CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

CNWRA
CONTROLLED
COPY 656

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Names, sample signatures, initials and phone numbers are shown on page 1

REPOSITORY DESIGN AND THERMAL-MECHANICAL EFFECTS (RDTME) - PRECLOSURE AND POSTCLOSURE

LJ. 09/12/06

This notebook documents the work being done to develop a seismic evaluation of the surface facilities for the planned geologic repository at Yucca Mountain, NV. This work reviews the seismic design methodology proposed by the applicant, and includes an evaluation of the seismic margin of the structural systems by means of the High Confidence of Low Probability of Failure (HCLPF) method

The qualifications required of the staff supporting this endeavor are as follows:

a) Civil (Structural) Engineering
b) Structural reliability
c) Finite element analysis
d) Soil-structure Interaction.

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The program SAP2000 it's likely to be used for the revision of the project RDTME - Preclosure. The following is the acceptance testing for SAP2000

Acceptance Testing for Configuration Control of SAP2000

7/6/2004

The CNWRA has recently acquired the structural software SAP 2000, and needs to put it under configuration control. Then, several tests were performed to assure that the program has been correctly installed and it is able to reproduce the structural response of sample models that have the potential to be analyzed in the Center. For this purpose, the problems included in SAP2000 program for internal software verification were employed. SAP 2000 contains 60 verification examples, some of them subdivided in several cases. The examples include frames, shells and systems with link elements (elements exhibiting some type of nonlinearity). Each example includes a pdf file with a description of the problem, main results and a comparison with independent calculations. These calculations are carried out by hand or using an independent structural software. These files can be found in the subdirectory of SAP2000:

C:\Program Files\Computers and Structures\SAP2000\Manuals

The SAP2000 files for each one of these problems (extension *.SDB) are located at:

C:\Program Files\Computers and Structures\SAP2000\Verification\

There is also a excel file with the main results for the proposed examples, the file is located at:

C:\Program Files\Computers and Structures\SAP2000\Verification\SAP2000_Verification_812

Once the software was properly installed, several problems were retrieved from the "Verification" subdirectory and the analyses were ran to verify that the results corresponded with those included in the pdf and excel files.

Among the problems included in this testing phase are: 1-022, 1-024, 2-008, 2-011, and 6-009. These problems cover most of the applications that Center staff will utilize when modeling structural systems in SAP2000 such as: diaphragm constraints, modal analysis, response spectrum analysis, linear and nonlinear direct integration time history analysis for base excitation, analysis of end element forces, etc. The selected structures comprise two-dimensional and tri-dimensional moment frames, plates modeled with shell elements, and plastic kinematic components. All the obtained results coincide with those reported in the SAP 2000 documentation. Therefore, the Center staff is confident that the program has been properly installed. The description of the selected problems and corresponding results have been submitted to the quality assurance staff of the CNWRA.

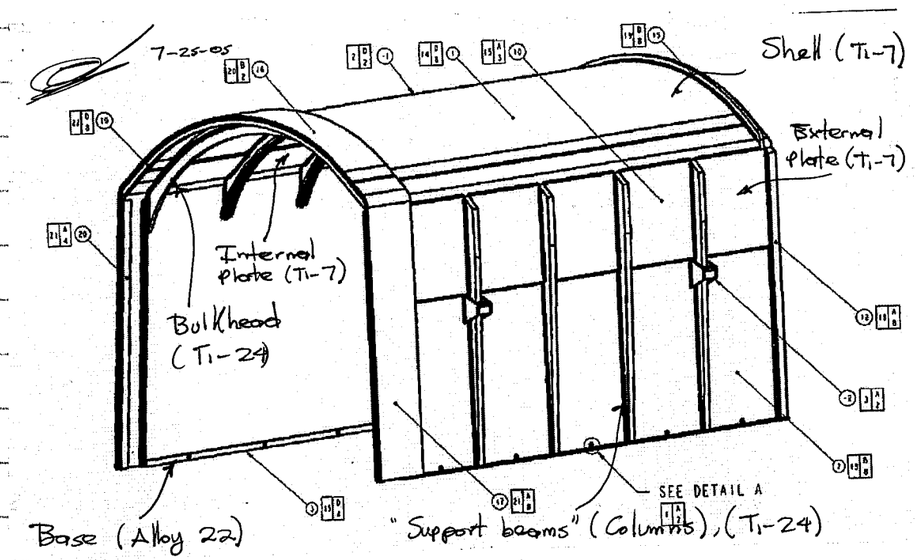
Problems Encountered

It was detected that structural problems involving direct integration time histories were not running. The Center got in contact with SAP 2000 staff located at Houston, TX: Darrell Foster, tel: (713) 533-4420. After describing the problem to him, it was decided to update the SAP 2000 version of the Center from 8.2.7 to 8.3.1. This modification is documented in the ticket 1700 of CNWRA Helpdesk.

July 25, 2005

The updated drip shield design proposed by the Department of Energy (DOE) (ref. 1) is being evaluated by CNWRA staff. The isometric view of the drip shield is in the following figure

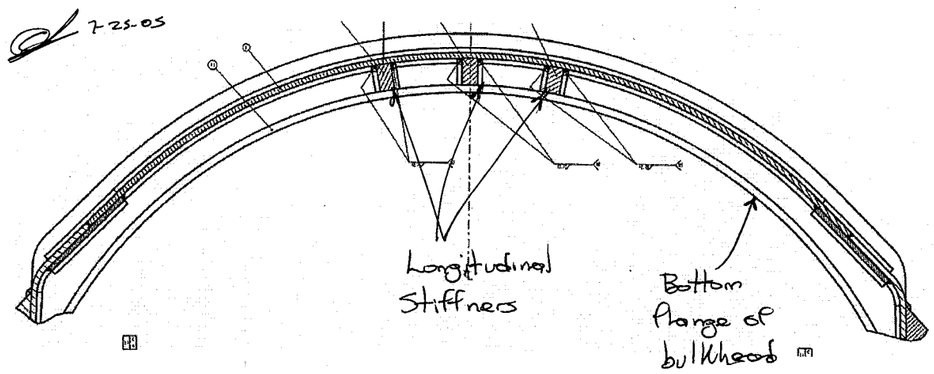
7-25-05



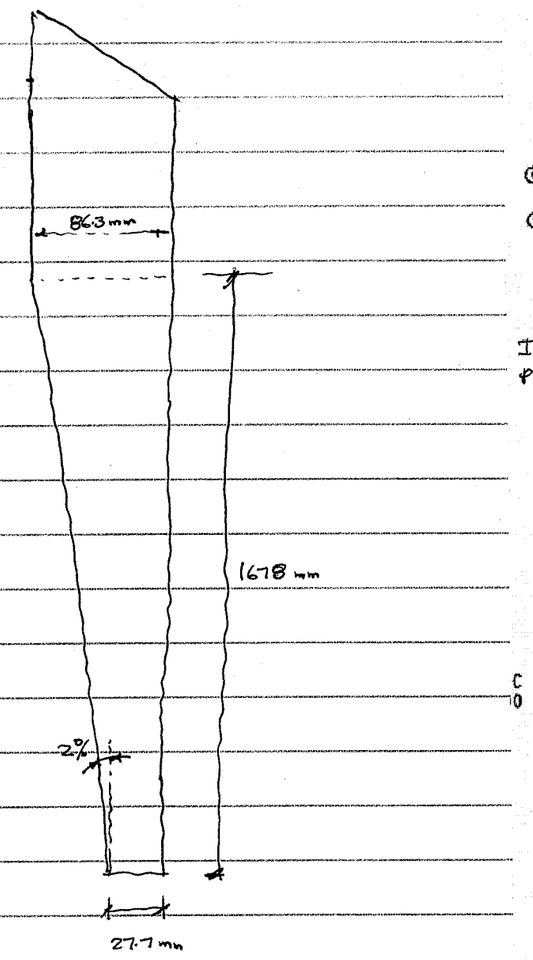
Each drip shield section has a length of 5805 mm [228.5 in], a cross section width of 2533 mm [99.7 in], and a total height of 2886 mm [113.6 in]. The drip shield (DS) consists of Titanium Grade 7 (Ti-7) plates that are supported with frames of Titanium Grade 24 (Ti-24) equally spaced at each 1,070 mm [42.1 in].

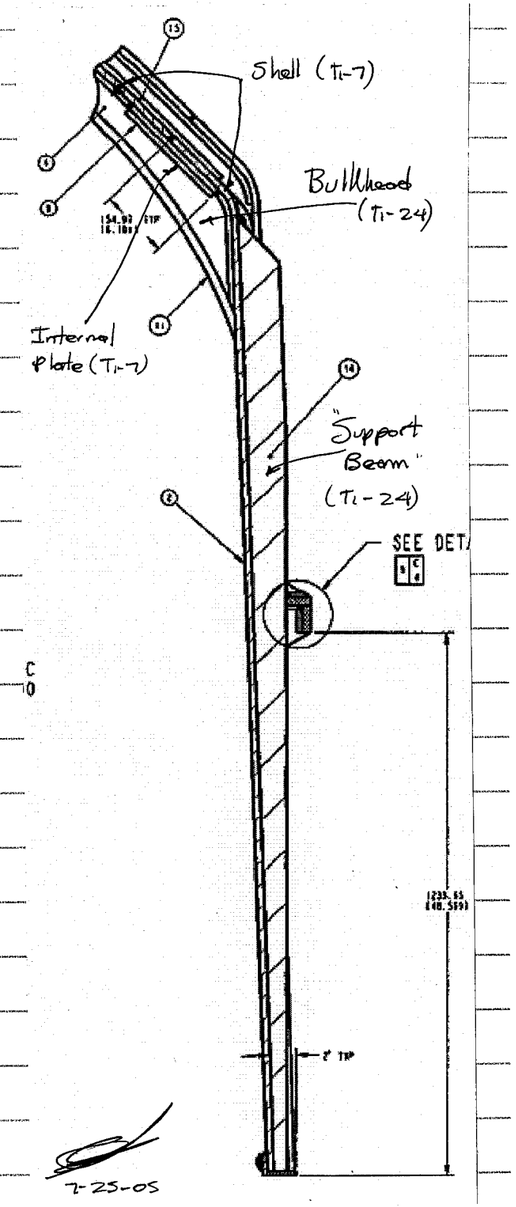
Ref 1:
Bechtel SAIC Company, LLC. 2004. "Drip Shield Structural Response to Rockfall." 000-00C-SSE0-00300-000-00A. Las Vegas, Nevada. Bechtel SAIC Company, ACC: ENG.20030327.0001

The updated drip shield is about one foot taller, incorporates three longitudinal stiffners, and a bottom flange in the bulkhead. See the following figure



A section of the support beam and "DS corner" is presented in page 5. The support beam -Ti-24- component is a non-prismatic element that has a depth of 27.7 mm at the base, which increases with a slope of 2% up to reach a depth of 86.3 mm at a height of 1678 mm.





In addition to the ABAQUS (ref 2) drip shield finite element model (FEM) discussed in the scientific notebook 391, a drip shield frame model is being generated in SAP2000 (ref 3) that is more computationally efficient and allow additional structural capabilities, such as asymmetric loading and time history analyses.

The unidimensional beam-column elements used in the DS frame model represent both the Ti-24 frame components and the equivalent cross section of the Ti-7 plates. The stiffness contribution of the Ti-7 plates is simplified by adopting an equivalent width (b) obtained from calibrating the DS frame model with elastic SAP2000 and ABAQUS FEM's.

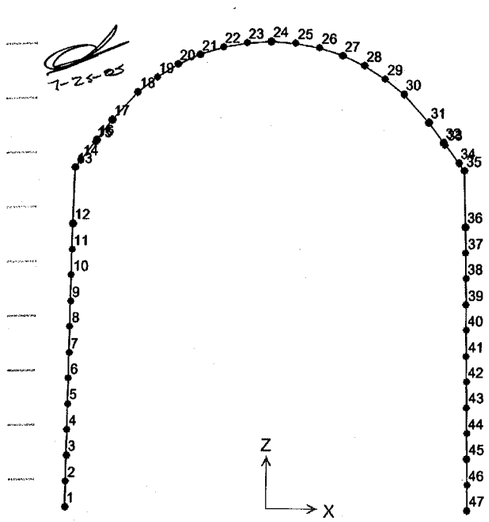
The node and element discretization of the DS frame model is the figures of page 7. The model prevents out-of-plane deformations, and its base assumes pin constraints. The DS columns and some of the bulkhead sections are non-prismatic sections.

Ref 2:

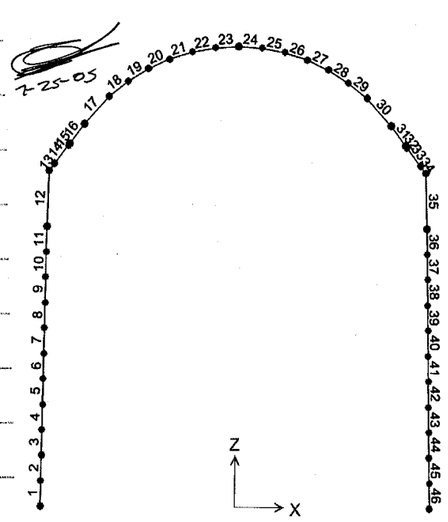
ABAQUS, Inc "ABAQUS User's Manual." Version 6.4. Providence, Rhode Island: ABAQUS, Inc. 2004

Ref 3:

Computers and Structures, Inc. "SAP2000 Version 8.3.1, Integrated Software for Structural Analysis and Design." Berkeley, CA. 2004



Node Labels



Element Levels

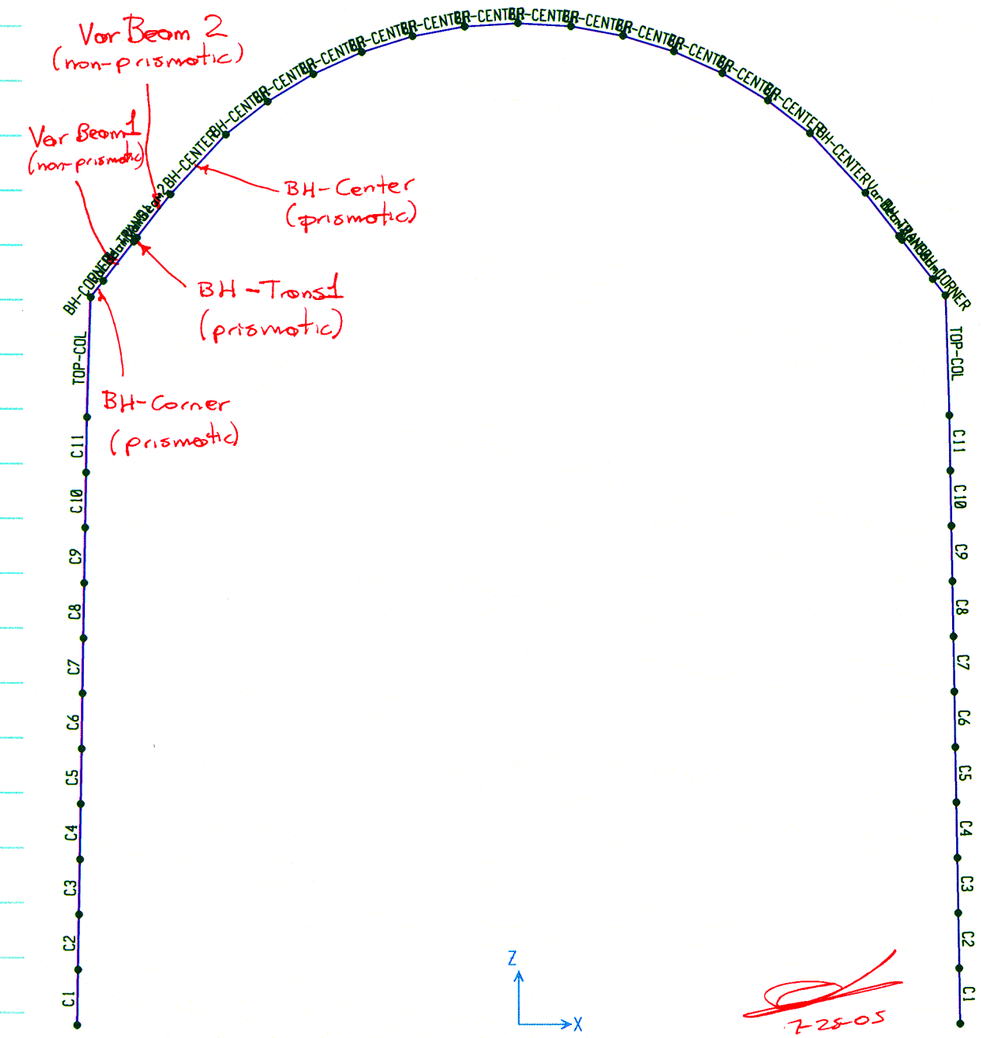
The columns are discretized in 12 prismatic elements, each having the average cross section of the corresponding longitudinal segment.

The node coordinates are presented in page 8

Joint	CoordSys	CoordType	XorR	Y	Z	SpecialJt	GlobalX
Text	Text	Text	mm	mm	mm	Yes/No	mm
1	GLOBAL	Cartesian	-1230.92	0.00	0.00	No	-1230.92
2	GLOBAL	Cartesian	-1228.26	0.00	152.55	Yes	-1228.26
3	GLOBAL	Cartesian	-1225.59	0.00	305.09	Yes	-1225.59
4	GLOBAL	Cartesian	-1222.93	0.00	457.64	Yes	-1222.93
5	GLOBAL	Cartesian	-1220.27	0.00	610.18	Yes	-1220.27
6	GLOBAL	Cartesian	-1217.60	0.00	762.73	Yes	-1217.60
7	GLOBAL	Cartesian	-1214.94	0.00	915.27	Yes	-1214.94
8	GLOBAL	Cartesian	-1212.27	0.00	1067.82	Yes	-1212.27
9	GLOBAL	Cartesian	-1209.61	0.00	1220.36	Yes	-1209.61
10	GLOBAL	Cartesian	-1206.95	0.00	1372.91	Yes	-1206.95
11	GLOBAL	Cartesian	-1204.28	0.00	1525.45	Yes	-1204.28
12	GLOBAL	Cartesian	-1201.62	0.00	1678.00	Yes	-1201.62
13	GLOBAL	Cartesian	-1191.02	0.00	2010.00	Yes	-1191.02
14	GLOBAL	Cartesian	-1155.36	0.00	2055.16	No	-1155.36
15	GLOBAL	Cartesian	-1070.18	0.00	2163.68	No	-1070.18
16	GLOBAL	Cartesian	-1061.66	0.00	2174.53	No	-1061.66
17	GLOBAL	Cartesian	-967.97	0.00	2293.90	No	-967.97
18	GLOBAL	Cartesian	-813.65	0.00	2459.44	No	-813.65
19	GLOBAL	Cartesian	-696.67	0.00	2549.88	No	-696.67
20	GLOBAL	Cartesian	-569.71	0.00	2625.73	No	-569.71
21	GLOBAL	Cartesian	-434.59	0.00	2685.88	No	-434.59
22	GLOBAL	Cartesian	-293.24	0.00	2729.48	No	-293.24
23	GLOBAL	Cartesian	-147.68	0.00	2755.89	No	-147.68
24	GLOBAL	Cartesian	0.00	0.00	2764.74	Yes	0.00
25	GLOBAL	Cartesian	147.68	0.00	2755.89	No	147.68
26	GLOBAL	Cartesian	293.24	0.00	2729.48	No	293.24
27	GLOBAL	Cartesian	434.59	0.00	2685.88	No	434.59
28	GLOBAL	Cartesian	569.71	0.00	2625.73	No	569.71
29	GLOBAL	Cartesian	696.67	0.00	2549.88	No	696.67
30	GLOBAL	Cartesian	813.65	0.00	2459.44	No	813.65
31	GLOBAL	Cartesian	967.97	0.00	2293.90	No	967.97
32	GLOBAL	Cartesian	1061.66	0.00	2174.53	No	1061.66
33	GLOBAL	Cartesian	1070.18	0.00	2163.68	No	1070.18
34	GLOBAL	Cartesian	1155.36	0.00	2055.16	No	1155.36
35	GLOBAL	Cartesian	1191.02	0.00	2010.00	Yes	1191.02
36	GLOBAL	Cartesian	1201.62	0.00	1678.00	Yes	1201.62
37	GLOBAL	Cartesian	1204.28	0.00	1525.45	Yes	1204.28
38	GLOBAL	Cartesian	1206.95	0.00	1372.91	Yes	1206.95
39	GLOBAL	Cartesian	1209.61	0.00	1220.36	Yes	1209.61
40	GLOBAL	Cartesian	1212.27	0.00	1067.82	Yes	1212.27
41	GLOBAL	Cartesian	1214.94	0.00	915.27	Yes	1214.94
42	GLOBAL	Cartesian	1217.60	0.00	762.73	Yes	1217.60
43	GLOBAL	Cartesian	1220.27	0.00	610.18	Yes	1220.27
44	GLOBAL	Cartesian	1222.93	0.00	457.64	Yes	1222.93
45	GLOBAL	Cartesian	1225.59	0.00	305.09	Yes	1225.59
46	GLOBAL	Cartesian	1228.26	0.00	152.55	Yes	1228.26
47	GLOBAL	Cartesian	1230.92	0.00	0.00	No	1230.92

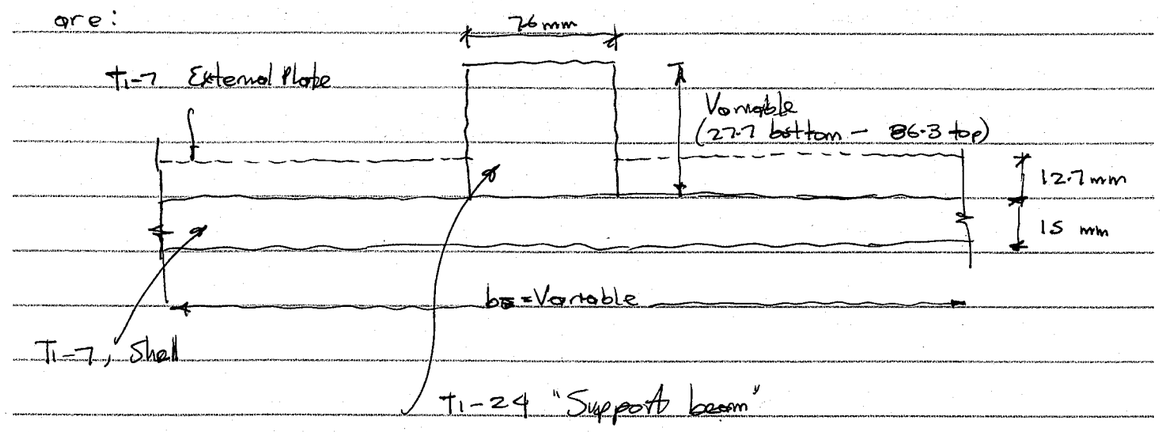
7-25-05

The beam-column sections are indicated in the following figure. All the column elements are prismatic sections, whereas two beam member sections are non-prismatic (Var Beam 1 and Var Beam 2). The element BH-Trans1 is included to accommodate a nonlinear spring between the two non-prismatic members. (SAP2000 allows the allocation of nonlinear springs only in prismatic beam-column elements.

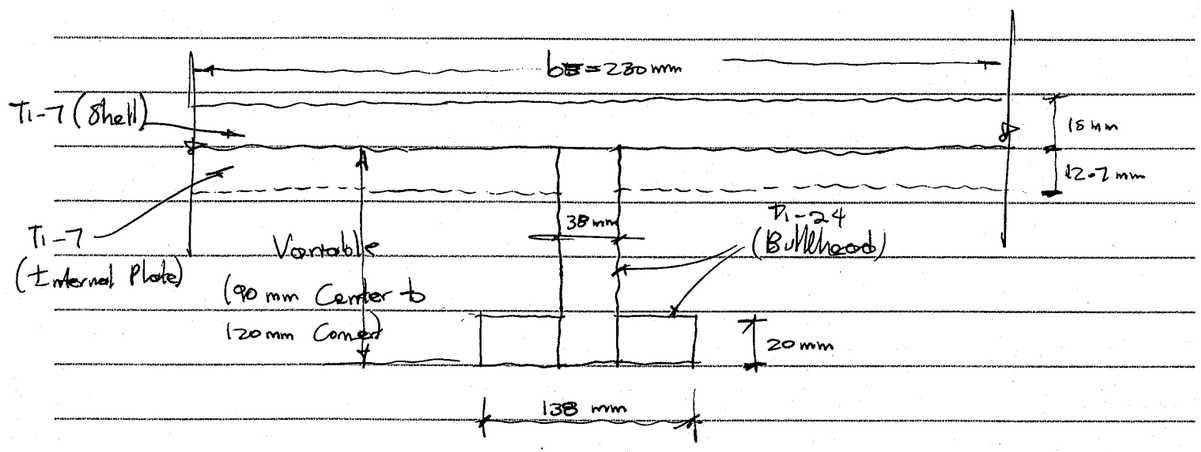


7-25-05

The typical cross sections for bulkhead and "support beam" (column) are:



SUPPORT BEAM CROSS SECTION



The variable dimensions of sections of page 10 are tabulated in the Table of page 11 for each of the sections in which the DS frame model was divided.

Bulkhead			
Section Label	Section Dept (mm)	Titanium Grade 7 Plate Width (mm)	Titanium Grade 7 Plate Thickness (mm)
Center	105	230	15.0
Transition	110	230	27.7
Corner	135	230	27.7

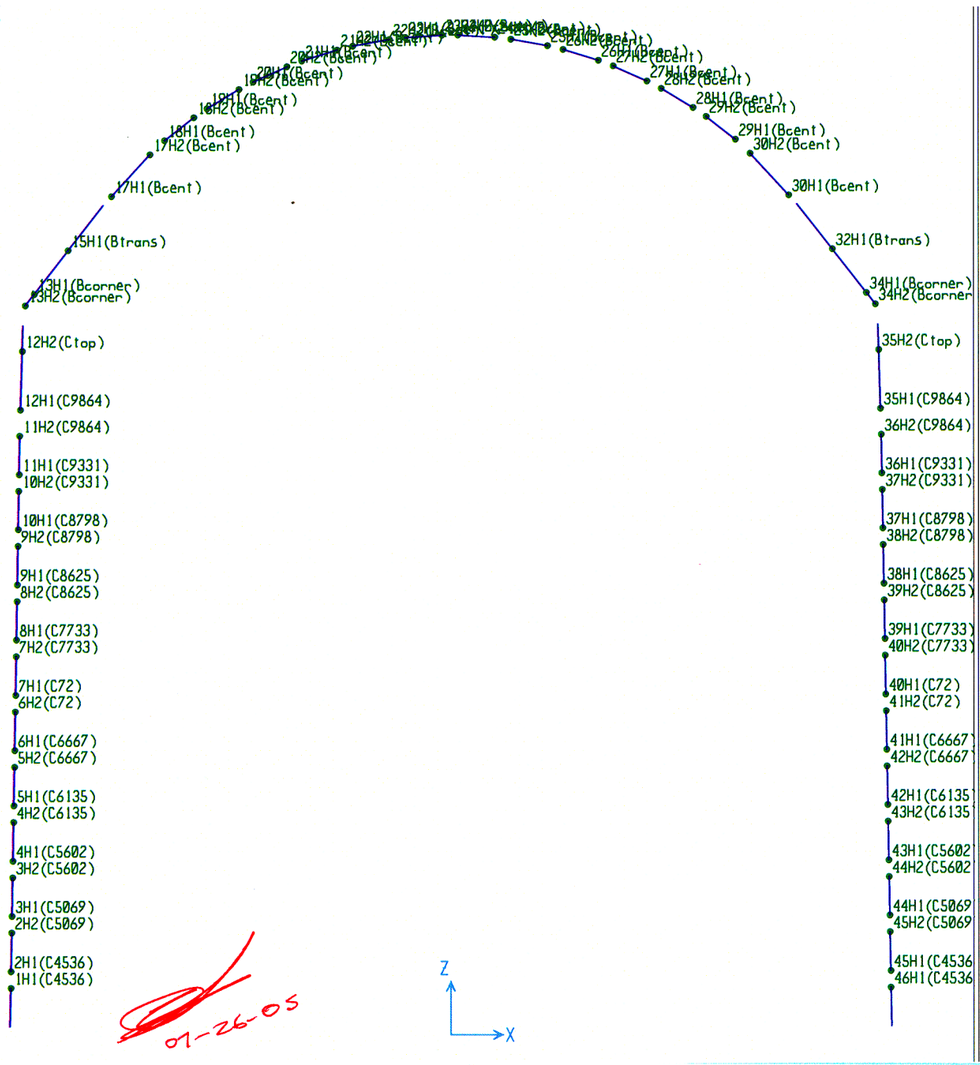
Support Beams (Columns)			
Section Label	Section Dept (mm)	Titanium Grade 7 Plate Width (mm)	Titanium Grade 7 Plate Thickness (mm)
C1 (base)	45.36	450	15.0
C2	50.69	441	15.0
C3	56.02	431	15.0
C4	61.35	418	15.0
C5	66.67	404	15.0
C6	72.00	387	15.0
C7	77.33	367	15.0
C8	86.25	345	15.0
C9	87.98	320	15.0
C10	93.31	282	27.7
C11	98.64	248	27.7
C12 (top)	101.3	230	27.7

07-25-05

July 26, 2005

* NON-LINEAR ROTATIONAL SPRINGS

The nonlinear response of the drip shield frame model is simulated by means of zero-length nonlinear inelastic rotational springs. These springs are located at the ends of all beam-column elements of the sections, with exception of the non-prismatic elements and the element BH-trans1 (which has the spring at the center of the section and is only used to allocate a spring between two non-prismatic sections, see Figure of page 9).



07-26-05

The figure of page 12 presents the distribution of nonlinear springs in the frame model. The bending moments for the moment-rotation relationships used in the springs of the SAP2000 model were obtained from classic strength of materials formulation (Ref 4), and compared to results from ABAQUS FEM's (see SN #39) and some ~~references~~ L.S. 7-26-05 examples later in this SN). The main assumption in this procedure is that plane sections remain plane under flexural deformations.

The titanium 7 and 24 material properties at 150°C [302°F] are the same for all sections:

$E_{Ti-24} = 107{,}000$ MPa $\qquad E_{Ti-7} = 101{,}000$ MPa

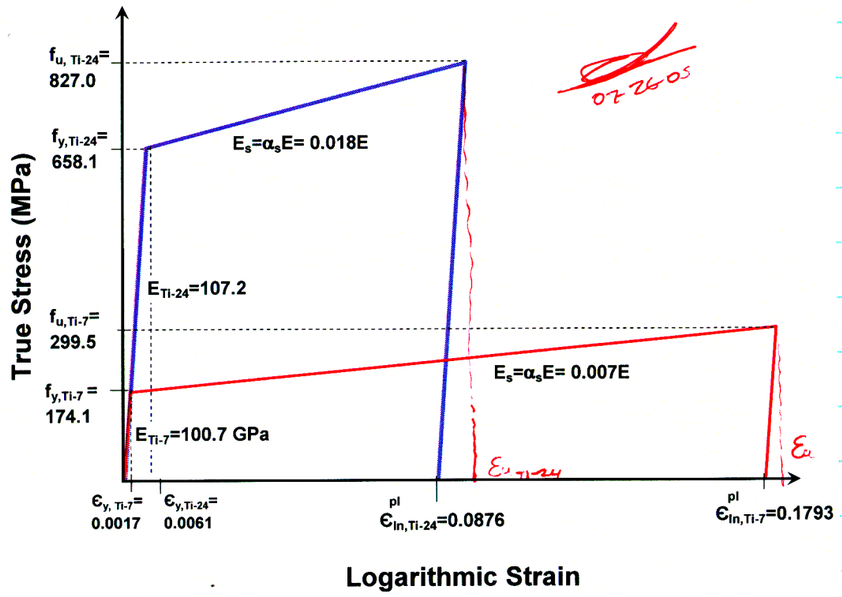
$F_{y,Ti-24} = 658.1$ MPa $\qquad F_{y,Ti-7} = 124.1$ MPa

$F_{u,Ti-24} = 827$ MPa $\qquad F_{u,Ti-7} = 299.5$ MPa

These properties are obtained from SN #391. It's also assumed a linear post-yielding stiffness until the ultimate strain is reached, see Figure of page 14.

Ref. 4

Salmon, C.G., and Johnson, J.E. (1996) "Steel Structures, Design and Behavior," Fourth Edition, Harper Collins College Publishers.



Additional material properties used in these calculations are:

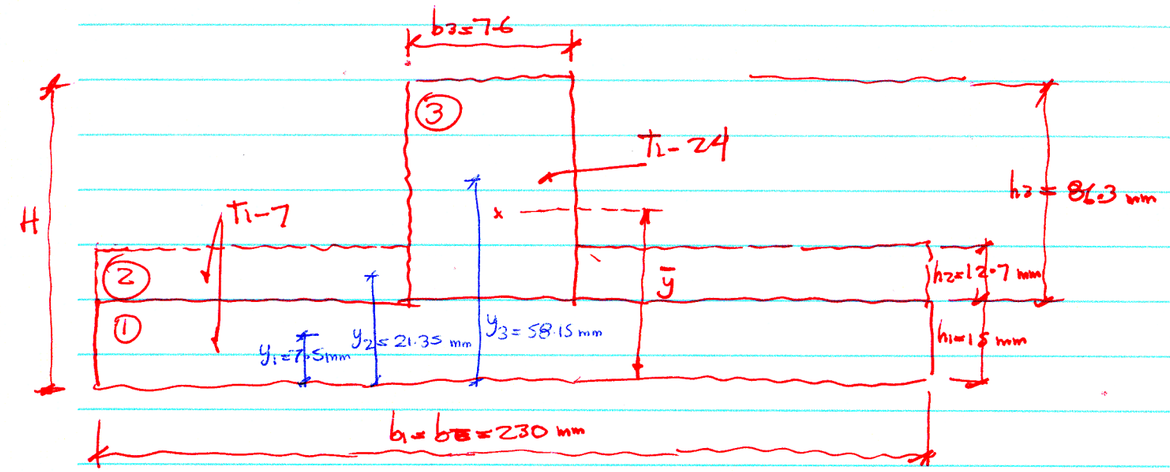
$\varepsilon_{y\,Ti-24} = 0.0065$ $\qquad$ $\varepsilon_{y\,Ti-7} = 0.0072$

$\varepsilon_{u\,Ti-24} = 0.0953$ $\qquad$ $\varepsilon_{u\,Ti-7} = 0.1823$

$E_s = \alpha_s E = 1890$ MPa $\qquad$ $E_{s\,Ti-7} = 696.6$ MPa

These properties are used to ~~generate~~ L.S. 07/26/05 moments for different sections. The following pages show the methodology used on hand of the top-column section.

Calculation of Yielding Moment for Top Column Section



The equivalent width of the section, b_E, is obtained from calibration of DS frame model and FEM's.

The yielding moment can be calculated by assuming that plane sections remain plane under bending deformations, and computing the corresponding strain and stresses. However, to calculate the yielding moment is used a simplified approach in which the Ti-7 plate area is transformed in Ti-24 area:

$$n = \frac{E_{s\,Ti-24}}{E_{s\,Ti-7}} = \frac{107{,}000 \text{ MPa}}{101{,}000 \text{ MPa}} = 1.06$$

Transformed area:

$A_1 = 230 * 15$ mm $= 3450$ mm^2 $\Rightarrow$ $A_1' = A_1/1.06 = 3256.5$ mm^2

$A_2 = (230-76)$mm $(\cancel{15}\ 12.7)$mm $= 1955.8$ mm^2 L.S. 07/26/05 $\Rightarrow$ $A_2' = A_2/1.06 = 1846.1$ mm^2

$A_3 = (76 * 86.3) = 6558.8$ mm^2 $\Rightarrow$ $A_3' = A_3 = 6558.8$ mm^2

Tot. $A' = 11{,}661.5$ mm^2

The neutral axis, $\bar{y}$, is located at:

$$\bar{y} = \frac{3256.5 * 7.5 + 1846.1 * 21.35 + 6558.8 * 58.15}{11,661.5} = 38.18 \text{ mm}$$

The moment of inertia is:

$$I = \frac{230(15)^3 + 154(12.7)^3 + 76(86.3)^3}{12} + 3256.5(\bar{y} - 7.5)^2 + 1846.1(\bar{y} - 21.35)^2$$

$$+ 6558.8(\bar{y} - 58.15)^2 = 10,360,363 \text{ mm}^4$$

The yielding moment at the top fiber is:

$$M_{y\,top} = \frac{f_{y\,Ti-24} * I}{(H - \bar{y})} = \frac{658 \times 10^6 * 10,360,363}{(101.3 - 38.18)} = 108,018,660 \text{ N-mm}$$

$$= 108.02 \text{ KN-m}$$

The yielding moment at the bottom is:

$$M_{y\,bottom} = \frac{f_{y\,Ti-7}\, I}{\bar{y}} = \frac{174.1 \times 10^6 * 10,360,363}{38.18} = 47,243,230 \text{ N-mm}$$

$$= 47.24 \text{ KN-m}$$

(controls)

The curvature is

$$\phi_y = 0.00172 / \underset{\bar{y}}{38.18} = 4.5 \times 10^{-5} \text{ rad/mm}$$

This information was systematized in Excel (Ref 5), as shown in page 17

CALCULATION OF My CONSIDERING PLASTIFICATION OF Tit-7
Top Column

b_1 =	230 mm	y1 =	7.5 mm	$E_{Tit\,24}$ =	107000 MPa
h_1 =	15 mm			$F_{y,Tit\,24}$ =	658.1 MPa
b_2 =	154 mm	y2 =	21.35 mm	$F_{u,Tit\,24}$ =	827 MPa
h_2 =	12.7 mm			$E_{Tit\,7}$ =	101000 MPa
b_3 =	76 mm	y2 =	58.15 mm	$F_{y,Tit\,7}$ =	174.1 MPa
h_3 =	86.3 mm			$F_{u,Tit\,7}$ =	299.5 MPa

H =	101.3 mm			
n =	1.06			
		For finding the neutral axis:		
A_1 =	3450 mm^2	A_1' =	3256.542 mm^2	
A_2 =	1955.8 mm^2	A_2' =	1846.129 mm^2	
A_3 =	6558.8 mm^2	A_3' =	6558.80 mm^2	
Tot A =	11964.6 mm^2	Tot A' =	11661.47 mm^2	

Neutral axis:
y = 38.18 mm

Moment of Inertia
Ix = 10360362.71 mm^4

$M_{y,top}$=	108,018,660 N-mm =	108.02 KN-m	
$M_{y,bottom}$=	47,243,230 N-mm =	47.24 KN-m	Titanium 7 yields

ϕ_y = 4.505E-05 rad/mm
ϕ_y = 4.505E-02 rad/m K_{y7} = 1048.69

07-26-05

K_{y7} refers to the initial elastic slope of the M-ϕ (moment-curvature relationship).

07-26-05

Ref 5:
Microsoft Corporation. "Microsoft Excel 2002-SP3." Redmond, Washington: Microsoft Corporation. 2002

* YIELDING OF Ti-24 FOR TOP-COLUMN SECTION

July 27, 2005

The calculations of moment at yielding of Ti-24 are presented in page 19. The neutral axis is obtained by using an iterative process included in the Excel worksheet. The neutral axis is obtained when the sum of tension and compression forces is equal to zero. The bending moments are computed at this stage.

The main assumption for finding the strain profile is that plane sections remain plane. Then, the maximum strain is fixed at the top fiber as 0.00615 ($\varepsilon_{y,Ti-24}$, i.e, the strain at which Ti-24 yields). The rest of the strains are obtained from geometric identities.

The stresses for Ti-24 is based on direct proportionality. For the case of stresses in Ti-7, the hardening of the post-yielding slope is accounted for. For instance, the Ti-7 stress at a distance of 30.99 mm from the neutral axis is:

$$\sigma_{Ti,7}(30.99\text{ mm}) = \underbrace{174.1}_{\sigma_{y,Ti-7}} + (0.00845 - 0.00172)\ \underbrace{696.6}_{E_{post\text{-}yielding}} = 175.3\ \text{MPa}$$

To obtain the moment, for instance, due to the force C_{7a}, the force is computed as:

$$C_{7a} = \left(\frac{174.32 + 175.3}{2}\right) * \underset{h}{12.7} * \underset{b}{154} = 341{,}895\ \text{N}$$

CALCULATION OF My CONSIDERING YIELD STRAIN IN OUTER FIBER OF Tit-24
TOP COLUMN, Configuration 1

b_1 =	230 mm	y1 =	7.5 mm	$E_{Tit\,24}$ =	107000 MPa
h_1 =	15 mm			$F_{y,Tit\,24}$ =	658.1 MPa
b_2 =	154 mm	y2 =	21.35 mm	$F_{u,Tit\,24}$ =	827 MPa
h_2 =	12.7 mm			$d_{y,Tit\,24}$ =	0.00615
b_3 =	76 mm	y2 =	58.15 mm	$E_{hard\,T24}$ =	1890 MPa
h_3 =	86.3 mm			$d_{u,Tit\,24}$ =	0.0953
Strain at	0 (from top) is given an equal to				
neutral axis =	45.99 mm		Requires iteration until Sum of Forces is equal to zero		

H tot =	101.30 mm										
H - y =	55.31 mm										
y - h1 =	30.99 mm										
y - h1-h2 =	18.29 mm										
Strain at	18.29	=	0.00203	(h_1 =	27.7 mm)						
Strain at	30.99	=	0.00345	(h_1 =	15 mm)						
Strain at	45.99	=	0.00511	(h_1 =	0 mm)						
Tit 24 stress comp	30.99	=	368.81 MPa								
Tit 7str at=	18.29	=	174.32 MPa								
Tit 7str at=	30.99	=	175.30 MPa								
T7 str at=	0.00511	=	176.46 MPa								

	Stress top	Stress bottom	Stress Average	h	b	Force (N)	Arm	Moment
T24	658.10	0.00	329.05	55.31	76	1,383,074	36.87	50.99 KN-m
C24	0.00	368.81	184.41	30.99	76	434,380	20.66	8.98 KN-m
C7a	174.32	175.30	174.81	12.70	154	341,895	24.65	8.43 KN-m
C7b	175.30	176.46	175.88	15.00	230	606,799	38.50	23.36 KN-m

Sum =	0 M_p =	91.76 KN-m
	ϕ_y =	0.1112 rad/m

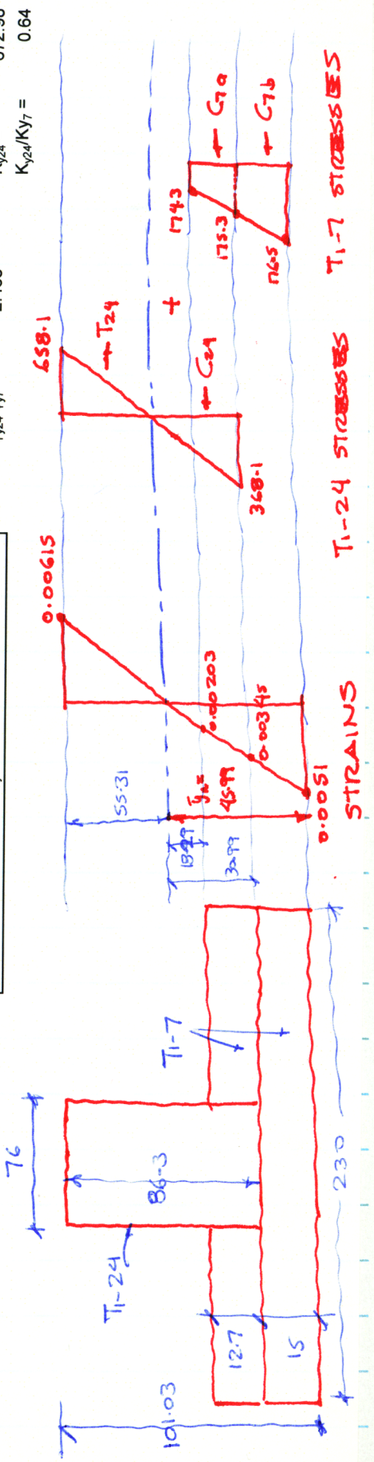
$E_{Tit\,7}$ =	101000 MPa		
$F_{y,Tit\,7}$ =	174.1 MPa		
$F_{u,Tit\,7}$ =	299.5 MPa		
$E_{hard\,T7}$ =	696.6 MPa		
$d_{y,Tit\,7}$ =	0.00172		
$d_{u,Tit\,7}$ =	0.1823		

neutral axis for a trapezoide

a	b	y
0.00	658.10	36.87
0.00	368.81	20.66
174.32	175.30	6.36
175.30	176.46	7.51

M_{y24}/M_{y7} =	1.942	K_{y7} =	1048.69
ϕ_{y24}/ϕ_{y7} =	2.468	K_{y24} =	672.98
		K_{y24}/K_{y7} =	0.64

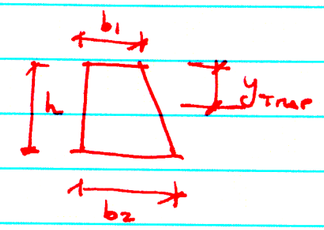
07-27-05



The lever arm at which the force is applied is:

$$\text{Arm}_{C7a} = 18.29 + \underbrace{\frac{12.7}{3}\left[\frac{174.32 + 2 * 175.3}{174.32 + 175.3}\right]}_{\text{Arm in a trapezoid}} = 18.29 + 6.36 = 24.65 \text{ mm}$$

$$y_{Trap} = \frac{h}{3}\left[\frac{b_1 + 2b_2}{b_1 + b_2}\right]$$



Then, the moment due to C_{7a} is:

$$M_{C7a} = (341.895 \text{ KN})(0.02465 \text{ m}) = 8.43 \text{ KN-m}$$

07-29-05

BENDING MOMENT AT THE REACHING OF
* ULTIMATE STRAIN OF Ti-24

July 28, 2005

Because of the low ductile characteristics of Ti-24 (compared with Ti-7 and conventional carbon-steel materials such as A-36), the peak moment is considered when the outer fiber of Ti-24 reaches its ultimate failure. That is, full plastification of the cross section is not considered.

Page 21 shows the calculation of the peak moment for the top-column section, assuming that this moment occurs when the Ti-24 outer fiber reaches its ultimate strain.

CALCULATION OF "Mp" CONSIDERING RUPTURE STRAIN IN OUTER FIBER OF Tit-24
TOP COLUMN

b_1 =	230 mm	y1 =	7.5 mm	$E_{Tit\,24}$ =	107000 MPa
h_1 =	15 mm			$F_{y,Tit\,24}$ =	658.1 MPa
b_2 =	154 mm	y2 =	21.35 mm	$F_{u,Tit\,24}$ =	827 MPa
h_2 =	12.7 mm			$d_{y,Tit\,24}$ =	0.00615
b_3 =	76 mm	y2 =	58.15 mm	$E_{hard\,T24}$ =	1890 MPa
h_3 =	86.3 mm			$d_{u,Tit\,24}$ =	0.0953
Strain at	101.3 is given an equal to		0.0953		

$E_{Tit\,7}$ =	101000 MPa				
$F_{y,Tit\,7}$ =	174.1 MPa				
$F_{u,Tit\,7}$ =	299.5 MPa				
$E_{hard\,T7}$ =	696.6 MPa				
$d_{y,Tit\,7}$ =	0.00172				
$d_{u,Tit\,7}$ =	0.1823				

H =	101.3 mm		
neutral axis =	48.388 mm	Requires iteration until Sum of Forces is equal to zero	
h - y =	52.91		
y - h1 =	33.39		
y - (h1+h2) =	20.69		
Strain at	20.69 =	0.037261	(h_1 = 27.7 mm)
Strain at	33.39 =	0.060135	(h_1 = 15 mm)
Strain at	48.39 =	0.087151	(h_1 = 0 mm)
Length at	0.00615 =	3.414588	

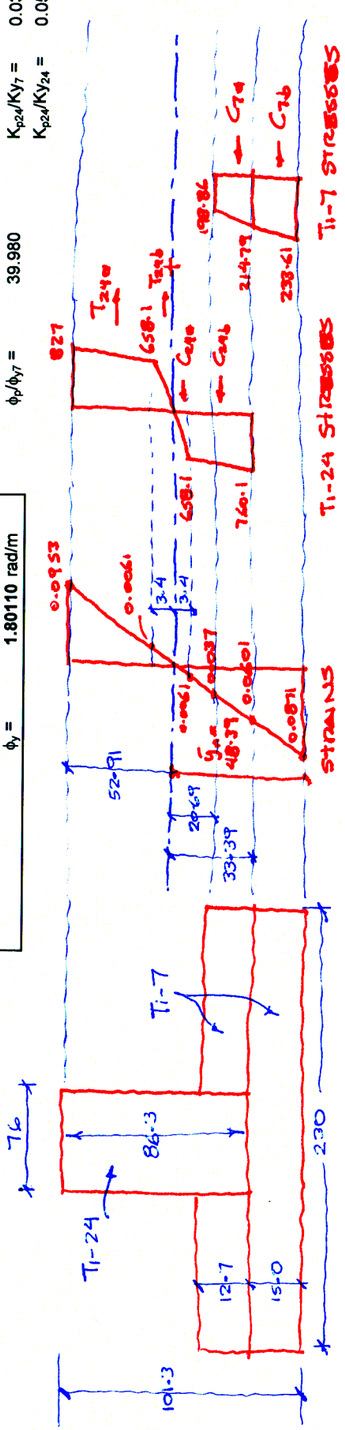
Tit 24 st at h =	15 =	760.13 MPa	
Tit 7str at h =	27.70 =	198.86 MPa	
Tit 7str at h =	15 =	214.79 MPa	
Tit 7str at h =	0 =	233.61 MPa	

	Stress top	Stress bottom	Stress Average	h	b	Force (N)	Arm	Moment
T24a	827.00	658.10	742.55	49.50	76	2,793,340	29.10	81.29 KN-m
T24b	658.10	0.00	329.05	3.41	76	85,391	2.28	0.19 KN-m
C24a	0.00	658.10	329.05	3.41	76	85,391	2.28	0.19 KN-m
C24b	658.10	760.13	709.12	29.97	76	1,615,338	18.76	30.30 KN-m
C7a	198.86	214.79	206.82	12.70	154	404,508	27.12	10.97 KN-m
C7b	214.79	233.61	224.20	15.00	230	773,495	40.99	31.71 KN-m
Sum =						0 M_p =		154.66 KN-m
						ϕ_y =		1.80110 rad/m

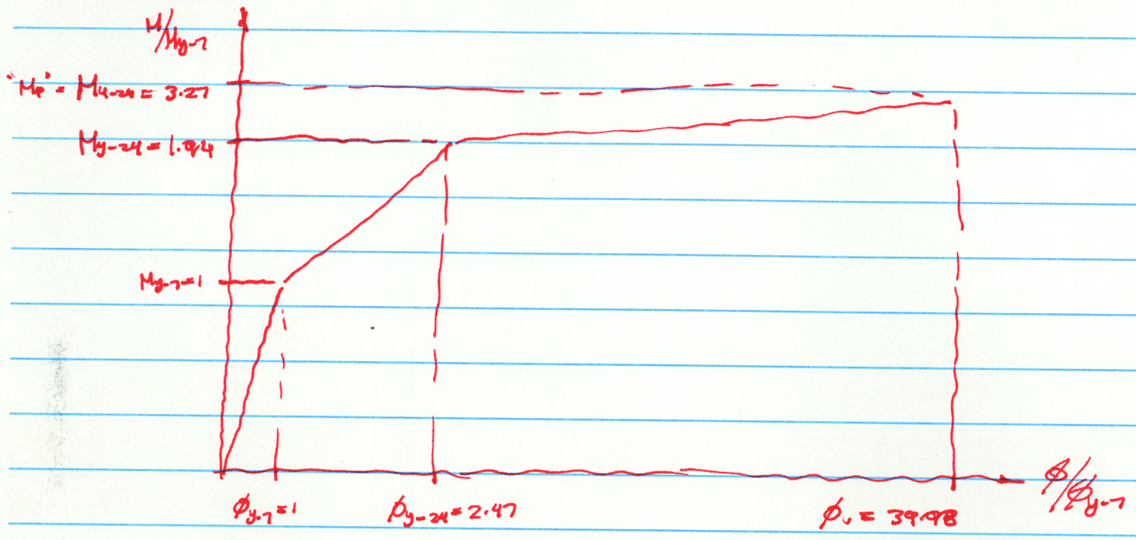
neutral axis for a trapezoide

a	b	y
658.10	827.00	25.69
0.00	658.10	2.28
0.00	658.10	2.28
658.10	760.13	15.35
198.86	214.79	6.43
214.79	233.61	7.60

M_p/M_{y7} =	3.274	K_{p24} =	37.22
ϕ_p/ϕ_{y7} =	39.980	K_{p24}/Ky_7 =	0.0355
		K_{p24}/Ky_{24} =	0.0553



The moment-curvature (M-ϕ) relationship can be generated using the information obtained at the three computed stages, i.e., yielding of Ti-7, yielding of Ti-24, & ultimate strain of Ti-24. Below is presented the normalized (LI, 7-28-05) diagram of M-ϕ for the top-column section



07-28-05

July 29, 2005

Similar moment-curvature relationships are computed for the rest of the member sections. Pages 23, ~~24~~ 25 and ~~25~~ 27 (LI, 7,29,05) present the calculation of yielding of Ti-7, yielding of Ti-24 and ~~Ti-28~~ LI (7,29,05) reaching of ultimate strain of Ti-24 moments for a bulkhead section (center beam).

CALCULATION OF My CONSIDERING PLASTIFICATION OF Tit-7
Center Beam Section

b_1 =	138 mm	y1 =	10 mm	$E_{Tit\ 24}$ =	107000 MPa
h_1 =	20 mm			$F_{y,Tit\ 24}$ =	658.1 MPa
b_2 =	38 mm	y2 =	55 mm	$F_{u,Tit\ 24}$ =	827 MPa
h_2 =	70 mm			$E_{Tit\ 7}$ =	101000 MPa
b_3 =	230 mm	y2 =	97.5 mm	$F_{y,Tit\ 7}$ =	174.1 MPa
h_3 =	15 mm			$F_{u,Tit\ 7}$ =	299.5 MPa

H = 105 mm
n = 1.06

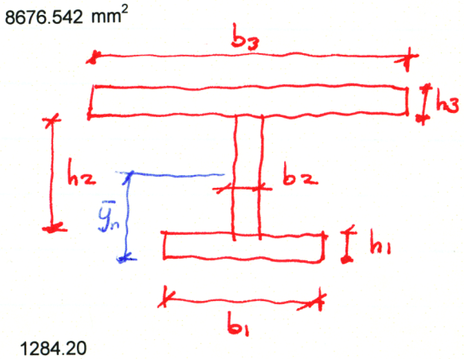
A_1 =	2760 mm^2	**For finding the neutral axis:**	
A_2 =	2660 mm^2	A_1' =	2760 mm^2
A_3 =	3450 mm^2	A_2' =	2660 mm^2
Tot A =	8870 mm^2	A_3' =	3256.54 mm^2
		Tot A' =	8676.542 mm^2

Neutral axis:
y = 56.64 mm

Moment of Inertia
Ix = 12687106.3 mm^4

$M_{y,top}$= 45,671,749 N-mm = **45.67** KN-m

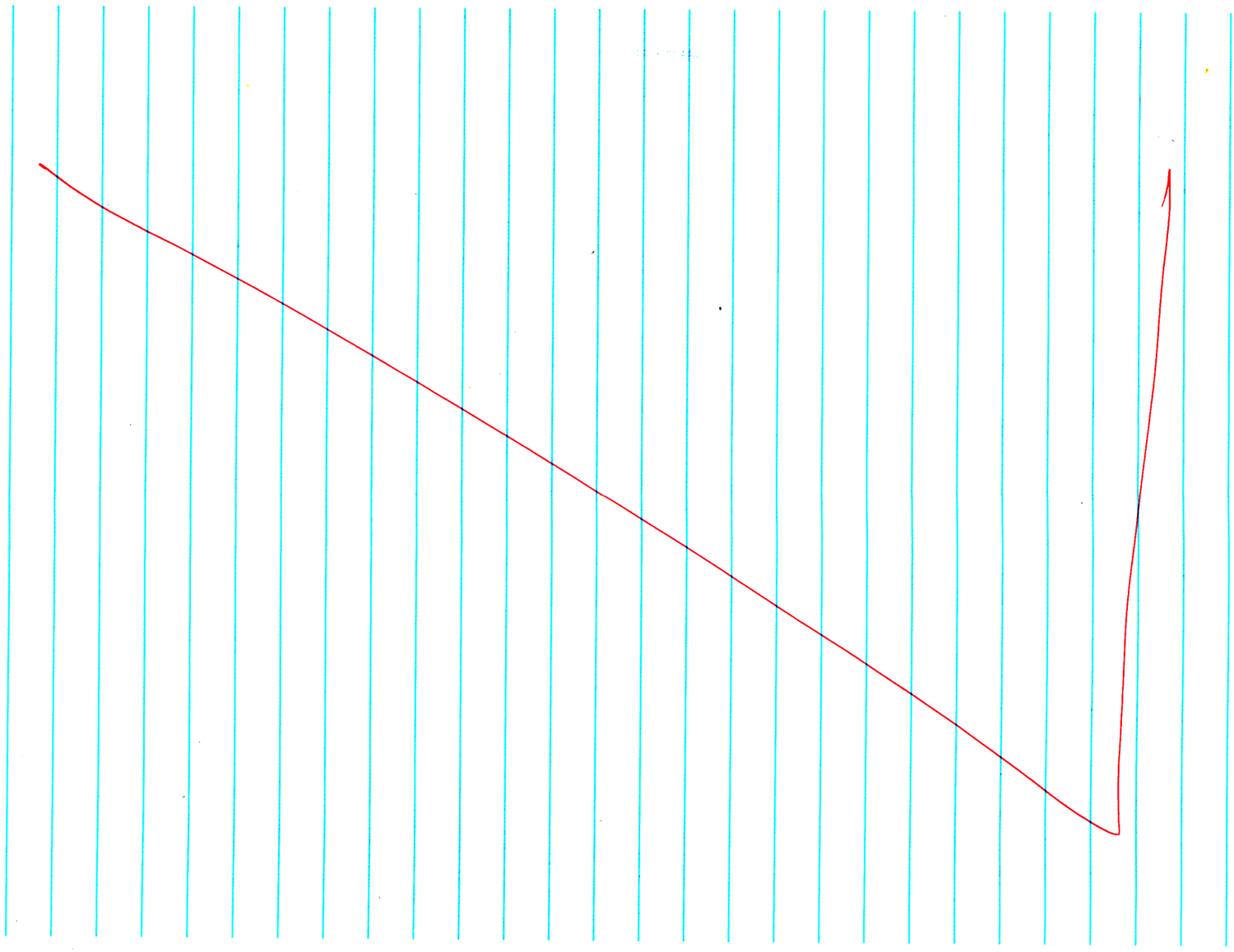
$M_{y,bottom}$= 147,419,399 N-mm = 147.42 KN-m



ϕ_y = 3.556E-05 rad/mm
ϕ_y = 3.556E-02 rad/m

K_{y7} = 1284.20

7-24-05



CALCULATION OF My CONSIDERING YIELD STRAIN IN OUTER FIBER OF Tit-24

Beam Center Section, Configuration 2

b_1 =	138 mm	y1 =	10 mm	$E_{Tit\ 24}$ =	107000 MPa	$E_{Tit\ 7}$ =	101000 MPa
h_1 =	20 mm			$F_{y,Tit\ 24}$ =	658.1 MPa	$F_{y,Tit\ 7}$ =	174.1 MPa
b_2 =	38 mm	y2 =	55 mm	$F_{u,Tit\ 24}$ =	827 MPa	$F_{u,Tit\ 7}$ =	299.5 MPa
h_2 =	70 mm			$d_{y,Tit\ 24}$ =	0.00615	$d_{y,Tit\ 7}$ =	0.00172
b_3 =	230 mm	y2 =	97.5 mm	$E_{hard\ T24}$ =	1890 MPa	$E_{hard\ T7}$ =	696.6 MPa
h_3 =	15 mm			$d_{u,Tit\ 24}$ =	0.0953	$d_{u,Tit\ 7}$ =	0.1823

neutral axis = 38.02 mm **Requires iteration until Sum of Forces is equal to zero**

h tot =	105.00 mm						
h - y =	66.98 mm	Strain at	66.98	=	0.01084	(h =	105.00 mm)
h1+h2-y =	51.98 mm	Strain at	51.98	=	0.00841	(h =	90 mm)
y - h1 =	18.02 mm	Strain at	18.02	=	0.00291	(h =	15 mm)

7-29-05

Tit 7 stress at	105.00	=	180.45 MPa
Tit 7 stress at	90.00	=	178.76 MPa
Tit 24 stress at	90.00	=	662.37 MPa
Tit 24 stress at	15.00	=	311.89 MPa

	Stress top	Stress bottom	Stress Average	h	b	Force (N)	Arm	Moment
C7 (flange)	180.45	178.76	179.60	15.00	230	619,636	59.49	36.86 KN-m
C24a (web)	662.37	658.10	660.23	13.96	38	350,357	45.01	15.77 KN-m
C24b (web)	658.10	0.00	329.05	38.02	38	475,370	25.35	12.05 KN-m
T24a (web)	0.00	311.89	155.95	18.02	38	106,772	12.01	1.28 KN-m
T24b (flange)	311.89	658.10	485.00	20.00	138	1,338,590	29.21	39.10 KN-m

neutral axis for a trapezoide

a	b	y
178.76	180.45	7.51
658.10	662.37	6.99
0.00	658.10	25.35
0.00	311.89	12.01
311.89	658.10	11.19

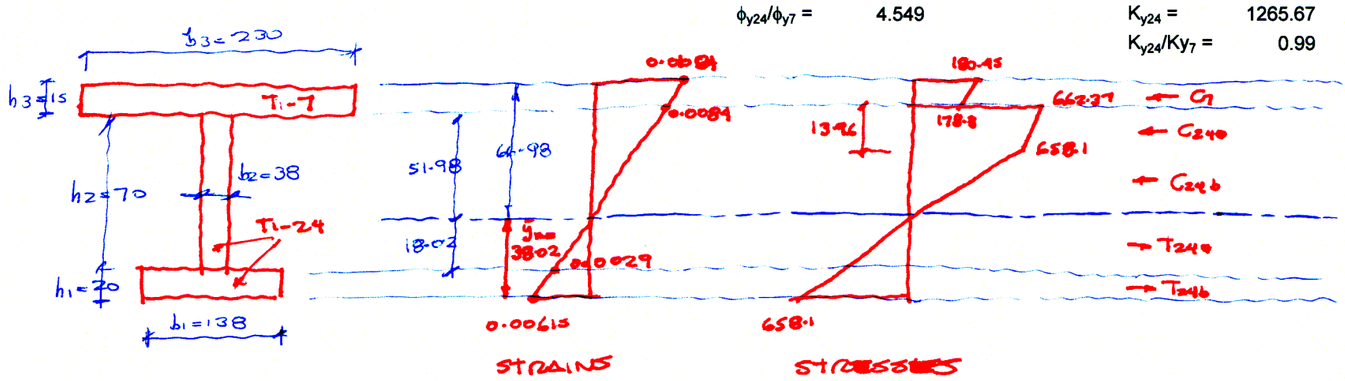
Sum =	0	M_p =	**105.06** KN-m
		ϕ_y =	**0.161767** rad/m

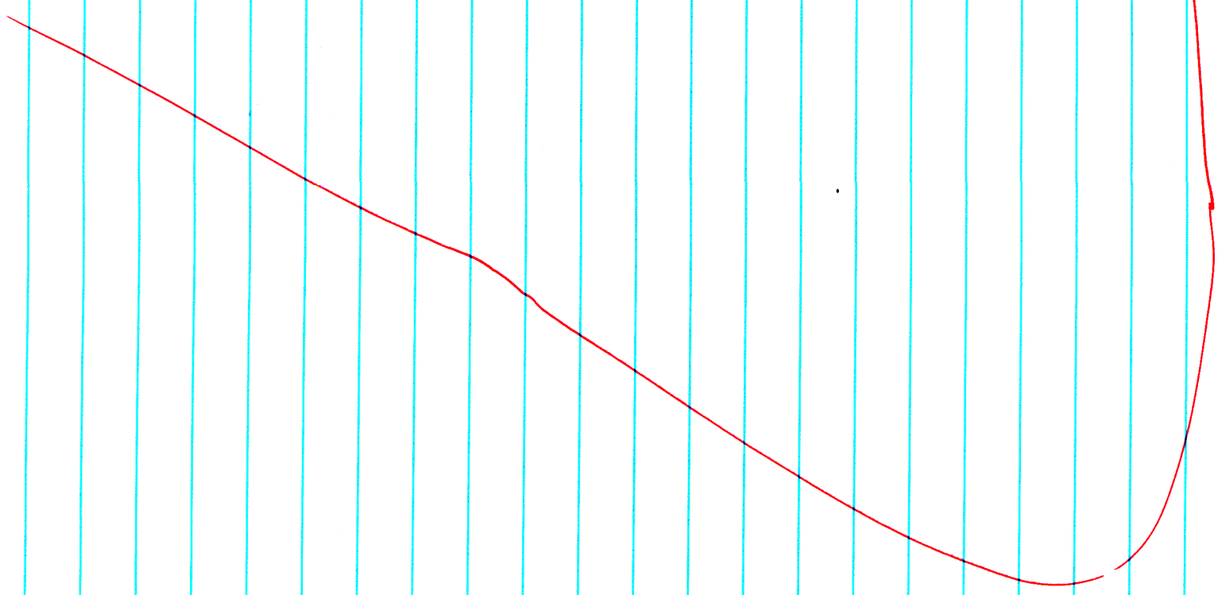
Right Assumption of neutral axis

Tit. 7 has not failed, Right Assumption

M_{y24}/M_{y7} =	2.300
ϕ_{y24}/ϕ_{y7} =	4.549

K_{y7} =	1284.20
K_{y24} =	1265.67
K_{y24}/Ky_7 =	0.99





A summary of all moment-curvature data is shown in page 28. The bending moments are presented also as normalized by the moment of yielding of T1-7 (M_{y7}) because this is the manner in which SAP2000 processes this information.

CALCULATION OF "M_p" CONSIDERING RUPTURE IN top OUTER FIBER OF Tit-24
Beam Center Section, Configuration 1

b_1 =	138 mm	y1 =	10 mm	$E_{Tit\ 24}$ =	107000 MPa	$E_{Tit\ 7}$ =	101000 MPa
h_1 =	20 mm			$F_{y,Tit\ 24}$ =	658.1 MPa	$F_{y,Tit\ 7}$ =	174.1 MPa
b_2 =	38 mm	y2 =	55 mm	$F_{u,Tit\ 24}$ =	827 MPa	$F_{u,Tit\ 7}$ =	299.5 MPa
h_2 =	70 mm			$d_{y,Tit\ 24}$ =	0.00615	$d_{y,Tit\ 7}$ =	0.00172
b_3 =	230 mm	y2 =	97.5 mm	$E_{hard\ T24}$ =	1890 MPa	$E_{hard\ T7}$ =	696.6 MPa
h_3 =	15 mm			$d_{u,Tit\ 24}$ =	0.0953	$d_{u,Tit\ 7}$ =	0.1823

Strain at h= 110 mm is given as **0.0953**

neutral axis = 35.293 mm **Requires iteration until Sum of Forces is equal to zero**

h tot = 105.00 mm
h - y = 69.71 mm
h1+h2-y = 54.71 mm
y - h1 = 15.29 mm
Yield of tit 24 3.53 mm

Strain at 105.00 = 0.12143 (h = 105.00 mm)
Strain at 35.29 = 0.06148 (h = 0.0000 mm)
Strain at 15.29 = 0.02664 (h = 15 mm)

Tit 7 stress at 105.00 = 257.49 MPa
Tit 7 stress at 110.00 = 239.29 MPa
Tit 24 stress at 0.00 = 762.67 MPa
Tit 24 stress at 15.00 = 696.83 MPa

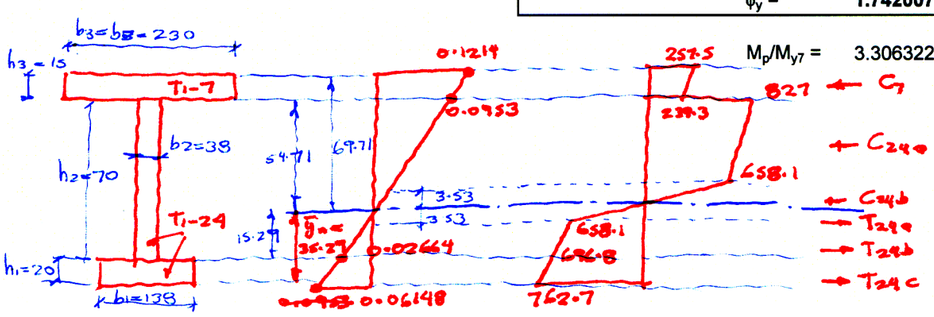
	Stress top	Stress bottom	Stress Average	h	b	Force (N)	Arm	Moment
C7 (flange)	257.49	239.29	248.39	15.00	230	856,942	62.30	53.39 KN-m
C24a (web)	827.00	658.10	742.55	51.18	38	1,444,045	30.09	43.45 KN-m
C24b (web)	658.10	0.00	329.05	3.53	38	44,144	2.35	0.10 KN-m
T24a (web)	0.00	658.10	329.05	3.53	38	44,144	2.35	0.10 KN-m
T24b (web)	658.10	696.83	677.46	11.76	36	286,874	9.47	2.72 KN-m
T24c (flange)	696.83	762.67	729.75	20.00	138	2,014,113	25.44	51.25 KN-m

neutral axis for a trapezoide

a	b	y
239.29	257.49	7.59
658.10	827.00	26.56
0.00	658.10	2.35
0.00	658.10	2.35
658.10	696.83	5.94
696.83	762.67	10.15

Sum =	0	M_p =	**151.01** KN-m
		ϕ_y =	**1.742007** rad/m

Right Assumption of neutral axis



M_p/M_{y7} = 3.306322 ϕ_p/ϕ_{y7} = 48.98185 K_{p24}/K_{y7} = 0.0226
K_{p24} = 29.07 K_{p24}/K_{y24} = 0.0230

7-29-05

BEAM SECTIONS

Section	Section Thick.(mm)	P_y (KN)	M_{y7} (KN-m)	ϕ_{y7}	K_{y7}	M_{y24} (KN-m)	ϕ_{y24}	K_{y24}	K_{y24}/K_{y7}	M_{y24}/M_{y7}	ϕ_{y24}/ϕ_{y7}
Center	105	4168	45.7	0.0356	1284	105.06	0.1618	470.59	0.37	2.30	4.55
Transition	110	4484	61.8	0.0384	1607	123.32	0.1355	633.95	0.39	2.00	3.53
Corner	135	5109	86.0	0.0313	2751	172.43	0.1103	1093.99	0.40	2.00	3.53

COLUMN SECTIONS

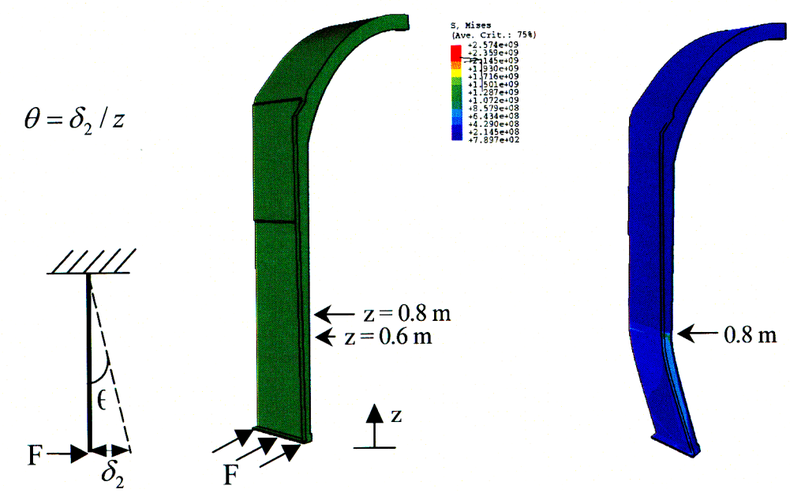
	Section Thick.(mm)	P_y (KN)	M_{y7} (KN-m)	ϕ_{y7}	K_{y7}	M_{y24} (KN-m)	ϕ_{y24}	K_{y24}	K_{y24}/K_{y7}	M_{y24}/M_{y7}	ϕ_{y24}/ϕ_{y7}
C1	45.36	2694	15.0	0.1271	118	21.45	0.2144	73.56	0.62	1.43	1.69
C2	50.69	2937	18.6	0.1133	164	27.00	0.1906	109.03	0.67	1.45	1.68
C3	56.02	3177	22.3	0.1013	220	33.12	0.1726	152.41	0.69	1.49	1.70
C4	61.35	3410	25.9	0.0908	285	39.72	0.1587	203.42	0.71	1.53	1.75
C5	66.67	3639	29.5	0.0816	361	46.76	0.1475	262.23	0.73	1.59	1.81
C6	72.00	3862	32.8	0.0735	446	53.99	0.1390	323.47	0.72	1.64	1.89
C7	77.33	4076	35.8	0.0663	540	59.67	0.1363	341.08	0.63	1.67	2.06
C8	86.25	4285	38.4	0.0599	641	65.46	0.1330	370.34	0.58	1.70	2.22
C9	87.98	4486	40.5	0.0542	746	71.27	0.1296	408.92	0.55	1.76	2.39
C10	93.31	5109	46.7	0.0527	885	83.82	0.1119	628.45	0.71	1.80	2.12
C11	98.64	5211	47.4	0.0475	997	89.62	0.1107	668.12	0.67	1.89	2.33
C12	101.30	5257	47.2	0.0450	1049	91.76	0.1112	672.98	0.64	1.94	2.47

M_{p24} (KN-m)	ϕ_{p24}	K_{p24}	K_{p24}/K_{y7}	M_{p24}/M_{y7}	ϕ_{p24}/ϕ_{y7}	M_{p24}/M_{y24}	ϕ_{p24}/ϕ_{y24}
151.01	1.7420	29.07	0.023	3.31	48.98	1.44	10.77
191.86	2.4167	30.05	0.019	3.11	62.88	1.56	17.83
264.34	1.8192	53.78	0.020	3.07	58.17	1.53	16.50

M_{p24} (KN-m)	ϕ_{p24}	K_{p24}	K_{p24}/K_{y7}	M_{p24}/M_{y7}	ϕ_{p24}/ϕ_{y7}	M_{p24}/M_{y24}	ϕ_{p24}/ϕ_{y24}
36.41	3.5261	4.52	0.038	2.42	27.74	1.70	16.45
44.99	3.2231	5.93	0.036	2.42	28.44	1.67	16.91
54.23	2.9722	7.54	0.034	2.44	29.33	1.64	17.22
66.82	3.1247	9.14	0.032	2.58	34.42	1.68	19.69
74.31	2.5877	11.29	0.031	2.52	31.70	1.59	17.54
85.02	2.4372	13.50	0.030	2.59	33.15	1.57	17.54
96.01	2.3082	16.73	0.031	2.68	34.81	1.61	16.94
107.24	2.1957	20.25	0.032	2.79	36.63	1.64	16.51
118.58	2.0977	24.04	0.032	2.93	38.68	1.66	16.19
138.90	1.8592	31.52	0.036	2.98	35.26	1.66	16.62
149.68	1.8185	35.17	0.035	3.16	38.24	1.67	16.42
154.66	1.8011	37.22	0.035	3.27	39.98	1.69	16.20

7-28-05

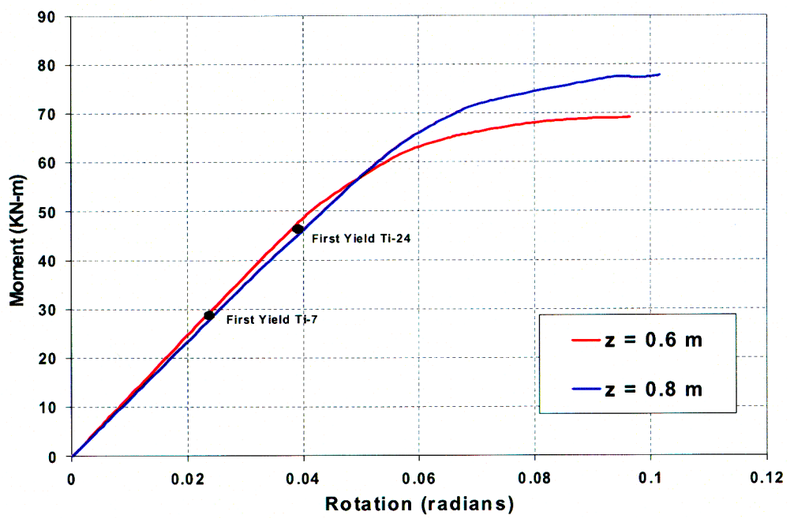
In addition to the moment-curvature relationships obtained from mechanics of materials formulation, moment-rotation (M-θ) curves were obtained from the ABAQUS FEM. Scientific notebook (SN) #391 shows the moment-rotation curve for the DS corner section. Below are (LS, 7-29-05) presented the moment-rotation curves for critical DS column sections. The M-θ curves are calculated at heights of 0.6 and 0.8 m (from the DS base). Although the DS FEM is used, the boundary conditions are modified. Then, the nodes above these critical locations are fixed in all degrees of freedom, which results in a cantilever beam (see figure below)



The resulting moment-rotation curves are presented in this page. For both critical locations the yielding of Ti-7 & Ti-24 occurs at about the same place ($M_{y_{Ti-7}} \approx 29$ KN-m, $M_{y_{Ti-24}} \approx 46$ KN-m). These values compare well with the moments obtained from the strength of materials formulation (C4 and C5 in table of page 28).

The ultimate moments (equivalent to moment when Ti-24 reaches the ultimate strain in the critical fibers*') of 69 KN-m and 77 KN-m for the heights of z = 0.6 and 0.8 m, respectively, also compares well with the results of page 28.

It is also noted that the initial slope of the M-Θ curve is not largely affected by the yielding of Ti-7. Also, the rotation



*' for the case of strength of materials formulation.

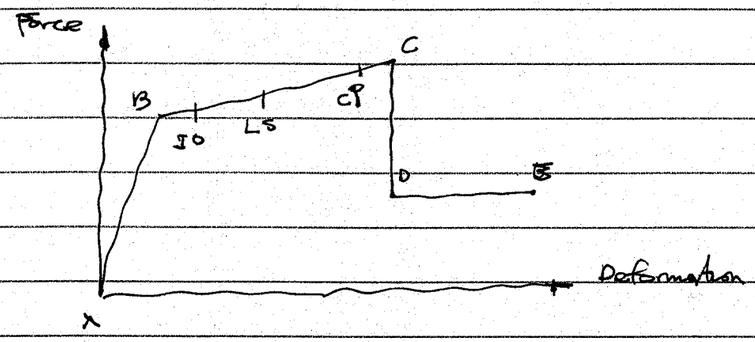
at failure is approximately 2.5 - 3 times the rotation when Ti-24 yields. These trends are also observed in the M-Θ curve of the DS corner section (SN #391).

For the implementation of the M-Θ curves in the nonlinear rotational springs of SAP2000 (see figure of page 12), the slope of the initial segment is reduced to 95% of the elastic one, and the rotation at the peak bending strength is 2.5 times $\Theta_{y_{Ti-24}}$

The negative slope segment has a steep slope to represent the expected brittle failure of the Ti-24 material.

The force-deformation for springs (LS, 7-21-05) in SAP2000 is based on the pushover procedures prescribed in the

FEMA results (ref 6). In this force-deformation criteria, there is an immediate occupancy (IO), life safety (LS), and collapse prevention (CP) thresholds. Nevertheless, these points are not required in the DS analysis. The curve proposed in FEMA and SAP2000 is as follows



Consequently, several of the color labels presented in the deformed shapes of the DS do not have a physical meaning, and should be ignored.

7-29-05

Ref. 6:
Federal Emergency Management Agency. "Prestandard and Commentary for the Seismic Rehabilitation of Buildings." Washington, D.C: FEMA 356, 2000

Aug 1, 2005

The moments of yielding of T1-7, T1-24 and peak of the backbone curve are presented in the table of this page, as well as the ratio of the above bending moments with respect to yield moment of T1-7. The rotations have been set at the same values for all the springs. As shown in Figure of page 31, $\theta_{y,T1-24}$ depends only on the ratio M_{y24}/M_{y7}, because the stiffness slope after $M_{y,T1-7}$ is 95% of the initial one. Also, θ_p has been set as $2.5\,\theta_{y,T1-24}$.

Beam Sections

Section Label	Section Dept (mm)	Titanium Grade 7 Plate Width (mm)	Titanium Grade 7 Plate Thickness (mm)	M_{y7} (KN-m)	M_{y24} (KN-m)	M_{p24} (KN-m)	M_{y24}/M_{y7}	M_{p24}/M_{p7}	M_{p24}/M_{y24}
Center	105	230	15.0	45.7	105.1	151.0	2.30	3.31	1.44
Transition	110	230	27.7	61.8	123.3	191.9	2.00	3.11	1.56
Corner	135	230	27.7	86.0	172.4	264.3	2.00	3.07	1.53

8-1-05

Column Sections

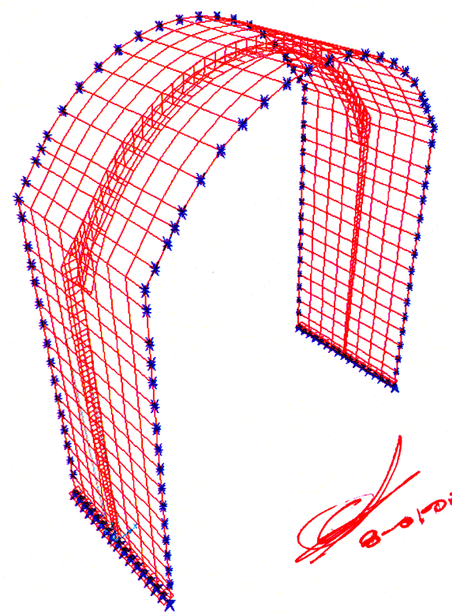
Section Label	Section Dept (mm)	Titanium Grade 7 Plate Width (mm)	Titanium Grade 7 Plate Thickness (mm)	M_{y7} (KN-m)	M_{y24} (KN-m)	M_{p24} (KN-m)	M_{y24}/M_{y7}	M_{p24}/M_{p7}	M_{p24}/M_{y24}
C1 (base)	45.36	450	15.0	15.0	21.5	36.4	1.43	2.42	1.70
C2	50.69	441	15.0	18.6	27.0	45.0	1.45	2.42	1.67
C3	56.02	431	15.0	22.3	33.1	54.2	1.49	2.44	1.64
C4	61.35	418	15.0	25.9	39.7	66.8	1.53	2.58	1.68
C5	66.67	404	15.0	29.5	46.8	74.3	1.59	2.52	1.59
C6	72.00	387	15.0	32.8	54.0	85.0	1.64	2.59	1.57
C7	77.33	367	15.0	35.8	59.7	96.0	1.67	2.68	1.61
C8	86.25	345	15.0	38.4	65.5	107.2	1.70	2.79	1.64
C9	87.98	320	15.0	40.5	71.3	118.6	1.76	2.93	1.66
C10	93.31	282	27.7	46.7	83.8	138.9	1.80	2.98	1.66
C11	98.64	248	27.7	47.4	89.6	149.7	1.89	3.16	1.67
C12 (top)	101.3	230	27.7	47.2	91.8	154.7	1.94	3.27	1.69

EQUIVALENT WIDTHS, b_E

The equivalent widths have been obtained from calibrating the DS frame model with a DS FEM developed in SAP2000. Also, the DS column b_E has been tuned up using a cantilever beam obtained from the original FEM created in ABAQUS.

A FEM of the complete transverse section was created in SAP2000 to obtain b_E. The SAP2000 FEM is an elastic system modeled with four-node shell elements (see Figure in this page). The elements are further subdivided automatically into 3x3 meshes.

The boundary conditions include a pin constrain at the base and ~~no~~ LE 8-1-05 springs are not included to account for DS-rubble interaction



By comparing the displacement, and forces and vibrational modes of the SAP2000 frame model, and the SAP2000 FEM; it was obtained a constant equivalent width of b_E = 230 mm.

It was observed, however, that the overall (global) response of the DS system was not very sensitive to modifications of b_E in the lower part of the columns, which were LE 8-1-05

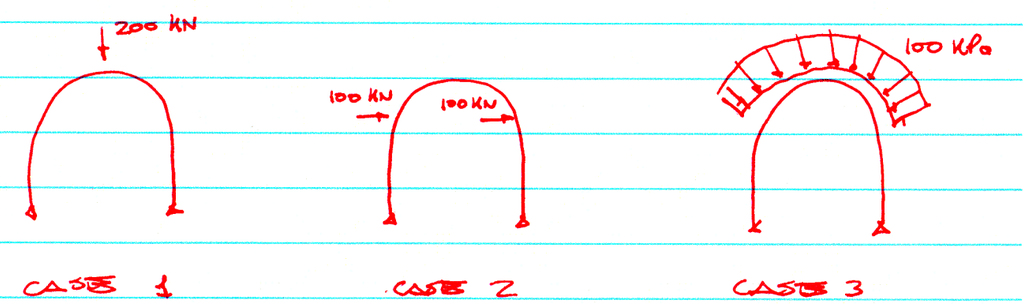
the critical sections of the DS.

For these reasons, a tune-up of the DS columns was performed by comparing cantilever DS columns' results from LE 8-1-05 the ABAQUS FEM and from the SAP2000 frame model. Based on both model calibrations, the equivalent width for the DS roof was set as b_E = 230 mm, whereas b_E for the DS columns is summarized in the third column of table of page 35.

Comparison of some critical displacements is shown in the table of this page. The load cases are also shown in this page

Table A–2. Displacements Comparison for SAP2000 Finite Element Model and SAP2000 Frame Model

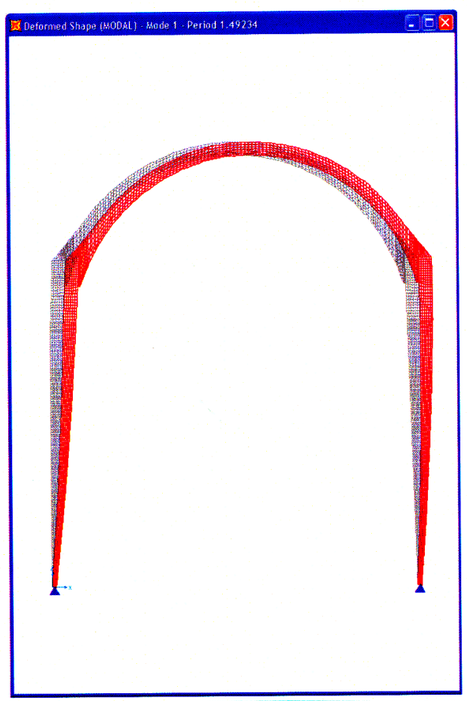
Loading Case	Displacement (mm)		
	SAP2000 Finite Element Model	SAP2000 Frame Model	T_{frame}/T_{FEM}
Case 1—Vertical Displacement at Crown Apex	-20.0	-19.9	1.00
Case 1—Horizontal Displacement at Left Drip Shield Corner	-14.8	-14.6	0.99
Case 2—Horizontal Displacement at Drip Shield Corner	407.9	414.2	1.02
Case 3—Vertical Displacement at Crown Apex	-8.9	-8.8	0.99
Case 3—Horizontal Displacement at Drip Shield Corner	-7.4	-7.0	0.95

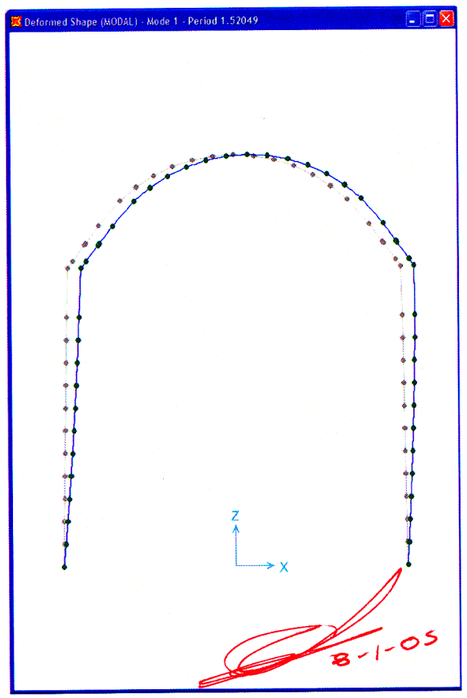


The displacement comparison shows good agreement. On the other hand, the vibrational modes are also compared, obtaining a difference of 2% for the first mode (see table in this page).

Vibrational Mode	Vibrational Period (Second)		
	SAP2000 Finite Element Model	SAP2000 Frame Model	T_{frame}/T_{FEM}
First Mode	1.52	1.49	1.02
Second Mode	0.24	0.22	1.09
Third Mode	0.09	0.08	1.11

The first vibrational mode is compared below for the DS frame model and the SAP2000 FEM

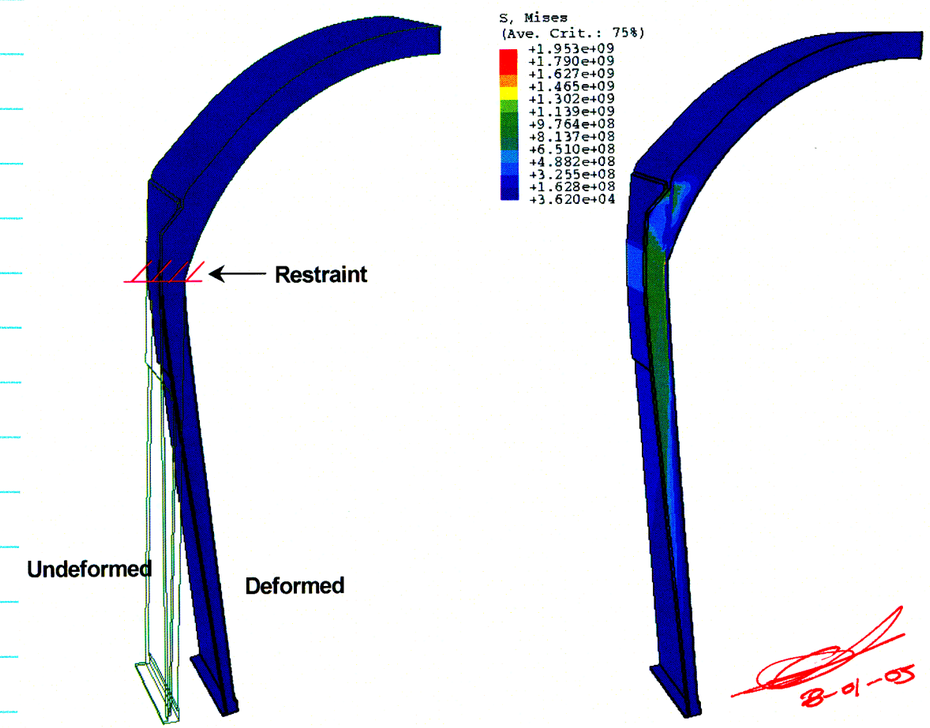




8-1-05

Note that the mesh in the graphs of page 36 has been refined automatically using the automatic mesh subdivision command of SAP2000 (compare with graph of page 34).

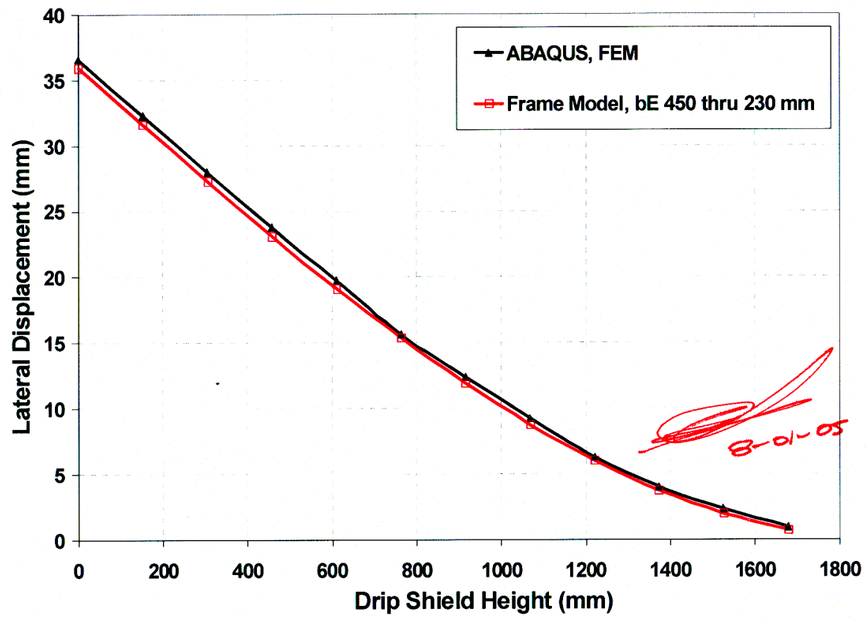
For the second stage of the calibration, the DS boundary conditions were modified, and a fixed restraint (no displacements allow in any degree of freedom) was implemented, as presented in the figure of this page.



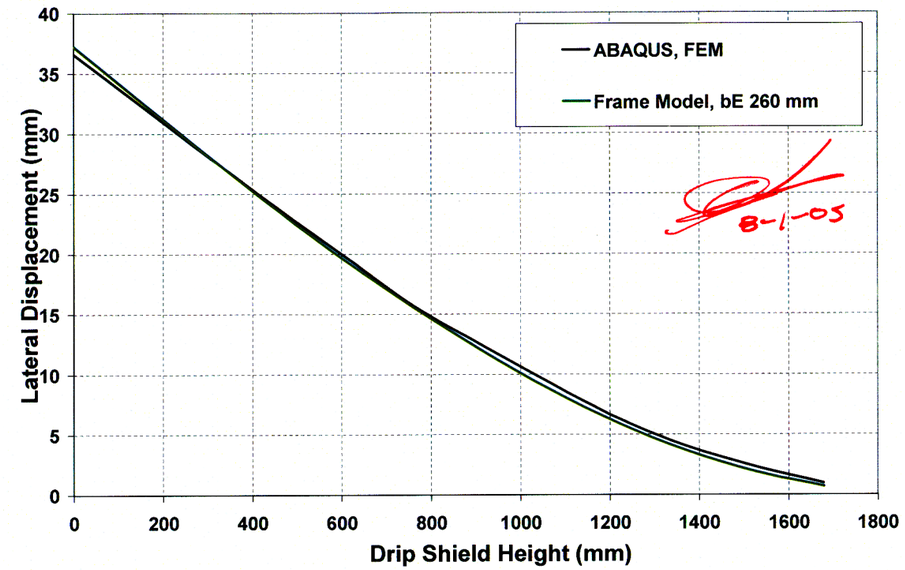
8-01-05

As observed, a cantilever beam was generated by modifying the boundary conditions. Then, a lateral uniform pressure of 20 kPa was applied.

The figure of this page presents the lateral displacement of the DS column as a function of the DS height ("0" corresponds to the DS base). Good correlation is observed.

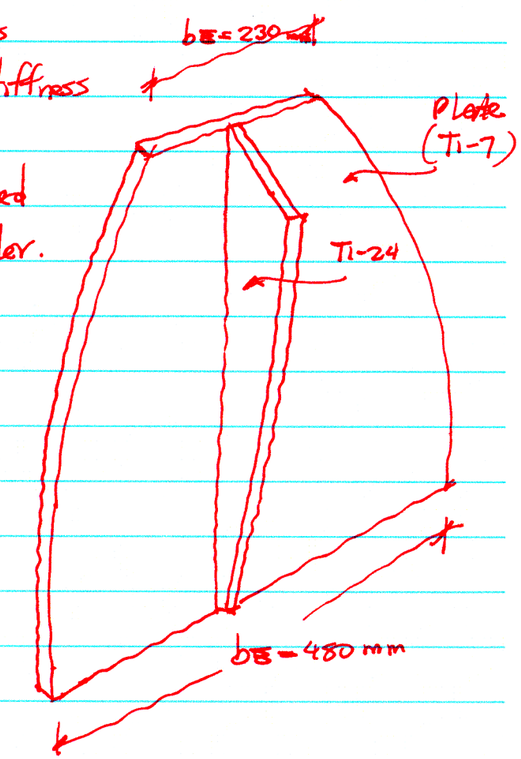


The figure of page 39 shows the same relationship for the first stage of the calibration, where all bE's were equal to 260 mm. As observed, the displacements still look similar. However, it is evident that ~~at~~ LE 8-1-05 close to the DS base (height close to 0 mm), the displacements of the frame model become more flexible than those of the FEM, whereas the opposite occurs for lateral displacements closer to the ~~roof~~ crown 8-1-05 LE of the DS.



Then, because the Ti-24 component (the "support beam") is not prismatic, the bE varies along the DS column. The stiffness contribution will be larger at the base, where the stiffness provided by the Ti-24 component is smaller.

As noted in the isometric shown at the right of these lines, the variation of the bE has not been defined proportional to the height (once the extreme values of bE = 230 and 480 mm are proposed).



The variation of b_E has been the result of one iteration based on the stiffness of the DS column for the first ~~try~~ LE 8-1-05, calibration (where b_E = 260 mm).

The table of this page shows a first column with DS height, corresponding to the node heights of the DS frame model. The second column corresponds to the stiffness of the discrete DS sections when b_E = 260 mm for all sections. The third column is the equivalent width that is directly (linearly) proportional to the elastic stiffness provided in the second column.

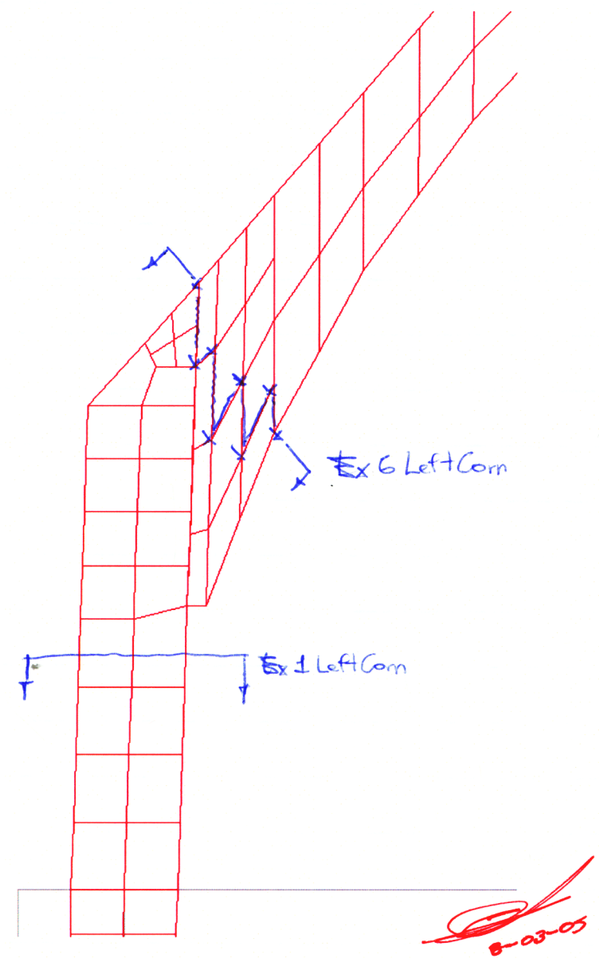
DS Height (mm)	Elastic Stiffness	Equivalent width
1678.0	1097.8	**230.0**
1525.5	1014.4	248.4
1372.9	859.7	282.4
1220.4	689.6	319.9
1067.8	576.3	344.8
915.3	475.7	367.0
762.7	386.8	386.6
610.2	309.1	403.7
457.6	242.3	418.4
305.1	185.3	430.9
152.6	137.7	441.4
0.0	98.8	**450.0**

8-01-05

8-01-05

* COMPARISON OF END FORCES

The FEM in SAP2000 has the option of providing the end forces (shear, moments) for defined section cuts. Then, some of the bending moments obtained in the SAP2000 frame model have been compared with those generated by the section cut forces option. The most representative section cuts are shown below.



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