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1. Introduction

Over the last several years, calculations have been performed to find the forces that are acting between modules and on the support saddles in the EB. This paper examines these forces and calculates the stresses in the connections between modules. In the Tile Calorimeter, the modules are only connected at three points. First, at the inner radius there is a bearing connection to support the force in the phi direction. Second, at the outer radius there is a bearing connection in the phi direction and, finally, there is a bolted connection designed to withstand the radial load. Each of these connections will be examined separately.

2. FEA Model

An extensive three-dimensional FEA model was created, which modeled the connections between modules, the girder, submodules and the connection to the girder, the connections between the modules and the support saddles, and the support saddles. Out of this analysis, the forces between modules have been extracted. Details of this analysis can be found in ANL Technical Report # ANL-HEP-TR-01-097, "Extended Barrel Support Saddle Design and Analysis". The largest forces between modules were found in load case C4 which had the following characteristics:

- The weight of the EB and cryostat was increased by 35% per Eurocode.
- A seismic load in the X- and Z-direction of .15g was applied.
- The magnetic load was applied and increased by 35% per Eurocode.
- The EB was supported on the hydraulic jacks.
- Module #'s begin at 1 at the 6 o'clock position and move counterclockwise

3. Forces Between Modules

The forces between modules are listed below for the front, middle, and back of the EB for the load case described above. Force P1 is the bearing force at the inner radius, force P2 is the bearing force at the outer radius, and force Pt is the radial force at the outer radius. The modules are numbered so that when the EB is viewed from the IP, module #1 is at the bottom (6 o'clock position) and the module #'s move in a counter clockwise direction, i.e. module 32 is at 3 o'clock.

Forces at the Front (N/mm)

Module #	P1	P2	Pt
2	680.00	1340.00	-350.00
3	705.00	1360.00	-362.00
4	761.00	1420.00	-396.00
5	865.00	1570.00	-403.00
6	1110.00	1640.00	488.00
7	1450.00	-2540.00	-171.00
8	1760.00	-2020.00	780.00
9	1910.00	-1550.00	1240.00
10	2190.00	-1160.00	1610.00
11	2620.00	-847.00	1670.00
12	783.00	-623.00	748.00
13	975.00	-429.00	560.00
14	1110.00	-274.00	391.00
15	1180.00	-148.00	208.00
16	1190.00	-45.90	76.00
17	1160.00	38.50	-43.80
18	1110.00	108.00	-147.00
19	1030.00	165.00	-246.00
20	934.00	210.00	-348.00
21	818.00	245.00	-408.00
22	696.00	273.00	-448.00
23	567.00	295.00	-497.00
24	437.00	313.00	-493.00
25	318.00	329.00	-477.00
26	215.00	347.00	-446.00
27	129.00	366.00	-415.00
28	59.60	388.00	-392.00
29	11.20	414.00	-335.00
30	0.00	448.00	-267.00
31	0.00	493.00	-218.00
32	0.00	549.00	-129.00
33	0.00	597.00	-38.70
34	0.00	597.00	52.10
35	0.00	564.00	127.00
36	0.00	504.00	178.00
37	0.00	450.00	248.00
38	2.30	406.00	312.00
39	31.60	370.00	341.00
40	84.50	339.00	395.00

41	164.00	312.00	433.00
42	261.00	287.00	457.00
43	371.00	261.00	453.00
44	479.00	231.00	412.00
45	581.00	196.00	379.00
46	678.00	153.00	331.00
47	757.00	102.00	239.00
48	810.00	37.00	166.00
49	836.00	-41.70	73.10
50	816.00	-137.00	-50.90
51	727.00	-258.00	-190.00
52	548.00	-412.00	-369.00
53	2680.00	-647.00	-1060.00
54	2260.00	-804.00	-849.00
55	1980.00	-931.00	-110.00
56	1830.00	-1160.00	456.00
57	1710.00	-1610.00	-21.70
58	1490.00	2520.00	-438.00
59	1250.00	2330.00	-376.00
60	1070.00	2020.00	-384.00
61	936.00	1800.00	-371.00
62	839.00	1620.00	-360.00
63	767.00	1500.00	-378.00
64	712.00	1420.00	-363.00

Force at the Middle (N/mm)			
Module #	**P1**	**P2**	**Pt**
2	354.00	948.00	-247.00
3	281.00	882.00	-257.00
4	199.00	785.00	-281.00
5	110.00	620.00	-269.00
6	37.80	184.00	-16.50
7	0.00	-346.00	-3.90
8	0.00	-434.00	413.00
9	28.60	-409.00	706.00
10	186.00	-317.00	917.00
11	364.00	-203.00	907.00
12	522.00	-110.00	596.00
13	624.00	-36.90	485.00
14	697.00	29.40	378.00

15	744.00	85.10	249.00
16	766.00	130.00	169.00
17	772.00	167.00	91.70
18	763.00	196.00	23.00
19	740.00	219.00	-52.00
20	702.00	231.00	-136.00
21	652.00	235.00	-182.00
22	594.00	234.00	-217.00
23	528.00	227.00	-269.00
24	457.00	215.00	-269.00
25	387.00	203.00	-263.00
26	318.00	191.00	-248.00
27	251.00	180.00	-241.00
28	185.00	166.00	-245.00
29	122.00	152.00	-213.00
30	65.50	140.00	-178.00
31	8.25	130.00	-164.00
32	0.00	120.00	-105.00
33	0.00	116.00	-49.20
34	0.00	117.00	6.47
35	0.00	119.00	45.50
36	0.00	123.00	62.80
37	33.70	127.00	105.00
38	72.30	135.00	142.00
39	120.00	142.00	146.00
40	173.00	148.00	184.00
41	234.00	156.00	209.00
42	299.00	164.00	225.00
43	366.00	172.00	216.00
44	430.00	175.00	176.00
45	489.00	171.00	155.00
46	546.00	164.00	123.00
47	595.00	149.00	52.20
48	636.00	127.00	12.90
49	670.00	99.40	-41.70
50	692.00	67.40	-120.00
51	699.00	26.90	-208.00
52	683.00	-20.30	-324.00
53	619.00	-89.80	-503.00
54	567.00	-128.00	-294.00
55	554.00	-107.00	-94.50
56	576.00	-37.50	53.00
57	613.00	98.50	-15.60

58	633.00	510.00	-111.00
59	637.00	947.00	-155.00
60	627.00	1040.00	-189.00
61	605.00	1080.00	-196.00
62	574.00	1080.00	-208.00
63	532.00	1070.00	-248.00
64	479.00	1040.00	-246.00

Forces at the Back (N/mm)

Module #	P1	P2	Pt
2	390.00	744.00	-127.00
3	309.00	791.00	-144.00
4	212.00	863.00	-169.00
5	100.00	951.00	-161.00
6	2.92	933.00	-236.00
7	0.00	241.00	-240.00
8	0.00	195.00	-326.00
9	0.00	150.00	-362.00
10	18.50	166.00	-149.00
11	125.00	198.00	45.90
12	278.00	224.00	378.00
13	367.00	224.00	353.00
14	447.00	224.00	321.00
15	513.00	225.00	264.00
16	563.00	222.00	242.00
17	605.00	218.00	217.00
18	638.00	210.00	191.00
19	658.00	198.00	150.00
20	662.00	184.00	94.50
21	650.00	164.00	66.70
22	630.00	140.00	39.50
23	598.00	114.00	-6.49
24	557.00	83.70	-12.60
25	516.00	51.20	-17.90
26	476.00	15.70	-22.10
27	435.00	-23.30	-38.20
28	388.00	-64.30	-66.90
29	337.00	-111.00	-67.80
30	290.00	-165.00	-68.20
31	242.00	-224.00	-88.40

32	158.00	-293.00	-70.30
33	15.60	-350.00	-54.20
34	0.00	-351.00	-40.70
35	61.70	-318.00	-42.10
36	190.00	-251.00	-58.20
37	215.00	-190.00	-50.50
38	241.00	-139.00	-45.90
39	265.00	-92.10	-64.90
40	288.00	-51.70	-49.60
41	315.00	-14.70	-39.20
42	344.00	18.50	-33.80
43	371.00	48.00	-46.30
44	388.00	75.50	-77.40
45	393.00	98.40	-86.50
46	392.00	116.00	-100.00
47	378.00	131.00	-138.00
48	350.00	143.00	-141.00
49	316.00	152.00	-150.00
50	272.00	158.00	-173.00
51	216.00	158.00	-199.00
52	145.00	158.00	-238.00
53	23.80	175.00	127.00
54	0.00	281.00	891.00
55	0.00	269.00	371.00
56	32.80	325.00	138.00
57	137.00	446.00	107.00
58	274.00	404.00	140.00
59	409.00	671.00	103.00
60	497.00	672.00	45.50
61	544.00	665.00	9.68
62	562.00	665.00	-28.00
63	550.00	674.00	-85.50
64	512.00	687.00	-102.00

4. Inner Radius Bearing Connection

The bearing stress on the inner radius weld bars has been calculated and is shown in the table below. A 5mm wide bearing area of the weld bar is used in this calculation. The force P1, which is the force per unit length, given above, was used in this calculation.

Front Plate Bearing Stress (MPa)
(P1/5mm)

Module #	Front	Middle	Back
2	136.00	70.80	78.00
3	141.00	56.20	61.80
4	152.20	39.80	42.40
5	173.00	22.00	20.00
6	222.00	7.56	0.58
7	290.00	0.00	0.00
8	352.00	0.00	0.00
9	382.00	5.72	0.00
10	438.00	37.20	3.70
11	524.00	72.80	25.00
12	156.60	104.40	55.60
13	195.00	124.80	73.40
14	222.00	139.40	89.40
15	236.00	148.80	102.60
16	238.00	153.20	112.60
17	232.00	154.40	121.00
18	222.00	152.60	127.60
19	206.00	148.00	131.60
20	186.80	140.40	132.40
21	163.60	130.40	130.00
22	139.20	118.80	126.00
23	113.40	105.60	119.60
24	87.40	91.40	111.40
25	63.60	77.40	103.20
26	43.00	63.60	95.20
27	25.80	50.20	87.00
28	11.92	37.00	77.60
29	2.24	24.40	67.40
30	0.00	13.10	58.00
31	0.00	1.65	48.40
32	0.00	0.00	31.60
33	0.00	0.00	3.12
34	0.00	0.00	0.00
35	0.00	0.00	12.34
36	0.00	0.00	38.00
37	0.00	6.74	43.00
38	0.46	14.46	48.20
39	6.32	24.00	53.00
40	16.90	34.60	57.60

41	32.80	46.80	63.00
42	52.20	59.80	68.80
43	74.20	73.20	74.20
44	95.80	86.00	77.60
45	116.20	97.80	78.60
46	135.60	109.20	78.40
47	151.40	119.00	75.60
48	162.00	127.20	70.00
49	167.20	134.00	63.20
50	163.20	138.40	54.40
51	145.40	139.80	43.20
52	109.60	136.60	29.00
53	536.00	123.80	4.76
54	452.00	113.40	0.00
55	396.00	110.80	0.00
56	366.00	115.20	6.56
57	342.00	122.60	27.40
58	298.00	126.60	54.80
59	250.00	127.40	81.80
60	214.00	125.40	99.40
61	187.20	121.00	108.80
62	167.80	114.80	112.40
63	153.40	106.40	110.00
64	142.40	95.80	102.40

The largest bearing stresses occur in the front of the EB in the modules that are directly below the cryostat load. These bearing stresses approach 536MPa in modules interface 53-54 and 11-12, which exceeds the ultimate stress of the weld bar material. An acceptable limit of the bearing stress is less than 240 MPa. Using this as a criteria, module interfaces 5-6, 6-7, 7-8, 8-9, 9-10, 10-11, 11-12 and 53-54, 54-55, 55-56, 56-57, 57-58, 58-59, 59-60 will need to have extra bearing material placed between the modules in order to distribute the bearing force at the inner radius onto the master plates.

Earlier tests on the ability of the front plate to withstand the bearing load at the inner radius have shown that plastic deformation of the front plate occurs when a bearing load of 38tons is applied to a submodule (1694 N/mm). Failure of the welds and the front plate occurred in these tests at a maximum load of 85 tons applied to three modules (3,789 N/mm). In these tests the entire bearing load was transferred through the front plate. In the back and middle of the EB, no modules have a force P1, which exceeds the yield load. In the front of the EB, however, modules 9-10, 10-11, 11-12, 12-13 and 54-55, 55-56, 56-57, 57-58, 58-59 exceed the yield load.

5. Connections Between Modules at the Outer Radius

The modules are connected together at their outer radius by a series of connecting plates. The details of this connection and the forces acting on it are shown in Fig. 1. M30 bolts and 33mm diameter pins must resist tension and shearing forces at the outer radius. At the bottom of the extended barrel, the bearing force, P2, results in tension between the modules. This is resisted by replacing a portion of the M30 bolts with 33mm diameter pins in modules 1-6 and 58-64. At the very top of the extended barrel, the bearing force, P2, is also tension, however, this is much smaller than at the bottom so it will be resisted by generating a friction force by the M30 bolts. In the remainder of the detector, the bearing force, P2, is compression and this is resisted by the bearing surface between the outer radiuses of the modules.

5.1 Bearing Force at Outer Radius

The bearing force at the outer radius, P2, is distributed over a 37.5mm thick plate on the outer radius of the girder. Therefore, the bearing stress can be simply calculated as P2/37.5mm and is listed in the table below. The positions that are blank are in tension and the force P2 in those locations are carried by a 33mm diameter pin below the saddle or friction above the saddle. It can be seen in the table below that the bearing stresses are all small and within acceptable limits.

Bearing Stress and their location at the Outer Radius

Module #	Front	Middle	Back
7	-67.73	-9.23	Tension
8	-53.87	-11.57	Tension
9	-41.33	-10.91	Tension
10	-30.93	-8.45	Tension
11	-22.59	-5.41	Tension
12	-16.61	-2.93	Tension
13	-11.44	-0.98	Tension
14	-7.31	Tension	Tension
15	-3.95	Tension	Tension
16	-1.22	Tension	Tension
27	Tension	Tension	-0.62
28	Tension	Tension	-1.71
29	Tension	Tension	-2.96
30	Tension	Tension	-4.40
31	Tension	Tension	-5.97
32	Tension	Tension	-7.81
33	Tension	Tension	-9.33
34	Tension	Tension	-9.36
35	Tension	Tension	-8.48

36	Tension	Tension	-6.69
37	Tension	Tension	-5.07
38	Tension	Tension	-3.71
39	Tension	Tension	-2.46
40	Tension	Tension	-1.38
41	Tension	Tension	-0.39
49	-1.11	Tension	Tension
50	-3.65	Tension	Tension
51	-6.88	Tension	Tension
52	-10.99	-0.54	Tension
53	-17.25	-2.39	Tension
54	-21.44	-3.41	Tension
55	-24.83	-2.85	Tension
56	-30.93	-1.00	Tension
57	-42.93	Tension	Tension

5.2 Tension Connection at the Outer Radius

The tension force, P2, at the outer radius will be carried by 33mm diameter pins in the modules below the saddle (module #'s 1-6 and 58-64) and by friction throughout the remainder of the EB.

The length of the module that a given set of 2 pins carries the force is 350mm. According to EUROCODE 3, chapter 6.5, the maximum design load on the pin connection is the minimal of

$$Fv = \frac{0.6 \bullet fur \bullet A}{yMr}$$

$$Fb = \frac{2.5 \bullet a \bullet fu \bullet do \bullet t}{yMr}$$

where

A = pin section
Fv = shear resistance per shear plane
fur = ultimate tensile strength of the pin
yMr = safety factor (1.25)
Fb = Bearing resistance
fu = ultimate tensile strength of the basis material
do = diameter of the pin hole

t = plate thickness
a = parameter (see ENV 1993-1-1, p.156)

Applying the above-mentioned formulas, we get the values:

Fv = 492 KN; Fb = 355 kN.

Thus, the design load per pin is 355 kN. A set of pins is 710 kN, which is equivalent to 2,028 N/mm (710kN/350mm). The force P2 is below this value everywhere except at the front at modules interface 58-59 and 59-60, which have the values of 2,520 N/mm and 2330 N/mm, respectively.

5.3 Tension Connection Carried by Friction

In modules #7 to 57, the tension force at the outer radius, P2, is carried by friction. The maximum tension force in these modules occurs at the front of module #33 and is 597 N/mm. Using a coefficient of friction of .2, a normal force of 2,985 N/mm can be calculated to be needed for this friction force. There are two bolts for every 175mm of length, so the normal force per bolt is

Fbolt = [(2,985 N/mm) * 175mm] / 2 = 261 kN.

The resulting normal force in the bolt is Fbolt / Area = 261 kN / 539mm^2 = 484MPa. Using a safety factor of 1.5 yields a pre-stress of 726. Therefore, a pre-stress must be applied to every bolt of 726 MPa in order to achieve the required friction force.

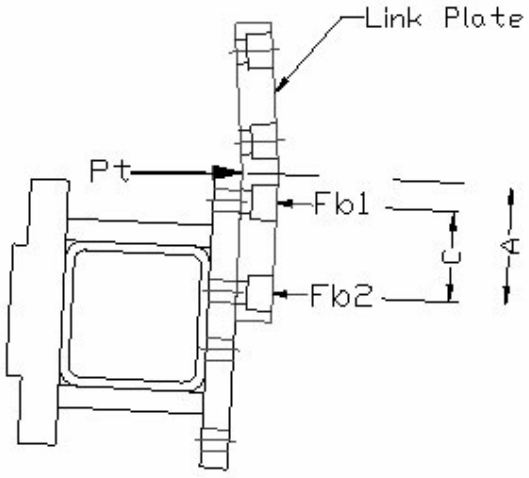

Figure 1. Forces Acting on Connecting Plate.

5.4 Calculation of the Girder/Link Plate Bolt Stresses

At a given connection between modules, the force, Pt, is resisted as shown in Fig. 1. Solving for the forces on the bolts we find

$$F_{b1} = \frac{P_t \bullet L \bullet A}{C}$$

$$F_{b2} = (P_t \bullet L) \bullet \left(1 - \frac{A}{C}\right)$$

A = 165mm
C = 125mm

Pt is a force distributed over the length of the module in Z. L is the length of the module that a given bolt is acting upon, on average; this is one bolt per 175mm in modules 7-57 and 350mm in modules 1-6 and 58-64.

Link Plate Bolt Forces (N)

	Fb1			Fb2		
Module #	Front	Middle	Back	Front	Middle	Back
2	-151,200	-106,704	-54,864	39,200	27,664	14,224
3	-156,384	-111,024	-62,208	40,544	28,784	16,128
4	-171,072	-121,392	-73,008	44,352	31,472	18,928
5	-174,096	-116,208	-69,552	45,136	30,128	18,032
6	210,816	-7,128	-101,952	-54,656	1,848	26,432
7	-39,501	-901	-55,440	9,576	218	13,440
8	180,180	95,403	-75,306	-43,680	-23,128	18,256
9	286,440	163,086	-83,622	-69,440	-39,536	20,272
10	371,910	211,827	-34,419	-90,160	-51,352	8,344
11	385,770	209,517	10,603	-93,520	-50,792	-2,570
12	172,788	137,676	87,318	-41,888	-33,376	-21,168
13	129,360	112,035	81,543	-31,360	-27,160	-19,768
14	90,321	87,318	74,151	-21,896	-21,168	-17,976
15	48,048	57,519	60,984	-11,648	-13,944	-14,784
16	17,556	39,039	55,902	-4,256	-9,464	-13,552
17	-10,118	21,183	50,127	2,453	-5,135	-12,152
18	-33,957	5,313	44,121	8,232	-1,288	-10,696
19	-56,826	-12,012	34,650	13,776	2,912	-8,400
20	-80,388	-31,416	21,830	19,488	7,616	-5,292
21	-94,248	-42,042	15,408	22,848	10,192	-3,735
22	-103,488	-50,127	9,125	25,088	12,152	-2,212
23	-114,807	-62,139	-1,499	27,832	15,064	363

24	-113,883	-62,139	-2,911	27,608	15,064	706
25	-110,187	-60,753	-4,135	26,712	14,728	1,002
26	-103,026	-57,288	-5,105	24,976	13,888	1,238
27	-95,865	-55,671	-8,824	23,240	13,496	2,139
28	-90,552	-56,595	-15,454	21,952	13,720	3,746
29	-77,385	-49,203	-15,662	18,760	11,928	3,797
30	-61,677	-41,118	-15,754	14,952	9,968	3,819
31	-50,358	-37,884	-20,420	12,208	9,184	4,950
32	-29,799	-24,255	-16,239	7,224	5,880	3,937
33	-8,940	-11,365	-12,520	2,167	2,755	3,035
34	12,035	1,495	-9,402	-2,918	-362	2,279
35	29,337	10,511	-9,725	-7,112	-2,548	2,358
36	41,118	14,507	-13,444	-9,968	-3,517	3,259
37	57,288	24,255	-11,666	-13,888	-5,880	2,828
38	72,072	32,802	-10,603	-17,472	-7,952	2,570
39	78,771	33,726	-14,992	-19,096	-8,176	3,634
40	91,245	42,504	-11,458	-22,120	-10,304	2,778
41	100,023	48,279	-9,055	-24,248	-11,704	2,195
42	105,567	51,975	-7,808	-25,592	-12,600	1,893
43	104,643	49,896	-10,695	-25,368	-12,096	2,593
44	95,172	40,656	-17,879	-23,072	-9,856	4,334
45	87,549	35,805	-19,982	-21,224	-8,680	4,844
46	76,461	28,413	-23,100	-18,536	-6,888	5,600
47	55,209	12,058	-31,878	-13,384	-2,923	7,728
48	38,346	2,980	-32,571	-9,296	-722	7,896
49	16,886	-9,633	-34,650	-4,094	2,335	8,400
50	-11,758	-27,720	-39,963	2,850	6,720	9,688
51	-43,890	-48,048	-45,969	10,640	11,648	11,144
52	-85,239	-74,844	-54,978	20,664	18,144	13,328
53	-244,860	-116,193	29,337	59,360	28,168	-7,112
54	-196,119	-67,914	205,821	47,544	16,464	-49,896
55	-25,410	-21,830	85,701	6,160	5,292	-20,776
56	105,336	12,243	31,878	-25,536	-2,968	-7,728
57	-5,013	-3,604	24,717	1,215	874	-5,992
58	-189,216	-47,952	60,480	49,056	12,432	-15,680
59	-162,432	-66,960	44,496	42,112	17,360	-11,536
60	-165,888	-81,648	19,656	43,008	21,168	-5,096
61	-160,272	-84,672	4,182	41,552	21,952	-1,084
62	-155,520	-89,856	-12,096	40,320	23,296	3,136
63	-163,296	-107,136	-36,936	42,336	27,776	9,576
64	-156,816	-106,272	-44,064	40,656	27,552	11,424

The stress in the bolts is

$$\sigma = \frac{F}{A}$$

F = bolt force (Fb1 or Fb2) increased by 25% per Eurocode
A = area of bolt = 539mm^2

The bolt normal stresses are shown in the table below.

Normal Stress in M30 bolts (MPa)
(Bolt Force increased by 25% per Eurocode)

	Fb1			Fb2		
Module #	Front	Middle	Back	Front	Middle	Back
2	-350.65	-247.46	-127.24	90.91	64.16	32.99
3	-362.67	-257.48	-144.27	94.03	66.75	37.40
4	-396.73	-281.52	-169.31	102.86	72.99	43.90
5	-403.75	-269.50	-161.30	104.68	69.87	41.82
6	488.91	-16.53	-236.44	-126.75	4.29	61.30
7	-91.61	-2.09	-128.57	22.21	0.51	31.17
8	417.86	221.25	-174.64	-101.30	-53.64	42.34
9	664.29	378.21	-193.93	-161.04	-91.69	47.01
10	862.50	491.25	-79.82	-209.09	-119.09	19.35
11	894.64	485.89	24.59	-216.88	-117.79	-5.96
12	400.71	319.29	202.50	-97.14	-77.40	-49.09
13	300.00	259.82	189.11	-72.73	-62.99	-45.84
14	209.46	202.50	171.96	-50.78	-49.09	-41.69
15	111.43	133.39	141.43	-27.01	-32.34	-34.29
16	40.71	90.54	129.64	-9.87	-21.95	-31.43
17	-23.46	49.13	116.25	5.69	-11.91	-28.18
18	-78.75	12.32	102.32	19.09	-2.99	-24.81
19	-131.79	-27.86	80.36	31.95	6.75	-19.48
20	-186.43	-72.86	50.63	45.19	17.66	-12.27
21	-218.57	-97.50	35.73	52.99	23.64	-8.66
22	-240.00	-116.25	21.16	58.18	28.18	-5.13
23	-266.25	-144.11	-3.48	64.55	34.94	0.84
24	-264.11	-144.11	-6.75	64.03	34.94	1.64
25	-255.54	-140.89	-9.59	61.95	34.16	2.32
26	-238.93	-132.86	-11.84	57.92	32.21	2.87
27	-222.32	-129.11	-20.46	53.90	31.30	4.96
28	-210.00	-131.25	-35.84	50.91	31.82	8.69
29	-179.46	-114.11	-36.32	43.51	27.66	8.81
30	-143.04	-95.36	-36.54	34.68	23.12	8.86
31	-116.79	-87.86	-47.36	28.31	21.30	11.48
32	-69.11	-56.25	-37.66	16.75	13.64	9.13
33	-20.73	-26.36	-29.04	5.03	6.39	7.04
34	27.91	3.47	-21.80	-6.77	-0.84	5.29

35	68.04	24.38	-22.55	-16.49	-5.91	5.47
36	95.36	33.64	-31.18	-23.12	-8.16	7.56
37	132.86	56.25	-27.05	-32.21	-13.64	6.56
38	167.14	76.07	-24.59	-40.52	-18.44	5.96
39	182.68	78.21	-34.77	-44.29	-18.96	8.43
40	211.61	98.57	-26.57	-51.30	-23.90	6.44
41	231.96	111.96	-21.00	-56.23	-27.14	5.09
42	244.82	120.54	-18.11	-59.35	-29.22	4.39
43	242.68	115.71	-24.80	-58.83	-28.05	6.01
44	220.71	94.29	-41.46	-53.51	-22.86	10.05
45	203.04	83.04	-46.34	-49.22	-20.13	11.23
46	177.32	65.89	-53.57	-42.99	-15.97	12.99
47	128.04	27.96	-73.93	-31.04	-6.78	17.92
48	88.93	6.91	-75.54	-21.56	-1.68	18.31
49	39.16	-22.34	-80.36	-9.49	5.42	19.48
50	-27.27	-64.29	-92.68	6.61	15.58	22.47
51	-101.79	-111.43	-106.61	24.68	27.01	25.84
52	-197.68	-173.57	-127.50	47.92	42.08	30.91
53	-567.86	-269.46	68.04	137.66	65.32	-16.49
54	-454.82	-157.50	477.32	110.26	38.18	-115.71
55	-58.93	-50.63	198.75	14.29	12.27	-48.18
56	244.29	28.39	73.93	-59.22	-6.88	-17.92
57	-11.63	-8.36	57.32	2.82	2.03	-13.90
58	-438.81	-111.21	140.26	113.77	28.83	-36.36
59	-376.70	-155.29	103.19	97.66	40.26	-26.75
60	-384.71	-189.35	45.58	99.74	49.09	-11.82
61	-371.69	-196.36	9.70	96.36	50.91	-2.51
62	-360.67	-208.39	-28.05	93.51	54.03	7.27
63	-378.70	-248.46	-85.66	98.18	64.42	22.21
64	-363.67	-246.46	-102.19	94.29	63.90	26.49

A M30 class 10.4 bolt will be used, which has a yield stress of 1,000 N/mm^2. The maximum normal stress occurs in the front part of Module #11 on bolt Fb1 and is 894 MPa. This is below the yield stress of the class 10.4 bolt, so all of the normal stresses on the bolts are within acceptable limits.

It had been planned to apply a pre-stress of 726 N/mm2 to the M30 bolts on the link plates in order to achieve the required friction force. A pre-stress of 726 N/mm^2 would give an additional safety factor of 1.72 (a safety factor of 1.25 per Eurode is already applied) on all of the bolts. This is an adequate pre-stress on all of the modules except at the front of module interfaces 10-11, 11-12, and by symmetry module interfaces 54-55, 55-56, which have normal stresses that exceed 726 N/mm^2. In these special cases, a pre-stress of 894 N/mm^2 will be applied, which equals the maximum expected normal stress.

The shear stress of the internal threads of the bolted connection is calculated by

$$\tau = \frac{F}{A}$$

F = bolt force (Fb1 or Fb2) increased by 25% per Eurocode

A = .87 * pi * D*L = 2,849 mm^2
D = minor diameter of the thread = 27.8mm
L = length of engagement = 37.5mm

The shears stresses on the internal threads are shown in the table below.

Internal Thread Shear Stress (MPa)
(Bolt Force increased by 25% per Eurocode)

	Fb1			Fb2		
Module #	Front	Middle	Back	Front	Middle	Back
2	-66.34	-46.82	-24.07	17.20	12.14	6.24
3	-68.61	-48.71	-27.29	17.79	12.63	7.08
4	-75.06	-53.26	-32.03	19.46	13.81	8.30
5	-76.38	-50.99	-30.52	19.80	13.22	7.91
6	92.50	-3.13	-44.73	-23.98	0.81	11.60
7	-17.33	-0.40	-24.32	4.20	0.10	5.90
8	79.05	41.86	-33.04	-19.16	-10.15	8.01
9	125.68	71.55	-36.69	-30.47	-17.35	8.89
10	163.18	92.94	-15.10	-39.56	-22.53	3.66
11	169.26	91.93	4.65	-41.03	-22.29	-1.13
12	75.81	60.41	38.31	-18.38	-14.64	-9.29
13	56.76	49.16	35.78	-13.76	-11.92	-8.67
14	39.63	38.31	32.53	-9.61	-9.29	-7.89
15	21.08	25.24	26.76	-5.11	-6.12	-6.49
16	7.70	17.13	24.53	-1.87	-4.15	-5.95
17	-4.44	9.29	21.99	1.08	-2.25	-5.33
18	-14.90	2.33	19.36	3.61	-0.57	-4.69
19	-24.93	-5.27	15.20	6.04	1.28	-3.69
20	-35.27	-13.78	9.58	8.55	3.34	-2.32
21	-41.35	-18.45	6.76	10.02	4.47	-1.64
22	-45.41	-21.99	4.00	11.01	5.33	-0.97
23	-50.37	-27.26	-0.66	12.21	6.61	0.16
24	-49.97	-27.26	-1.28	12.11	6.61	0.31
25	-48.34	-26.66	-1.81	11.72	6.46	0.44
26	-45.20	-25.14	-2.24	10.96	6.09	0.54
27	-42.06	-24.43	-3.87	10.20	5.92	0.94
28	-39.73	-24.83	-6.78	9.63	6.02	1.64
29	-33.95	-21.59	-6.87	8.23	5.23	1.67
30	-27.06	-18.04	-6.91	6.56	4.37	1.68
31	-22.09	-16.62	-8.96	5.36	4.03	2.17
32	-13.07	-10.64	-7.13	3.17	2.58	1.73

33	-3.92	-4.99	-5.49	0.95	1.21	1.33
34	5.28	0.66	-4.13	-1.28	-0.16	1.00
35	12.87	4.61	-4.27	-3.12	-1.12	1.03
36	18.04	6.36	-5.90	-4.37	-1.54	1.43
37	25.14	10.64	-5.12	-6.09	-2.58	1.24
38	31.62	14.39	-4.65	-7.67	-3.49	1.13
39	34.56	14.80	-6.58	-8.38	-3.59	1.59
40	40.03	18.65	-5.03	-9.71	-4.52	1.22
41	43.89	21.18	-3.97	-10.64	-5.14	0.96
42	46.32	22.80	-3.43	-11.23	-5.53	0.83
43	45.91	21.89	-4.69	-11.13	-5.31	1.14
44	41.76	17.84	-7.84	-10.12	-4.32	1.90
45	38.41	15.71	-8.77	-9.31	-3.81	2.13
46	33.55	12.47	-10.14	-8.13	-3.02	2.46
47	24.22	5.29	-13.99	-5.87	-1.28	3.39
48	16.82	1.31	-14.29	-4.08	-0.32	3.46
49	7.41	-4.23	-15.20	-1.80	1.02	3.69
50	-5.16	-12.16	-17.53	1.25	2.95	4.25
51	-19.26	-21.08	-20.17	4.67	5.11	4.89
52	-37.40	-32.84	-24.12	9.07	7.96	5.85
53	-107.43	-50.98	12.87	26.04	12.36	-3.12
54	-86.05	-29.80	90.30	20.86	7.22	-21.89
55	-11.15	-9.58	37.60	2.70	2.32	-9.12
56	46.22	5.37	13.99	-11.20	-1.30	-3.39
57	-2.20	-1.58	10.84	0.53	0.38	-2.63
58	-83.02	-21.04	26.54	21.52	5.45	-6.88
59	-71.27	-29.38	19.52	18.48	7.62	-5.06
60	-72.78	-35.82	8.62	18.87	9.29	-2.24
61	-70.32	-37.15	1.83	18.23	9.63	-0.48
62	-68.23	-39.42	-5.31	17.69	10.22	1.38
63	-71.65	-47.01	-16.21	18.57	12.19	4.20
64	-68.80	-46.63	-19.33	17.84	12.09	5.01

The maximum allowable shear stress in the girder material is 138Mpa. This stress is exceeded at the front part of module interfaces 10-11, 11-12, and by symmetry module interfaces 54-55, 55-56, which have shears stresses of 163 Mpa and 169 Mpa, respectively.

6. Conclusion

In general, the connections between modules are safe; however, there are several exceptions which must be addressed.

- There are 14 modules in which the bearing stress on the inner radius weld bars exceeds acceptable stresses. Additional bearing area between the modules will be needed.
- The loads on the front plate exceed the load limits found through very early experiments on a large number of modules. This would require that the bearing force at the inner

radius be transferred between modules by placing shim material on the master plates between the modules.

- The stresses on the pins are within acceptable limits except on two modules where the pin loads exceed the maximum acceptable limits.
- A 726 MPa pre-stress is required on the M30 link plate bolts in order to carry the tension force in the upper part of the EB in friction.
- The normal stresses in all of the M30 link plate bolts are within acceptable limits. However, on 4 modules the pre-stress will have to be 894Mpa rather than 726 MPa, because of the high loads on those modules, in order to prevent separation of the link plate from the girder.
- The shear stresses in the M30 link plate bolts are within acceptable limits except on 2 modules where the acceptable level of stress is exceeded in the front of the EB.

In order to address the minor problems encountered in the connections described above, the following steps should be taken during the assembly of the EB.

1. Front Plate Bearing Load: In order to reduce the bearing stress at the Inner Radius, the following module interfaces will have a 30mm-wide aluminum placed on the master plates to better distribute the inner radius force, P1. A 30mm-wide shim was chosen, because it is known from earlier tests that the load will not be evenly distributed over this area and it is felt that this is a sufficient width to reduce the bearing force. Whereas, the high bearing stresses occur in the front of the EB, the shim will be placed along the entire length of the EB in order to avoid problems of distributing the load between the Inner Radius weld bars and the shims on the master plates.

   Module interfaces: 5-6
   6-7
   7-8
   8-9
   9-10
   10-11
   11-12
   12-13
   13-14
   51-52
   52-53
   53-54
   54-55
   55-56
   56-57
   57-58
   58-59
   59-60

2. Pin Stresses: The pin stresses are exceeded on 2 modules. This problem can be resolved by using 42mm diameter pins on the front link plate in the following module interfaces:
   5-6
   6-7
   58-59
   59-60

3. Pre-Stress: A pre-stress of 726 Mpa should be used on all modules except module interfaces 10-11, 11-12, 54-55, and 55-56, which should use a pre-stress of 894.

4. M30 Thread Shear Stresses: The maximum allowable shear stresses in the M30 bolts are exceeded at the front of 4 modules. This problem can be resolved by replacing the M30 bolts with M36 bolts in the front link plates of the problem modules. This will require that the problem modules will have the current M30 tapped holes in the back of the girder drilled out and tapped in place for a M36 thread. Several machinists have been consulted and feel that, if the modules are laid horizontally and a magnetic based drill is used, the M30 holes can be drilled out and the M36 thread can be power tapped. The most the drill/tap would protrude into the fiber area of the girder is 12-15mm and there is already this clearance between the fibers and the bottom of the girder. This solution would be required of the following module interfaces:
   10-11
   11-12
   54-55
   55-56