DMJM HARRIS
999 TOWN & COUNTRY ROAD
ORANGE, CALIFORNIA 92668

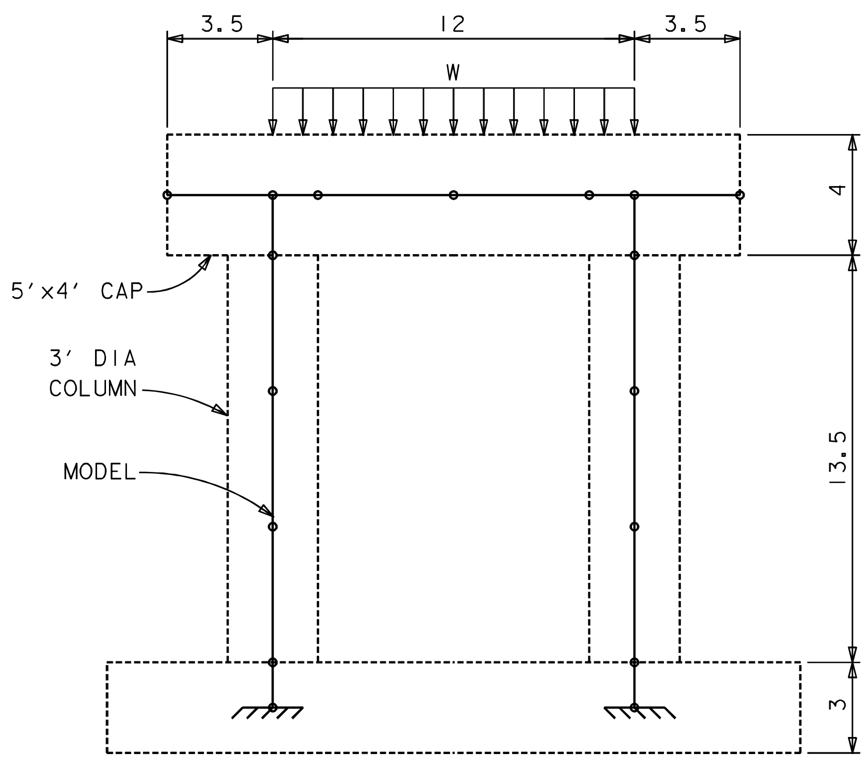
DESCRIPTION

Nonlinear static (pushover) analysis will be performed on a railroad bridge bent using several methods to determine its ultimate lateral deflection capability.

1. SAP2000 Nonlinear with axial-moment interaction hinges and default properties
2. SAP2000 Nonlinear with moment hinges based on Caltrans material properties
3. SAP2000 Nonlinear with axial-moment interaction hinges based on AASHTO/AREMA material properties

ANALYSIS MODEL

The analysis model configuration shown below will be used with all methods.



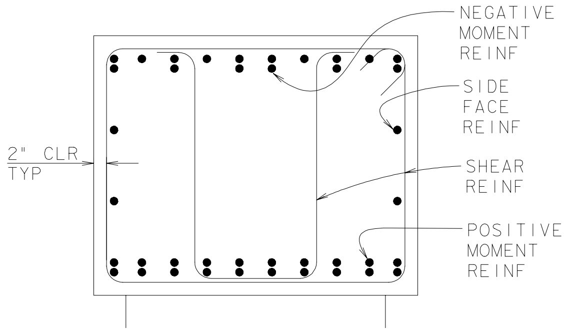
BENT MODEL

Superstructure load, w = 653 / 12 = 54.42 k/ft

CHECKED____________ DATE____________	DMJM HARRIS	JOB NO.____________	
APPROVED____________ DATE____________	999 TOWN & COUNTRY ROAD ORANGE, CALIFORNIA 92668	SHEET____________	OF____________
TITLE **PUSHOVER ANALYSIS EXAMPLE**		BY R. MATTHEWS	DATE 5/21/01

MEMBER PROPERTIES

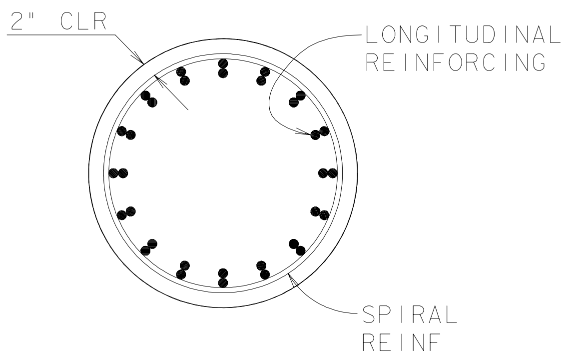
- CAP



BENT CAP SECTION

width = 5 ft.
height = 4 ft.
Area = 4 x 5 = 20 ft^2
$I_g = 5(4)^3 / 12 = 26.67\ ft^4$
Use $I_e = 0.75 \times 26.67 = 20\ ft^4$
Use 10 x I_e at joint area

- COLUMN



COLUMN SECTION

diameter = 3 ft.
radius = 13.875" to centerline longitudinal reinforcement
Area = 3.1416 x (1.5)2 = 7.07 ft^2
$I_g = 3.1416 \times (1.5)^4 / 4 = 3.976\ ft^4$
Use $I_e = 0.5 \times 3.976 = 1.988\ ft^4$
Use 10 x I_e at joint area

METHOD 1 ANALYSIS

SAP2000 Nonlinear with axial-moment interaction hinges and default properties.

- Procedure:

A. Define model as usual with DEAD load condition

B. Define reinforcement for column frame section

C. Define PUSHY load pattern for push load as static load case

D. Select joint for PUSHY load application and assign joint static load force with unit value (magnitude does not matter, only load configuration).

E. Define static pushover case for DEAD load condition (PUSH1)

- push to load level defined by pattern
- monitor U2 at joint
- no p-delta effects
- add DEAD load pattern

F. Define static pushover case for PUSHY load condition (PUSH2)

- push to displacement magnitude
- monitor U2 at joint
– start from previous pushover (PUSH1)
- no p-delta effects
- add PUSHY load pattern

G. Select column elements for bottom hinges

- assign frame hinges
– add default PMM at relative distance

H. Select column elements for top hinges

- assign frame hinges
– add default PMM at relative distance

I. Run model

J. Run static pushover from analyze menu

K. Display static pushover curve

- to save pushover curve

  select File – Display Tables
  select File – Print Tables to File

L. Display deformed shape for PUSH2

- display steps and watch hinges change color to indicate stress level

M. Display element forces at frames to view moment, shear and axial forces

N. Print output tables to save hinge output

- Default axial-moment interaction (PMM) hinges

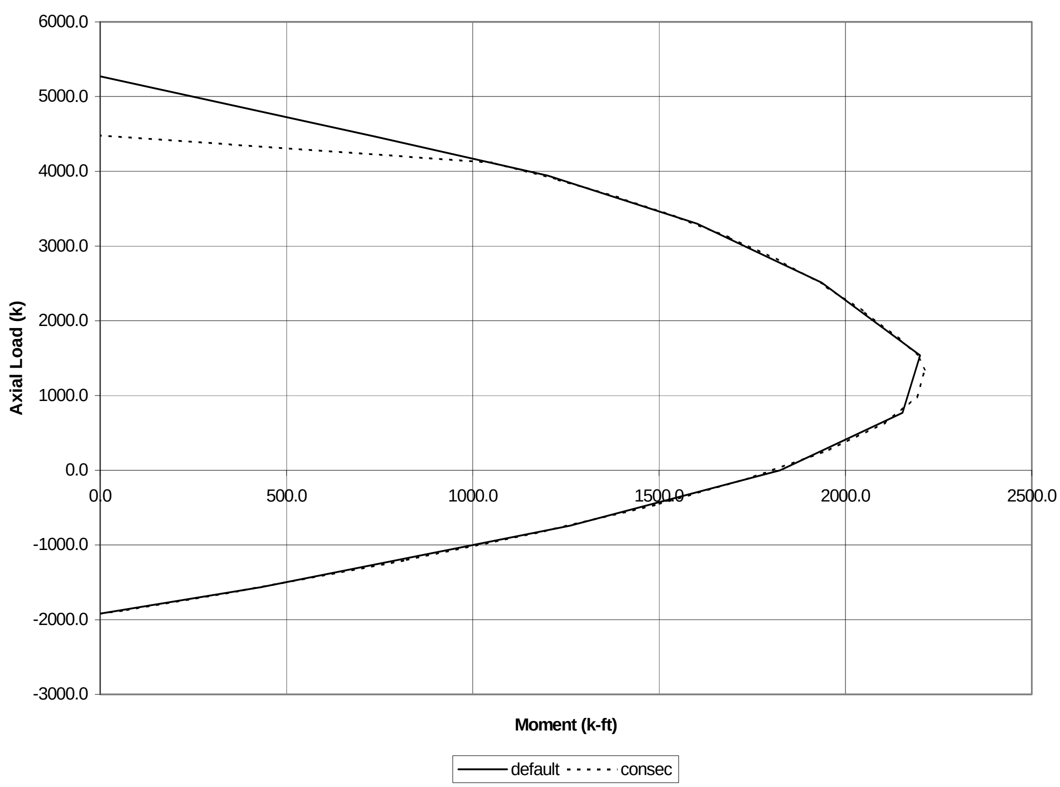
The default PMM hinges are based on recommendations from ATC 40. The nominal axial-moment interaction curve is used (See spreadsheet and chart below for comparison).

Pscale = 5272
Mscale = 2200

SAP 2000 default interaction			
M	default	M	default
0	1	0.0	5272.0
0.335	0.8473	737.0	4467.0
0.5463	0.7474	1201.9	3940.3
0.7282	0.6258	1602.0	3299.2
0.8799	0.4764	1935.8	2511.6
1	0.2917	2200.0	1537.8
0.9786	0.1458	2152.9	768.7
0.8296	0	1825.1	0.0
0.5728	-0.1411	1260.2	-743.9
0.1972	-0.2966	433.8	-1563.7
0	-0.3642	0.0	-1920.1

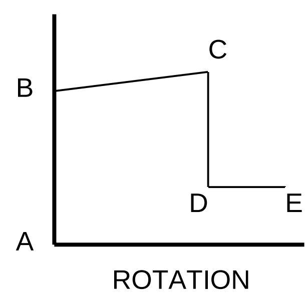
Consec interaction			
c	Mn	consec	
	0	-1920	Maximum tension
1.8	72.3	-1869.2	
3.6	384.4	-1606.1	
5.4	823.4	-1197.9	
7.2	1193.2	-814.4	
9	1501.2	-448.5	
10.8	1755.4	-86.4	
11.22	1805.4	1.7	Pure bending
12.6	1956.9	272.3	
14.4	2106.5	634.5	
16.2	2192.5	986.8	
18	2213.9	1350.2	
18.87	2193.7	1540.7	Balanced strain
19.8	2145.1	1756.8	
21.6	2046.2	2137.7	
23.4	1937.4	2491.7	
25.2	1819.7	2813.5	
27	1687.4	3118.6	
28.8	1543.9	3394.7	
30.6	1390.1	3652.2	
32.4	1222	3898.3	
34.2	1051.3	4117.3	
	0	4481.2	Maximum comp

Axial-Moment Interaction Comparison



The moment values for a given axial load are modified depending on the rotation as shown in the table below.

POINT	MOMENT/SF	ROTATION/SF
A	0.0	0.0
B	1.0	0.0
C	1.1	0.015
D	0.2	0.015
E	0.2	0.025

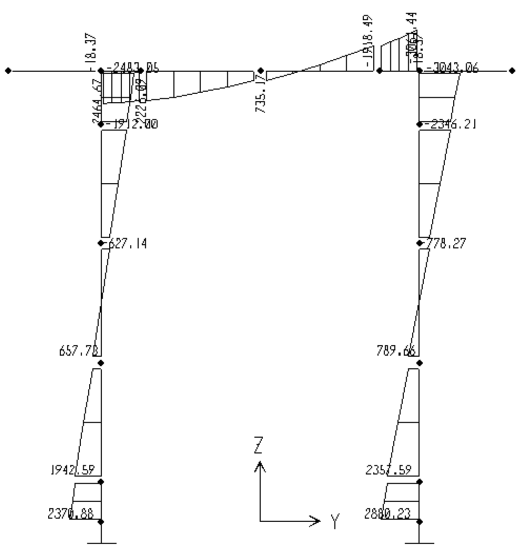


- Pushover analysis results

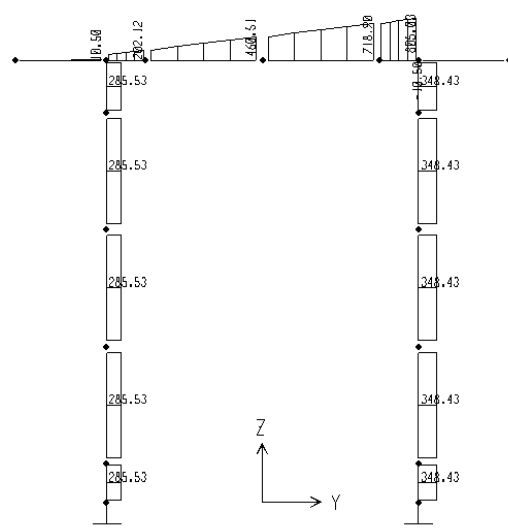
SAP2000N file = push1.sdb
Pushover curve file = push1_pd.txt

Ultimate deflection = 0.27 ft. at step 12
Maximum lateral force = 634 kips
Axial loads = 87 kip (tension) / 834 kips (compression)

The moment and shear diagrams at step 12 are shown below.



MOMENT DIAGRAM



SHEAR DIAGRAM

METHOD 2 ANALYSIS

SAP2000 Nonlinear with moment hinges and based on Caltrans material properties.

- Procedure:

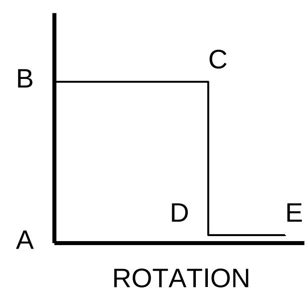
A. Perform METHOD 1 analysis to approximate final axial loads in columns.

B. Perform moment-curvature analysis using material properties from Caltrans Seismic Design Criteria section 3.2. This analysis will determine the plastic moment and rotation of the column hinges.

C. Define hinge properties for each column

- select Default-M3 and define new property
– uncheck default M3 and modify
– uncheck "use yield moment" and "use yield rotation"
– fill in spreadsheet values as follows

POINT	MOMENT/SF	ROTATION/SF
A	0.0	0.0
B	M_p	0.0
C	M_p	θ_p
D	[1]0.0	θ_p
E	[1]0.0	[2]θ_p



1. solution may converge quicker using $0.1M_p$
2. solution may converge quicker using $2 \times \theta_p$

D. Select / assign column element hinges

E. Perform steps I through N of METHOD 1 analysis

- Moment-curvature analysis

Use CONSEC program

P = -87 kips (file = push2_mc2.out)
P = 834 kips (file = push2_mc1.out)

CONSEC results (see output):

COLUMN	LOAD	Icr	Mp	ϕyi	ϕu	Lp
1	-87	42152	2295	0.00018151	0.0022685	24.5
2	834	47150	2775	0.00019621	0.0018254	24.5

θp1 = 24.5(.0022685 - .00018151) = 0.0511
θp2 = 24.5(.0018254 - .00019621) = 0.0399

```
* * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                   *
*           P R O G R A M   C O N S E C             *
*                                                   *
*                 INPUT DATA ECHO                   *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *
4/26/01, 11:15 am FILE = PUSH2_MC2.OUT

S T R E S S - S T R A I N   I N F O R M A T IO N
=====================================================

CONCRETE MODEL:

     Mander concrete model

          Unconfined strain     = 0.002
          Unconfined stress     = 5200
          Modulus of elasticity = 3600000
          Ultimate strain       = 0.02288
          Ultimate stress       = 0
          Spalling strain       = 0.005
          Confined stress       = 8595.5

          Spiral confinement:

               Bar diameter      = 0.75
               Long spacing      = 3
               Concrete cover    = 2.44
               Yield strength    = 68000
               Ultimate strain   = 0.09
               Spiral diameter   = 31.1

REINFORCING MODEL:

    Park reinforcing model
    (with complex strain hardening)

         Point     Strain    Stress

          1        -0.09     -95000
          2        -0.0125   -68000
          3        -0.0023   -68000
          4         0.0023    68000
          5         0.0125    68000
          6         0.09      95000
```

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C O N C R E T E   C O N F I G U R A T I O N

1 CIRCULAR SECTIONS:

Ycenter	Radius	Add
18	18	1

R E I N F O R C I N G   C O N F I G U R A T I O N

1 REINFORCING ARCS:

Ycenter	Radius	Abeg	Atot	Nbar	Abar
18	13.87	0	348.75	32	1

L O A D   C O N D I T I O N S

(Units = K-ft)

1 LOAD CONDITIONS:

No	Axial	Moment	Shear	Torsion
1	-87.0	0.0	0.0	0.0

M E M B E R   P R O P E R T I E S

MEMBER PROPERTIES:

Member length = 162

BOUNDARY CONDITIONS:

Condition	End i	End j
Shear restraint	0	1
Moment restraint	1	1

```
* * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                   *
*           P R O G R A M   C O N S E C             *
*                                                   *
*                   OUTPUT DATA                     *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *
```

S E C T I O N   P R O P E R T I E S
===

GROSS CONCRETE SECTION:

```
     Area    = 1.0179E+03
     Ybar    = 1.8000E+01
     Io      = 8.2448E+04 About concrete CG
```

REINFORCING STEEL:

```
     Area    = 3.2000E+01
     Ybar    = 1.8000E+01
     Io      = 3.0780E+03 About reinf CG
```

TRANSFORMED CONCRETE SECTION:

```
     Area    = 1.2433E+03
     Ybar    = 1.8000E+01
     Inertia = 1.0413E+05
```

M O M E N T   C U R V A T U R E
===

Moments about centroid of gross concrete section
(Units = K-ft)

Load Condition Number 1
Axial Load = -87.0

Strain	c	Axial	Curvature	Moment
0.00010	8.25	-86.8	0.000012	122.3
0.00050	11.30	-86.9	0.000044	550.3
0.00100	11.85	-85.3	0.000084	1081.8
0.00150	12.05	-85.4	0.000124	1574.1
Reinf tens yield				
0.00200	11.57	-86.6	0.000173	1825.4
0.00250	11.07	-85.2	0.000226	1952.1
0.00300	10.66	-86.3	0.000281	2018.0
0.00350	10.35	-86.0	0.000338	2057.4
0.00390	10.15	-85.1	0.000384	2078.1
Reinf comp yield				
0.00400	10.11	-85.8	0.000396	2081.8
0.00450	9.99	-86.7	0.000450	2091.6
0.00500	9.92	-85.7	0.000504	2087.9
0.00510	9.92	-84.8	0.000514	2086.5
Conc spalling				
0.00550	9.90	-86.5	0.000556	2078.0
0.00600	9.89	-85.5	0.000607	2080.7

0.00650	9.88	-84.2	0.000658	2098.1
0.00700	9.87	-86.8	0.000709	2117.9
0.00750	9.89	-84.2	0.000758	2142.2
0.00800	9.91	-84.0	0.000808	2165.6
0.00850	9.90	-85.8	0.000859	2188.4
0.00900	9.89	-84.2	0.000910	2211.8
0.00950	9.87	-86.7	0.000962	2233.1
0.01000	9.88	-84.1	0.001013	2256.9
0.01050	9.87	-84.6	0.001064	2277.8
0.01100	9.86	-84.6	0.001115	2298.0
0.01150	9.86	-85.8	0.001167	2316.6
0.01200	9.86	-84.2	0.001217	2337.1
0.01250	9.85	-86.4	0.001269	2354.2
0.01300	9.86	-84.7	0.001319	2372.7
0.01350	9.85	-86.7	0.001371	2388.3
0.01400	9.86	-85.6	0.001419	2403.7
0.01450	9.88	-85.9	0.001468	2417.1
0.01500	9.89	-86.4	0.001517	2429.6
0.01550	9.91	-86.8	0.001565	2441.9
0.01600	9.92	-86.8	0.001613	2454.2
0.01650	9.94	-83.4	0.001659	2467.7
0.01700	9.96	-83.5	0.001707	2478.6
0.01750	9.96	-86.5	0.001756	2487.7
0.01800	9.98	-85.9	0.001804	2498.2
0.01850	9.99	-85.4	0.001851	2507.9
0.01900	10.01	-85.0	0.001898	2517.1
0.01950	10.02	-83.8	0.001945	2526.6
0.02000	10.03	-86.2	0.001994	2533.6
0.02050	10.05	-84.8	0.002041	2542.3
0.02100	10.06	-83.6	0.002087	2550.4
0.02150	10.07	-85.9	0.002136	2556.4
0.02200	10.08	-83.7	0.002182	2564.8
0.02250	10.09	-84.5	0.002230	2571.6
0.02290	10.09	-84.8	0.002269	2577.1

```
Yield curvature          = 1.2448E-04
Ultimate curvature       = 2.2685E-03
Idealized plastic moment = 2295.3
Maximum tension          = -1767. At moment = 2577.1

Cracked moment of inertia = 4.2152E+04
Based on 1st yield strain = -0.00247

LOCAL MEMBER DUCTILITY:

    Idealized yield curvature = 1.8151E-04
    Plastic hinge length      = 24.5
    Yield deflection          = 0.794
    Ultimate deflection       = 7.817
    Local member ductility    = 9.8
```

```
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*           P R O G R A M   C O N S E C             *
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*                 INPUT DATA ECHO                   *
*                                                   *
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4/26/01, 11:14 am   FILE = PUSH2_MC1.OUT

S T R E S S - S T R A I N   I N F O R M A T IO N
=====================================================

CONCRETE MODEL:

     Mander concrete model

          Unconfined strain     = 0.002
          Unconfined stress     = 5200
          Modulus of elasticity = 3600000
          Ultimate strain       = 0.02288
          Ultimate stress       = 0
          Spalling strain       = 0.005
          Confined stress       = 8595.5

          Spiral confinement:

               Bar diameter      = 0.75
               Long spacing      = 3
               Concrete cover    = 2.44
               Yield strength    = 68000
               Ultimate strain   = 0.09
               Spiral diameter   = 31.1

REINFORCING MODEL:

    Park reinforcing model
    (with complex strain hardening)

         Point     Strain    Stress

          1        -0.09     -95000
          2        -0.0125   -68000
          3        -0.0023   -68000
          4         0.0023    68000
          5         0.0125    68000
          6         0.09      95000
```

C O N C R E T E   C O N F I G U R A T I O N

===

1 CIRCULAR SECTIONS:

Ycenter	Radius	Add
18	18	1

R E I N F O R C I N G   C O N F I G U R A T I O N

===

1 REINFORCING ARCS:

Ycenter	Radius	Abeg	Atot	Nbar	Abar
18	13.87	0	348.75	32	1

L O A D   C O N D I T I O N S

===

(Units = K-ft)

1 LOAD CONDITIONS:

No	Axial	Moment	Shear	Torsion
1	834.0	0.0	0.0	0.0

M E M B E R   P R O P E R T I E S

===

MEMBER PROPERTIES:

Member length = 162

BOUNDARY CONDITIONS:

Condition	End i	End j
Shear restraint	0	1
Moment restraint	1	1

CHECKED______________ DATE______________ DMJM HARRIS JOB NO.________________________________

APPROVED____________DATE______________ 999 TOWN & COUNTRY ROAD SHEET________________OF______________

TITLE **PUSHOVER ANALYSIS EXAMPLE** ORANGE, CALIFORNIA 92668 BY R. MATTHEWS DATE 5/21/01

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*                                                   *
*           P R O G R A M   C O N S E C             *
*                                                   *
*                   OUTPUT DATA                     *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *

S E C T I O N   P R O P E R T I E S
=====================================================

GROSS CONCRETE SECTION:

     Area    = 1.0179E+03
     Ybar    = 1.8000E+01
     Io      = 8.2448E+04 About concrete CG

REINFORCING STEEL:

     Area    = 3.2000E+01
     Ybar    = 1.8000E+01
     Io      = 3.0780E+03 About reinf CG

TRANSFORMED CONCRETE SECTION:

     Area    = 1.2433E+03
     Ybar    = 1.8000E+01
     Inertia = 1.0413E+05

M O M E N T   C U R V A T U R E
=====================================================
Moments about centroid of gross concrete section
(Units = K-ft)

Load Condition Number 1
Axial Load = 834.0

Strain        c             Axial          Curvature      Moment
0.00050       28.25         835.7          0.000018       509.6
0.00100       19.10         835.8          0.000052       1056.1
0.00150       16.75         838.2          0.000090       1543.1
0.00200       15.80         834.3          0.000127       1986.2
0.00250       15.25         837.5          0.000164       2318.9
Reinf tens yield
0.00300       14.65         843.5          0.000205       2487.1
0.00350       14.15         839.2          0.000247       2575.9
Reinf comp yield
0.00400       13.85         843.2          0.000289       2615.9
0.00450       13.65         841.4          0.000330       2638.5
0.00500       13.50         834.6          0.000370       2629.8
0.00550       13.45         842.6          0.000409       2625.6
Conc spalling
0.00600       13.35         840.0          0.000449       2626.5
0.00650       13.30         846.2          0.000489       2637.0
0.00700       13.15         837.1          0.000532       2636.7
0.00750       13.05         839.4          0.000575       2643.2
```

0.00800	12.95	837.7	0.000618	2648.2
0.00850	12.90	847.3	0.000659	2659.3
0.00900	12.80	834.4	0.000703	2665.6
0.00950	12.80	849.5	0.000742	2687.5
0.01000	12.75	844.7	0.000784	2702.8
0.01050	12.70	838.2	0.000827	2716.8
0.01100	12.70	846.0	0.000866	2738.3
0.01150	12.65	840.2	0.000909	2752.3
0.01200	12.60	835.8	0.000952	2765.5
0.01250	12.60	845.4	0.000992	2785.6
0.01300	12.55	834.4	0.001036	2795.7
0.01350	12.55	837.4	0.001076	2810.4
0.01400	12.55	839.3	0.001116	2823.7
0.01450	12.55	841.3	0.001155	2836.5
0.01500	12.55	841.7	0.001195	2848.9
0.01550	12.55	841.3	0.001235	2860.4
0.01600	12.55	840.9	0.001275	2871.5
0.01650	12.55	840.1	0.001315	2881.8
0.01700	12.55	839.0	0.001355	2891.3
0.01750	12.55	837.8	0.001394	2900.5
0.01800	12.55	836.3	0.001434	2908.9
0.01850	12.55	834.4	0.001474	2916.8
0.01900	12.60	850.5	0.001508	2931.2
0.01950	12.60	849.5	0.001548	2939.5
0.02000	12.60	847.8	0.001587	2947.9
0.02050	12.60	845.9	0.001627	2955.8
0.02100	12.60	844.3	0.001667	2963.5
0.02150	12.60	843.0	0.001706	2971.3
0.02200	12.60	841.8	0.001746	2979.1
0.02250	12.60	840.3	0.001786	2986.3
0.02300	12.60	838.7	0.001825	2993.2

```
Yield curvature          = 1.6393E-04
Ultimate curvature       = 1.8254E-03
Idealized plastic moment = 2775.4
Maximum tension          = -1507. At moment = 2993.2

Cracked moment of inertia = 4.7150E+04
Based on 1st yield strain = -0.00272

LOCAL MEMBER DUCTILITY:

    Idealized yield curvature = 1.9621E-04
    Plastic hinge length      = 24.5
    Yield deflection          = 0.858
    Ultimate deflection       = 6.341
    Local member ductility    = 7.4
```

CHECKED_____________ DATE_____________

APPROVED___________DATE_____________

TITLE **PUSHOVER ANALYSIS EXAMPLE**

DMJM HARRIS

999 TOWN & COUNTRY ROAD
ORANGE, CALIFORNIA 92668

JOB NO.______________________________

SHEET_______________OF_____________

BY R. MATTHEWS DATE 5/21/01

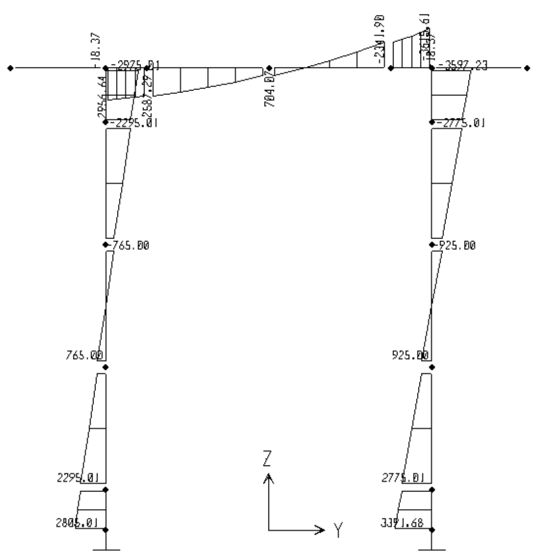
- Pushover analysis results

SAP2000 file = push2.sdb
Pushover curve file = push2_pd.txt

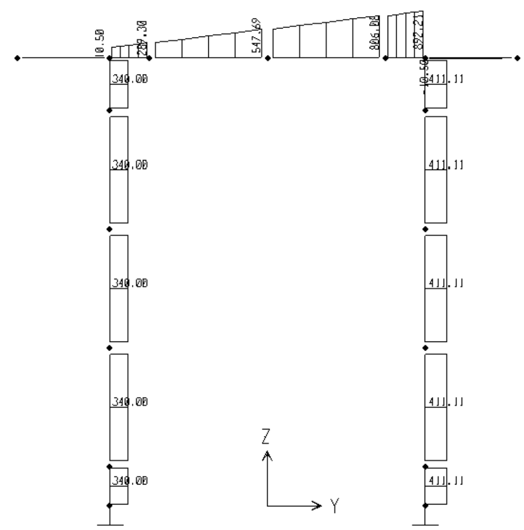
Ultimate deflection = 0.63 ft. at step 12
Maximum lateral force = 751 kips
Axial loads = 176 kips (tension) / 928 kips (compression)

Note: Iteration may be performed using the calculated axial loads until the solution converges or you can input multiple PMM curves and SAP2000 will interpolate.

The moment and shear diagrams at step 12 are shown below.



MOMENT DIAGRAM



SHEAR DIAGRAM

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TITLE **PUSHOVER ANALYSIS EXAMPLE** BY R. MATTHEWS DATE 5/21/01

METHOD 3 ANALYSIS

SAP2000 Nonlinear with axial-moment interaction hinges based on AASHTO/AREMA material properties.

- Procedure:

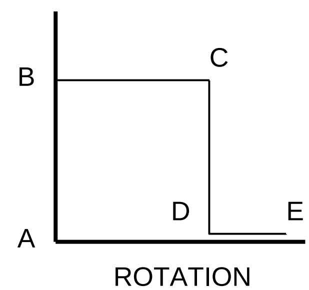
A. Perform steps A – F from METHOD 1 analysis

B. Develop column axial-moment interaction diagram

Define axial-moment interaction hinge properties

- select Default-PMM and modify
– uncheck default P-M2-M3 and modify
– uncheck "use yield rotation"
– fill in spreadsheet values as follows

POINT	MOMENT/SF	ROTATION/SF
A	0.0	0.0
B	1.0	0.0
C	1.0	θ_p
D	0.1	θ_p
E	0.1	2 x θ_p



1. The value of θ_p can be obtained from moment-curvature analysis if the failure deflection is needed. Note that the AASHTO/AREMA pushover analysis only needs the load distribution after all hinges are formed, therefore an accurate value of θ_p is not necessary.

– select define/show interaction
– change number of curves to 2
– select define/show surface
– fill in column axial-moment interaction diagram (can cut and paste)
– change scaling factor to 1.3

C. Perform steps G – N from METHOD 1 analysis

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ORANGE, CALIFORNIA 92668

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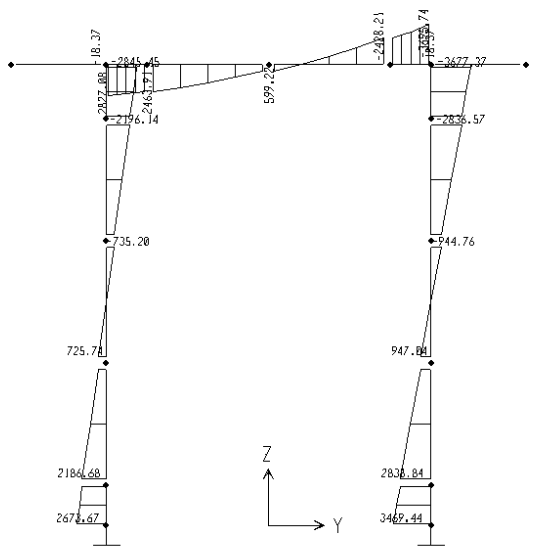
BY R. MATTHEWS DATE 5/21/01

- Pushover analysis results

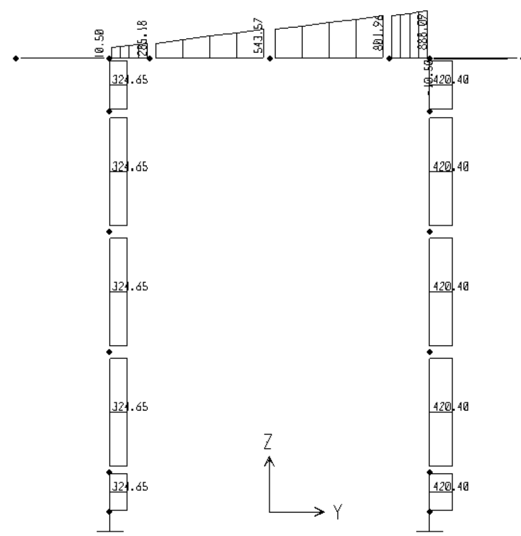
  SAP2000 file = push3.sdb
  Pushover curve file = push3_pd.txt

  Maximum lateral force = 745 kips at step 7
  Axial loads = 172 kips (tension) / 915 kips (compression)

  The moment and shear diagrams at step 12 are shown below.



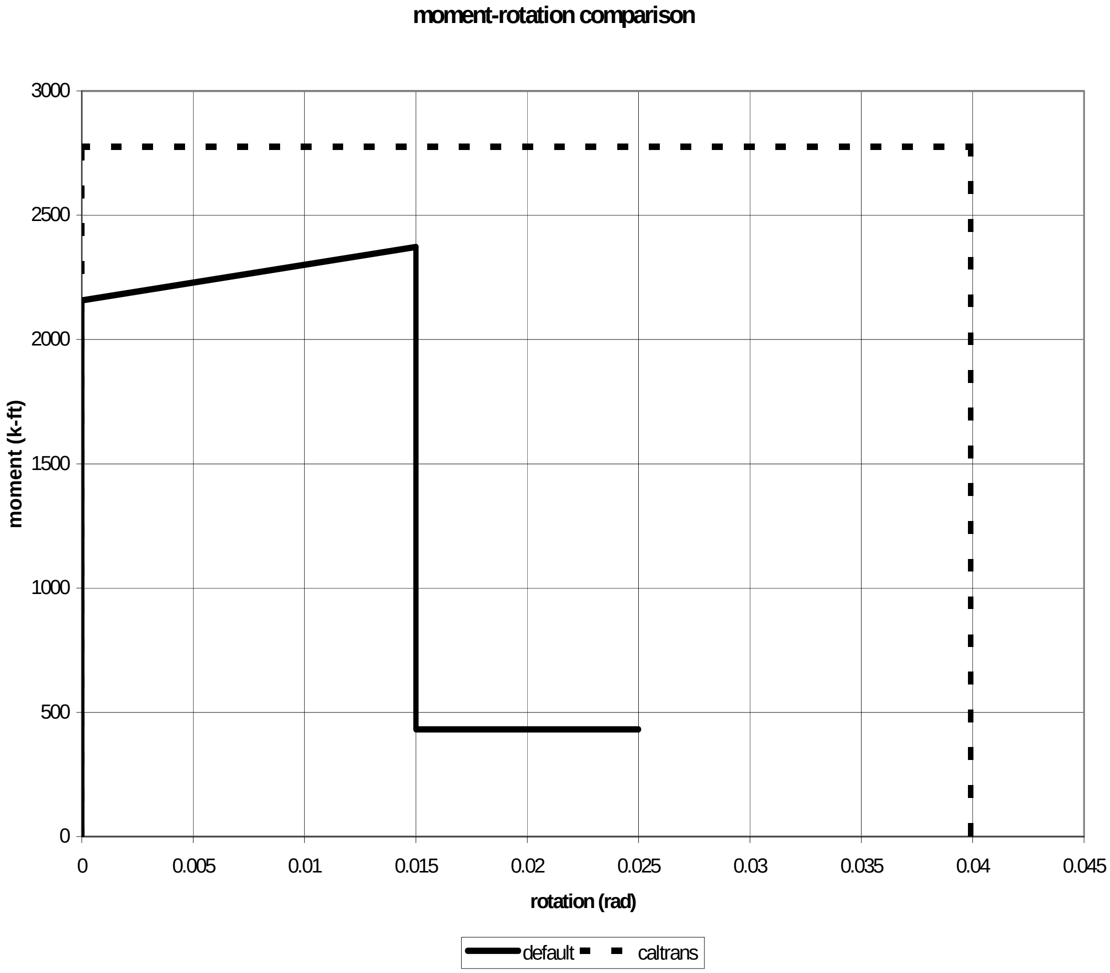
MOMENT DIAGRAM



SHEAR DIAGRAM

- SAP2000 pushover comparison

  The moment-rotation capabilities using METHODS 1 and 2 are compared in the graph below at one of the columns. This comparison shows that the default SAP2000 values are significantly more conservative than the values calculated using Caltrans material properties. This is because Caltrans uses expected strengths and curvatures rather than nominal strengths and code-based curvatures.



The load-deflection capabilities using METHODS 1, 2 and 3 are compared in the graph below. This comparison shows that the default SAP2000 values are significantly more conservative than the values calculated using Caltrans material properties or the AASHTO/AREMA procedures. The METHOD 2 and METHOD 3 results are almost identical.