following conclusions and recommendations.

- a. Comparisons of FLASH-35 simulations with the test data demonstrate that the bi-linear hysteresis option is a sufficiently accurate representation of reality that flexible member motion in the elastic and beyond-yield ranges can be adequately treated by FLASH-35.

- b. Uncertainties in the values of yield points and stiffnesses which describe the test section are primarily responsible for the disagreement between FLASH-35 calculations and test results. These uncertainties are due to (1) the use of different test sections in static and dynamic tests, (2) possible property variations at the test section ends due to the method of construction, (3) different wall thicknesses in the same test section and (4) uncertainties in the mode of deformation.
- c. There is a strong sensitivity of the FLASH-35 predicted results to the yield points and beyond-yield stiffnesses of the various flexible members. One manifestation of this sensitivity is what might be referred to as a "weak wall" effect, in which the weakest wall deforms extensively and thereby relieves the pressure load on the remaining unyielded members.

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TABLE I

FLASH-35 Input Parameters for 'Most Conservative' and 'Least Conservative' Cases

Case	Flexible Member(s)	Mass (lbs)	Surface Area (ft ²)	Elastic Stiffness (psi/ft ³)	Beyond-Yield Stiffness (psi/ft ³)	Yield Point (ft ³)
Base* (least conservative)	14-20 (middle)	0.1511	0.1249	6.046 (10 ⁶)	3.839 (10 ⁵)	4.487 (10 ⁻⁵)
	13 (A-D top) & 21 (A-D bottom)	0.07556	0.06245	1.243 (10 ⁷)	7.890 (10 ⁵)	1.924 (10 ⁻⁵)
	22 (B top & 24 (B bottom)	0.03778	0.03123	2.382 (10 ⁷)	1.512 (10 ⁶)	0.9812 (10 ⁻⁵)
	23 (C top) & 25 (C bottom)	0.03778	0.03123	2.321 (10 ⁷)	1.474 (10 ⁶)	0.9897 (10 ⁻⁵)
YP-T/S-B** (most conservative)	14-20 (middle)	0.1511	0.1249	5.573 (10 ⁶)	3.539 (10 ⁵)	4.278 (10 ⁻⁵)
	13 (A-D top) & 21 (A-D bottom)	0.07556	0.06245	1.163 (10 ⁷)	7.385 (10 ⁵)	1.850 (10 ⁻⁵)
	22 (B top) & 24 (B bottom)	0.03778	0.03123	2.182 (10 ⁷)	1.386 (10 ⁶)	0.9302 (10 ⁻⁵)
	23 (C top) & 25 (C bottom)	0.03778	0.03123	2.100 (10 ⁷)	1.333 (10 ⁶)	0.9333 (10 ⁻⁵)

* Base Case = yield point-Bending/stiffness-Tension (least conservative)

** YP-T/S-B = yield point-Tension/stiffness-Bending (most conservative)

TABLE II

Comparison of 'Most Conservative' and 'Least Conservative' FLASH-35 Calculations
with Test Results

Run No.	Drop Height (inches)	Peak Pressure (psid)			Peak Deflection ($\text{ft}^3 \times 10^5$)			Final Deflection ($\text{ft}^3 \times 10^5$)	
		Top	Middle (17)	Bottom	A-D Bottom	C Bottom	Middle	Bottom	Bottom
1Y (test)	2	130	130	130	0.933	0.487	1.79	0	0
301} FLASH-35*	2	151	138	145	1.22	0.650	2.25	0	0
391}	2	151	131	138	1.25	0.690	2.40	0	0
2Y (test)	4	220	200	200	1.87	1.13	2.77	0.400	0.367
302} FLASH-35*	4	200	191	195	1.63	1.05	3.12	0	0.200
392}	4	193	177	179	1.50	1.40	3.17	0	0.580
3Y (test)	6	238	212	200	2.67	2.13	3.31	0.933	1.13
303} FLASH-35*	6	237	214	225	1.88	1.61	3.58	0.150	0.680
393}	6	201	193	192	1.73	2.32	3.45	0	1.38
4Y (test)	8	225	215	210	3.27	2.74	3.78	1.20	1.53
304} FLASH-35*	8	245	225	227	2.82	2.10	3.69	0.950	1.11
394}	8	207	197	200	2.86	2.91	3.56	1.00	1.92
5Y (test)	10	265	230	215	4.64	---	2.13***	2.45	---
305} FLASH-35*	10	245	230	232	3.67	2.57	3.80	1.87	1.50
395}	10	219	207	208	3.89	3.50	3.69	1.80	2.33

* The 301-305 series assumes bending yield points and tension stiffness (least conservative case).
The 391-395 series assumes the reverse (most conservative case).

** Strain gage failure.

*** This value appears to be inconsistent with the data of previous runs. However, the same value was obtained on both strain gage A and strain gage B, so it is not a strain gage malfunction. It may be due to an incorrectly recorded amplification factor.

FIGURE 1
SCHEMATIC OF TEST CONFIGURATION

Pressure Pulse Test Facility

FIGURE 2

Negative No. 49710

FIGURE 3
G.3 BENCH TEST
PRESSURE PULSE RIG ASSY

FIGURE 4
LOCATION OF STRAIN GAGES ON TEST SECTIONS AND
FLEXIBLE MEMBER MODELING FOR FLASH-35 CALCULATIONS

FIGURE 5
DETERMINATION OF LOAD-DISPLACEMENT CURVE OF STATIC
TEST SECTION BASED ON MEASURED VOLUME DISPLACEMENT

FIGURE 6

FLASH-35 MODEL USED IN BEYOND-YIELD CALCULATIONS

FIGURE 7
COMPARISON OF FLASH-35 CALCULATED (RUN 304) AND
EXPERIMENTALLY DETERMINED VOLUME DISPLACEMENTS
OF WALL A-D

FIGURE 8
COMPARISON OF FLASH-35 CALCULATED (RUN 304) AND
EXPERIMENTALLY DETERMINED VOLUME DISPLACEMENT
OF MIDDLE WALL

FIGURE 9
COMPARISON OF FLASH-35 CALCULATED (RUN 304) AND
EXPERIMENTALLY DETERMINED VOLUME DISPLACEMENT OF WALL C

FIGURE 10
COMPARISON OF FLASH-35 CALCULATED (RUN 305) AND
EXPERIMENTALLY DETERMINED PRESSURE IN NODE I

FIGURE II
COMPARISON OF FLASH-35 CALCULATED (RUN 305) AND
EXPERIMENTALLY DETERMINED PRESSURE IN NODE 7

FIGURE 12
COMPARISON OF FLASH-35 CALCULATED (RUN 305) AND
EXPERIMENTALLY DETERMINED PRESSURE IN NODE 10

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FIGURE 13
LONGITUDINAL VIEW OF THE DEFORMATIONS
OF THE STATIC AND DYNAMIC TEST SECTIONS

(a) DYNAMIC TEST SECTION

(b) STATIC TEST SECTION

FIGURE 14

CROSS-SECTIONAL VIEW OF THE DEFORMATIONS OF THE STATIC AND DYNAMIC TEST SECTIONS 3/4 INCH FROM EACH END

APPENDIX A

Determination of the FLASH-35 Bi-Linear Hysteresis Flexible Member Model

Determination of the FLASH-35 Bi-Linear Hysteresis Flexible Member Model

Appendices A of References A-1 and A-2 describe static measurements which were used to determine the elastic stiffness K_e (psi/ft³) of the test sections, test vessel and surge tank used in those test series. Essentially, the method consisted of loading lead bricks on the piston at the top of the test vessel (see Figure 1 in the text) and measuring the test vessel pressure and piston volume displacement. After correcting for water compressibility and the displacement of other structurals whose load-displacement characteristics were known, the load-displacement characteristics of the test structural could be determined. Since these static tests involved only stresses that were well below yield, the same test section could be used in later dynamic pressure pulse tests. Thus, subsequent FLASH calculations of the dynamic pressure pulse runs could be and were based on the measured load-deflection characteristics of the actual test section used in those runs.

The same method can be used to determine the beyond-yield load-displacement characteristics of a test section as well as its elastic characteristics. However, there is a difficulty in using the same test section in subsequent dynamic tests. The problem is that a test section which has been strained beyond-yield in static testing cannot be cycled through the same range of loads and deflections in the dynamic tests that follow. It has been permanently deformed by the static tests. Therefore, any beyond-yield dynamic testing performed with this test section will necessarily involve testing in a region where the beyond-yield characteristics have not been determined experimentally and are likely to be somewhat different than those which have been determined experimentally.

To avoid this problem, two test sections were used in the present test series. The first, which will be referred to as the 'static' test section, was tested statically in the elastic and beyond-yield ranges. The second test section, which will be referred to as the 'dynamic' test section, was statically tested in the elastic range only. By using certain scaling laws (Reference A-3), the ratio of the elastic stiffnesses of the static and dynamic test sections was then used to estimate the yield point and beyond-yield stiffnesses of the dynamic test section. These scaling laws and their application to the present problem will be discussed later in this appendix. By using this method, the dynamic test section could be and was used in subsequent dynamic tests without an initial permanent deformation.

Even with this approach, there are difficulties, as enumerated below:

1. The static and dynamic test sections may have different elastic characteristics.
2. Differences in the assembly of the static and dynamic test sections may lead to differences in the beyond-yield characteristics which cannot be accounted for with simple scaling laws.
3. There are four walls in both the static and dynamic test section. Slight differences in the beyond-yield characteristics of the walls of each test section could lead to significant differences

in the beyond-yield behaviors of the various walls. This further complicates estimating beyond-yield characteristics of the dynamic test section based on static test section characteristics.

All of the above occurred to some extent in the current series of tests. The walls of each test section behaved differently from each other as well as from those of the other test section. Also, the assembly of the test sections was such that welds had to be used at the ends to attach the caps and bases. Welding of aluminum is difficult because of its high conductivity. Conduction of heat permits a significant amount of metal in the vicinity of the weld to experience the high temperature of the welding process in the case of aluminum. This can anneal the metal, and cause its stress-strain characteristics to be different from that of the metal which is more distant from the weld. The data from the static tests suggest that such annealing did, in fact, take place at the test section ends. The means of dealing with these and other problems is discussed in the following sections.

1. Static Test Procedure and Results

In essence, the procedure calls for taking the static test section through a series of hysteresis cycles of increasing magnitude, the purpose being to determine a) the load-displacement characteristics of the static test section and b) whether or not the FLASH-35 bi-linear hysteresis model is a reasonable representation of the behavior of the static test section in the beyond-yield range.

The load on the test section was provided by piling lead bricks on top of the one inch diameter piston at the top of the test vessel (see Figure 1 in the text). In addition to producing the load, this method also permitted a means of determining the net volume displacement of the test section. This was done by measuring the net displacement of the piston as a result of increasing the load by a given amount, and subtracting out the amount of displacement due to fluid compressibility and test vessel displacement. The method is described in more detail in Appendix A of Reference A-1. The load was determined by means of a static pressure gage.

The brick-loading sequence was necessarily somewhat more elaborate than that of Reference A-1, however. To take the test section through a given hysteresis cycle, bricks were loaded, one at a time, until a number of bricks $N_{\max}$ was reached. Measurements of pressure and piston displacement were made after the addition of each brick. Upon reaching $N_{\max}$ the bricks were unloaded one at a time, with pressure and piston displacement measurements taken at each unloading, until no bricks remained. The number of bricks $N_{\max}$ reached was increased by one brick each cycle. Thus, the loading sequence for $N_{\max} = 1$ was 0-1-0, for $N_{\max} = 2$ it was 0-1-2-1-0, etc. The highest value of $N_{\max}$ was 10, with the loading sequence, 0-1-2-3-4-5-6-7-8-9-10-9-8-7-6-5-4-3-2-1-0. The results of the static test are shown in Figure 5 in the text. The solid lines show the measured pressure loads and volume displacements as the load was increased brick by brick; the dashed lines show the behavior as the load was decreased. The X's are the $N_{\max}$ points for a given cycle, the

lowest being $N_{\max}=1$, the next lowest $N_{\max}=2$, etc. Because the first four cycles are essentially in the elastic range of the test section, and for ease of illustration, only the increasing load halves of these cycles are shown. For those cycles which are shown, typical hysteresis behavior is evident. That is, the curve followed on the increasing half of a cycle is essentially the same as the unloading curve of the previous cycle, until the maximum load of the previous cycle is reached. For loads greater than this, the new increasing-load curve becomes basically an extension of the increasing-load curve of the previous cycle. This is the type of behavior on which the FLASH-35 bi-linear hysteresis model is based.

Also shown in Figure 5 in the text is the load-displacement curve which results when the fluid volume compression and test vessel displacement are subtracted from the measured volume displacement of each $N_{\max}$ point. This can be interpreted as the true load-displacement curve of the test section. Also shown is a tangent line whose slope can be used as an estimate of the elastic stiffness of the test section.

In previous FLASH-35 models (Reference A-1 and A-2), the test section was divided into nine axial segments, each with the same elastic stiffness. It was necessary to use the same elastic stiffness for each segment because the method used to determine the stiffness yielded only an overall value for the entire test section. In the present test series, it was decided to use strain gages in addition to a proximeter to obtain measurements of the displacement of several parts of the test section. The purpose of this was to determine if the load-displacement behavior at the ends of the test section differed significantly from that in the center. It was thought that the attachment of the test section to rigid boundaries at the ends would tend to inhibit its ability to deflect in the vicinities of the two ends.

Figure 4 in the text shows the locations of the strain gages relative to the nine axial segments of the FLASH-35 model. The different faces of the test section are labeled A, B, C and D. Strain gages were placed in the very center of the test section on faces A and B. At the bottom, approximately 1.25 inches from the lower end, strain gages were located on faces C and D. It was not possible to place strain gages on the upper end because the cap would have had to be welded on after the strain gages were installed, a process which most probably would have damaged the strain gages. All strain gages were placed on the inside (i.e., the dry side) of the test section. A proximeter was also placed at the approximate axial location of the strain gages on walls C and D, to measure the deflection of wall A at this point.

Figure A-1 reproduces the true load-displacement curve of the static test section from Figure 5 in the text and shows how the normalized strain gage and proximeter measurements compare with it. For purposes of illustration, the strain gage and proximeter measurements were normalized to the measured elastic stiffness of the test section (7.875×10^5 psi/ft³) so that comparisons of yield and beyond-yield behavior could be more readily accomplished. It may be noted that the strain gage on wall A is not shown. It was discovered early in the testing that this strain gage was

not functioning properly. Rather than remove the test section it was decided to proceed with the testing, using the proximeter to monitor wall A.

From Figure A-1 it is evident that the strain gage and proximeter measurements suggest a higher yield point than do the measurements of piston displacement. A post-test inspection of the static test section makes it clear why this phenomenon occurs. Figure 13 in the text shows the static test section, after testing was completed, with wall B in the foreground. The photograph clearly shows that most of the wall displacement occurred at the top of the test section where no strain gage or proximeter measurements were made. Although the other walls are not clearly shown, they behaved similarly, although the displacement of wall B was the most extreme. Therefore, the piston displacement measurements, which gave an indication of the overall test section displacement, were strongly influenced by the displacement of the walls at the top of the test section. Since the strain gages and proximeter were all at considerably lower elevations, they could not sense these large displacements.

The question remains as to why the walls should deflect so much more at the top of the test section than elsewhere. Care was taken to load the bricks without impact, so that transient pressure pulses of a duration short enough to cause time delays between the arrival of the pressure pulse at different axial locations should be absent. Even if there had been pulses of this type, the maximum loading would have been at the bottom of the test section, where the pressure wave doubles after reflection, not at the top. This was borne out in later dynamic tests and is clearly evident in Figures 13 and 14 in the text. The most logical explanation is that the high temperature associated with welding the cap on the test section lowered the yield point of the test section metal in the vicinity of the weld. To set up a proper model for FLASH-35 calculations, this effect must be taken into account.

The basic parameters on which the FLASH-35 model is based are illustrated in Figure A-1. These are the elastic stiffness K_e (psi/ft³), the beyond-yield stiffness K_y (psi/ft³) and the two yield points (ft³) which are referred to as "Normal yield" and "Low yield". The values of these quantities for the static test section are given in Table A-1 below.

TABLE A-1

K_e	=	7.875×10^5 psi/ft ³
K_y	=	5.00×10^4 psi/ft ³
yield point (normal yield)	=	3.429×10^{-4} ft ³
yield point (low yield)	=	2.921×10^{-4} ft ³

It is important to remember that the above quantities are overall static test section values. When applied to only a fraction of the test section, they must be adjusted accordingly. For instance, if these quantities were to be applied to one wall of one of the nine axial

segments illustrated in Figure 4 in the text, the appropriate stiffnesses K_e and K_y would be $9 \times 4 = 36$ times the above values and the yield points would be $1/36$ of the above values.

2. Relating the Dynamic Test Section and Static Test Section Flexible Member Parameters

To obtain values of K_e , K_y and yield points, the dynamic test section was taken through the first three of the hysteresis cycles which were also undergone by the static test section. The loads applied were, therefore, well below yield. The placement of strain gages and proximeter were the same for both test sections (see Figure 4 in the text). The values of pressure load and strain are given below in Table A-2 for both test sections at the 2-brick level of the third cycle.

TABLE A-2

<u>Test Section</u>	<u>Pressure Load (psi)</u>	<u>Wall A Strain (μ-in/in)</u>	<u>Wall B Strain (μ-in/in)</u>	<u>Wall C Strain (μ-in/in)</u>	<u>Wall D Strain (μ-in/in)</u>
Static	64.0	same as Wall D	545	530	477
Dynamic	64.8	590	611	627	581

It will be noted that, even after accounting for the differences in the pressure load, the strain values for the dynamic test section are significantly higher than those of the static test section. Although strain gage A was not working in the static test section, a post-test inspection indicated that the deflection of wall A was about the same as that of wall D. It will therefore be assumed that the strain value for wall A is the same as that for wall D.

A post-test inspection of the static and dynamic test sections revealed the reason for the scatter of strain values from wall-to-wall and test section-to-test section. Measurements of wall thickness were taken at various points on all the walls of each test section. The average values of these measurements are given in Table A-3 below.

TABLE A-3

<u>Wall</u>	<u>Average Thickness (inches)</u>	
	<u>Static</u>	<u>Dynamic</u>
A	0.0595	0.0558
B	0.0578	0.0539
C	0.0577	0.0539
D	0.0596	0.0558

It can be seen that the thicknesses of the dynamic test section walls are significantly less than those of the static test section. This is not too surprising since the test sections were not cut from the same piece of tubing. Also evident from Tables A-2 and A-3 is the fact that, for both test sections, the thinnest walls are the ones with the highest strains. This is confirmed by post-test photographs of the tube cross-sections, shown in Figure 14 of the text. The cross-sections of the final deformations at points 3/4 of an inch from each end. Again, the largest deformations occur in the thinnest walls.

Table A-2 does not appear to support the hypothesis that the deflection at the bottom of the test section is significantly less than that closer to the middle because of the restraint provided by the base. It will be recalled that the strain gages on walls A and B are at the axial middle of the test section whereas those on walls C and D are 1.25 inches from the test section bottom and 0.75 inches from the top of the base. In fact, the strain gage at the bottom of wall C indicates the greatest deflection for the dynamic test section.

With these assumptions it is now possible to calculate the ratio of the elastic stiffnesses of the static and dynamic test section. Since a ratio between test sections is desired, it is appropriate to define an average stiffness for each test section based on the strain readings of all four walls.

The manner in which this is to be done is not clear, however. Since all walls of a given test section experience the same load, the elastic stiffness can be defined as the ratio of the load to the sum of the resulting deflections of all walls. If it is assumed that the measured strain on each wall is linearly proportional to the deflection of that wall then the quantity

$$K_T = \frac{\text{load}}{\text{strain A} + \text{strain B} + \text{strain C} + \text{strain D}} \quad (\text{A-1})$$

is proportional to the elastic stiffness.

In the present test series, the measured strains and displacements were found to be linearly related to a good degree of approximation. Figure A-2 shows a comparison of the proximeter trace from wall A of the dynamic test section with the strain gage trace from wall D of the same test section for run 5Y, which had a drop height of 10 inches. The two instruments were at the same axial location at the bottom of the test section. As was mentioned earlier, walls A and D behaved almost identically, so it would be expected that, if strain were linearly related to displacement, the two traces should be identical except for scaling factors. Figure A-2 bears out this hypothesis. Although it is not, strictly speaking, accurate to do so, the mode of deformation characterized by Equation (A-1) will be referred to as "tension dominant", for reasons which will be discussed shortly.

If the applied load produces only bending stresses, then the appropriate quantity for the determination of the elastic stiffness is

$$K_B = \frac{(\text{load})^{3/2}}{(\text{strain A})^{3/2} + (\text{strain B})^{3/2} + (\text{strain C})^{3/2} + (\text{strain D})^{3/2}} \quad (\text{A-2})$$

This is because the deflection of a given wall in bending is proportional to the ratio of the load to the cube of the wall thickness whereas the strain on its surface is proportional to the ratio of the load to the square of the wall thickness (see Reference A3). This means that, for a given wall, displacement and strain are linearly related as Figure A7 indicates they should be. If wall thickness is eliminated as a parameter, however, it can be shown that wall displacement is proportional to strain to the $3/2$ power divided by load to the $1/2$ power. Defining the elastic stiffness of a given test section as the ratio of the load to the sum of the wall displacements gives Equation (A-2) after appropriate substitutions are made.

Using the load and strain values in Table A-3, Equations (A-1) and (A-2) give

$$\frac{K_T \text{ (dynamic)}}{K_T \text{ (static)}} = 0.853 \quad (\text{A-3})$$

$$\frac{K_B \text{ (dynamic)}}{K_B \text{ (static)}} = 0.786 \quad (\text{A-4})$$

Which of these quantities is most representative of the elastic stiffness ratio of the two test sections is not clear. Intuitively, it would seem likely that, for the type of load applied (highest pressure on the outside of the tube), bending should be the dominant mode. A check on this can be made by computing the stiffnesses of each test section based on the wall thicknesses in Table A-3. In bending, the stiffness of a beam is proportional to the cube of the wall thickness. Without going into the details, it can be shown that such a calculation gives a stiffness ratio of approximately 0.817, which is only slightly closer to 0.786 than it is to 0.853.

The elastic stiffness ratio can also be obtained from the piston displacement data. Using the data from the 2-brick level of the third cycle yields a value of 0.864 for the stiffness ratio. This is fairly close to the value of 0.853 given in Equation (A-3).

Determination of the yield points of the dynamic test section from those of the static test section is also a function of the mode of deformation assumed. If bending is the dominant mode, then the ratio of the yield point (in cubic feet) of the two test sections goes inversely as the cube root of the elastic stiffness ratio or

$$\frac{\text{Y.P. (dynamic)}_B}{\text{Y.P. (static)}_B} = \left[\frac{K_e \text{ (static)}}{K_e \text{ (dynamic)}} \right]^{1/3} \quad (\text{A-5})$$

If tension is the dominant mode of deformation, the ratio of the yield points (in cubic feet) is equal to unity.

$$\frac{\text{Y.P. (dynamic)}_T}{\text{Y.P. (static)}_T} = 1 \quad (\text{A-6})$$

It should be remembered that the yield point referred to here is the strain at which yield occurs, not the stress. All Equation (A-6) means is that the strain, not the stress, at yield is the same for all walls regardless of thickness when tension dominates. Equation (A-6) together with Equation (A-1) constitute the scaling laws desired when tension dominates even though, as mentioned earlier, Equation (A-1) is not quite correct. For pure tension or membrane stretching, strain is approximately proportional to the square of the wall displacement, not linearly proportional. A linear relationship of strain and displacement has been used instead because of the experimental evidence. No such inconsistency arises in bending since, in this mode, strain and displacement are linearly related for a given wall.

Because of the uncertainty in the mode of deformation, several flexible member models of the dynamic test section were set up for subsequent FLASH-35 calculations. These models accounted for the differences in stiffness of the walls at the ends of the test section based on the strains given in Table A-2. Stiffnesses (both elastic and beyond-yield) were based on either Equation (A-1) or (A-2) and yield points were based on either Equation (A-5) or (A-6). The basic flexible member model is shown in Figure 4 in the text. For each of the seven axial segments in the middle of the test section, the flexible member is comprised of all four walls and "normal" yield points are used. At each end walls A and D, because of the fact that their load-displacement behavior was almost the same, are combined into one flexible member. Walls B and C have independent identities at each end, however, except for certain parametric studies, all flexible members representing end walls are given "low" yield points. A summary of the flexible member parameters is given in Table A-4 for both "tension dominant" and "bending dominant" cases. The yield points for a hybrid case are also listed. The hybridization involves the use of "tension dominant" elastic stiffness ratios to compute yield points from Equation (A-5), the derivation of which is based on the assumption that bending is dominant.

REFERENCES

- A1. D. A. Prelewicz, "Hydraulic Pressure Pulses with Structural Flexibility: Test and Analysis," WAPD-TM-1227, dated April 1976
- A2. R. E. Schwirian, "Pressure Pulse Test Results and Qualification of the FLASH-35 Flexible Structural Member Model with a Surge Tank Attached to the Test Vessel," WAPD-TM-1290, dated August 1977
- A3. S. H. Crandall and N. C. Dahl, "An Introduction to the Mechanics of Solids," Ch. 7, McGraw-Hill Book Co., 1959

TABLE A-4

Flexible Member Parameters for
"Tension Dominant" and "Bending Dominant" Cases

Flexible Member(s)	Mass (lbs)	Surface Area (ft ²)	Elastic Stiffness (psi/ft ³ x 10 ⁶)		Beyond-Yield Stiffness (psi/ft ³ x 10 ⁵)		Yield Point (ft ³ x 10 ⁵)	
			Tension Dominant	Bending Dominant	Tension Dominant	Bending Dominant	Tension Dominant	Bending Dominant
14-20 (middle)	0.1511	0.1249	6.046	5.573	3.839	3.539	4.278	4.636* 4.487**
13 (A-D top) & 21 (A-D bottom)	0.07556	0.06245	12.43	11.63	7.890	7.385	1.850	1.976* 1.924**
22 (B top) & 24 (bottom)	0.03778	0.03123	23.82	21.82	15.12	13.86	0.9302	1.015* 0.9812**
23 (C top) & 25 (C bottom)	0.03778	0.03123	23.21	21.00	14.74	13.33	0.9333	1.032* 0.9897**

* Based on Equation (A-5) using "bending dominant" elastic stiffness ratio

** Based on Equation (A-5) using "tension dominant" elastic stiffness ratio

FIGURE A1
DETERMINATION OF FLASH-35 FLEXIBLE MEMBER PARAMETERS
FROM STATIC TEST SECTION MEASUREMENTS

(a) STRAIN GAGE - WALL D

(b) PROXIMETER - WALL A

FIGURE A-2
COMPARISON OF STRAIN GAGE (WALL D) AND PROXIMETER (WALL A)
TRACES FOR A 10 INCH DROP HEIGHT

APPENDIX B

FLASH-35 Parameter Study

1. PARAMETERS VARIED

Basically, six complete sets of FLASH-35 calculations were performed in the parameter study, all with the flexible member model illustrated in Figure 4 in the text. In series 331-335 and 381-385, stiffnesses and yield points were based on the assumption of pure bending or pure tension, respectively. In series 301-305, stiffnesses were based on a tension mode and yield points were based on a bending mode assumption. This is the least conservative combination of bending and tension because it may lead to considerable underprediction of the peak and final wall displacements. Series 391-395, on the other hand, assumes bending mode stiffnesses and tension mode yield points, and is the most conservative.

The yield point-bending/stiffness-tension (series 301-305) model was used as a base (and is identified as such in Tables B1 and B2) for two other models, the load-displacement behavior of which is shown in Figure B-1. In Figure B-2.a the beyond-yield behavior of series 301-305 is shown. Here, the load at yield is the same from one drop height to the next and the elastic and beyond-yield stiffnesses are both non-zero quantities. In Figure B-1.b the behavior of series 311-315 is shown. In this model, the load at yield depends on the previous history of the flexible member, such that the beyond-yield behavior always follows the same straight line. Finally, Figure B-1.c shows the beyond-yield behavior of series 321-325, which has a zero beyond-yield stiffness and is a degenerate case of either Figure B-1.a or Figure B-1.b. This case is of interest in that it permits the 'weakest wall' effect to be maximized. That is, with a zero beyond-yield stiffness, the only thing restraining the deformation of the weakest wall is its inertia. It is quite likely that this case will show very large deformations of the weakest wall and minimal deformations of the remaining walls.

In these six sets of FLASH-35 runs the progression 3_1 to 3_5 represents drop heights of 2 to 10 inches, increasing by 2 inches each time. In addition to these complete sets, a number of calculations were made assuming a drop height of 8 inches, with yield point and beyond-yield stiffness as variables. The numerical values of the variables is given in Table B1 and the various combinations are given in Table B2. In all cases, the type of behavior depicted in Figure B-1.a was assumed.

2. COMPARISON OF FLASH-35 SIMULATIONS WITH TEST DATA

Tables B1, B2, B3 and B4 summarize the various input parameters and show the results of comparisons between the test data and the various FLASH-35 calculations. Generally speaking, the comparisons are reasonably good and demonstrate that the bi-linear hysteresis model is a sufficiently accurate representation of reality that flexible member motion in the elastic and beyond-yield ranges can be adequately treated by FLASH-35. There is, however, a strong sensitivity of the predicted results to the yield points and beyond-yield stiffnesses of the various walls. Also, it appears that the estimates of yield points and/or beyond-yield stiffnesses used in the calculations are somewhat high. Given the uncertainties associated with the computation of these quantities, it is not surprising that the estimates of their magnitudes might be somewhat in error. In fact, it

is probably safe to say that the major part of the disagreement between predicted and experimental results is caused by the uncertainties in these input quantities, rather than by FLASH-35 inadequacies.

Table B2 compares experimental results with calculations based on several yield point stiffness models for a drop height of 8 inches. The results from this drop height were used rather than those at 10 inches because the test results for the latter are not complete, the wall C strain gage having failed during that test. The table lists experimental and calculated peak pressures at the bottom of the test section, the peak and final deflections of walls A-D and C at the bottom of the test section, and the peak deflection of the wall at the axial middle of the test section (which experiences no permanent deformation). In comparing the deflection results, it should be remembered that wall A-D represents two faces of the test section, wall C one face, and the middle wall four faces.

The main thing that stands out in Table B2 is the sensitivity of the predicted results to the assumed values of yield point and beyond-yield stiffness. In the base case, run 304, the predicted and final deflections are all somewhat low, but they are all low by about the same percentage. This would suggest that, even though the estimates of yield point and beyond-yield stiffness for the various walls may be in error, they are in error by approximately the same percentage. This is to be contrasted with, for instance, runs 364 and 374, in which walls A-D and B were treated as normal, and the yield-point and beyond-yield stiffness of wall C were decreased below their run 304 values. The effect of this maldistribution was to increase substantially the peak and final deflection of wall C while substantially diminishing the same quantities for wall A-D. An extreme example is illustrated by run 324, in which the beyond-yield stiffnesses of all top and bottom walls was set equal to zero. Here the deflections of wall C are grossly overpredicted and those of wall A-D grossly underpredicted. The motion of wall C provides so much pressure relief that wall A-D never does reach yield.

Run 334, 354, 384 and 394 are like run 304 in that the distributions of yield points and beyond-yield stiffnesses at the bottom of the test section are in approximately the correct proportion. Also, like run 304, the magnitudes of the yield points and beyond-yield stiffnesses are somewhat in error. In effect, each of these runs represents a different magnitude level of yield point and/or beyond-yield stiffness, at least for the walls at the bottom of the test section. An examination of the results indicates that when pressure pulse magnitudes are high, deflections are low, and vice-versa. The impression is left that if only the right combination of yield points and beyond-yield stiffnesses could be found, the resulting predictions could be made to match the test results almost exactly. In fact, in none of these cases are predictions grossly in error.

The fact that the flexible member model in run series 300 overpredicts pressure pulse magnitudes and underpredicts wall deflections strongly suggests that either the yield point or beyond-yield stiffness estimates of the various walls - or both - are too high. There is some reason

to believe that the estimates of beyond-yield stiffness may be somewhat high. The reason for this is that, in the static tests which were used to determine the beyond-yield stiffness, only the top of the test section deformed plastically. The estimates of beyond-yield stiffness, however, assumed that the entire test section deformed uniformly. The upshot of this is that the actual beyond-yield stiffnesses at the ends of the test section are most probably somewhat lower than the values used in the calculations. However, since there are no sharp dividing lines between the ends of the test section and the middle, it is impossible to tell how much lower these stiffness values should actually be.

It will be noted that the bulk of the FLASH-35 runs listed in Tables B1 and B2 employ "normal" yield points in the middle of the test section and lower yield points at both ends. The exceptions are runs 344 and 404. In run 344 the "normal" yield points are used in the middle and at the bottom end, and the "low-yield" values are used at the upper end. The purpose of this was to determine if reasonable results could be obtained if the dynamic test section were assumed to have "low yield" properties only at the top end, as was the case in the static tests. Comparisons of the resulting deflection calculations with the test results in Table B2 show the predictions to be considerably below the data. The tests show permanent deformation at the bottom of the test section; the calculations in run 344 do not. The logical conclusion from this is that, unlike the static test section, the dynamic test section has approximately the same yield behavior at both ends, presumably characterized by "low yield" values of the yield point. There is no way of determining this for sure, but it would not be surprising if slight differences in the assembly of the two test sections (i.e., the welding) caused such a result. For this reason, the bulk of the FLASH-35 calculations assumed that the top and bottom ends of the dynamic test section behaved similarly.

In run 404 "normal" yield points were used everywhere. The purpose of this was to determine if reasonable results could be obtained without assuming that end yield points were different than those in the middle. The results do indicate that yielding can occur at the ends of the test section without permanent deformation in the middle, even without a difference in yield points. However, the predicted deflections are substantially lower, and the predicted pressures substantially higher than the test results.

Tables B3 and B4 summarize the results from the flexible member models for which calculations were performed at all drop heights. In general, the results are as good and the behavior similar to the 8 inch drop height cases of Table B2. An exception is the 311-315 (history-dependent) series, for which the calculation of the wall C deflection becomes less accurate as drop height is increased. This is probably because, with this model, the yield points increase from one drop height to another. It was postulated earlier that the yield points and beyond-yield stiffnesses used in the bulk of the calculations were too high. If this is the case, then a yield point which is estimated too high at the lowest drop height would - because of the fact that the beyond-yield stiffness is also overestimated - become increasingly inaccurate as

drop height was increased. Thus, the progressively inaccurate deflection predictions in run series 311-315 are most likely a consequence of the inaccuracy in the yield point/stiffness estimates rather than a shortcoming of the "history-dependent" model.

TABLE B1

FLASH-35 Flexible Member Input Parameters - Variations on the Base Case*

<u>Flexible Member(s)</u>	<u>Mass (lbs)</u>	<u>Surface Area (ft²)</u>	<u>Elastic Stiffness (psi/ft³)</u>	<u>Beyond-Yield Stiffness (psi/ft³)</u>	<u>Yield Point (ft³)</u>
14-20 (middle)	0.1511	0.1249	6.046 (10 ⁶) (base)	3.839 (10 ⁵) (base)	4.487 (10 ⁻⁵) (base)
13 (A-D top) & 21 (A-D bottom)	0.07556	0.06245	1.243 (10 ⁷) (base)	7.890 (10 ⁵) (base)	2.215 (10 ⁻⁵) - normal yield 1.924 (10 ⁻⁵) - low yield (base) 1.780 (10 ⁻⁵) - 92.5% of low yield 1.924 (10 ⁻⁵) - A-D top, history- dependent yield, run 314 1.938 (10 ⁻⁵) - A-D bottom, history- dependent yield, run 314
22 (B top) & 24 (B bottom)	0.03778	0.03123	2.382 (10 ⁷) (base)	1.512 (10 ⁶) (base)	1.130 (10 ⁻⁵) - normal yield 0.9812 (10 ⁻⁵) - low yield (base) 0.9077 (10 ⁻⁵) - 92.5% of low yield 0.9968 (10 ⁻⁵) - B top 1.012 (10 ⁻⁵) - B bottom } run 314
23 (C top) & 25 (C bottom)	0.03778	0.03123	2.321 (10 ⁷) (base)	1.474 (10 ⁶)- normal (base) 0.737 (10 ⁶)- ½ normal	1.140 (10 ⁻⁵) - normal yield 0.9897 (10 ⁻⁵) - low yield (base) 0.9156 (10 ⁻⁵) - 92.5% of low yield 1.023 (10 ⁻⁵) - C top 1.038 (10 ⁻⁵) - C bottom } run 314

* Base Case = yield point-Bending/stiffness-Tension

TABLE B2

Comparison of All FLASH-35 Model Calculations With
Test Results at A Drop Height of 8 Inches

Run No.	Yield Point (ft ³)		Beyond-Yield Stiffness (KY) (psi/ft ³)		Peak Bottom Pressure (psid)	Bottom Pressure Pulse Duration (msecs)	Peak Deflection (ft ³)			Perm. Deflection (ft ⁷)	
	top	bottom	top	bottom			A-D bottom	C bottom	Middle	A-D bottom	C bottom
Test (4Y)		--	--	--	210	51.0	0.327(10 ⁻⁴)	0.274(10 ⁻⁴)	0.378(10 ⁻⁴)	0.120(10 ⁻⁴)	0.153(10 ⁻⁴)
304 (base)*	low yield	low yield	normal	normal	227	56.0	0.282(10 ⁻⁴)	0.210(10 ⁻⁴)	0.369(10 ⁻⁴)	0.950(10 ⁻⁵)	0.111(10 ⁻⁴)
314	history-dependent	history-dependent	normal	normal	253	56.0	0.300(10 ⁻⁴)	0.160(10 ⁻⁴)	0.375(10 ⁻⁴)	0.102(10 ⁻⁴)	0.650(10 ⁻⁵)
324	low yield	low yield	zero	zero	219	57.0	0.164(10 ⁻⁴)	0.805(10 ⁻⁴)	0.350(10 ⁻⁴)	0.0	0.710(10 ⁻⁴)
334	bending mode	bending mode	bending mode	bending mode	219	59.0	0.273(10 ⁻⁴)	0.242(10 ⁻⁴)	0.382(10 ⁻⁴)	0.900(10 ⁻⁵)	0.140(10 ⁻⁴)
344	low yield	normal yield	normal	normal	236	55.5	0.188(10 ⁻⁴)	0.102(10 ⁻⁴)	0.390(10 ⁻⁴)	0.0	0.0
354	92.5% of low yield	92.5% of low yield	normal	normal	217	57.0	0.334(10 ⁻⁴)	0.233(10 ⁻⁴)	0.350(10 ⁻⁴)	0.150(10 ⁻⁴)	0.138(10 ⁻⁴)
364	low yield	A-D, B-normal C-low	normal	normal	230	56.5	0.181(10 ⁻⁴)	0.268(10 ⁻⁴)	0.377(10 ⁻⁴)	0.0	0.167(10 ⁻⁴)
374	low yield	A-D, B-normal C-low	normal	A-D, B-normal C-1/2 normal	229	56.5	0.178(10 ⁻⁴)	0.372(10 ⁻⁴)	0.371(10 ⁻⁴)	0.0	0.275(10 ⁻⁴)
384	tension mode	tension mode	tension mode	tension mode	224	56.3	0.294(10 ⁻⁴)	0.212(10 ⁻⁴)	0.357(10 ⁻⁴)	0.128(10 ⁻⁴)	0.143(10 ⁻⁴)
394	YP-T/S-B**	YP-T/S-B**	YP-T/S-B**	YP-T/S-B**	200	59.8	0.286(10 ⁻⁴)	0.291(10 ⁻⁴)	0.356(10 ⁻⁴)	0.100(10 ⁻⁴)	0.192(10 ⁻⁴)
404	normal	normal	normal	normal	244	55.1	0.194(10 ⁻⁴)	0.154(10 ⁻⁴)	0.400(10 ⁻⁴)	0.0	0.050(10 ⁻⁴)

* Base Case = yield point-Bending/stiffness-Tension

** YP-T/S-B = yield point-Tension/stiffness-Bending

TABLE B3

Comparison of Peak and Final Deflection Calculations
of Various FLASH-35 Models with Test Results

Run No.	Drop Height (inches)	Peak Deflection (ft ³ x 10 ⁵)			Final Deflection (ft ³ x 10 ⁵)		
		A-D	C	Middle	A-D	C	
		Bottom	Bottom				
FLASH-35 {	1Y (test)	2	0.933	0.487	1.79	0	0
	301 (base)*	2	1.22	0.650	2.25	0	0
	311	2	1.22	0.650	2.25	0	0
	321	2	1.22	0.650	2.25	0	0
	331	2	1.25	0.690	2.40	0	0
	381	2	1.22	0.650	2.25	0	0
	391	2	1.25	0.690	2.40	0	0
FLASH-35 {	2Y (test)	4	1.87	1.13	2.77	0.400	0.367
	302 (base)*	4	1.63	1.05	3.12	0	0.200
	312	4	1.63	1.05	3.12	0	0.200
	322	4	1.62	1.12	3.12	0	0.260
	332	4	1.64	1.17	3.25	0	0.270
	382	4	1.55	1.18	3.05	0	0.360
	392	4	1.50	1.40	3.17	0	0.580
FLASH-35 {	3Y (test)	6	2.67	2.13	3.31	0.933	1.13
	303 (base)*	6	1.88	1.61	3.58	0.150	0.680
	313	6	1.92	1.44	3.58	0.200	0.520
	323	6	1.62	2.84	3.45	0	1.95
	333	6	1.86	1.74	3.70	0	0.900
	383	6	1.83	1.83	3.38	0.200	0.950
	393	6	1.73	2.32	3.45	0	1.38
FLASH-35 {	4Y (test)	8	3.27	2.74	3.78	1.20	1.53
	304 (base)*	8	2.82	2.10	3.69	0.950	1.11
	314	8	3.00	1.60	3.75	1.015	0.650
	324	8	1.64	8.05	3.50	0	7.10
	334	8	2.73	2.42	3.82	0.900	1.40
	384	8	2.94	2.42	3.57	1.28	1.43
	394	8	2.86	2.91	3.56	1.00	1.92
FLASH-35 {	5Y (test)	10	4.64	--**	2.13***	2.45	--**
	305 (base)*	10	3.67	2.57	3.80	1.87	1.50
	315	10	3.60	1.82	3.93	1.64	0.770
	325	10	1.64	10.4	3.55	0	9.30
	335	10	3.59	2.91	3.91	1.50	1.75
	385	10	3.75	2.87	3.65	1.80	1.80
	395	10	3.89	3.50	3.69	1.80	2.33

* Base case = yield point-Bending/stiffness-Tension

** Strain gage failed

*** This may or may not be a bad data point. It does not appear to fit with the rest of the data. However, virtually the same result was obtained on both strain gages A and B, indicating that it is not due to strain gage failure. However, the possibility exists that the gain adjustments on the strain gage instrumentation were different than what they were recorded to be.

TABLE B4

Comparison of Peak Pressures Calculated by
Various FLASH-35 Models with Test Results

	Run No.	Drop Height (inches)	Peak Pressure (psid)		
			Top	Middle (17)	Bottom
FLASH-35	1Y (test)	2	130	130	130
	301 (base)*	2	151	138	145
	311	2	151	138	145
	321	2	151	138	145
	331	2	151	132	143
	381	2	151	138	145
	391	2	151	131	138
FLASH-35	2Y (test)	4	220	200	200
	302 (base)*	4	200	191	195
	312	4	200	191	195
	322	4	200	191	194
	332	4	212	182	188
	382	4	195	184	191
	392	4	193	177	179
FLASH-35	3Y (test)	6	238	212	200
	303 (base)*	6	237	214	225
	313	6	238	214	220
	323	6	239	206	209
	333	6	212	204	205
	383	6	230	204	207
	393	6	201	193	192
FLASH-35	4Y (test)	8	225	215	210
	304 (base)*	8	245	225	227
	314	8	254	230	253
	324	8	220	212	219
	334	8	229	211	219
	384	8	227	214	224
	394	8	207	197	200
FLASH-35	5Y (test)	10	265	230	215
	305 (base)*	10	245	230	232
	315	10	259	240	241
	325	10	244	216	226
	335	10	229	224	220
	385	10	232	220	225
	395	10	219	207	208

* Base case = yield point-Bending/stiffness-Tension

(a) CONSTANT YIELD POINT

(b) HISTORY-DEPENDENT YIELD POINT

(c) ZERO BEYOND YIELD STIFFNESS

FIGURE B-1
TYPES OF BI-LINEAR HYSTERESIS
MODELS USED IN FLASH-35 CALCULATIONS

APPENDIX C

FLASH-35 Input Listing (Run 304)

G.3 1 IN. PISTON, 1/16 INCH TEST SECTION, 8 INCH DROP

201,1,1,1

1001,.080,2.0,1.0

2001,2.5-6,.080

*CONTROL VOLUME SPECIFICATIONS

3001,.02182,.41705, 3.17, 3.17,3.157,37.70,36.0,0.0

3002,.02182,.41705, 2.76, 3.14,2.740,37.88,36.0,0.0

3003,.01097,.3044,2.450,2.700,2.435,38.060,36.0,0.0

3004,.01097,.3044,2.140,2.400,2.131,38.192,36.0,0.0

3005,.01097,.3044,1.840,2.100,1.826,38.324,36.0,0.0

3006,.01097,.3044,1.530,1.800,1.522,38.456,36.0,0.0

3007,.01097,.3044,1.230,1.500,1.218,38.588,36.0,0.0

3008,.01097,.3044,0.930,1.200,.9132,38.720,36.0,0.0

3009,.01097,.3044,0.620,0.900,.6088,38.852,36.0,0.0

3010,.01097,.3044,0.320,0.590,.3044,38.984,36.0,0.0

3011,.01097,.3044,0.290,0.290,0.000,39.116,36.0,0.0

3012, 1.+10,100.0, 0.0, 0.0, 0.0,14.700,1300.,0.0

\$ATMOSPHERE

*FLOW PATH SPECIFICATIONS

4001,8,1,2,0.0,23.9,.02182,0.188

4002,8,2,3,0.0,25.9,.01097,4.310

4003,8,3,4,0.0,27.8,.01097,0.39

4004,8,4,5,0.0,27.8,.01097,0.39

4005,8,5,6,0.0,27.8,.01097,0.39

4006,8,6,7,0.0,27.8,.01097,0.39

4007,8,7,8,0.0,27.8,.01097,0.39

4008,8,8,9,0.0,27.8,.01097,0.39

4009,8,9,10,0.0,27.8,.01097,0.39

4010,8,10,11,0.0,27.8,.01097,0.39

*FLEXIBLE PLATES

7501,3.39,16.4,.005454,-1,1,0.0,6.550,9.0

7502,3.04,7.24+6,0.265,12,1,1.10-5,1.29+8

7503,3.04,7.24+6,0.265,12,2,1.10-5,1.29+8

7504,1.66,1.24+7,0.155,12,3,0.643-5,2.21+8

7505,1.66,1.24+7,0.155,12,4,0.643-5,2.21+8

7506,1.66,1.24+7,0.155,12,5,0.643-5,2.21+8

7507,1.66,1.24+7,0.155,12,6,0.643-5,2.21+8

7508,1.66,1.24+7,0.155,12,7,0.643-5,2.21+8

7509,1.66,1.24+7,0.155,12,8,0.643-5,2.21+8

7510,1.66,1.24+7,0.155,12,9,0.643-5,2.21+8

7511,1.66,1.24+7,0.155,12,10,.643-5,2.21+8

7512,1.66,1.24+7,0.155,12,11,.643-5,2.21+8

\$ 1 IN. PISTON, 8 IN. DROP
\$ VESSEL STIFFNESS

7513,.07556,1.243+7,.06245,12, 3,-1.924-5,7.890+5
 7514,0.1511,6.046+6,0.1249,12, 4,-4.487-5,3.839+5
 7515,0.1511,6.046+6,0.1249,12, 5,-4.487-5,3.839+5
 7516,0.1511,6.046+6,0.1249,12, 6,-4.487-5,3.839+5
 7517,0.1511,6.046+6,0.1249,12, 7,-4.487-5,3.839+5
 7518,0.1511,6.046+6,0.1249,12, 8,-4.487-5,3.839+5
 7519,0.1511,6.046+6,0.1249,12, 9,-4.487-5,3.839+5
 7520,0.1511,6.046+6,0.1249,12,10,-4.437-5,3.839+5
 7521,.07556,1.243+7,.06245,12,11,-1.924-5,7.890+5
 7522,.03778,2.382+7,.03123,12, 3,-.9812-5,1.512+6
 7523,.03778,2.321+7,.03123,12, 3,-.9897-5,1.474+6
 7524,.03778,2.382+7,.03123,12,11,-.9812-5,1.512+6
 7525,.03778,2.321+7,.03123,12,11,-.9897-5,1.474+6

\$ A, D. TOP

\$ A, D BOTTOM
 \$ B TOP
 \$ C TOP
 \$ B BOTTOM
 \$ C BOTTOM

*PLOTING INFORMATION

20001,1,0,1
 20002,.4,.2,.2,.2
 20011,4,1
 20012,4,7
 20013,4,10
 20014,5,35
 20015,5,23,32,33
 20016,5,27
 20017,5,31
 20018,5,34
 20019,4,11

APPENDIX D

FLASH Flexible Structural Member Model

D. A. Prelewicz

FLASH Flexible Structural Member Model

A flexible structural member model is available in FLASH-35 to account for the coupled effects of structural deflection and coolant hydrodynamics. The flexible structural member is represented as a movable wall located between two FLASH nodes. Figure D-1 is a schematic of a flexible structural member located between nodes a and b. The governing equation of motion for the plate is:

$$\frac{m}{g_c} \frac{d^2 x}{dt^2} + c \frac{dx}{dt} + f(x, \frac{dx}{dt}) = 144A (p_a - p_b) \quad (D-1)$$

where:

x = linear displacement of wall from node a into node b (ft)

t = time (seconds)

m = mass of wall including any water expected to move with the wall (lbm)

g_c = gravitational constant (lbm-ft/lbf-sec²)

p = node pressure (psia)

A = wall area (ft²)

c = damping coefficient (lbf-sec/ft)

$f(x, \frac{dx}{dt})$ = restoring force (lbf)

In terms of volume displacement $X = xA$,

$$\frac{m}{144g_c A^2} \frac{d^2 X}{dt^2} + \frac{c}{144A^2} \frac{dX}{dt} + F(X, \frac{dX}{dt}) = (p_a - p_b) \quad (D-2)$$

In the above equation ($F(X, \frac{dX}{dt})$) is the restoring force per unit area of the plate in lbf/in². Defining

$$M = \frac{m}{144g_c A^2} \quad (D-3)$$

$$C = \frac{c}{144A^2} \quad (D-4)$$

the governing equation may be written as

$$M \frac{d^2 X}{dt^2} + C \frac{dX}{dt} + F(X, \frac{dX}{dt}) = p_a - p_b \quad (D-5)$$

Three representations of the restoring force $F(X, \frac{dX}{dt})$ are available in the structural member model. These are the linear elastic, bi-linear elastic and bi-linear hysteresis models.

1. Linear Elastic Model

$$F(X, \frac{dX}{dt}) = K_1 X \quad (D-6)$$

where K_1 (lbf/in²-ft³) is a user specified constant, referred to as the plate stiffness.

2. Bi-Linear Elastic Model

$$F(X, \frac{dX}{dt}) = \begin{cases} K_2 X + XDV (K_2 - K_1), & X < -XDV \\ K_1 X, & -XDV \leq X \leq XDV \\ K_2 X + XDV (K_1 - K_2), & X > XDV \end{cases} \quad (D-7)$$

where K_1 and K_2 (lbf/in²-ft³) are user specified constant stiffnesses and XDV (ft³) is a user specified plate volume displacement. The restoring force for this case is shown schematically in Figure D-2. Note that there is no restriction on K_2 . It may be greater or less than K_1 . However, both K_1 and K_2 must be positive.

3. Bi-Linear Hysteresis

This restoring force is most easily described by examples. Figure D-3 shows the restoring force history for a case where the member is loaded in such a way as to cause large positive displacement, and stress the structural member beyond the yield point. Elastic deflection first occurs along the line AB. Plastic deflection occurs along BC. When the load is removed, unloading occurs along CD, and the distance AD is a measure of the permanent set.

Figure D-4 shows a case where the member has been loaded beyond the yield point. Elastic deflection occurs along AB, followed by plastic deflection along BC. Subsequently, the member is only partially unloaded along CD and then loaded again with a load exceeding the original applied load. When the member is loaded this second time, loading first occurs along DC and then

along CE. Unloading will occur along EF. If the member is then loaded so as to produce negative displacement, the member first deflects elastically along FG and then plastically along GH. Unloading occurs along HI. Subsequent loading and unloading will result in elastic deformation along HJ until either the point H or J is encountered.

This restoring force is a function of the previous displacement history (hence the term hysteresis) as well as the present displacement and velocity. Mathematically this restoring force may be described as follows:

a. Plastic Deformation (refer to Figure D-5)

Plastic deformation occurs only along the lines AB (when $\frac{dX}{dt} > 0$) and CD (when $\frac{dX}{dt} < 0$). When plastic deformation occurs the restoring force is:

$$F(X, \frac{dX}{dt}) = \begin{cases} K_2 X + XDV (K_1 - K_2), & \frac{dX}{dt} > 0 \text{ (along AB)} \\ K_2 X + XDV (K_2 - K_1), & \frac{dX}{dt} < 0 \text{ (along CD)} \end{cases} \quad (D-8)$$

K_1 and K_2 are user input constant stiffnesses. K_1 (lbf/in²-ft³) is the elastic stiffness and K_2 (lbf/in²-ft³) is the stiffness beyond the yield point (which coincides with the elastic limit for this model). XDV (ft³) is the volume displacement corresponding to the elastic limit. For this model K_1 must be greater than K_2 .

b. Elastic Deformation (refer to Figure D-5)

In this case, the formula to be used for $F(X, \frac{dX}{dt})$ depends upon whether the most recent plastic deformation occurred along the line AB or along the line CD. The formulas are:

$$F(X, \frac{dX}{dt}) = \begin{cases} K_1 X + (XDV - XP)(K_1 - K_2), & XP - 2 XDV \leq X \leq XP, \\ \text{most recent plastic deformation along line AB} \\ K_1 X + (XDV + XN)(K_2 - K_1), & XN \leq X \leq XN + 2 XDV, \\ \text{most recent plastic deformation along line CD} \end{cases} \quad (D-9)$$

In the above equations XP (ft³) is the volume displacement from which unloading occurred after plastic deformation along line AB. Similarly XN (ft³) is the volume displacement from which unloading occurred after plastic deformation along line CD (see Figure D-5).

4. Initialization

With any of the three restoring force models, the initial displacement of the plate, X_0 (ft³) is calculated from:

$$F(X_o, 0) = p_a(o) - p_b(o) \quad (D-10)$$

That is, X_o is first calculated using

$$X_o = \frac{p_a(o) - p_b(o)}{K_1} \quad (D-11)$$

This value is always used for the linear elastic model. For the other two models, the above value of X_o is used provided $|X_o| \leq XDV$. If $|X_o| > XDV$, then X_o must be recalculated as follows:

a. If X_o (from D-11) is greater than XDV , then

$$X_o = \frac{1}{K_2} [p_a(o) - p_b(o) - XDV (K_1 - K_2)] \quad (D-12)$$

b. If X_o (from D-11) is less than $-XDV$, then

$$X_o = \frac{1}{K_2} [p_a(o) - p_b(o) - XDV (K_2 - K_1)] \quad (D-13)$$

For the bi-linear hysteresis model the initial displacement is identical to that for the bi-linear elastic model. Displacement from the initial position, $X_1 = X - X_o$ is edited and plotted by the FLASH program.

5. Finite Difference Equations

The numerical method used to solve the governing differential equations is as follows. Let $V = dX/dt$. Then X_1 and V are updated at the $(i+1)$ time step as below:

$$V^{i+1} = V^i + \frac{\Delta t}{M} [p_a^{i+1} - p_b^{i+1} - F(X^i, V^i) - CV^i] \quad (D-14)$$

$$X_1^{i+1} = X_1^i + \Delta t V^{i+1} \quad (D-15)$$

$$X^{i+1} = X_1^{i+1} + X_o \quad (D-16)$$

where Δt is the time step size in seconds.

6. Input

The input required by the FLASH-35 flexible structural member model is specified in the 7501-7999 card series. Each card specifies one member with a set of eight parameters:

7501, F1, F2, F3, X1, X2, F4, F5, F6

F1 = flexible member mass m (lbm) which should include the mass of any water which is expected to move with it

F2 = flexible member stiffness $K1$ (psi/ft³)

F3 = effective flexible member area A (ft³)

X1 = number of control volume (node) on one side of the flexible member

X2 = number of control volume (node) on the other side of the flexible member

F4 = deflection at stiffness change XDV (ft³)

F5 = flexible member stiffness beyond stiffness change $K2$ (psi/ft³)

F6 = damping coefficient c (lbf-sec/ft)

If only the first five entries are specified (F1 - X2), the linear elastic model without damping is assumed. The linear elastic model with damping is obtained by setting F4 and F5 equal to zero and entering the desired value for c in the F6 slot. Input of the stiffness parameters $K1$, $K2$ and XDV is identical for the bi-linear elastic and bi-linear hysteresis models, except that XDV (F4) is given a negative value if the bi-linear hysteresis option is to be used and a positive value if the bi-linear elastic model is to be used. After the trigger function of the XDV value is served, the value of XDV is changed to $|XDV|$ before being used in the computer calculations.

FIGURE D-1
FLEXIBLE MEMBER SCHEMATIC

FIGURE D-2
BI-LINEAR ELASTIC MODEL

FIGURE D-3
BI-LINEAR HYSTERESIS -EXAMPLE 1

FIGURE D-4
BI-LINEAR HYSTERESIS-EXAMPLE 2

FIGURE D-5
BI-LINEAR HYSTERESIS SCHEMATIC