MFH Strap Design

D-Zero Engineering Note #3740.222-EN-197

11-18-88

**Revised
4-4-89**

Approved by Keith Primdahl

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Background

In the end calorimeter of the D-zero experiment, uranium and stainless steel plates are assembled into modules which are to be installed into the cryostat as individual units. A single inner module will be surrounded by sixteen middle modules, which are surrounded by sixteen outer modules.

The earlier design of the support structure of each middle hadronic module of the end calorimeter consisted of a stainless steel skin "wrapped" around the plates. Recently, it became clear that a system of straps, instead of skin, offered several advantages. Specifically, high voltage and read-out cables could be attached after assembly, most signal wire ganging connectors could be accessible for maintenance, and there would be less resistance to convective flow of argon vapor during cool-down and warm-up. Unlike the stainless steel plates of the coarse section, uranium plates cannot be welded to the straps.

A series of four configurations were designed, constructed, and tested. This report describes testing of the fourth design, which has been selected for construction. Drawings are included in appendix 1.

Module Orientation

The modules of the end calorimeter are trapezoidal shapes arranged in a ring, centered around the beam path. The test modeled the MFH in the 6:00 position of the ring. For several reasons this module is expected to be the most severely loaded:

- The two outer radius angles are at the bottom of the module and will be required to support the weight of the uranium plates in addition to the moment induced by the connection to the coarse section.
- The outer radius angles are smaller than the inner radius angles. Specifically, the flange on the side between modules is 1.625" for the outer radius angle, and 3.000" for the inner radius angle.

•The 6:00 orientation is the case where the module is closest to being simply supported. Since the modules are connected at the outer radius, other orientations are supported in a manner that could be described as between simply supported and fixed/guided.

•In all orientations except 6:00, the "wedge" shape may allow for some sharing of loads with other module support members. Also, the flanges facing the IH and OH are 0.188" thick, while the side flanges are 0.075" thick (0.060" for test).

Comparison of Test Conditions and Installed Conditions

The loading of the test module, cantilevered from the test stand, with lead bricks, and tip force from below, nearly duplicate the loads expected when attached to a coarse section and installed in the end calorimeter (see appendix 2 for calculations):

<u>Support Loads</u>	<u>As Installed</u>	<u>As Tested</u>
Weight of fine section (lb)	5450	4820 (88%)
Support Force, max. shear (lb)	5030	6000 (119%)
Moment (max) at back of center plate (in lb)	69,800	111,700 (160%)
Shear at back of center plate (lb)	-410	1180 (246%)

The above results for the installed module assume a "beam" of uniform properties. The moment may be slightly different since the coarse section is much more stiff than the fine section. The test stand was assumed to be infinitely stiff for the tested case. Strap thickness for the tested case was 0.060", while actual construction will utilize 0.075" thick material. Hence, actual modules can be expected to be 20% stronger than the tested MFH. All data presented in this report is for the 0.060" straps, no adjustment has been made for increased strength of 0.075" straps.

Pre-Load (Modeling the Warm-up Case)

When assembled, the stack of uranium plates and pins will be compressed while straps are welded to the stainless steel end plates. When released from the welding fixture, the plates and pins will be in compression, the straps in tension. The cool-down case, where the straps are at 250K while the plates and pins are at 293K results in

the highest pre-load stresses on the plates, pins and straps (a pre-weld 15,000 $\pm$ compression has been assumed for these estimates):

Maximum Pin & Plate Stress	-21,200 psi
Maximum Strap Stress	4,800 psi

During warm-up it is possible for the stainless steel straps to be warmer than the bulk of the uranium plates and stainless steel pins. This difference in temperature, and corresponding difference in thermal expansion, will reduce the compressive pre-load on the stack. For the case where the plates and pins are at 250K and the straps are at 293K, the stack might expand 0.023" . (appendix 3).

In order to simulate the warm-up, or loose, condition during testing, the relation between stack height and pre-load was measured. The stack was compressed, released, then compressed again. In previous stack compression tests, the first set of data indicates a "shake-down" occurs, possibly due to movement of pins on plates. Second and subsequent compressions have always shown good repeatability. In appendix 4, the change in stack length is plotted as a function of compressive load. It can be seen that the data tends toward a linear relation as the compressive force is increased. For this upper region the compressive force is plotted as a function of change in stack length (axes switched w/respect to the first plot). Here, the spring constant of the stack is the slope of a straight line through the data. This result can be compared to the theoretical value based on the plate and pin thickness, and their Young's modulus:

Theoretical spring constant, k (lb/in)	937,500
Measured spring constant, k (lb/in)	398,000

The difference is due to the waviness and/or thickness variation of the uranium plates.

It is presently anticipated that during production, the stacks will be compressed to 10,000 lb and welded. For the test module, its stack height at 10,000 lb was noted, then it was allowed to expand by .022". While subject to this expanded pre-load, the corner straps were welded and allowed to cool, then the struts were welded. The final pre-load on the stack was estimated to be 7500 lb. A significant portion of this pre-load can be attributed to weld shrinkage in the corner angles.

Pre-load carried by the struts is small, compared to the total pre-load. In fact, we have learned that the more massive corner angles must be welded and allowed to shrink before the struts are welded; otherwise, there will be no pre-load in the struts. Also, the bending component of this pre-load is in the opposite direction of the loaded module case. For this test, the strut pre-load stress was as follows:

Primary Pre-Load Stresses Larger of the 2 Sides

Membrane stress (psi)	720
Bending at the gage (psi)	290
Bending extrapolated to the extreme fiber (psi)	520
Membrane plus bending at the extreme fiber (psi)	1240

Measured Stresses

The critical stress areas are the strut near its weld to the front plate, and the joint of the struts with the center of the outer radius angle. The jack force was cycled from zero to 6000 lb twice. At 1875 lb jack force, the module is supported in a neutral position; that is, the tip deflection (from beam theory) is zero. For a jack force less than 1875 lb, the module is bending towards the floor due to the weight of the plates and bricks, for a jack force above 1875 lb, the module is bending toward the ceiling. The data shows a "kick" where the bending changes direction. The data is nearly linear, with good repeatability. This indicates no yielding or permanent shape change occurred.

By comparing the stress intensity measured near the upper and lower fiber of the strut, the membrane stress can be separated from the bending stress. Considering the second and third loadings

to 6000 lb (a complete set of plots appears in appendix 4):

Strut, Near Front Plate Larger of the 2 Sides

Membrane stress (psi)	11,750
Bending at the gage (psi)	930
Bending extrapolated to the extreme fiber (psi)	1670
Membrane plus bending at the extreme fiber (psi)	13,420

Strut/Outer Radius Joint Larger of the 2 Sides

Membrane stress (psi)	13,700
Bending at the gage (psi)	3010
Bending extrapolated to the extreme fiber (psi)	6010
Membrane plus bending at the extreme fiber (psi)	19,710

Where the struts connect with the outer radius angle; that is, the other end of the strut, the stresses can be no greater than the case above.

There was no buckling during the testing of this design. An earlier design had buckled near the inner radius' (the tallest flange of the straps) connection to the front plate; however, the resulting tip deflection of that test was still acceptable. Since the actual straps will be 20% thicker than those tested, there is sufficient safety margin against buckling.

In earlier tests performed under the direction of Kurt Krempetz, it was found that the strength of butt welds in stainless steel was equal to the strength of the material itself. This is as expected, since the filler rod is of the same material. No effort has been made to take advantage of the increased strength of stainless steel due to cold rolling.

Comparison of Stresses With Code Allowed Limits

The ASME Pressure Vessel Code gives the following guidelines:

For primary membrane stress	$(1.0)(S_m)$
For primary membrane plus primary bending stress	$(1.5)(S_m)$
For primary and secondary membrane plus bending stress	$(3.0)(S_m)$

Where S_m is the Design Stress Intensity. For AISI 304 (UNS S30400) stainless Steel, the ASME tables (Section VIII, Division 2) list $S_m = 20,000$ psi. This results in limits of:

For primary membrane stress	20,000 psi
For primary membrane plus primary bending stress	30,000 psi
For primary and secondary membrane plus bending stress	60,000 psi

So the measured stress is acceptable under the ASME Pressure Vessel Code. However, the MH module is not a pressure vessel; hence, it is wise to consider the guidelines of the AISC code for structural steel. Although the AISC code does not directly address the use of stainless steel, allowable stresses can be calculated from code formulas, using a yield strength, F_y of 30,000 psi for 304 stainless steel.

Tension	$(0.6)(F_y) = 18,000$ psi
Bending	$(0.66)(F_y) = 19,800$ psi
Compression	$(0.9)(F_y) = 27,000$ psi

For tension plus bending, the following formula is provided:

$$f_a/(0.60F_y) + f_{bx}/(0.9F_y) < 1.0$$

f_a = axial tension

f_{bx} = in plane bending force

F_y = yield strength

Using data from the larger of the two sides, with 5000 lb (design load) jack force, for the stress in the strut/outer radius joint extrapolated to the extreme fiber (the worst case):

$$13700 \text{ psi}/18000 \text{ psi} + 6010 \text{ psi}/27000 \text{ psi} = 0.98$$

which is acceptable.

Deflections (Permanent Shape Change)

For a cantilevered beam with an evenly distributed weight, and a tip load equal to three-eighths the weight there is no tip deflection. Accordingly, the deflection results have been adjusted to approximate this horizontal starting position. The largest tip deflection, with 6000 lb jack force, was 0.021 in. With no jack force, the largest tip deflection was -0.005 in. Hence, the largest deflection possible, regardless of the selected zero point, is 0.026 in, which is acceptable. Tip deflections for the two cycles, plotted in appendix 4, were nearly identical.

Even though the module nearly returned to its horizontal position in the tests, there is no reason to believe that this would occur when installed in the cryostat. In fact, since the module will be cycled thermally, with constant support forces (just the opposite of test conditions), It is believed that the module will sag at the center plate approximately the same distance as the above tip deflection during the first warm-up, then remain in this position.

Conclusion

The fourth MFH strap design described in this report is adequate for the expected loads during cool down and warm up in the end calorimeter.

Appendix 1

Drawings

REV.	DESCRIPTION	QUANTITY	DATE
		APPL.	DATE
A	30.750 WAS 28.750	S.L.M.	9-13-8
B	30.600 WAS 30.750	S.L.M.	10-6-8

GEN. NOTE:

1. UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE FROM SHARP CORNERS.

ITEM	PART NO.	DESCRIPTION OR SIZE		QTY.
PARTS LIST				
ALUMINUM BRACKET OF		ORIGINATOR	K. KREMPETZ	3-2-BR
FUNCTION	ORIGINATOR	DESIGN	S.L.MEREDITH	3-2-BR
2	1.016 x .5"	CHECKED		
		APPROVED		
1. 2000 GRADE ALUMINUM		USED ON		
2. 1/4" X 1/2" HOLE SPACED.		3740.222-ME-255186		
3. 2000. 10 HOLE 711.0.		NATIONAL		
4. 2000. 1/4" HOLE SPACED		10 GAGE(.075) SST TY-304 SHEET-METAL
FERMI NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY				
DO DETECTOR END CALORIMETER MIDDLE FINE HADRONIC MODEL OUTER-RAD. PEAK-TOP ANGLE STRAP				
SIZE	FILED	SHOWN	ISSUED	REV.
1 X				B
3740.222-ME-255190				
CREATED WITH ICFMCON VERSION 1.6A				

REV.	DESCRIPTION	DATE	BY
A	ADDED 6.25H HOLES & WELD SYMBOLS/NOTES S.02 DIA. HOLES 1.000 DIA. 1.000 DIA.	S.L.M.	9-21-88
B	6.00 DIA. HOLES 1.000 DIA. 1.000 DIA. 1.000 DIA. AND 15.000 DIA. HOLES 1.000 DIA. 1.000 DIA.	S.L.M.	10-1-88
C	38.125 DIA. 12.375 DIA. 12.125 DIA. & RELOCATED AND REDIMENSIONED .250 DIA. SLOT	S.L.M.	10-6-88
D	ADDED 4.000	S.L.M.	10-31-88

NOTE:

1. UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE FROM SHARP CORNERS.

2	REINFORCEMENT BAR	1
1	ANGLE STRAP	1
ITEM	PART NO.	DESCRIPTION OR SIZE
PARTS LIST		
UNLESS OTHERWISE SPECIFIED	ORIGINATOR	K. KREMPETZ
DATE	DATE	S.L. MEREDITH
1. DRAW ALL GROUPS	APPROVED	
2. DO NOT SCALE DIMENSIONS	USED ON	
3. DIM. TO SHARP VTL'S		
4. DIM. ALL HOLE SURFACES		
MATERIAL		
FERRI NATIONAL ACCELERATOR LABORATORY		
UNITED STATES DEPARTMENT OF ENERGY		
DO DETECTOR END CALORIMETER		
MIDDLE HADRONIC MODULE		
INNER-RAD. CORNER ANGLE STRAP		
SCALE	FILED	ISSUING NUMBER
1 X		3740.222-MD-273210
CREATED WITH ICDON VERSION 1.64		

Appendix 2

**Comparison of
Expected and Tested Loads**

FIND SHEAR ON BACK OF CENTER PLATE

$$V = 6000 \text{ LB} - 4816 \text{ LB} = 1184 \text{ LB}$$

$$V = 1184 \text{ LB}$$

FORCES ON MFH, AS INSTALLED IN EC

FIND REACTION FORCE ON FRONT PLATE

$$\begin{aligned}\sum M_B = & (59.28 \text{ IN} - 0.5 \text{ IN})(154.2 \text{ LB}) + (182.908 \text{ LB/IN})(27.404 \text{ IN}) \\ & (59.28 \text{ IN} - 1 \text{ IN} - \frac{27.404 \text{ IN}}{2}) + (138.366 \text{ LB/IN})(30.876 \text{ IN}) \\ & (\frac{30.876 \text{ IN}}{2}) - (F_F)(59.28 \text{ IN}) = 0\end{aligned}$$

$$F_F = 5034.2 \text{ LB}$$

FIND MOMENT AT EACH OF CENTER PLATE

$$\begin{aligned}\sum M = & -(5034.2 \text{ LB})(27.404 \text{ IN} + 1.83 \text{ IN} + 1 \text{ IN}) + (154.2 \text{ LB}) \\ & (27.404 \text{ IN} + 0.5 \text{ IN}) + (182.908 \text{ LB/IN})(27.404 \text{ IN}) \\ & (\frac{27.404 \text{ IN}}{2} + 1.83 \text{ IN}) + (282.1 \text{ LB})(\frac{1.83 \text{ IN}}{2}) + M_C = 0\end{aligned}$$

$$M_C = 69790.3 \text{ IN LB}$$

FIND TOTAL WEIGHT OF FRONT PLATE, CENTER PLATE
AND FINE SECTION

$$W = 154.2 \text{ LB} + (182.908 \text{ LB/IN})(27.404 \text{ IN}) + (282.1 \text{ LB})$$

$$W = 5448.7 \text{ LB}$$

FEND SHEAR ON BACK OF CENTER PLATE

$$V = (-154.2 \text{ LB}) - (182.908 \text{ LB/in})(27.40 \text{ in}) \\ - (282.1 \text{ LB}) + 5034.2 \text{ LB}$$

$$V = -414.5 \text{ LB}$$

Appendix 3
Spring Constant
&
Thermal Expansion Differential
Calculations

UNSTRESSED LENGTH OF PLATES & PINS AT 293 K:
(UNSTRESSED, BUT TOUCHING)

$$(55 \text{ PLATES})(.236 \text{ in}) = 13.524 \text{ in}$$

$$(35 \text{ PINS})(.224 \text{ in}) + (4 \text{ PINS})(.302 \text{ in}) = 13.528 \text{ in}$$

$$L_{\text{UNSTRESSED}} = 13.524 \text{ in} + 13.528 \text{ in} = 27.452 \text{ in}$$

COMPRESS STACK W/ 60 PSI;

$$F = (60 \text{ psi})(250 \text{ in}^2) = 15000 \text{ LB}$$

$$E_{SS} = 28.3 \times 10^6 \text{ psi}$$

$$E_U = 25.5 \times 10^6 \text{ psi}$$

$$L_{\text{COMPRESSED}} = (L_{\text{UNSTRESSED}}) \left(1 - \frac{F}{EA} \right)$$

FOR A, USE AVERAGE AREA (NO CONE SHAPE) OF
THE PINS IN CONTACT WITH THE URANIUM.
THIS WILL YIELD THE "SOFTEST" RESULT:

$$(L_{\text{COMPRESSED}})_{SS} = (13.524 \text{ in}) \left[1 - \frac{(15,000 \text{ LB})}{(25.5 \times 10^6 \text{ psi})(.97 \text{ in}^2)} \right] = 13.516 \text{ in}$$

$$(L_{\text{COMPRESSED}})_{SS} = (13.528 \text{ in}) \left[1 - \frac{(15,000 \text{ LB})}{(28.3 \times 10^6 \text{ psi})(.91 \text{ in}^2)} \right] = 13.521 \text{ in}$$

$$(L_{\text{COMPRESSED}}) = 13.516 \text{ in} + 13.521 \text{ in} = 27.457 \text{ in}$$

SPRING CONSTANT FOR STACK:

$$K = \frac{F}{\delta} = \frac{15000 \text{ LB}}{(27.452 \text{ in} - 27.457 \text{ in})} = 1,000,000 \text{ LB/in}$$

COMPRESSION DATA FOR SEVERAL STACK TESTS WITH DIFFERENT PEN PATTERNS AND STEEL INDICATE:

$$(400,000 \frac{\text{LB}}{\text{in}}) < k < (500,000 \frac{\text{LB}}{\text{in}})$$

ASSUME, FOR THIS ANALYSIS:

$$k = 400,000 \frac{\text{LB}}{\text{in}}$$

$$(L_{\text{COMPRESSED}})_{\text{PLATES STRAPS}} = 27.452 \text{ in} - \frac{15,000 \text{ LB}}{400,000 \frac{\text{LB}}{\text{in}}} = 27.414 \text{ in}$$

ACCEPTED!!!

$$(L_{\text{UNSTRESSED}})_{\text{STRAPS}} = 27.414 \text{ in}$$

AREA OF STRAPS

$$(2) [(4 \text{ in})(.262 \text{ in}) + (3 \text{ in})(.075 \text{ in})] +$$

$$(2) [(2.875 \text{ in})(.262 \text{ in}) + (1.625 \text{ in})(.075 \text{ in})] = 4.296 \text{ in}^2$$

$$K_{\text{STRAPS}} = \frac{F \cdot A}{L}$$

$$K_{\text{STRAPS}} = \frac{(28.3 \times 10^6 \text{ psi})(4.296 \text{ in}^2)}{27.374 \text{ in}} = 4,441,000 \frac{\text{LB}}{\text{in}}$$

FIND FINAL STATE OF STRESS AFTER INCLUDING THE PRE-LOADING FORCE

$$\delta_{\text{PLATES \& PINS}} = \frac{F_{\text{PLATES \& PINS}}}{K_{\text{PLATES \& PINS}}}$$

$$\delta_{\text{STRAPS}} = \frac{F_{\text{STRAPS}}}{K_{\text{STRAPS}}}$$

$$\text{LET } F = F_{\text{STRAPS}} = -F_{\text{PLATES \& PINS}}$$

$$\delta_{\text{STRAPS}} - \delta_{\text{PLATES \& PINS}} = 27.452 \text{ in} - 27.414 \text{ in} = .038 \text{ in}$$

COMBINING THE ABOVE:

$$.038 \text{ in} = F \left[\frac{1}{K_{\text{STRAPS}}} + \frac{1}{K_{\text{PLATES \& PINS}}} \right]$$

$$F = \frac{.038 \text{ in}}{\left[\frac{1}{K_{\text{STRAPS}}} + \frac{1}{K_{\text{PLATES \& PINS}}} \right]}$$

$$F = \frac{.038 \text{ in}}{\left[\frac{1}{4,441,000 \frac{\text{LB}}{\text{in}}} + \frac{1}{400,000 \frac{\text{LB}}{\text{in}}} \right]} = 13944 \text{ LB}$$

$$\delta_{\text{PLATES \& PINS}} = \frac{-13944 \text{ LB}}{400,000 \frac{\text{LB}}{\text{in}}} = -.035 \text{ in}$$

$$\delta_{\text{STRAPS}} = \frac{13944 \text{ LB}}{4,441,000 \frac{\text{LB}}{\text{in}}} = .003 \text{ in}$$

CHECK:

$$\delta_{\text{STRAPS}} - \delta_{\text{PLATES \& PINS}} = (.003 \text{ in}) - (-.035 \text{ in}) = .038 \text{ in} \quad \text{OKAY}$$

$$\sigma_{\text{PLATES \& PINS}} = \frac{-13944 \text{ LB}}{.971 \text{ in}^2} = -14360 \text{ psi}$$

$$\sigma_{\text{STRAPS}} = \frac{13944 \text{ LB}}{4.296 \text{ in}^2} = 3246 \text{ psi}$$

CHILL PLATES & PINS TO 250 K, WHILE STRAPS REMAIN AT 293 K:

$$\left(\frac{\Delta L}{L_{293}} \right)_{\text{U}} = -.00097$$

$$\left(\frac{\Delta L}{L_{293}} \right)_{\text{S}} = -.00067$$

$$(L_{\text{UNSTRESSED}})_{\text{U}} = (13.924 \text{ in})(1-.00097) = 13.910 \text{ in}$$

$$(L_{\text{UNSTRESSED}})_{\text{S}} = (13.928 \text{ in})(1-.00067) = 13.519 \text{ in}$$

$$(L_{\text{UNSTRESSED}})_{\text{PLATES \& PINS}} = 13.910 \text{ in} + 13.519 \text{ in} = 27.429 \text{ in}$$

$$(\Delta L)_{\text{THERMAL}} = (27.432 \text{ in}) - (27.429 \text{ in}) = 0.003 \text{ in}$$

$$\delta_{\text{STRAPS}} - \delta_{\text{PLATES \& PINS}} = 27.429 \text{ in} - 27.414 \text{ in} = .015 \text{ in}$$

$$F = \frac{.015 \text{ in}}{\left[\frac{1}{4,441,000 \frac{\text{LB}}{\text{in}^2}} + \frac{1}{400,000 \frac{\text{LB}}{\text{in}^2}} \right]} = 5504 \text{ LB}$$

$$\sigma_{\text{PLATES \& PINS}} = \frac{-5504 \text{ LB}}{.971 \text{ in}^2} = -5668 \text{ psi}$$

$$\sigma_{\text{STRAPS}} = \frac{5504 \text{ LB}}{4.296 \text{ in}^2} = 1281 \text{ psi}$$

CHILL STRAPS TO 250 K, WHILE PLATES & PINS
REMAIN AT 295 K:

$$(L_{\text{UNSTRESSED}})_{\text{STRAPS}} = (27.414 \text{ in}) (1 - .00067) = 27.396 \text{ in}$$

$$\delta_{\text{STRAPS}} - \delta_{\text{PLATES \& PINS}} = 27.452 \text{ in} - 27.396 \text{ in} = .056 \text{ in}$$

$$F = \frac{.056 \text{ in}}{\left[\frac{1}{4,441,000 \frac{\text{LB}}{\text{in}^2}} + \frac{1}{400,000 \frac{\text{LB}}{\text{in}^2}} \right]} = 20549 \text{ LB}$$

$$\sigma_{\text{PINS}} = \frac{-20549 \text{ LB}}{.971 \text{ in}^2} = -21163 \text{ PSI}$$

$$\sigma_{\text{STRAPS}} = \frac{20549 \text{ LB}}{4.286 \text{ in}^2} = 4783 \text{ PSI}$$

USE 45° FOR ZONE OF POSSIBLE DEFORMATION
(SEE KAL PARTIAN 90), AND AVERAGE CROSS-
SECTIONAL AREA

(1) PINS:

$$A = \frac{\frac{\pi}{4} [(0.5)^2 - (.371)^2] + \frac{\pi}{4} [(0.5)^2 - (.128)^2]}{2} = 0.1359 \text{ in}^2$$

$$11(A) = 1.494 \text{ in}^2$$

(2) URANEUM

$$A = \frac{\frac{\pi}{4} [(0.5)^2 - (.371)^2] + \frac{\pi}{4} [(0.736)^2 - (.5)^2]}{2} = 0.1587 \text{ in}^2$$

$$11(A) = 1.745 \text{ in}^2$$

(3) URANEUM

$$A = \frac{\frac{\pi}{4} [(0.5)^2 - (.128)^2] + \frac{\pi}{4} [(0.736)^2 - (.5)^2]}{2} = 0.2063 \text{ in}^2$$

$$11(A) = 2.269 \text{ in}^2$$

(4) SS SURFACE

$$A = \frac{\pi}{4} [(0.5)^2 - (.128)^2] = 0.1835 \text{ in}^2$$

$$11(A) = 2.018 \text{ in}^2$$

(5) SS SURFACE

$$A = \frac{\pi}{4} [(0.5)^2 - (.371)^2] = 0.0882 \text{ in}^2$$

$$11(A) = 0.971 \text{ in}^2$$

Appendix 4

Plots

Data from "Fourth MFH Model, 8-23-88"

Gage #1, Top of Strut, Near Front Plate

Data from "Fourth MFH Model, 8-23-88"

Gage #2, Bottom Strut, Near Front Plate

Data from "Fourth MFH Model, 8-23-88"

Gage #3, O.R. Side Flange, Near Front Plate

Data from "Fourth MFH Model, 8-23-88"

Gage #4, O.R. /Strut Connection (Front)

Data from "Fourth MFH Model, 8-23-88"

Gage #5, O.R./Strut Connection (Back)

Data from "Fourth MFH Model, 8-23-88"

Gage #6, Top of Strut, Near Front Plate

Data from "Fourth MFH Model, 8-23-88"

Gage #7, Bottom Strut, Near Front Plate

Data from "Fourth MFH Model, 8-23-88"

Gage #8, O.R. Side Flange, Near Front Plate

Data from "Fourth MFH Model, 8-23-88"

Gage #9, O.R./Strut Connection (Front)

Data from "Fourth MFH Model, 8-23-88"

Gage #10, O.R./Strut Connection (Back)

Fourth MFH Model, Tested 8-23-88

MFH Fourth Model, Tested August 23, 1988

Spring Constant of Stack (Above 5000 lb)

$$y = -2.037e+4 + 3.979e+5x \quad R = 1.00$$

Appendix 5

Data

MFH Fourth Model Test, August 23, 1988

Dial Indicator Readings (W/2500 lb of Bricks)					Deflections (W/2500 lb of Bricks)					
Jack Force (lb)	North Ctr (in)	North Tip (in)	South Ctr (in)	South Tip (in)	North Ctr (in)	North Tip (in)	South Ctr (in)	South Tip (in)	Average Ctr (in)	Average Tip (in)
0	0.223	0.475	0.222	0.475	-0.005	-0.010	-0.004	-0.009	-0.004	-0.010
1800	0.218	0.465	0.218	0.466	0.000	0.000	0.000	0.000	0.000	0.000
3000	0.216	0.460	0.216	0.461	0.002	0.005	0.002	0.005	0.002	0.005
4500	0.212	0.453	0.212	0.454	0.006	0.012	0.006	0.012	0.006	0.012
5500	0.210	0.448	0.209	0.448	0.008	0.017	0.009	0.018	0.009	0.018
6000	0.209	0.445	0.207	0.445	0.009	0.020	0.011	0.021	0.010	0.021
5500	0.211	0.452	0.209	0.449	0.008	0.013	0.009	0.018	0.008	0.015
4500	0.213	0.457	0.212	0.454	0.006	0.008	0.006	0.012	0.006	0.010
3000	0.216	0.464	0.216	0.462	0.002	0.001	0.002	0.005	0.002	0.003
1800	0.220	0.471	0.219	0.467	-0.002	-0.005	-0.001	-0.001	-0.001	-0.003
0	0.223	0.478	0.222	0.474	-0.005	-0.013	-0.004	-0.008	-0.004	-0.011
1800	0.219	0.469	0.218	0.465	-0.001	-0.004	0.000	0.001	-0.001	-0.002
3000	0.216	0.463	0.215	0.459	0.002	0.002	0.003	0.007	0.003	0.005
4500	0.213	0.456	0.211	0.452	0.005	0.009	0.007	0.014	0.006	0.012
5500	0.210	0.452	0.208	0.446	0.008	0.014	0.010	0.020	0.009	0.017
6000	0.209	0.449	0.206	0.444	0.009	0.016	0.012	0.023	0.011	0.019
5500	0.211	0.448	0.209	0.453	0.007	0.017	0.009	0.014	0.008	0.015
4500	0.213	0.457	0.211	0.453	0.005	0.008	0.007	0.013	0.006	0.011
3000	0.217	0.465	0.216	0.461	0.002	0.000	0.002	0.005	0.002	0.003
1800	0.219	0.471	0.218	0.466	-0.001	-0.005	0.000	0.000	-0.001	-0.003
0	0.223	0.478	0.222	0.474	-0.005	-0.013	-0.004	-0.008	-0.005	-0.011

MFH Fourth Model Test, August 23, 1988

Stack Compression						
Bag Pressure (psi)	Bag Force (lb)	IRR (in)	IRL (in)	OPR (in)	ORL (in)	Average (in)
0	0	0.000	0.000	0.000	0.000	0.000
5	1250	0.045	0.012	0.029	0.027	0.028
10	2500	0.058	0.024	0.070	0.047	0.050
15	3750	0.066	0.028	0.077	0.056	0.057
20	5000	0.073	0.034	0.082	0.062	0.063
25	6250	0.079	0.038	0.085	0.065	0.067
30	7500	0.084	0.041	0.089	0.068	0.071
35	8750	0.090	0.043	0.091	0.071	0.074
40	10000	0.092	0.046	0.094	0.073	0.076
45	11250	0.096	0.047	0.097	0.076	0.079
50	12500	0.101	0.050	0.098	0.078	0.082
55	13750	0.104	0.057	0.101	0.080	0.086
Welded (0.022" Expansion)						
10	2500	0.059	0.031	0.073	0.052	0.054
After Welding W/O Bag						
0	7500	0.079	0.045	0.092	0.068	0.071

MFH Fourth Model Test, August 23, 1988

Pre-Load Stress (Before and After Bag Removal)

	Measured Strains (x10e6)	Measured Strains (x10e6)	Adjust for Drift (x10e6)	Adjusted Strain (x10e6)	Stress Intensity (psi)	Max Princ Stress (psi)	Min Princ Stress (psi)	Theta (degrees)	Maximum Shear (psi)	X-Dir Stress (psi)	Y-Dir Stress (psi)	XY Shear (psi)
E = 28300000 v = 0.3												
# 1	141	143		- 2								
Truss gage top	-198	-188		-10	428	146	-281	44.0	214	-60	-75	214
near front pl.	164	157		7								
# 2	343	310		33								
Truss gage bot	-203	-199		- 4	1007	1007	71	-11.9	468	967	111	-189
near front pl.	198	187		11								
# 3	-29	-15		-14								
O.R. side flange	18	7		11	686	154	-532	-26.8	343	15	-392	-277
near front pl.	-38	-27		-11								
# 4	194	186		8								
O.R. Truss	175	148		27	869	869	344	-27.3	262	759	454	-214
Joint (Front)	239	229		10								
# 5	273	254		19								
O.R. Truss	233	196		37	1230	1230	494	-41.0	368	913	812	-364
Joint (Back)	22	14		8								
# 6	550	557		- 7								
Truss gage top	-95	-96		1	236	-33	-236	-19.1	102	-55	-215	-63
near front pl.	137	141		- 4								
# 7	- 9	-26		17								
Truss gage bot	-24	-26		2	485	485	0	4.5	242	482	3	38
near front pl.	55	56		- 1								
# 8	46	39		7								
O.R. side flange	-11	1		-12	809	607	-202	-41.9	405	246	159	-402
near front pl.	7	-13		20								
# 9	319	319		0								
O.R. Truss	159	159		0	726	700	-26	30.0	363	518	155	314
Joint (Front)	174	149		25								
# 10	303	286		17								
O.R. Truss	202	188		14	1398	1398	596	32.7	401	1164	830	364
Joint (Back)	216	173		43								

MFH Fourth Model Test, August 23, 1988

Stress Intensity Summary, Set 1/Set 2

Jack Force	0 (lb)	1800 (lb)	3000 (lb)	4500 (lb)	5500 (lb)	6000 (lb)	5500 (lb)	4500 (lb)	3000 (lb)	1800 (lb)	0 (lb)
# 1											
Truss gage top	952	3198	5328	7952	9796	10647	9032	7187	4476	2117	944
near front pl.	944	2942	5164	7860	9860	10818	9258	7649	4706	2521	915
# 2											
Truss gage bot	2299	5250	7222	9681	11678	12363	11182	9522	7057	4935	2751
near front pl.	2751	5631	7579	10007	11825	12676	11312	9910	7259	5341	2803
# 3											
O.R. side flange	2001	2630	3083	3639	4127	4428	4146	3764	3210	2765	2309
near front pl.	2309	2933	3302	3876	4198	4444	4150	3838	3257	2849	2300
# 4											
O.R. Truss	3255	2336	4553	7919	9779	10501	9216	7447	4551	2510	2876
Joint (Front)	2876	3148	5055	8102	9932	10691	9419	7927	4788	2954	2858
# 5											
O.R. Truss	1785	3944	6730	11437	14852	16366	14125	11006	6273	3128	1810
Joint (Back)	1810	4043	7107	11981	15212	16704	14680	12071	6837	3793	1890
# 6											
Truss gage top	3079	514	2026	4684	6446	7314	5909	4164	1587	752	2948
near front pl.	2948	264	1977	4494	6315	7215	5820	4383	1606	448	2922
# 7											
Truss gage bot	1007	1465	2952	5182	6708	7552	6327	4997	2725	1216	930
near front pl.	930	1626	3085	5099	6674	7523	6276	5099	2822	1405	900
# 8											
O.R. side flange	1875	2533	3911	5633	6795	7308	6484	5290	3317	2028	2085
near front pl.	2085	2331	3568	5374	6522	7097	6236	5282	3270	2107	2050
# 9											
O.R. Truss	4951	1312	3675	6991	9006	9970	8856	7230	4287	2171	4421
Joint (Front)	4421	2436	4710	7464	9124	10018	8803	7399	4368	2261	4372
# 10											
O.R. Truss	5046	1618	2608	5790	8209	9353	7502	5133	1772	1997	5078
Joint (Back)	5078	1577	2182	5562	8001	9277	7390	5468	1838	1739	5029

GAGE IN FRONT
O.M. STRUT;
PRE-LOAD ONLY

11-11-88

KAP

1

GAGE #

σ_i (psi)

1	428
2	1007
6	236
7	485

MEMBRANE STRESS

$$\sigma_m = \frac{428 + 1007}{2} = 717 \text{ psi}$$

$$\sigma_m = \frac{236 + 485}{2} = 360 \text{ psi}$$

BENDING UNDER GAGE

$$\sigma_b = 1007 \text{ psi} - 717 \text{ psi} = 290 \text{ psi}$$

$$\sigma_b = 485 \text{ psi} - 360 \text{ psi} = 125 \text{ psi}$$

BENDING EXTRAPOLATED TO EXTREME FIBER:

$$\sigma_b' = (290 \text{ psi}) \left(\frac{1.125''}{.625''} \right) = 522 \text{ psi}$$

$$\sigma_b' = (125 \text{ psi}) \left(\frac{1.125''}{.625''} \right) = 225 \text{ psi}$$

WORST CASE MEMBRANE PLUS BENDING:

$$\sigma_{m+b} = 717 \text{ psi} + 522 \text{ psi} = 1239 \text{ psi}$$

TAKING LARGER VALUE FROM SET 1 OR 2 @ 6000 LB

GAGE #	σ_i (psi)
1	10818
2	12676
6	7314
7	7552

MEMBRANE STRESS

$$\sigma_m = \frac{10818 + 12676}{2} = \underline{\underline{11747 \text{ psi}}}$$

$$\sigma_m = \frac{7314 + 7552}{2} = 7433 \text{ psi}$$

BENDING UNDER GAGE:

$$\sigma_B = 12676 \text{ psi} - 11747 \text{ psi} = 929 \text{ psi}$$

$$\sigma_B = 7552 \text{ psi} - 7433 \text{ psi} = 119 \text{ psi}$$

BENDING EXTRAPOLATED TO EXTREME FIBER

$$\sigma_{B'} = (929 \text{ psi}) \left(\frac{1.125''}{.625''} \right) = 1672 \text{ psi}$$

$$\sigma_{B'} = (119 \text{ psi}) \left(\frac{1.125''}{.625''} \right) = 214 \text{ psi}$$

WORST CASE MEMBRANE PLUS BENDING:

$$\sigma_{M+B} = 11747 \text{ psi} + 1672 \text{ psi} = \underline{\underline{13419 \text{ psi}}}$$

TAKING THE LARGER VALUE FROM SET 1 OR 2 @ 6000 LB:

GAGE #	σ_{SI} (psi)
4	10691
5	16704
9	10018
10	9353

USING σ_{SI} IS VERY SIMPLISTIC SINCE THE PRINCIPAL AXES ARE NOT ORIENTATED AS NECESSARY AS IN THE CASE OF THE STRUT. HOWEVER, THIS APPROACH SHOULD YIELD CONSERVATIVE RESULTS

MEMBRANE STRESS

$$\sigma_m = \frac{10691 + 16704}{2} = \underline{\underline{13698 \text{ psi}}}$$

$$\sigma_m = \frac{10018 + 9353}{2} = 9686 \text{ psi}$$

"BENDING" UNDER GAGE

$$\sigma_b = 16704 - 13698 = 3006 \text{ psi}$$

$$\sigma_b = 10018 - 9686 = 332 \text{ psi}$$

BENDING EXTRAPOLATED TO EXTREME FIBER

$$\sigma'_b = (3006 \text{ psi}) \left(\frac{2.25''}{1.125''} \right) = 6012 \text{ psi}$$

$$\sigma'_b = (332 \text{ psi}) \left(\frac{2.25''}{1.125''} \right) = 662 \text{ psi}$$

WORST CASE MEMBRANE + BENDING

$$\sigma_{m+b} = 13698 \text{ psi} + 6012 \text{ psi} = \underline{\underline{19710 \text{ psi}}}$$

TAKING THE LARGER VALUE FROM SET 1 OR 2 @ 6000 LB

GAGE #

σ_{ss} (psi)

3

4444

8

7308

USING σ_{ss} IS VERY SIMPLISTIC SINCE THE PRINCIPLE AXIS DID NOT LIE NEAR THE X-AXIS; HOWEVER, THIS APPROACH SHOULD YIELD CONSERVATIVE RESULTS.

FROM ICEA (SIN) $\rho = .2219$

ASSUME $\sigma_{MEMBRANE} = 0$

BENDING STRESS EXTRAPOLATED TO EXTREME FIBER:

$$\sigma_{B'} = (4444 \text{ psi}) \left(\frac{1.372''}{.872''} \right) = 6992 \text{ psi}$$

$$\sigma_{B''} = (7308 \text{ psi}) \left(\frac{1.372''}{.872''} \right) = 11498 \text{ psi}$$

SO WORST CASE MEMBRANE + BENDING

$$\sigma_{M+B} = \underline{\underline{11,498 \text{ psi}}}$$