RESPONSE TO NRC/NRR ON PIPE WHIP RESTRAINT EAM LICENSING CONDITION

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I. INTRODUCTION AND SUMMARY

Sargent & Lundy Report No. SAD-443 entitled, "Evaluation of Tests Performed on Energy Absorbing Material for Pipe Whip Restraints," Revision 0, dated September 1984, provided information related to the Energy Absorbing Material (EAM) issues on Byron/Braidwood pipe whip restraints.

In the October 23, 1984 meeting between NRC/NRR, NRC Region III, Commonwealth Edison Company (CECo) and Sargent & Lundy (S&L) personnel held in the NRC/Region III offices, the contents and the remaining questions on Report No. SAD-443 were discussed. At the conclusion of the meeting, it was agreed that the Byron pipe whip restraint EAM concerns would be resolved subject to the condition that prior to exceeding 5% power, the licensee shall complete the following confirmatory measures related to the qualification of energy absorbing material (EAM) applications in the pipe whip restraints:

1. Complete EAM testing (per the technical requirements of S&L specification 117, Amendment 4) and evaluation of the test data related to the resolution of field-cut EAM installations.

2. Remove rubbing interference between compression leg and side plates for restraints MSR-33, MSR-48, and MSR-11.

3. Submit a report to Region III describing:

   a. the results of Item 1 above.
   b. the completion of Item 2 above.

4. Submit a report to NRR describing:

   a. The sensitivity analysis to evaluate the effect of EAM crush strength on the function of restraint SI3R-640A.

   b. Reconcile the conclusions from the Byron/Braidwood and LaSalle tests regarding reduction in EAM crush strength as a function of load angularities.

   c. Results of the effective crush angle calculation for Byron.

Sargent & Lundy Report No. SAD-451 entitled, "Response to NRC/Region III on Pipe Whip Restraint EAM Licensing Conditions," Revision 0, dated December 1984, provided information related to licensing conditions 1, 2 and 3. The present report provides the information requested in licensing condition 4 above. In addition, the recalibration data for the 3500,000 pound and the 1,000,000 pound tups is provided, as recommended in Report No. SAD-443.

Section II describes the sensitivity analysis for restraint SI3R-640A to evaluate the effects of the variation in EAM crush strength on the function of the restraint. The sensitivity analysis showed that the restraint will perform its intended function for EAM crush strengths from 4.0 KSI to 8.0 KSI. The 4.0 KSI to 8.0 KSI crush strength envelops the 5.1 KSI to 7.5 KSI crush strength values obtained in the Byron Angular Tests.

Section III compares the Byron angular configuration test setup with the Hexcel off axis test setup to show that their different conclusions are related to the differences in the EAM load angularity in the two tests. It is shown that the Hexcel off axis setup is not representative of the two-legged Byron/Braidwood pipe whip restraint behavior, whereas the Byron angular test setup simulates the two-legged Byron pipe whip restraint behavior. The presence of the second leg in the Byron restraints and Byron angularity tests drastically reduces the effective EAM load angularity. In addition to the loading, the estimated Average Dynamic Crush Strength, the material variability within the core block, and the possible accidental increase in load angularity due to specimen alignment in the off axis tests may also have contributed to the differences.

Section IV provides the results of the effective off set angle computations performed in January 1983. These computations show that most of the off set angles are less than 5°, with all angles less than 15°. Through this effort, it was concluded that the Hexcel off axis tests were not fully representative of the Byron two-legged pipe whip restraint behavior. For this reason the detailed finite element analysis of the worst case restraints and the Byron angular configuration tests were performed.

Section V presents the results of the recalibration of the 1,000,000 and the 325,000 pound tups. The recalibration showed that loads measured by the 1,000,000 pound tup were 18% too high and those by the 325,000 pound tup were 3% too low. This compares with the approximately 30% too high assumption for the 1,000,000 pound tup for the original test results. The EAM crush strengths for all the test specimens were recomputed using new calibration results and are summarized in Section V. It is shown that the new calculations support the original conclusions on the EAM behavior.

II. SENSITIVITY ANALYSIS FOR RESTRAINT SI3R-640A

In response to the NRC staff's request, we performed a detailed finite element nonlinear, large deflection analysis of pipe whip restraints SI3R-640A, FWR-35 and FWR-16. The analysis model and resulting responses are summarized in Sargent & Lundy Report No. SAD-442 entitled, "Finite Element Analysis of Pipe Whip Restraint SI3R-640A, FWR-35 and FWR-16," Revision 0, dated September 1984. In this analysis, possible buckling of the tension rod and the direct compression with shear and bending moments on the EAM were considered. Based on these three worst case restraint analyses, it was concluded that the Byron pipe whip restraint design is conservative and the restraints will perform their intended functions. As stated in Report SAD-442, subsequent to this analysis, restraints FWR-35 and FWR-16 were deleted; they are no longer required.

In their review, the NRC staff agreed with the finite element methodology used in Report SAD-442; however, the staff expressed concern that the use of a nominal 6 KSI value for the average dynamic crush strength (ADCS) for the Energy Absorbing Material (EAM) does not envelop the range of EAM crush strengths observed in the Byron Angularity Tests. The NRC staff requested a sensitivity analysis to evaluate the effect of EAM crush strength on the function of restraint SI3R-640A. This section presents the results of the requested analysis.

For the sensitivity analysis, the method of analysis and the restraint model were identical to those used for the initial analysis described in Report SAD-442, except the EAM crush strength was varied and a lower EAM strain hardening ratio was used. Restraint SI3R-640A was analyzed for EAM crush strengths of 4.0 KSI, 5.0 KSI, 6.0 KSI, 7.0 KSI and 8.0 KSI. No EAM strain hardening was used for the 5.0 KSI, 6.0 KSI, 7.0 KSI and 8.0 KSI case and a 0.0125 strain hardening ratio was used for the 4.0 KSI case. In Report SAD-442 a strain hardening ratio of 0.05 was used. The small strain hardening was used to stabilize the numerical solution because of the zero damping assumed. The 4.0 KSI to 8.0 KSI EAM crush strength envelops the 5.1 KSI to 7.5 KSI crush strength values obtained in the Byron Angular Tests.

The results of the sensitivity analysis are presented in Table II-1. This sensitivity analysis shows that the EAM strains are higher for the lower EAM crush strengths, whereas the structural reactions are higher for the higher crush strengths when compared to the nominal 6 KSI crush strength case. The restraint, however, is structurally stable and the stresses in the supporting structure and the restraint are within allowable limits. The maximum EAM strains are also less than the design allowable strain of 0.50, except for the 4.0 KSI case, where the maximum strain is 0.53. The 0.53 in/in strain is marginally above the design allowable strain of 0.5 in/in and does not adversely affect the restraint function.

Based on this sensitivity analysis, we conclude that the Byron pipe whip design is adequate and the restraints will perform their intended functions for a range of EAM crush strengths.

III. BYRON ANGULAR TESTS VERSUS HEXCEL OFF AXIS TESTS

In July 1982, Hexcel performed scoping tests on four EAM specimens to study the possible loss in the energy absorbing capacity of the EAM specimen when loaded in combined compression and shear. Based on these scoping tests, Hexcel concluded that there appears to be a 20% loss in energy absorbing capacity when the EAM is loaded at a load angularity equal to or greater than 5°. These tests are documented in the Hexcel Technical Report entitled, "Hexcel/Solarib Off Axis Crush Tests With Surface of Impact Perpendicular to Cell Axis" dated November 28, 1984. They will be referred to as the off axis tests in this report.

In October 1983, the Byron angular tests were conducted at Hexcel to determine the possible loss in the energy absorbing capacity of the EAM when loaded in a configuration similar to that in a pipe whip restraint subject to the pipe whip load. Based on these tests, it was concluded that the EAM energy absorbing capacity is not significantly affected when loaded in an angular configuration. These test results are described in S&L Report No. SAD-431 entitled, "Evaluation of Energy Absorbing Material for Pipe Whip Restraints," Revision 2, dated January 1985.

The NRC staff has requested that the different conclusions of the Hexcel off axis tests and the Byron angular tests be reconciled. This section provides the requested information.

The two test setups, their applicability to Byron pipe whip restraint design and the basis of the conclusions reached for the Byron angular test program and the Hexcel off axis test program are described in paragraphs A and B below. It is concluded that the EAM load angularity in the two test setups is different. This difference in EAM load angularity is the primary reason for the different conclusions of the two test programs. It is shown that the off axis tests setup is not representative of the two-legged Byron pipe whip restraint EAM loading, whereas the Byron angular test setup simulates the two-legged Byron pipe whip restraint EAM loading. The presence of the second leg in the Byron restraints and the Byron angularity tests drastically reduces the effective EAM load angularity. In addition to the loading, the estimated ADCS value, material variability with a core block, and the possible accidental increase in the load angularity due to specimen alignment in the off axis tests may also have contributed to the differences.

A. Byron Angular Tests

The test setup for the Byron angular tests is schematically shown in Figure III-1. The two EAM specimens were crushed by the anvil-shaped hammer. The load angularity on the EAM specimens was controlled by the anvil angle. These tests were performed for a 90° and 120° anvil angle θ. The test setup was specifically designed to simulate the crushing of the EAM in a typical two-legged pipe whip restraint at Byron. Fourteen tests were performed for specimens ranging in size from 3 x 3 inches to 6 x 6 inches.

Figure III-2 shows a typical two-legged pipe whip restraint where both legs are in compression and the pipe whip energy is being absorbed by the crushing of the EAM. Figure III-3 schematically shows the similarity between the deformation of the EAM in the pipe whip restraint and the Byron angular test setup. Note that the deformed shape of the EAM is very similar in the two cases.

Figure III-4 shows a typical tension-compression type two-legged pipe whip restraint. The pipe whip energy is absorbed either by the crushing of the EAM or the yielding of the tension rod. For cases where the pipe whip energy is absorbed by EAM, Figure III-5 schematically shows the similarities between the deformation of the EAM in the pipe whip restraint and the Byron angular test setup. For easy comparison, the test setup is drawn at an angle. Again note that the deformed shape of the EAM is very similar in both cases.

The 14 Byron angular tests showed that the specimen ADCS varied from 5.1 KSI to 7.5 KSI. This range was comparable to the 5.3 KSI to 7.8 KSI range obtained for the benchmark tests performed on five specimens from the same core block. In these benchmark tests, the EAM specimens were crushed in direct compression. Based on this comparison, it was concluded that there is no significant loss of EAM energy absorbing capacity when the EAM is loaded in an angular configuration.

B. Off Axis Tests

The setup for the off axis tests is shown in Figure III-6. The EAM specimen was tack-welded to the wedge-shaped steel plates. When impacted by the falling hammer, the wedge plates impose a combined axial and shear loading on the EAM. The off axis tests were conducted on one 4 x 4 x 4 inch specimen with off set angles of 5°, 10°, 15° and 20°. The off set angle controlled the relative magnitude of the axial to shear load on the EAM specimen.

The off axis tests are representative of the EAM loading in a pipe whip restraint employing a single-leg, single-EAM configuration where the pipe loading is skewed to the EAM axis. This is shown in Figure III-7. Byron/Braidwood pipe whip design does not use this single EAM configuration when the pipe whip load is skewed to the EAM axis. The single-leg configuration is only used when pipe loading is aligned with the EAM axis. When the pipe whip is skewed to the EAM axis, the Byron design uses the two-legged configurations shown in Figures III-2 and III-4. When the restraint legs can be assumed to be pinned, the presence of the second leg eliminates the load angularity on the EAM. This condition is shown in Figure III-8 where the loading on the EAM is axial both before and after the EAM crushing. When the pin connection assumption is not fully satisfied, the presence of the second leg considerably reduces the load angularity on the EAM. This condition is shown in Figure III-9. The EAM loading is axial at the start of EAM crushing. At the end of EAM crushing, the EAM load angularity is a function of restraint configuration and the pipe movement. Based on the above evaluation, it is concluded that the off axis tests do not simulate the two-legged Byron pipe whip restraint behavior.

The results of the off axis test can be summarized in the following table:

Test Number	Wedge Angle	ADCS (KSI)
Benchmark	0°	7.4*
A	5°	6.0
B	10°	6.0
C	15°	6.0
D	20°	5.0

The off axis tests A, B, C and D were performed at room temperature with all four specimens fabricated from a single core block. The specimen ADCS was obtained by dividing the hammer impact energy by the nominal change in specimen volume during crushing. The benchmark ADCS for this core block was established by a direct compression test of one specimen at $180^{\circ}F$. The benchmark ADCS at room temperature was estimated to be 7.4 KSI.

Based on these tests, Hexcel concluded that there is a 20% reduction in energy absorbing capacity of the EAM when loaded in the off axis setup with an off set angle equal to cr greater than 5°. Note that these tests show an ADCS reduction of 20% between 0° and 5°, no reduction in ADCS between 5°, 10° and 15° tests, and then a 20% reduction in ADCS between 15° and 20° tests. This atypical material behavior cannot be explained from the available data. In our opinion, this atypical behavior is related to factors in addition to the off axis loading. These factors include the estimated benchmark ADCS value, material variability within a core block, and the possible accidental increase in the load angularity due to specimen alignment during the test.

* Estimated ADCS at room temperature

IV. EFFECTIVE OFF SET ANGLES FOR BYRON RESTRAINTS

In January 1983, an effort was made to correlate the EAM loading angularities in Byron pipe whip restraints to the off set angles in the Hexcel off axis tests. Through this effort it was concluded that the Hexcel off axis tests were not fully representative of the Byron two-legged pipe whip restraint behavior. For this reason, the Byron angular tests and the detailed finite element analysis of the three worst case restraints were performed.

The NRC staff has requested the results of the off set angle calculations. This section presents the off set angles for the Byron restraints as computed in January 1983.

Figure III-8 shows the analytical model which was used in the initial design of pipe whip restraint in Byron. The restraint structure was modeled as a two-legged truss. The loading on the EAM was axial both at the start of the EAM crushing and at the end of the EAM crushing. The off set angle of EAM was thus zero throughout the pipe whip event. This was accomplished by rotating the restraint legs at the structure and the pipe collar. The required compression leg rotations were a function of the restraint deflections necessary to resist the pipe whip load, the length of the compression and tension legs, and the included angle between the compression and tension legs. Table IV-1 shows these rotations for all Byron two-legged restraints where pipe whip energy was being absorbed by the EAM.

Note that the above restraint model assumes that rotations are possible at the restraint to structure connections. When the restraint to structure connection detail does not permit rotation, the EAM deformation can accommodate the required rotation. This is shown in Figure III-9. For this model, the off set angles are zero at the start of the EAM crushing, and the off set angles at the end of the EAM crushing are approximately equal to the required compression leg rotation shown in Table IV-1. Note that the off set angles are all less than 15°, with eight out of fourteen less than 5°. This model assumes that the shear deformation or bending of the compression leg is small or not possible. The computed off set angles will be smaller if the EAM shear deformation or the bending of the compression leg is accounted for in the angle calculation.

The above model assumptions are not valid when the pipe whip restraint legs are short and rigid or when the EAM is located next to the pipe collar rather than at the bottom of the compression leg. EAM deformation patterns under these conditions are simulated by the Byron angular tests as was discussed in Section III. In our judgment no accurate off set angle calculation is practical for this case.

V. RECALIBRATION OF TUPS

The Byron Angular Configuration Tests were conducted in 1983 to evaluate the possible reduction in the average dynamic crush strength of the EAM specimens when the EAM is subjected to the action of combined lateral shear and axial loads. The test results were presented in Sargent & Lundy Report No. SAD-431 entitled, "Evaluation of Energy Absorbing Material for Pipe Whip Restraint," Revision 1, dated April 1984. Sargent & Lundy Report No. SAD-443 entitled, "Evaluation of Tests Performed on Energy Absorbing Material for Pipe Whip Restraints," Revision 0, dated September 1984, provided further clarification of results presented in Report SAD-431, including the basis for the 30% reduction of recorded force data for the new one million pound instrumented tup. The report concludes that the 30% reduction in the computed force magnitude was appropriate to account for what we believe was an inadequate calibration for the 1,000,000 pound tup. The report recommended that the tup be recalibrated to confirm this judgment. This section describes the recalibration results. The instrumented tup is a strain gauge type load cell. It is part of the ETI-300 Instrumented Impact System used by Hexcel to compute the ADCS of the EAM specimens.

The recalibration of the new 1,000,000 and the 325,000 pound tups was performed for up to 100% of their rated capacities at the National Standards Testing Laboratory, Rockville, Maryland, in October 1984. The calibration was performed using the pin connections and loading procedure specified by the General Research Corporation (the tup manufacturer) and S&L Specification No. 117, Amendment 4. The recalibration results can be summarized as follows:

1. The tup output voltage is proportional to the applied load for the entire load range. For the 1,000,000

pound tup, the tup output varies from 9,191 lb/mv/v at 200,000 pounds to 8,845 at 1,000,000 pounds. For the 325,000 pound tup, the tup output varies from 3,942 lbs/mv/v at 60,000 pounds to 3,754 lb/mv/v at 325,000 pounds.

2. The tup sensitivity was computed to be 642,205 pounds and 322,621 pounds for the 1,000,000 pound and the 325,000 pound tups, respectively. These values should be compared to the old values of 773,500 pounds and 311,400 pounds used previously.

3. This recalibration shows that all loads computed for the 325,000 pound tup should be increased by 3% and all loads computed for the 1,000,000 pound tup should be reduced by 18%. These compare with the 0% increase and the 30% reduction assumed in calculations presented in Report SAD-431.

The new sensitivities were used to recompute the ADCS for each of the specimens in the Byron Angular Test program. These ADCS values, as well as those reported in Report SAD-431, are presented in Table V-1. Based on this comparison, the conclusions of Report SAD-431 are valid when the new calibration data is used. The conclusions were:

1. There is no scaling effect on the behavior of the EAM. The test results are thus applicable to full-size EAM pieces in the pipe whip restraints.

2. There is no loss of energy absorbing capacity when the EAM is loaded under shear and direct compression. The EAM load angularity was 45° for the 90° tests and 60° for the 120° tests.

3. There is no significant difference in the energy absorbing capacity of the EAM with or without bolts.

4. There is no significant difference in the energy absorbing capacity of the EAM whether it is loaded in the strong shear direction or the weak shear direction.

TABLE II-1

Results of Sensitivity Analysis for Restraint SI3R-640A

		MAXIMUM STRUCTURAL REACTION			
EAM	EAM	Tension	Compression Leg		
Strength (KSI)	Strain (IN/IN)	Leg (KIPS)	Compression (KIPS)	Shear (KIPS)	Moment (KIP-IN)
4.0	0.53	56.	162.	13.	565.
5.0	0.46	53.	152.	11.	599.
6.0	0.34	60.	170.	10.	579.
7.0	0.27	66.	187.	11.	599.
8.0	0.15	67.	193.	13.	719.

TABLE IV-1

Maximum Rotation of the Compression Leg for Two-Legged Pipe Whip Restraint

Restraint	Maximum Rotation
SI1R-10B	2.3°
SI3R-640A	2.9°
SI4R-15B	2.7°
FWR-2	2.4°
FWR-3	1.7°
MS-R1	2.1°
MS-R2	6.9°
MS-R4	1.4°
MS-R9	10.6°
MS-R10	7.0°
MS-R33	4.0°
MS-R48	6.8°
RH-R1	7.0°
RH-R3	13.5°

Table V-1

Computed Average Dynamic Crush Strengths
for the Angular Tests

Specimen Identification	Anvil Angle	Average Dynamic Crush Strength (KSI) New Calibration	SAD-431
4x4x4 SS	90°	6.4	6.5
4x4x4 WS	90°	5.5	5.5
4x4x3 WS	90°	5.4	5.5
4x4x2-5/16 SS	120°	7.5	8.2
4x4x2-5/16 WS	120°	6.4	6.5
4x4x2 SS	90°	7.5	7.6
4x4x2 WS	90°	5.1	5.2
3x3x3 SS	90°	5.4	6.1
3x3x3 WS	90°	5.6	5.6
6x6x3 SS	90°	7.3	7.6
6x6x3 WS	90°	6.9	7.2
5x5x4 SS	90°	6.6	6.8
5x5x4 WS	90°	5.9	5.9
4x4x4 - Bolt	90°	7.5	6.6

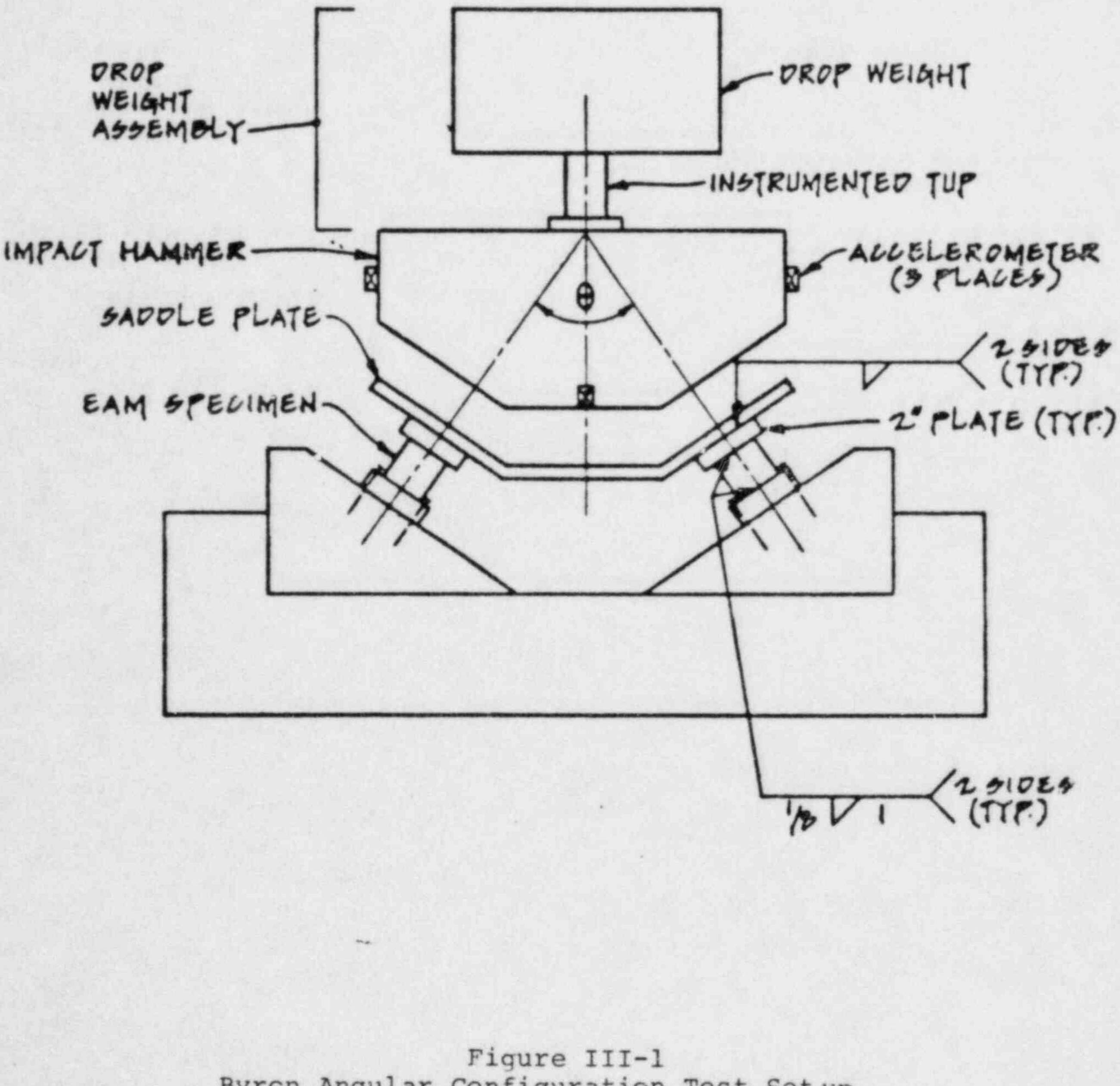


Figure III-1
Byrcn Angular Configuration Test Set up

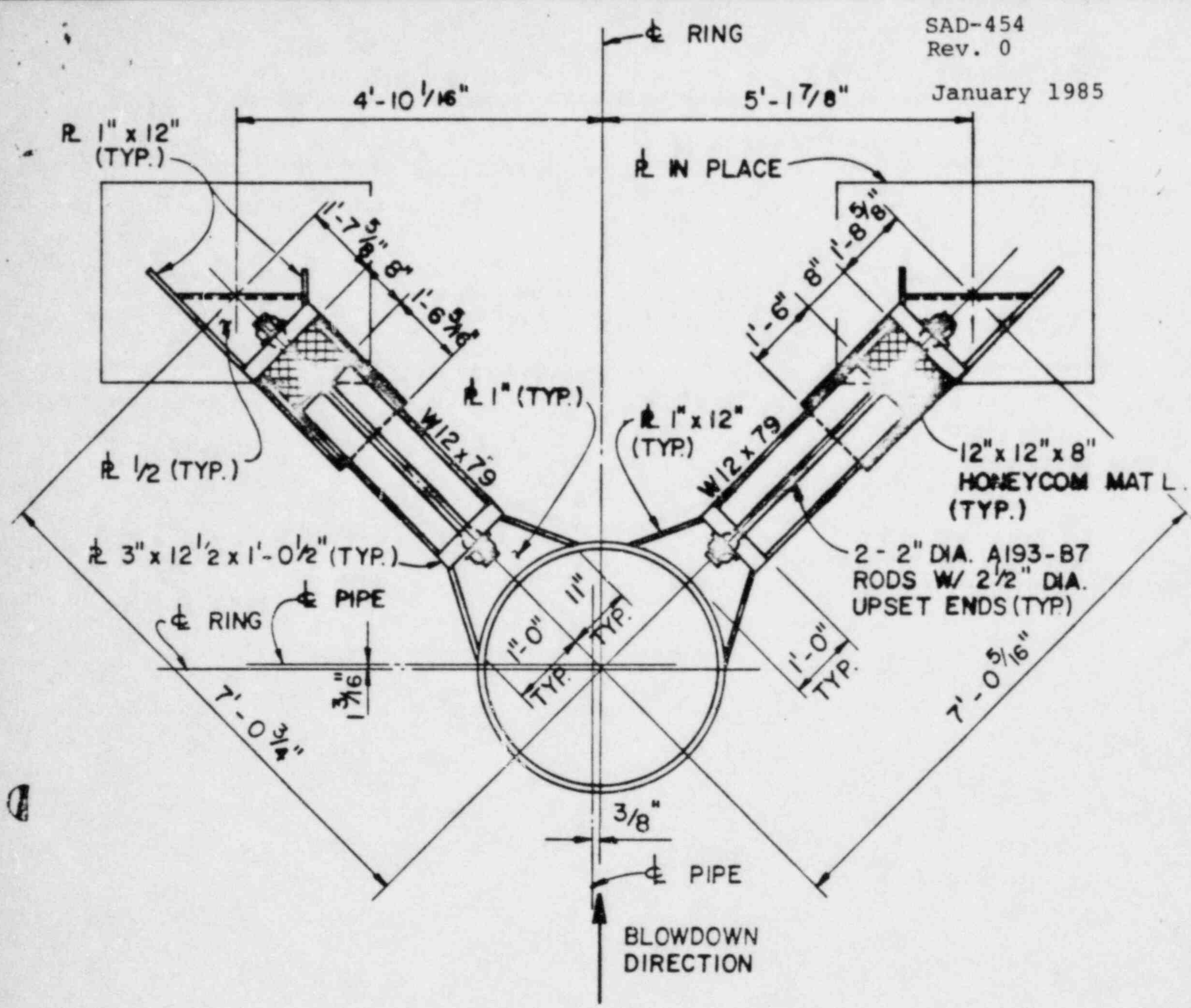
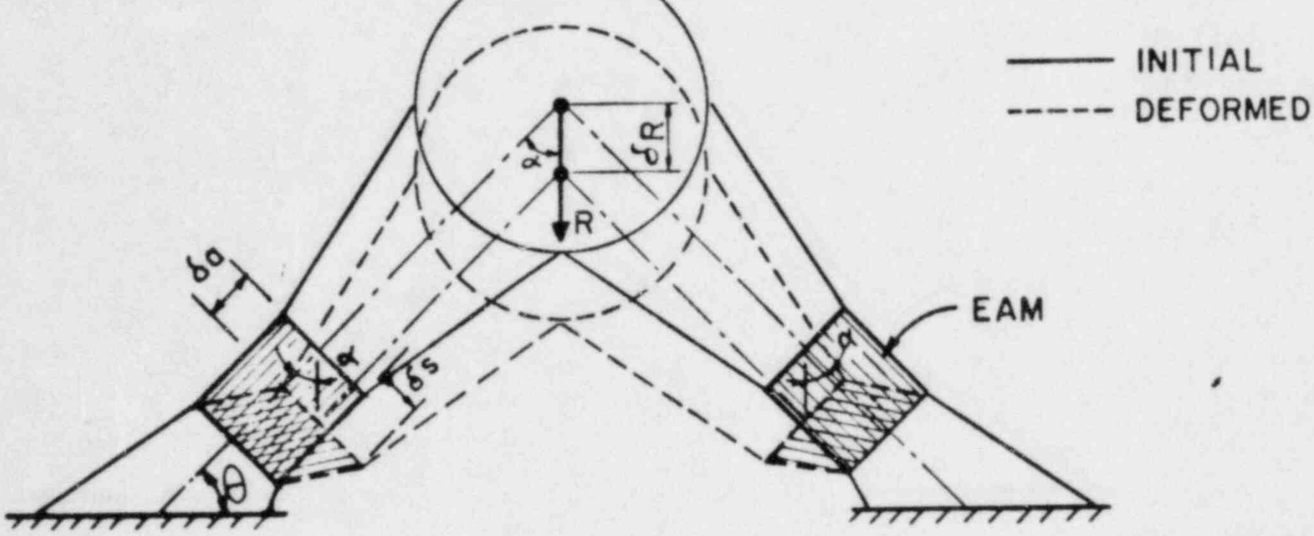
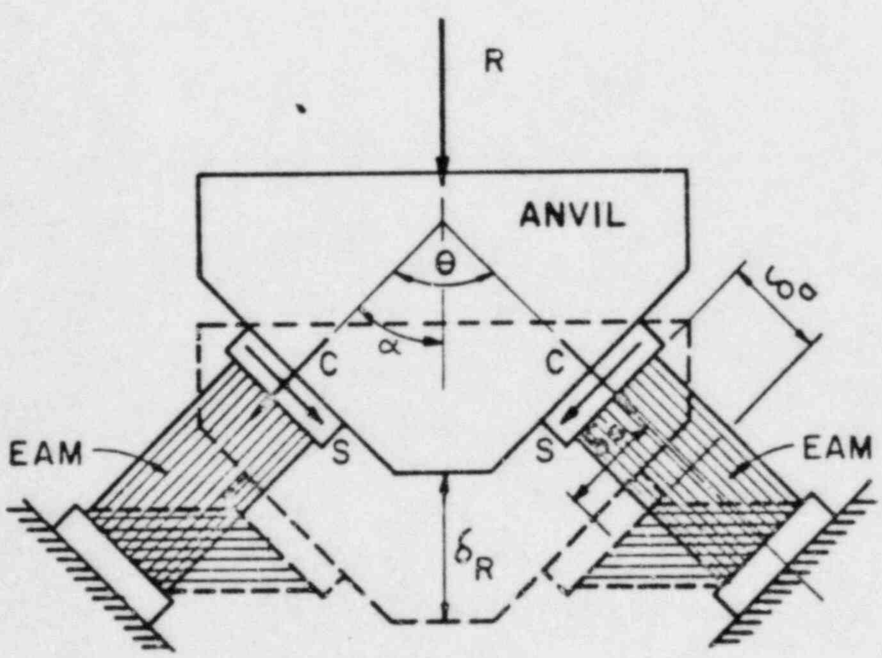


Figure III-2

TYPICAL WHIP RESTRAINT UTILIZING TWO COMPRESSION MEMBERS CONCEPT



a) RESTRAINT



b) TEST SETUP

Figure III-3
Comparison Between Two-Legged Compression Whip Restraint and Byron Test Setup

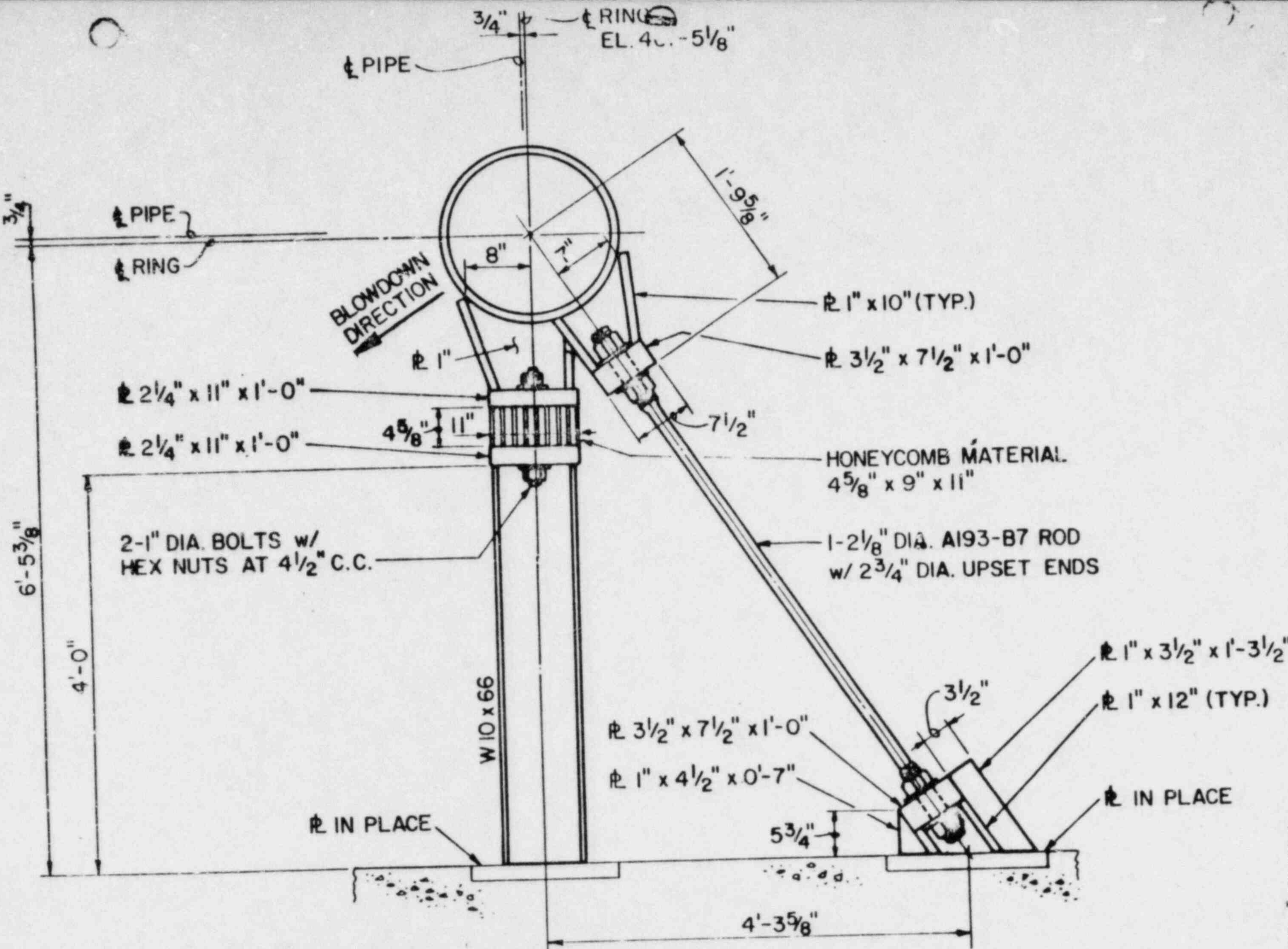
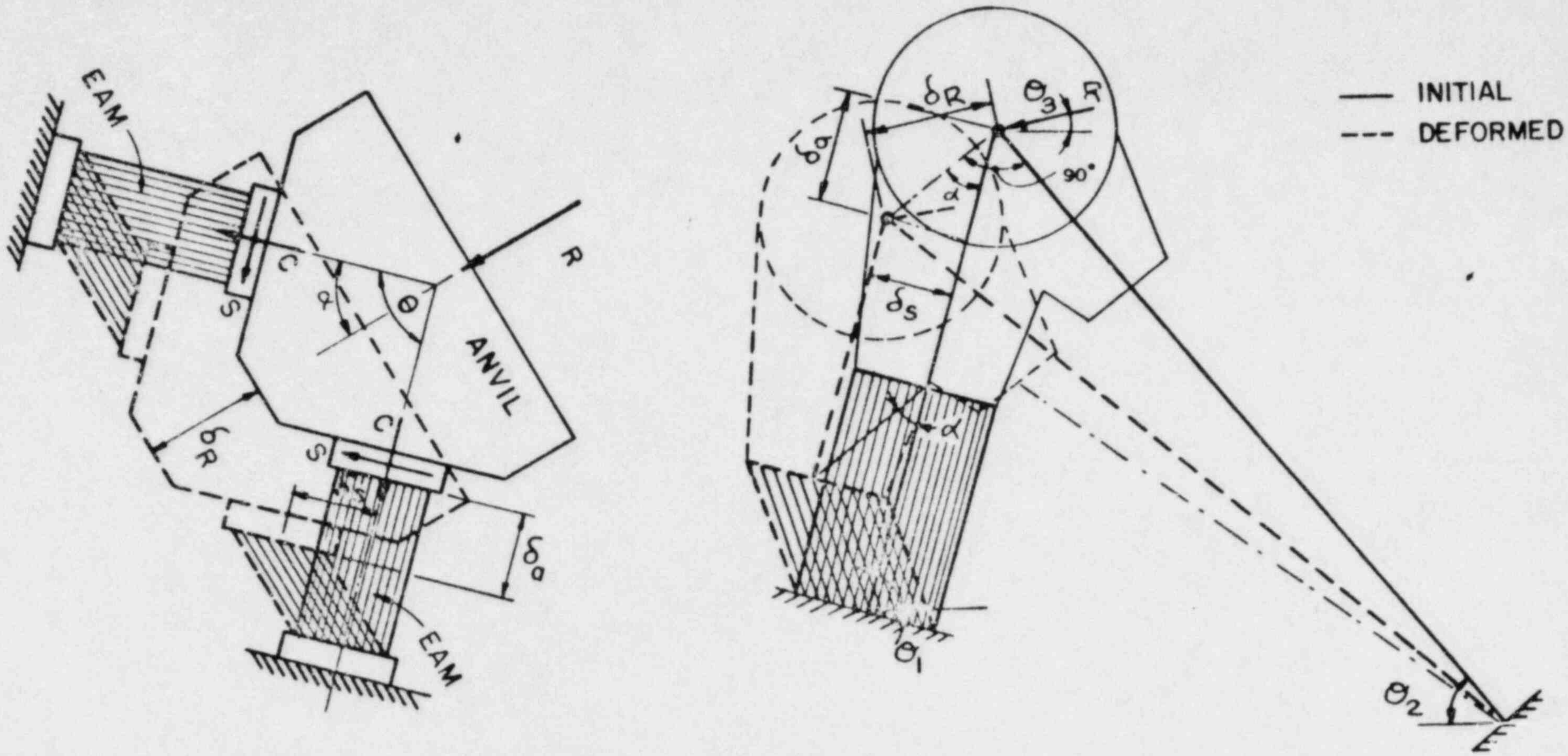


Figure III-4

TYPICAL WHIP RESTRAINT UTILIZING TENSION-COMPRESSION MEMBER CONCEPT



a) Test

b) Restraint

Figure III-5
Comparison Between Two-Legged Tension-Compression Whip Restraint and Byron Test Setup

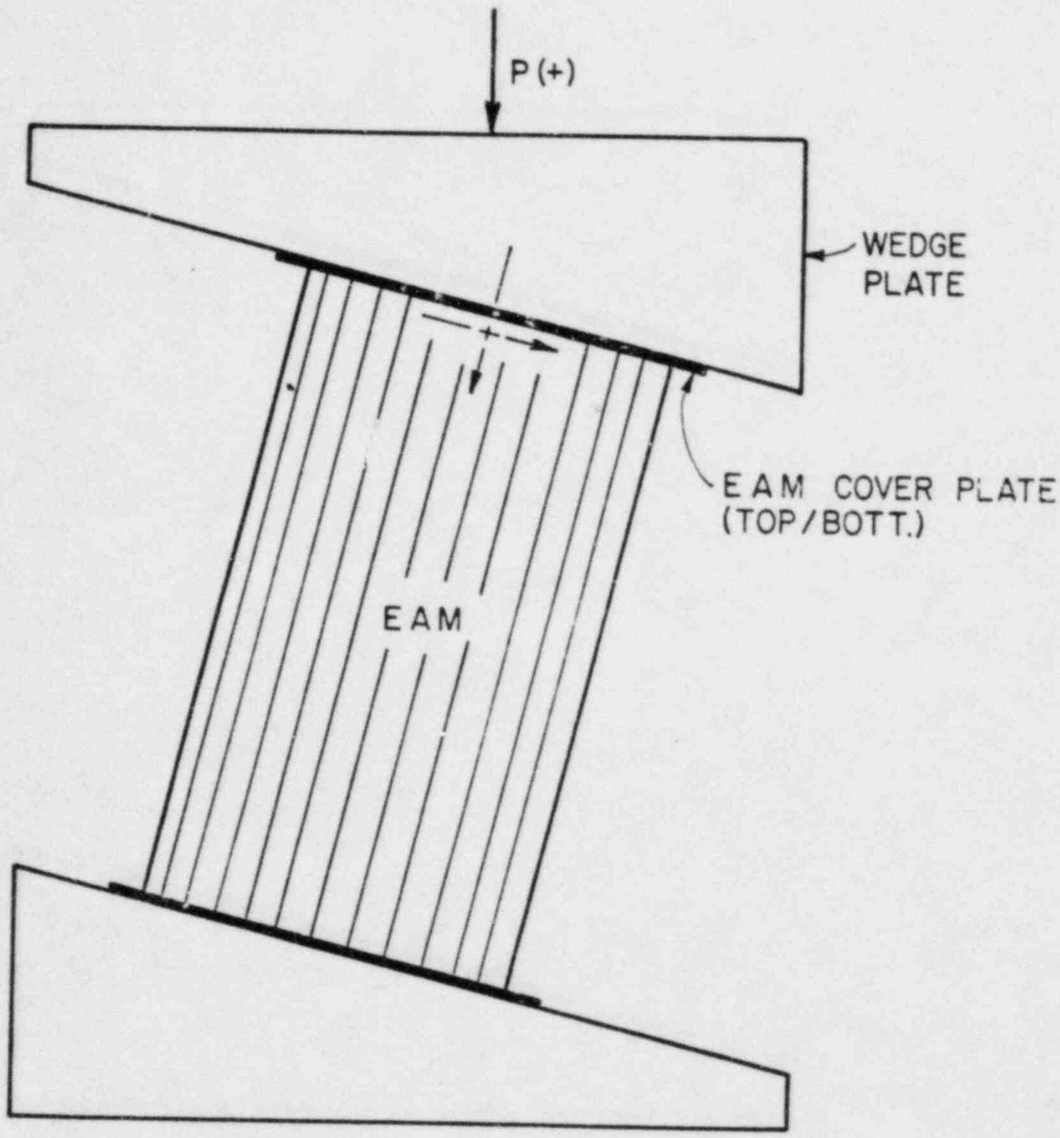


Figure III-6

Off Axis Test Setup

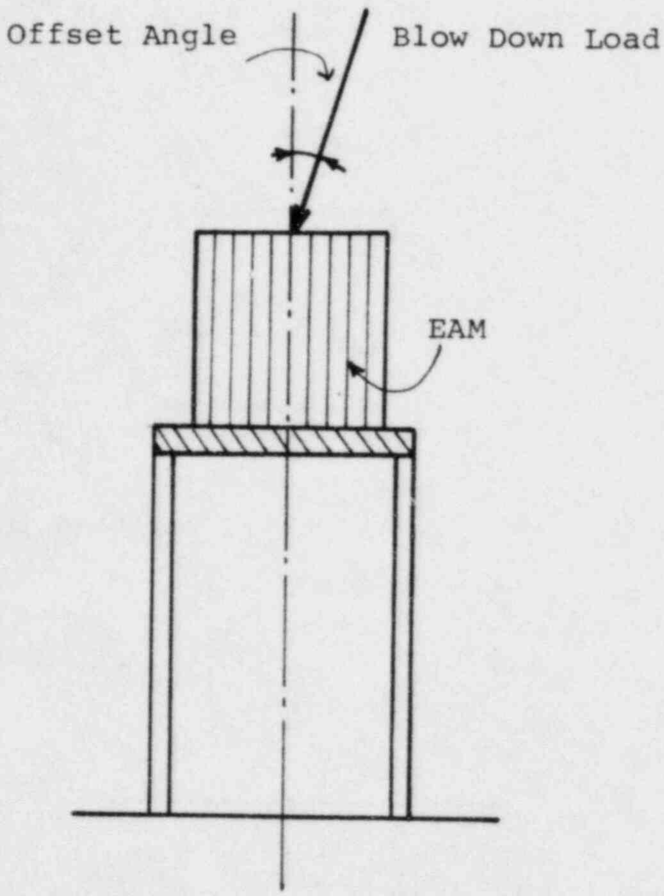


Figure III-7

Representative Whip Restraint Configuration for Off Axis Test Setup

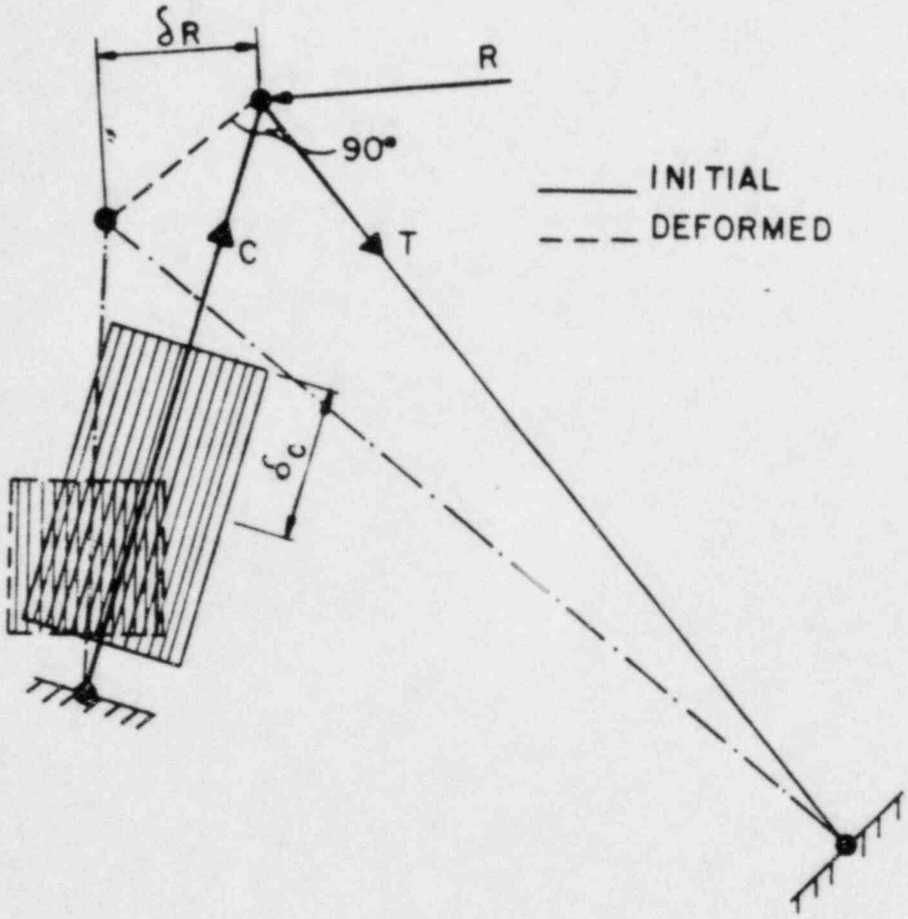


Figure III-8

Restraint Deformation Model When Rotation At Structural Connections Are Possible

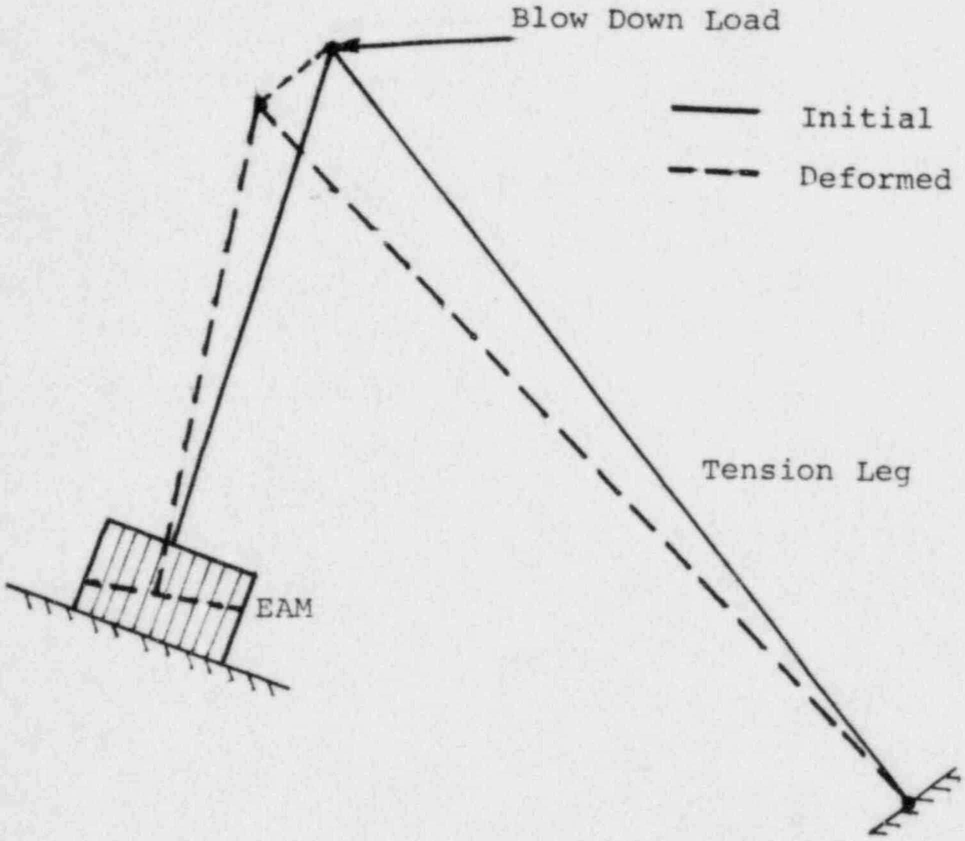


Figure III-9

Restraint Deformation Model When Rotation At Structural Connections Are Not Possible