TRIAL DESIGN BRIDGE DESCRIPTION

State: *Tennessee*

Trial Design Designation: *TN-2*

Bridge Name: *SR-385 over Bailey Station Road*

Superstructure Type: *Continuous, steel welded plate girders, composite concrete deck*

Span Length(s): *Three spans @ 105ft.-216ft.-105ft.*

Substructure Type: *Three 3.5ft. dia. concrete columns per bent*

Foundation: *Prestressed concrete friction piles*

Abutments: *Integral on prestressed friction piles*

Seismic Design Category (SDC): *"C"*

Additional Description (Optional): *A pushover analysis was conducted on one of the bents of this bridge. The pushover analysis included structure stiffness modifications to account for P-Delta effects.*

TRIAL DESIGN BRIDGE DESCRIPTION

Pushover Analysis Example
Tennessee DOT

A pushover analysis was performed on a bridge bent. Section analysis of members was accomplished using KSU_RC for the columns and RESPONSE2000 for the beams. All other calculations were done by hand.

P-Delta effects were considered by modifying the structure stiffness accordingly.

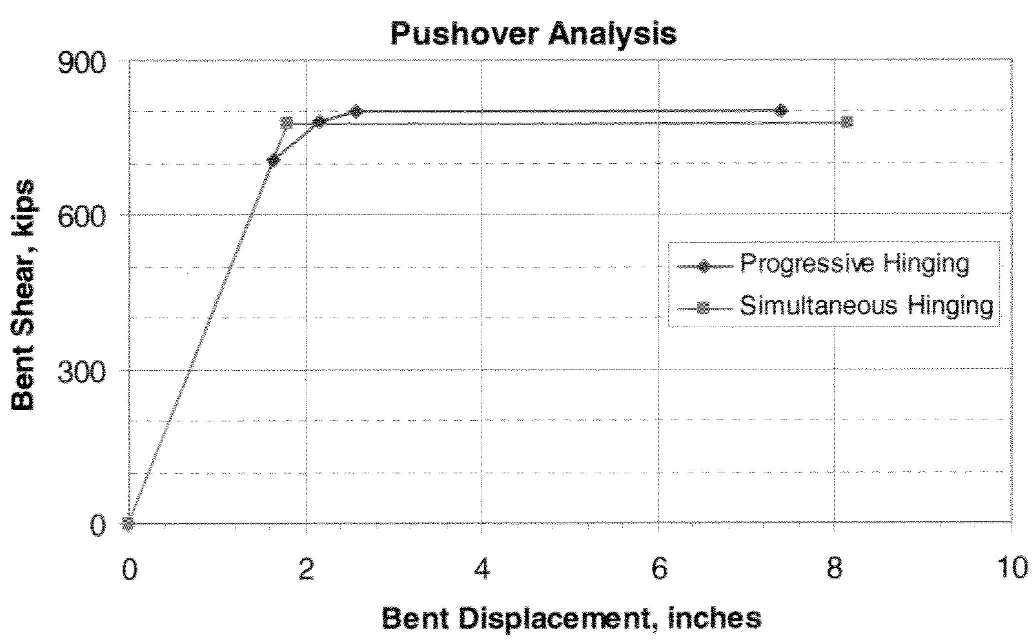
Two separate conditions were studied:

1. Simultaneous hinging of all 3 bent columns

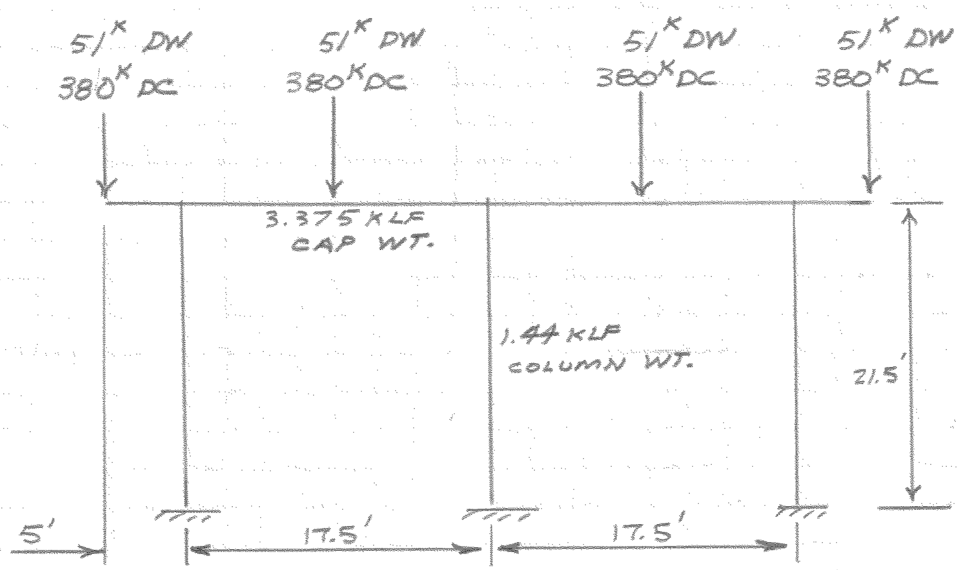
2. Progressive hinging of the 3 bent columns

The results are summarized below.

Condition	Simultaneous Hinging		Progressive Hinging	
	Bent V, kips	Bent δ, in.	Bent V, kips	Bent δ, in.
Hinging at leeward column	780	1.80	709	1.64
Hinging at center column	780	1.80	782	2.18
Hinging at windward column	780	1.80	800	2.58
Collapse	780	8.14	800	7.39

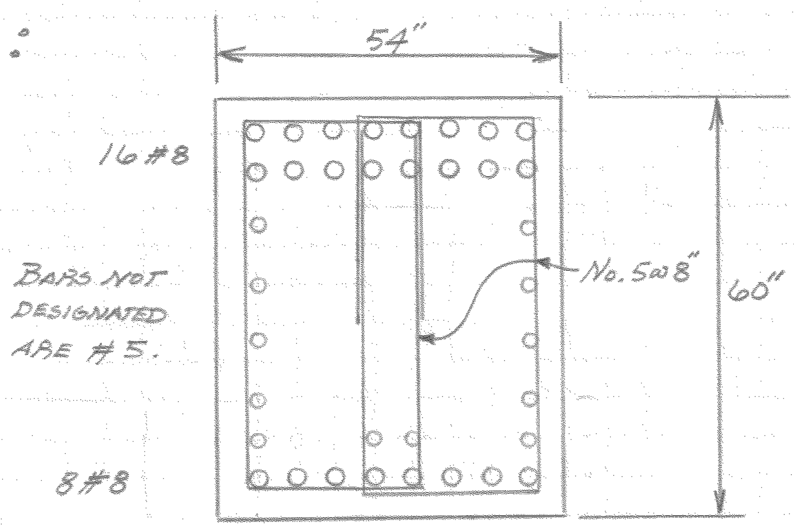


PUSHOVER ANALYSIS



COLUMNS: 42" DIAMETER
30 No. 8 BARS
No. 5 SPIRALS @ 5"

CAP:



FOUNDATION SPRINGS: 12 PILES × 20 K/IN / PILE

= 240 K/IN
PER COLUMN

SUPERSTRUCTURE C.G. IS LOCATED 70" ABOVE TOP OF CAP = 100" ABOVE CAP ℄.

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COUNTY: CROSSING: | NOTES

FOR SDC "D", A706 REBAR IS REQ'D: — 8.4.2

$\varepsilon_{su} = 0.120$, No. 8 BARS

$\varepsilon_{sh} = 0.015$, No. 8 BARS

$\varepsilon_{su}^{R} = 0.06$

$f_{ye} = 1.1 \times 60 = 66$ ksi

$f_{ue} = 1.4 \times 66 = 92.4$ ksi

XSU-RC WILL BE USED FOR SECTION ANALYSIS.

$K_1 = \dfrac{\varepsilon_{sh}}{\varepsilon_y}$ $\varepsilon_y = 66/29{,}000 = 0.002276$

$K_1 = 0.015/0.002276 = \underline{6.59}$

$K_2 = \dfrac{\varepsilon_{su}^{R}}{\varepsilon_y}$

$K_2 = 0.06/0.002276 = \underline{26.4}$

$K_3 = \dfrac{\varepsilon_{su}}{\varepsilon_y}$

$K_3 = 0.120/0.002276 = \underline{52.7}$

$K_4 = f_{ue}/f_{ye}$

$\underline{K_4 = 1.4}$

USE MANDER'S CONCRETE MODEL — 8.4.4

$f'_{ce} = \max\{1.3 \times 3, 5\}$
$= \max\{3.9, 5\}$

$\underline{f'_{ce} = 5 \text{ ksi}}$

COLUMN AXIAL LOAD RANGE: 200^{K} TO $2{,}000^{K}$ (APPROXIMATE)

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KSU-RC WILL BE USED TO OBTAIN VALUES OF:

ϕ_y - YIELD CURVATURE

ϕ_u - ULTIMATE CURVATURE

M_P - PLASTIC MOMENT

EI - STIFFNESS

A RANGE OF AXIAL LOADS WILL BE ANALYZED.

THE DATA WILL BE FIT TO A STRAIGHT LINE (LEAST SQUARES FIT) OVER THE RANGE OF AXIAL LOADS.

NOTE THAT THE STIFFNESS, EI, FROM ZERO LOAD TO YIELD, IS GIVEN BY:

$$(EI)_1 = M_P / \phi_y$$

THIS VALUE WILL BE REDUCED TO ACCOUNT FOR P-DELTA EFFECTS AS FOLLOWS:

RIGID-FRAME: $\Delta_1 = VH^3/12(EI)_1$ — 1ST-ORDER Δ

$$M_{TOP} = M_{BOTT} = VH/2$$

$\Rightarrow \Delta_1 = \frac{MH^2}{6(EI)_1}$. FOR 2ND-ORDER, SET $M = VH/2 + P\Delta_2/2$

$$\Delta_2 = \frac{(VH/2 + P\Delta_2/2)H^2}{6(EI)_1} = \frac{(VH + P\Delta_2)H^2}{12(EI)_1}$$

$$\Delta_2 \left(1 - \frac{PH^2}{12(EI)_1}\right) = \frac{VH^3}{12(EI)_1}$$

$$\Delta_2 \left(\frac{12(EI)_1 - PH^2}{12(EI)_1}\right) = \frac{VH^3}{12(EI)_1}$$

$$\Delta_2 = \frac{VH^3}{12(EI)_1 - PH^2} = \frac{VH^3}{12(EI)_{EFF}}$$

$$\boxed{(EI)_{EFF} = \frac{12(EI)_1 - PH^2}{12}}$$

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COUNTY: CROSSING: NOTES

P, KIPS	ϕ_y	ϕ_u	M_p, IN·K
500	0.000177	0.00154	33,500
700	0.000162	0.00145	35,500
900	0.000149	0.00137	37,000
1,100	0.000141	0.00130	38,000
1,300	0.000134	0.00123	39,500
1,500	0.000131	0.00117	41,000

KSU-RC OUTPUT FOR THE 500^K AXIAL LOAD AND THE $1,500^K$ AXIAL LOAD CASES IS SHOWN ON PAGE 5.

PLOTS OF THE ABOVE DATA ARE SHOWN ON PAGES 6-10.

FORCE-DEFLECTION CURVES ARE GENERATED FOR THE FIRST & LAST CASES AS WELL. THESE ARE TO BE FOUND ON PAGES 11-12.

KSU-RC IS NOT PARTICULARLY WELL-SUITED FOR ANALYSIS OF THE CAP, SO RESPONSE-2000 WILL BE USED. THIS IS FINE SINCE WE ARE NOT INTERESTED IN M-ϕ CURVES FOR THE CAP, ONLY MOMENT CAPACITIES FOR POSITIVE AND NEGATIVE FLEXURE.
SEE PAGES 14-16 FOR RESPONSE-2000 CAP ANALYSIS.

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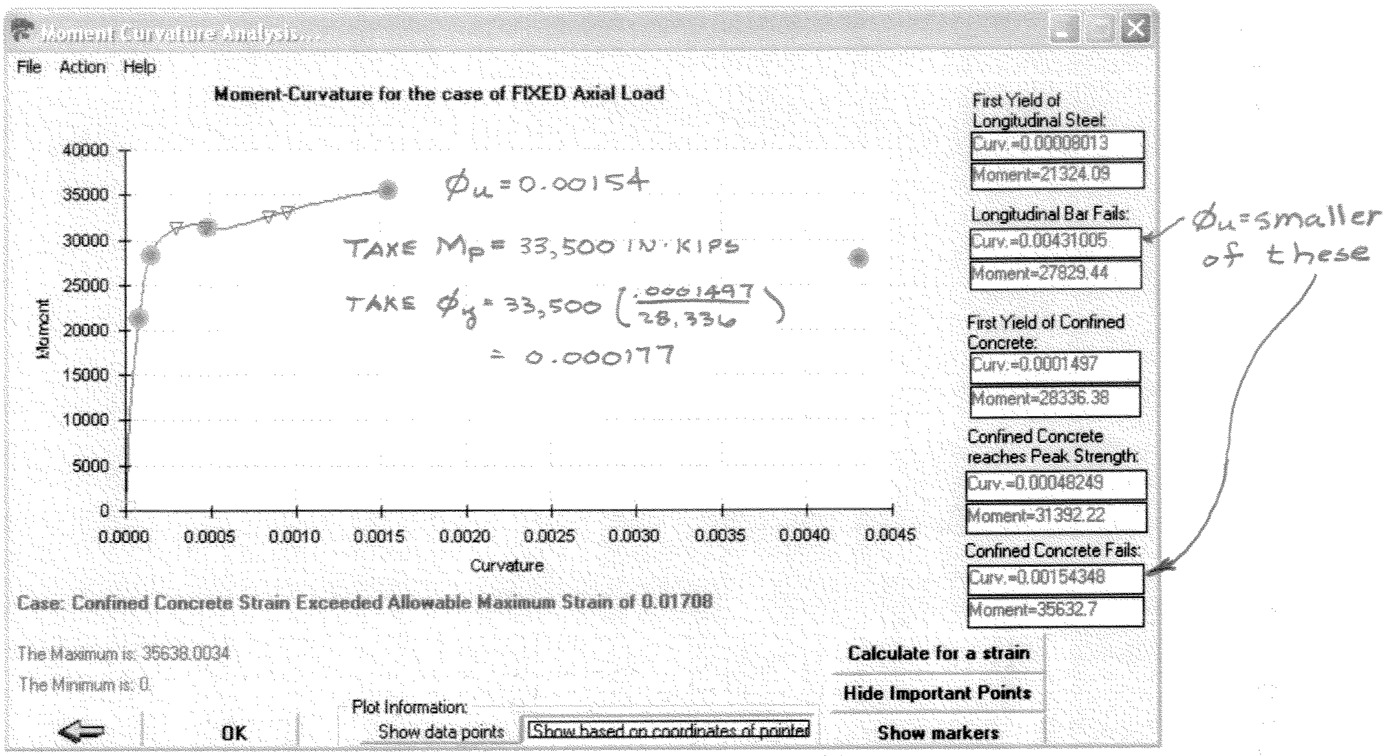
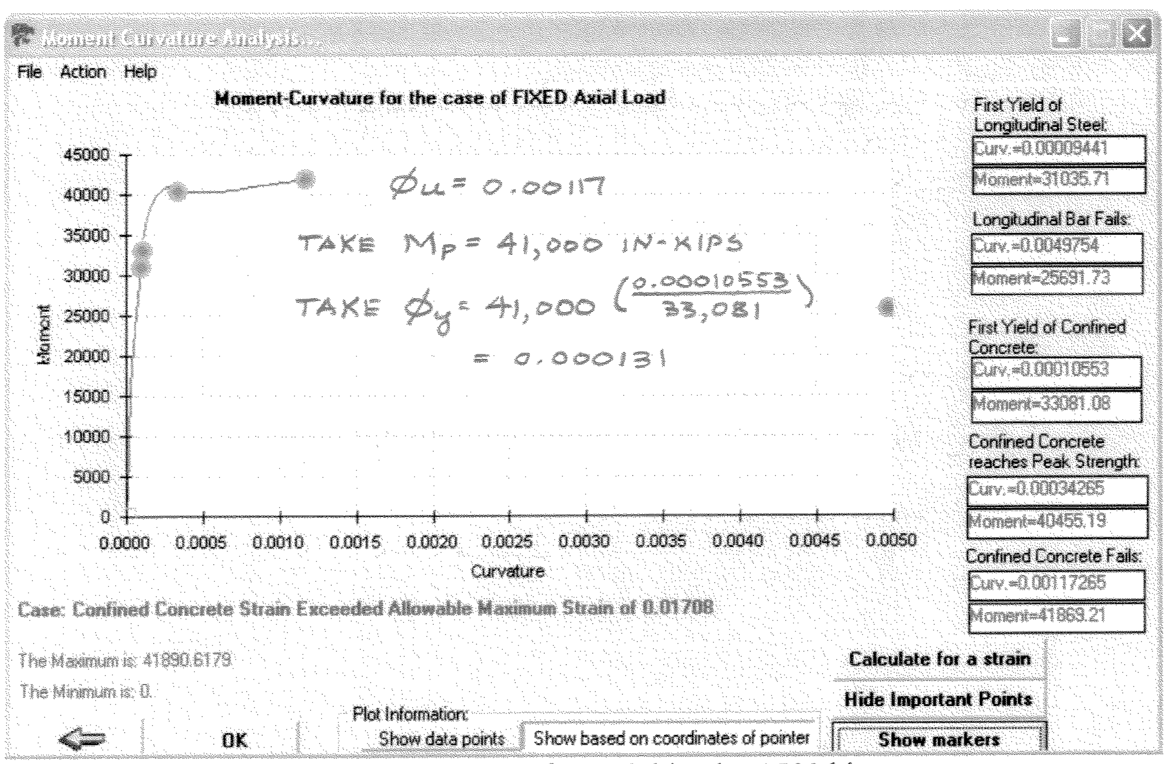


Moment-Curvature for Axial load = 500 kips



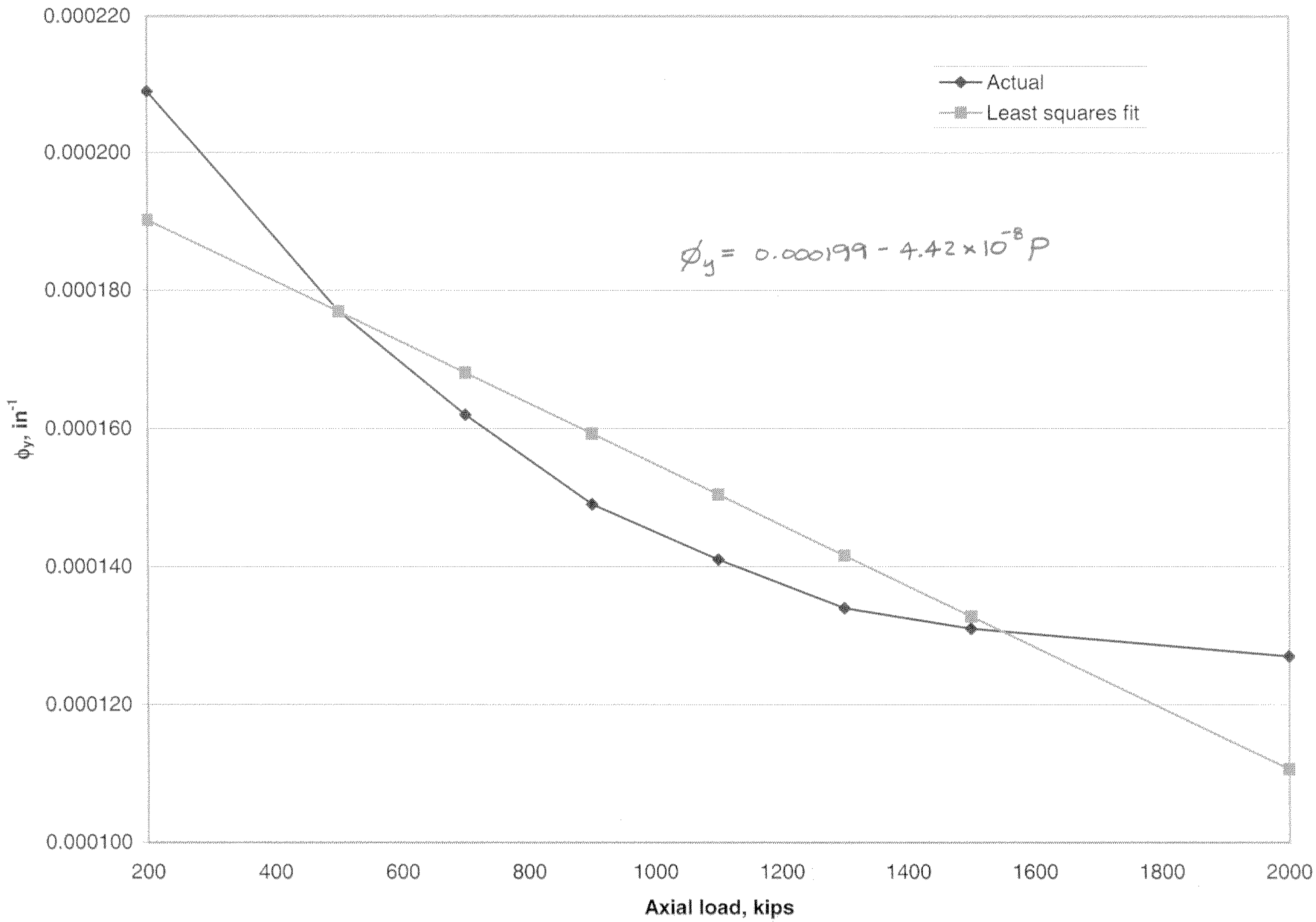
Moment-Curvature for Axial load = 1500 kips

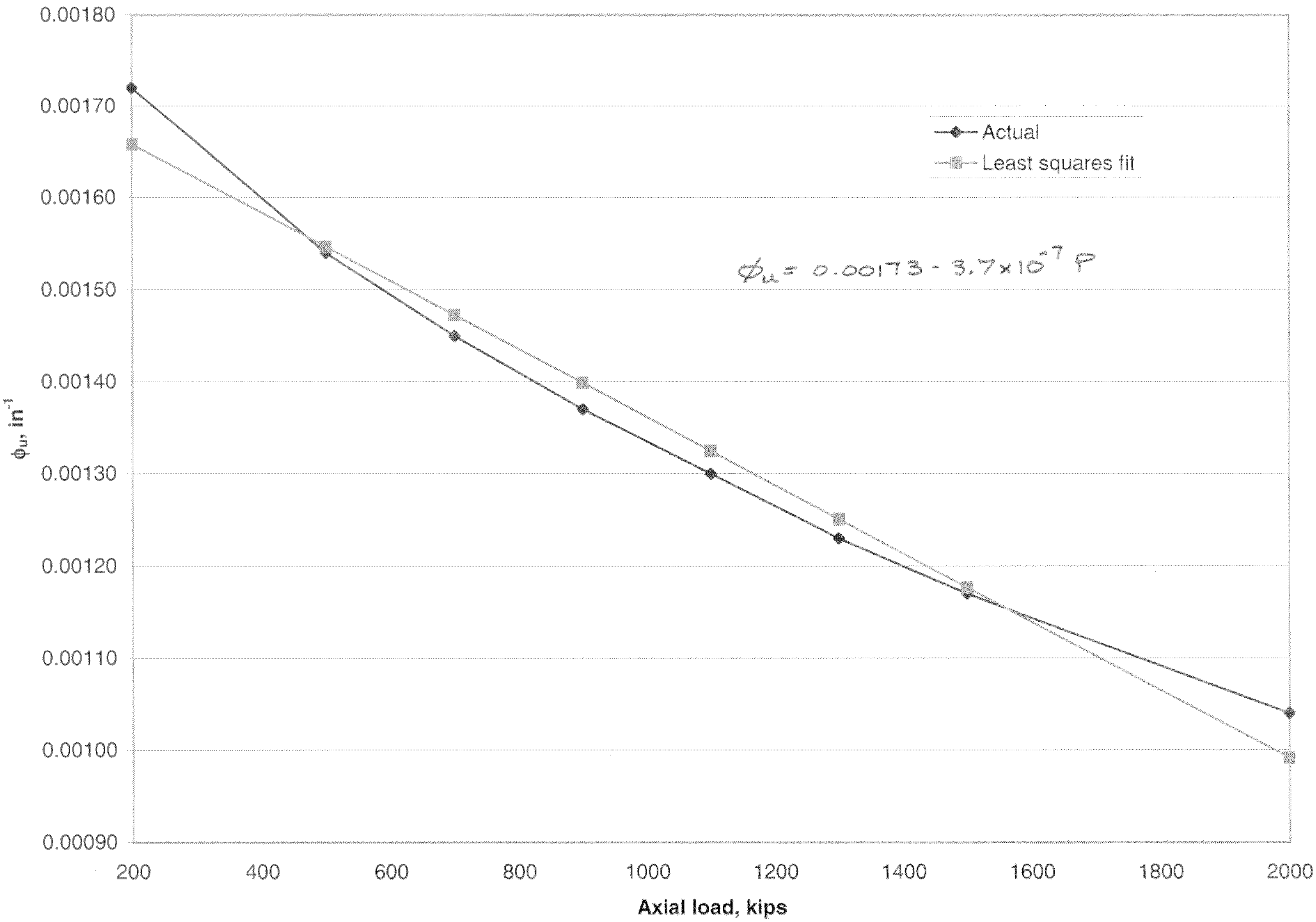
P	M_p	Fitted M_p
200	31,000	31,515
500	33,500	33,669
700	35,500	35,104
900	37,000	36,540
1100	38,000	37,976
1300	39,500	39,412
1500	41,000	40,847
2000	44,000	44,437
7.18	30,079	

P	M_p / ϕ_y	Fitted M_p / ϕ_y
200	148,325,359	160,409,731
500	189,265,537	194,295,388
700	219,135,802	216,885,826
900	248,322,148	239,476,264
1100	269,503,546	262,066,702
1300	294,776,119	284,657,140
1500	312,977,099	307,247,578
2000	346,456,693	363,723,673
112952.19	137,819,293	

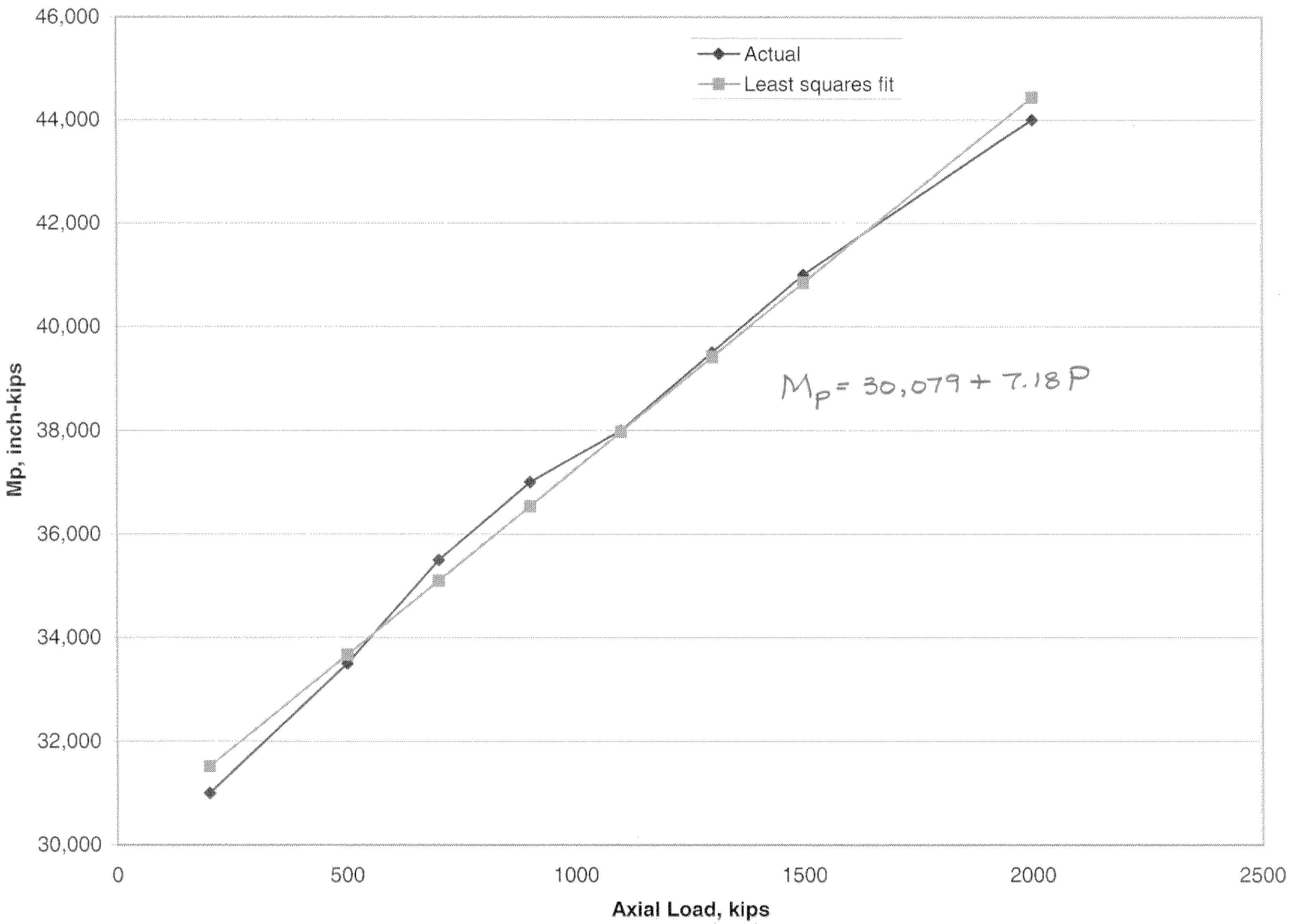
P	ϕ_y	Fitted ϕ_y
200	0.000209	0.000190
500	0.000177	0.000177
700	0.000162	0.000168
900	0.000149	0.000159
1100	0.000141	0.000150
1300	0.000134	0.000142
1500	0.000131	0.000133
2000	0.000127	0.000111
-4.418E-08	0.000199	

P	ϕ_u	Fitted ϕ_u
200	0.00172	0.00166
500	0.00154	0.00155
700	0.00145	0.00147
900	0.00137	0.00140
1100	0.00130	0.00132
1300	0.00123	0.00125
1500	0.00117	0.00118
2000	0.00104	0.00099
-3.702E-07	0.00173	

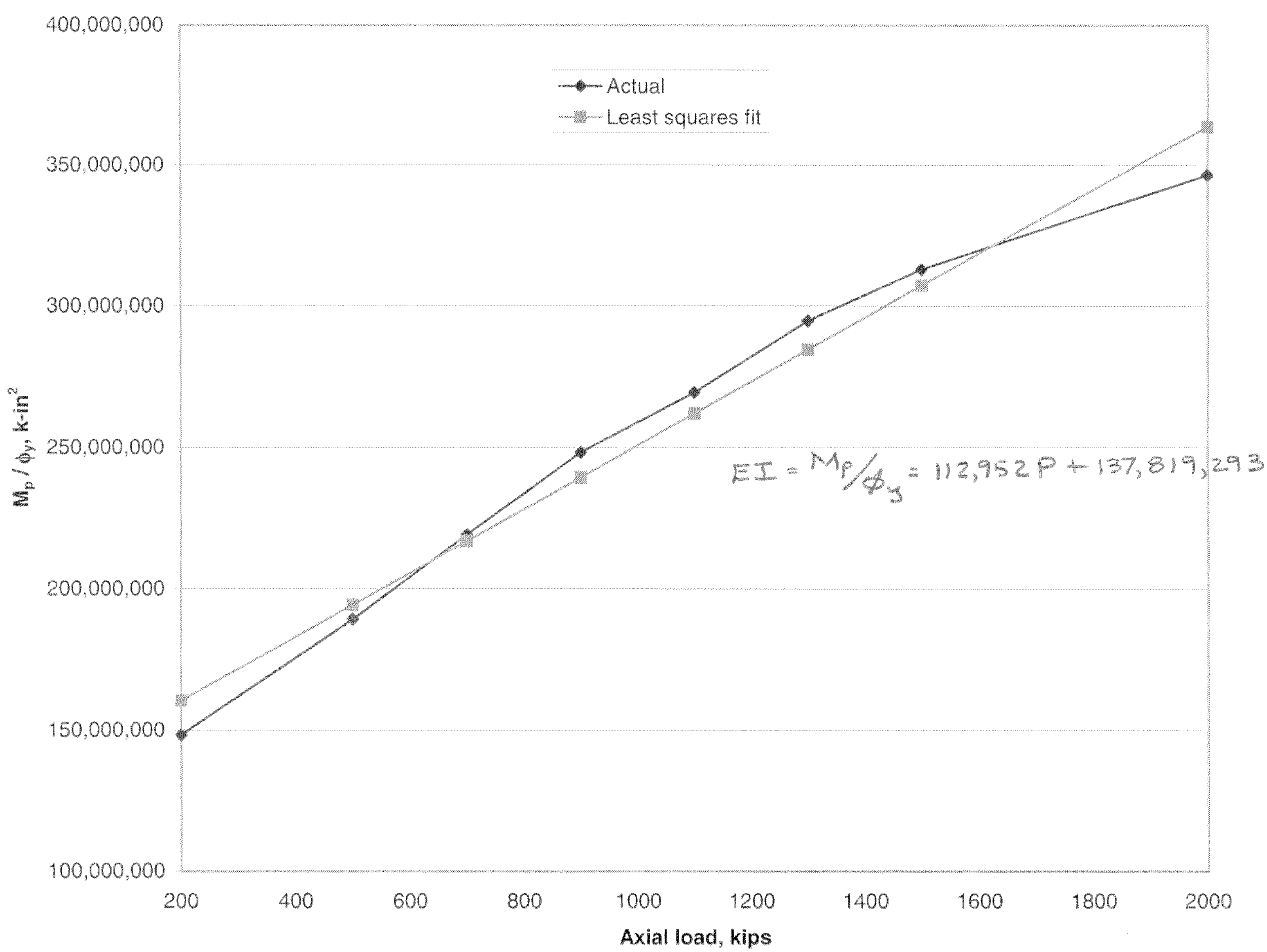

0.000220
0.000200
0.000180
0.000160
0.000140
0.000120
0.000100
ϕ_y, in^{-1}
200
400
600
800
1000
1200
1400
1600
1800
2000
Axial load, kips
Actual
Least squares fit
$\phi_y = 0.000199 - 4.42 \times 10^{-8} P$



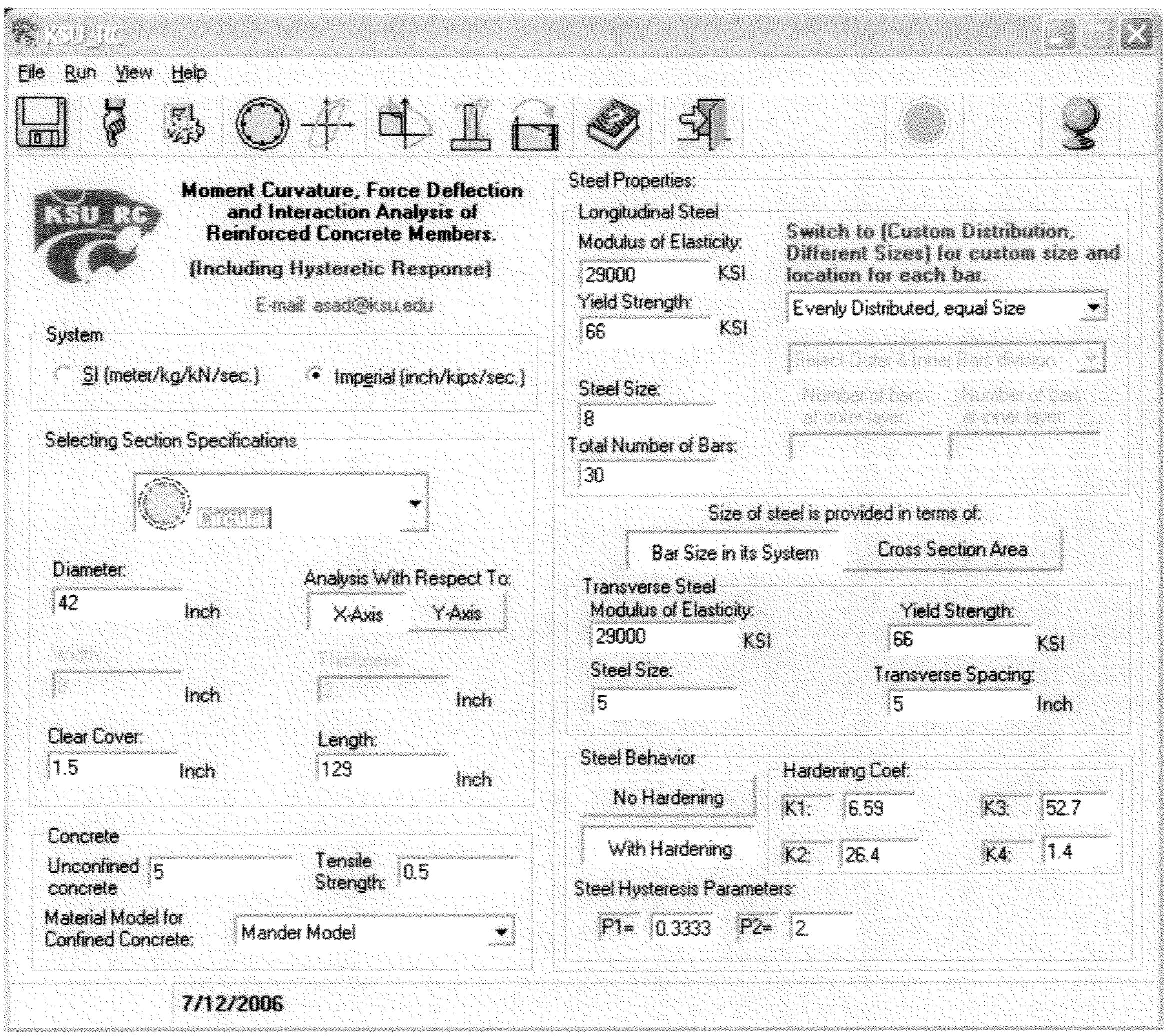
0.00180
0.00170
0.00160
0.00150
0.00140
0.00130
0.00120
0.00110
0.00100
0.00090
ϕ_u, in^{-1}
200
400
600
800
1000
1200
1400
1600
1800
2000
Axial load, kips
Actual
Least squares fit
$\phi_u = 0.00173 - 3.7\times10^{-7} P$



46,000
44,000
42,000
40,000
38,000
36,000
34,000
32,000
30,000
Mp, inch-kips
0
500
1000
1500
2000
2500
Axial Load, kips
Actual
Least squares fit
Mp= 30,079 + 7.18P


400,000,000
350,000,000
300,000,000
250,000,000
200,000,000
150,000,000
100,000,000
Mp / φy, k-in2
Actual
Least squares fit
EI = Mp/φy = 112,952 P + 137,819,293
200
400
600
800
1000
1200
1400
1600
1800
2000
Axial load, kips

KSU_RC Input screen

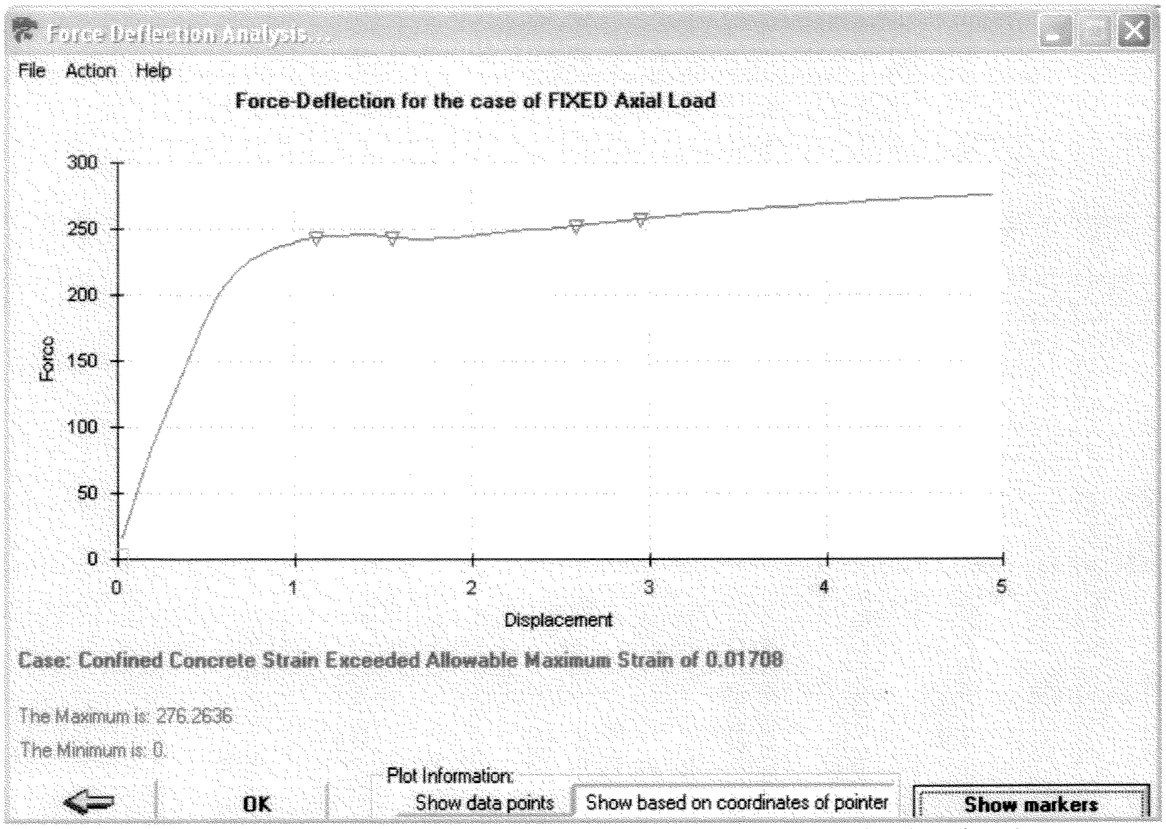


Note that the input Length is 129":

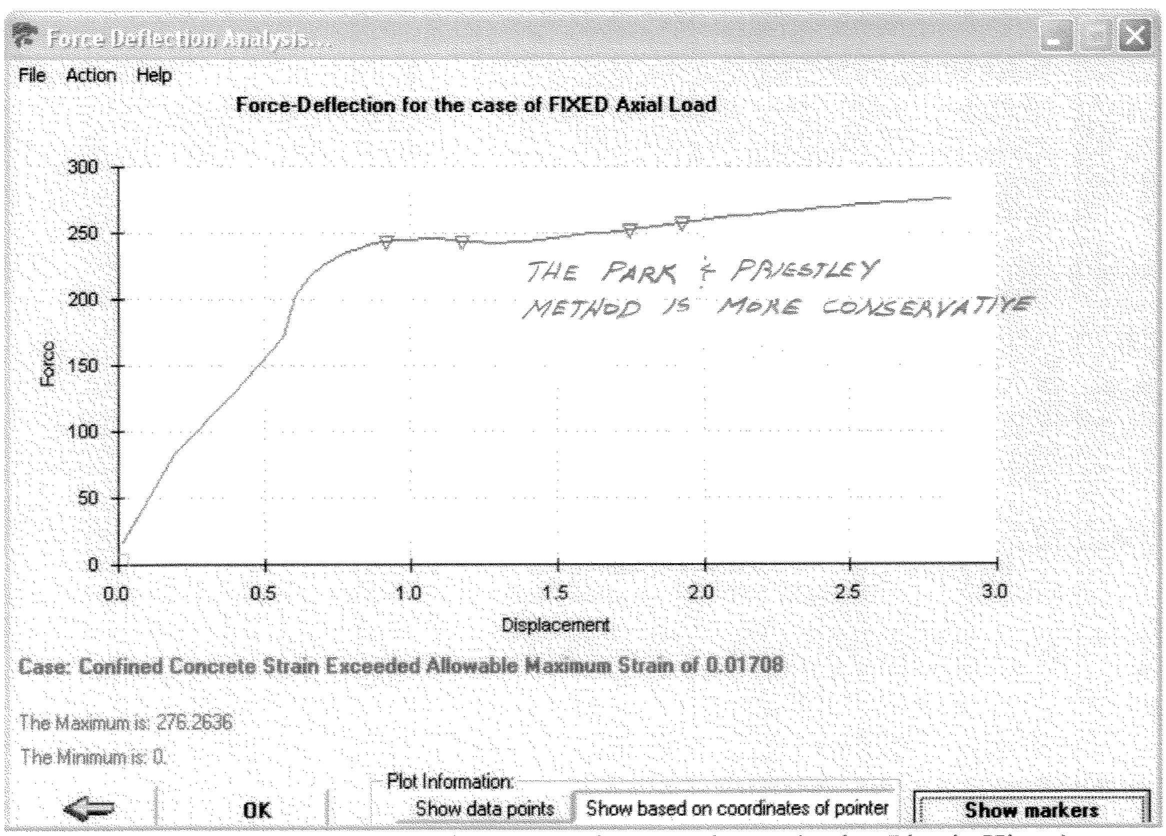
$$L = \frac{21.5 \times 12}{2} = 129"$$

This will be the case whenever rigid-frame behavior is assumed with contra-flexure at mid-height of the columns. Essentially, this will be our assumption for transverse analysis of multi-post bents.

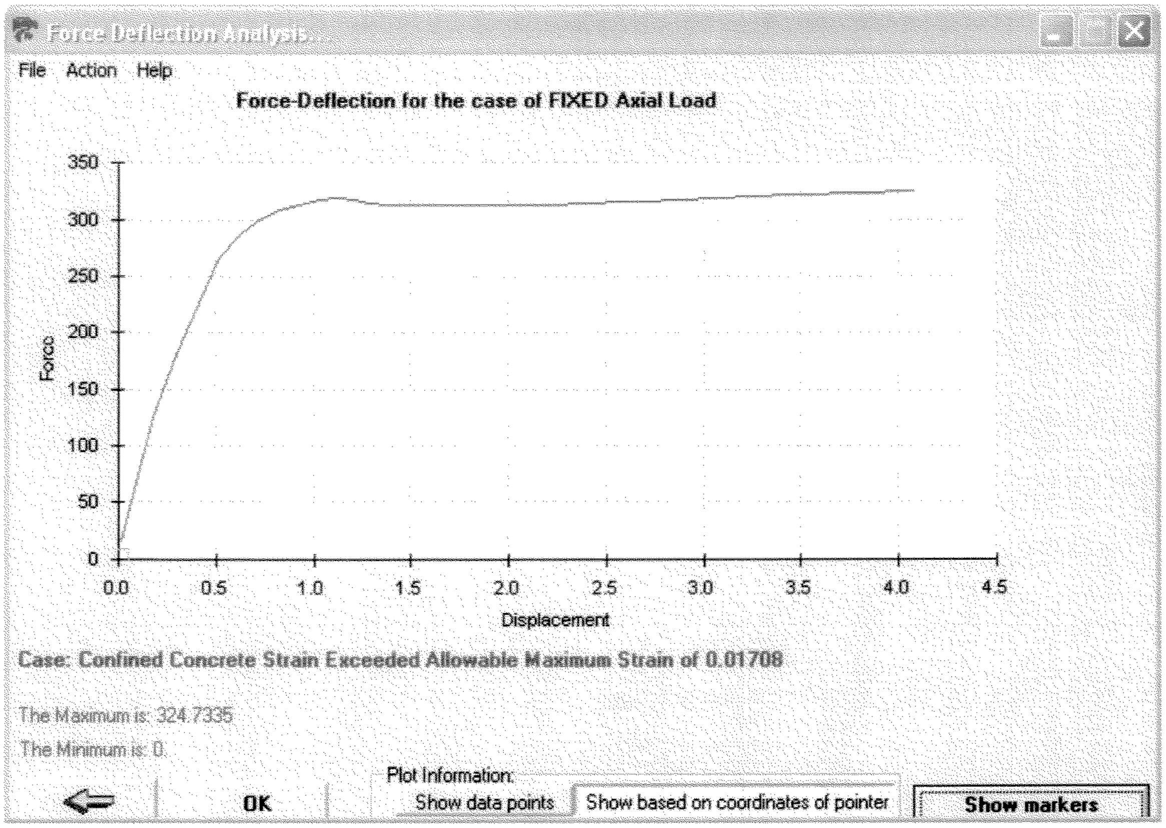
As a result, the calculated deflections should be multiplies by 2 to obtain yield displacements and ultimate displacements. This is true since what we are calculating is the deflection between the contra-flexure point and the maximum point. For rigid frame behavior with contra-flexure at mid-height, we have this much deflection (a) between the column base and mid-height and (b) between mid-height and the top of the column. This gives a total displacement of twice the calculated deflection.



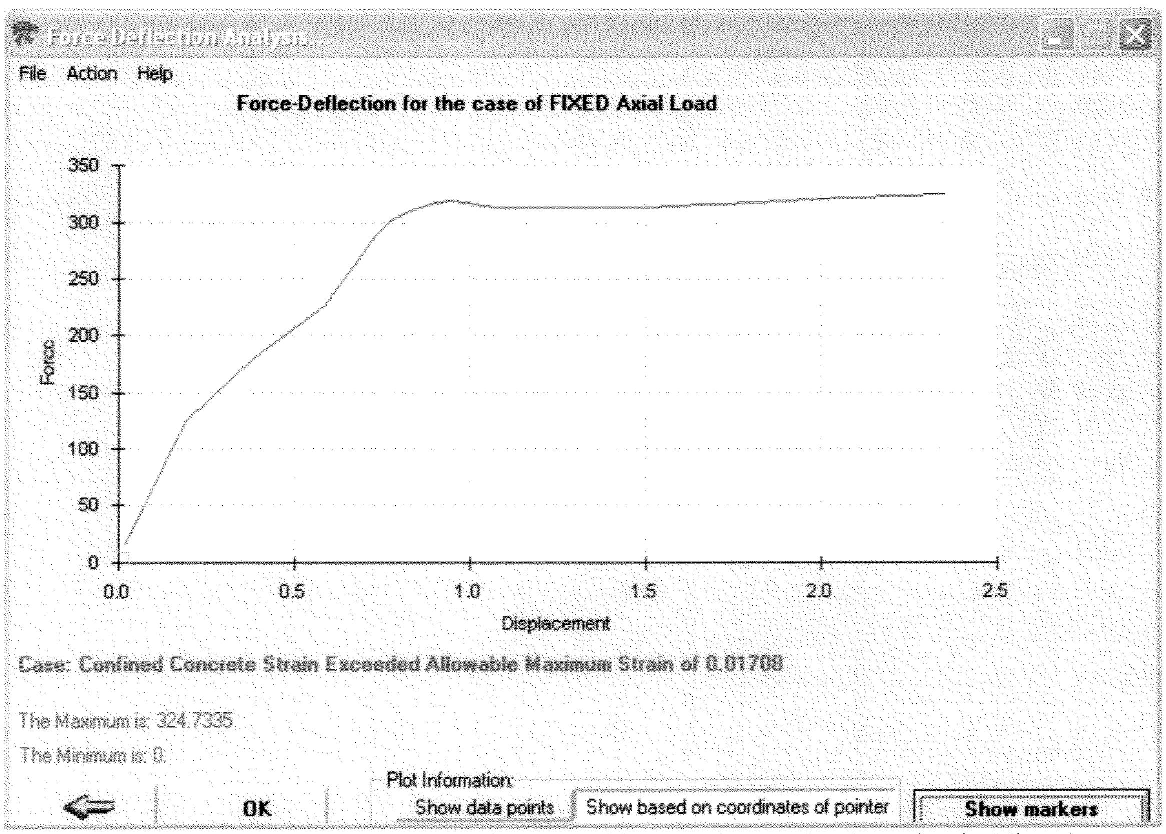
Force-Deflection for Axial load = 500 kips (KSU_RC Plastic Hinge)



Force-Deflection for Axial load = 500 kips (Park & Priestley Plastic Hinge)



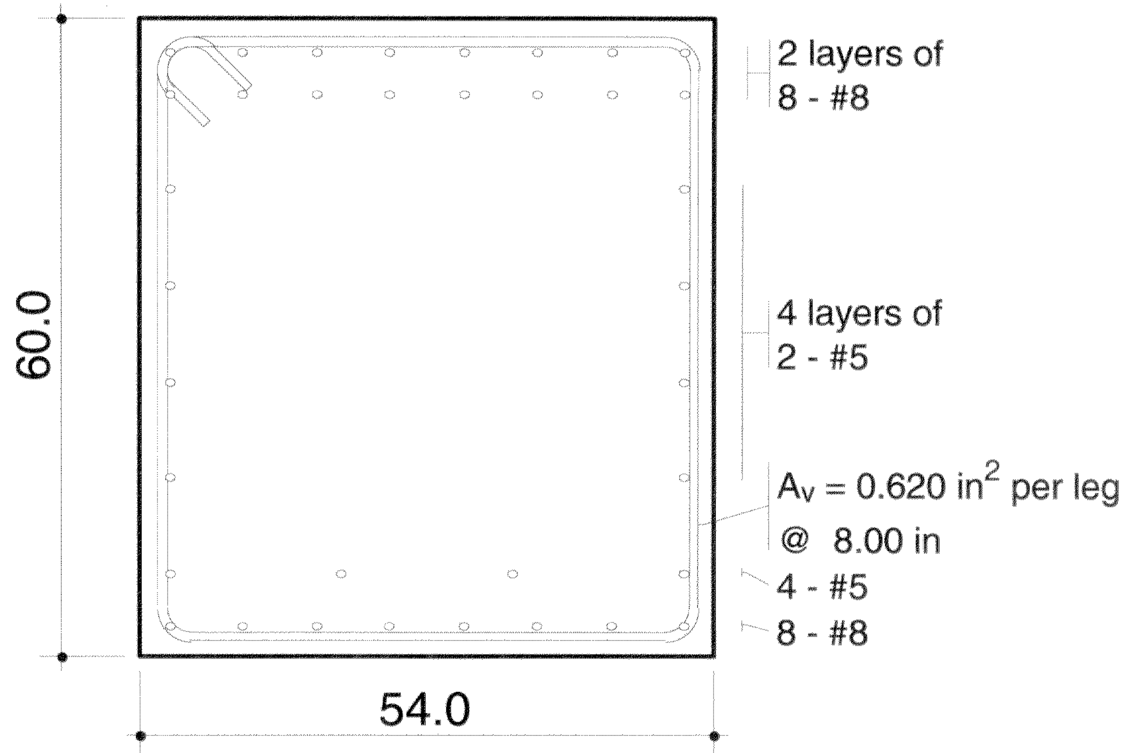
Force-Deflection for Axial load = 1500 kips (KSU_RC Plastic Hinge)



Force-Deflection for Axial load = 1500 kips (Park & Priestley Plastic Hinge)

Geometric Properties

	Gross Conc.	Trans (n=7.58)
Area (in^2)	3240.0	3389.2
Inertia (in^4)	971999.6	1060024.8
y_t (in)	30.0	29.8
y_b (in)	30.0	30.2
S_t (in^3)	32400.0	35609.0
S_b (in^3)	32400.0	35063.5

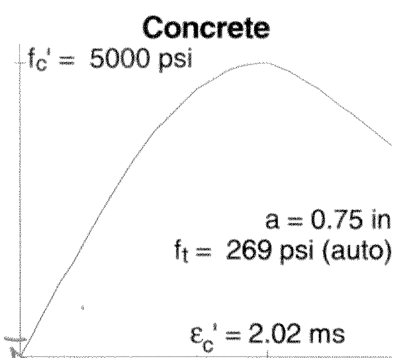


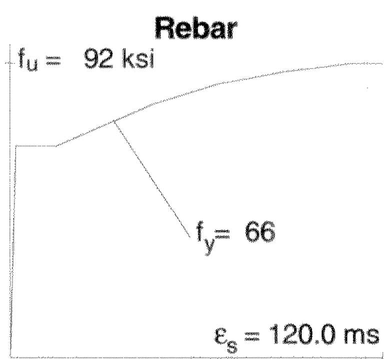
Crack Spacing

2 x dist + 0.1 d_b /ρ

Loading (N,M,V + dN,dM,dV)

0.0 , 0.0 , 0.0 + 0.0 , -1.0 , 0.0





All dimensions in inches
Clear cover to transverse reinforcement = 1.50 in

CAP

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Response-2000 v 1.0.5

CAP

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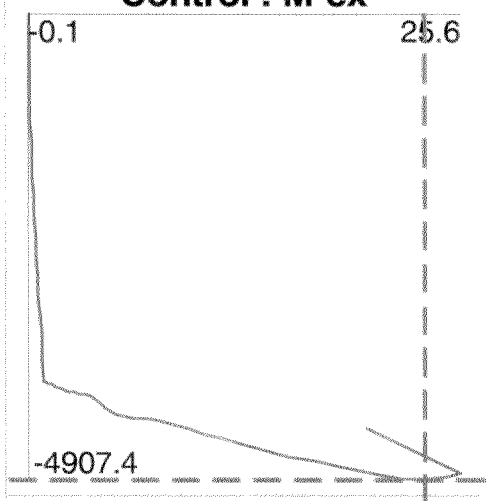
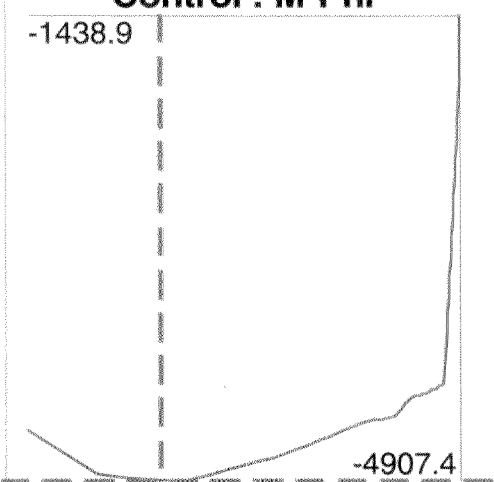
Control : M-ex



Control : M-Phi



ε_{x0} = 23.50 ms

ϕ = -999.27 rad/10^6 in

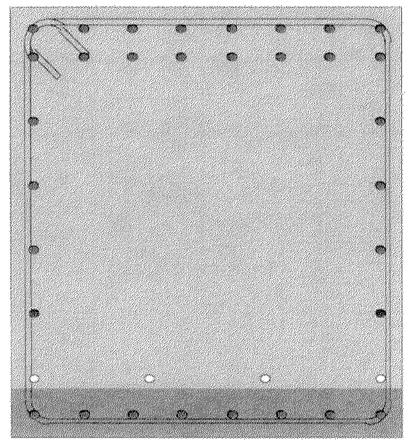
γ_{xy}(avg) = 0.00 ms

Axial Load = 0.5 kips

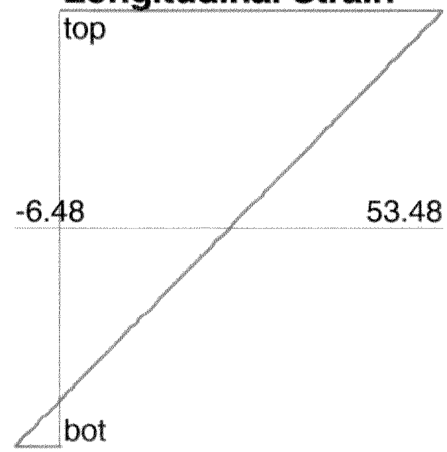
Moment:= -4907.4 ft-kips

Shear = 0.0 kips

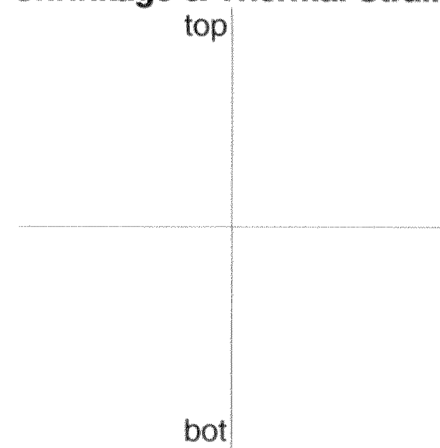
Cross Section



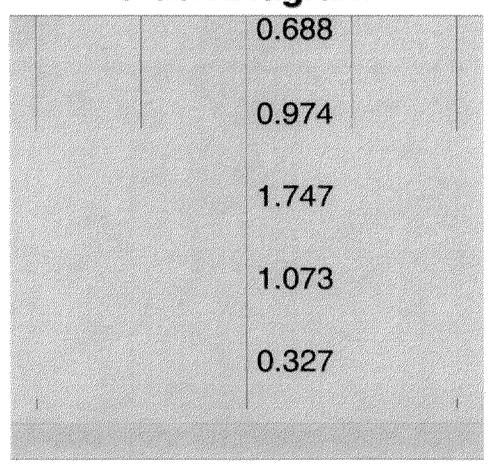
Longitudinal Strain



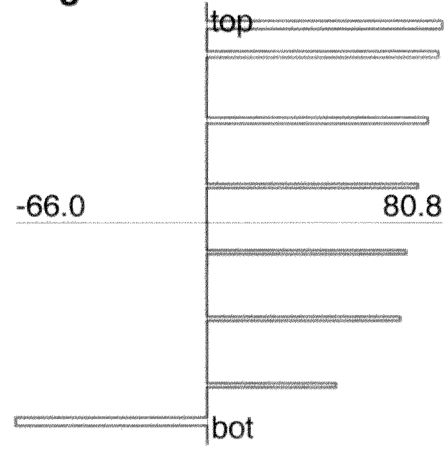
Shrinkage & Thermal Strain



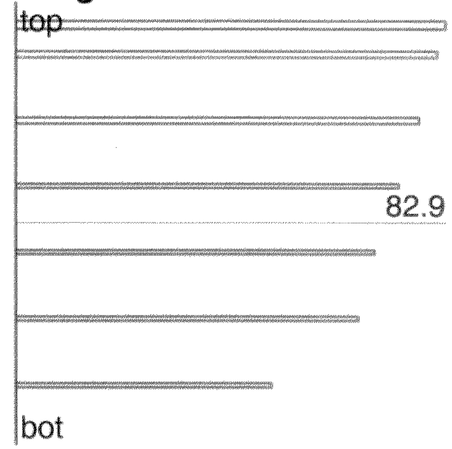
Crack Diagram



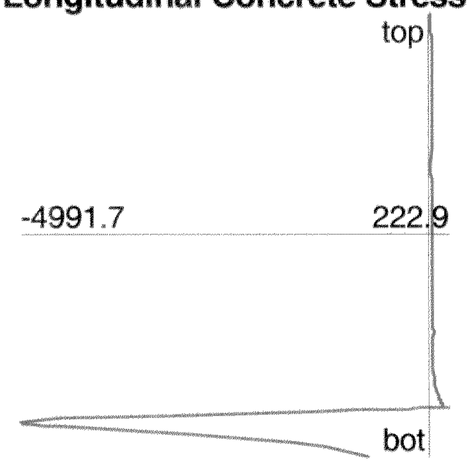
Long. Reinforcement Stress



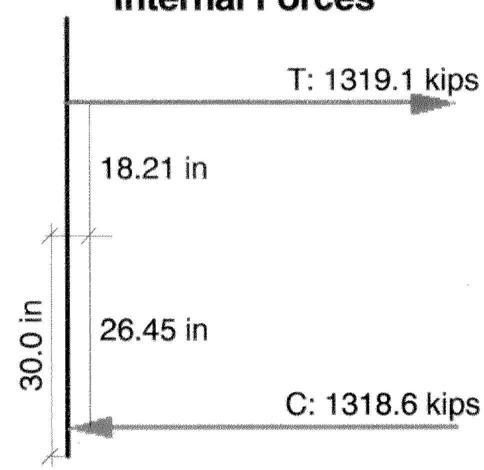
Long. Reinf Stress at Crack



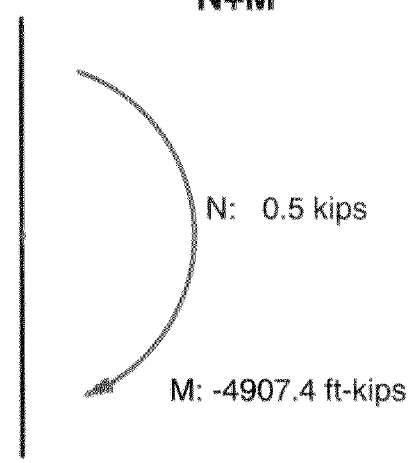
Longitudinal Concrete Stress



Internal Forces



N+M



Response-2000 v 1.0.5

CAP

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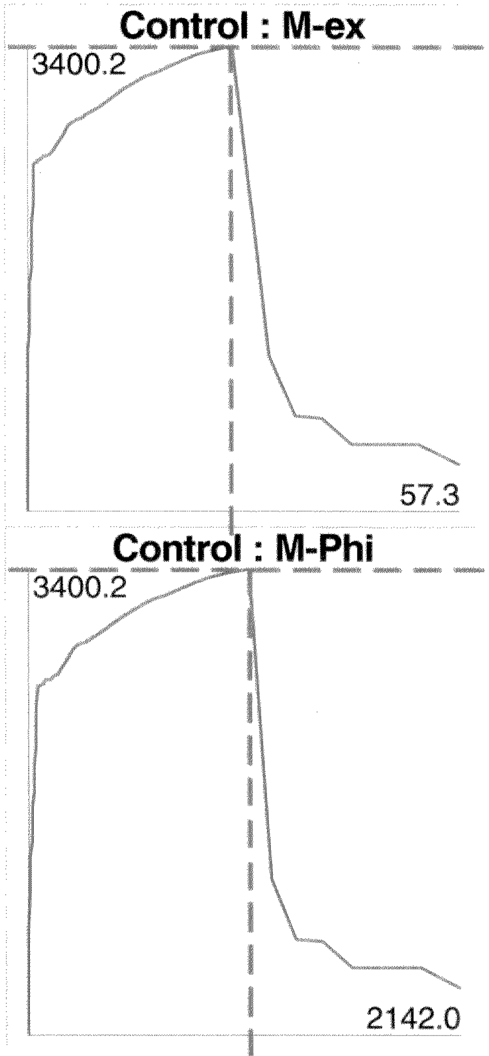


ε_{x0} = 27.06 ms

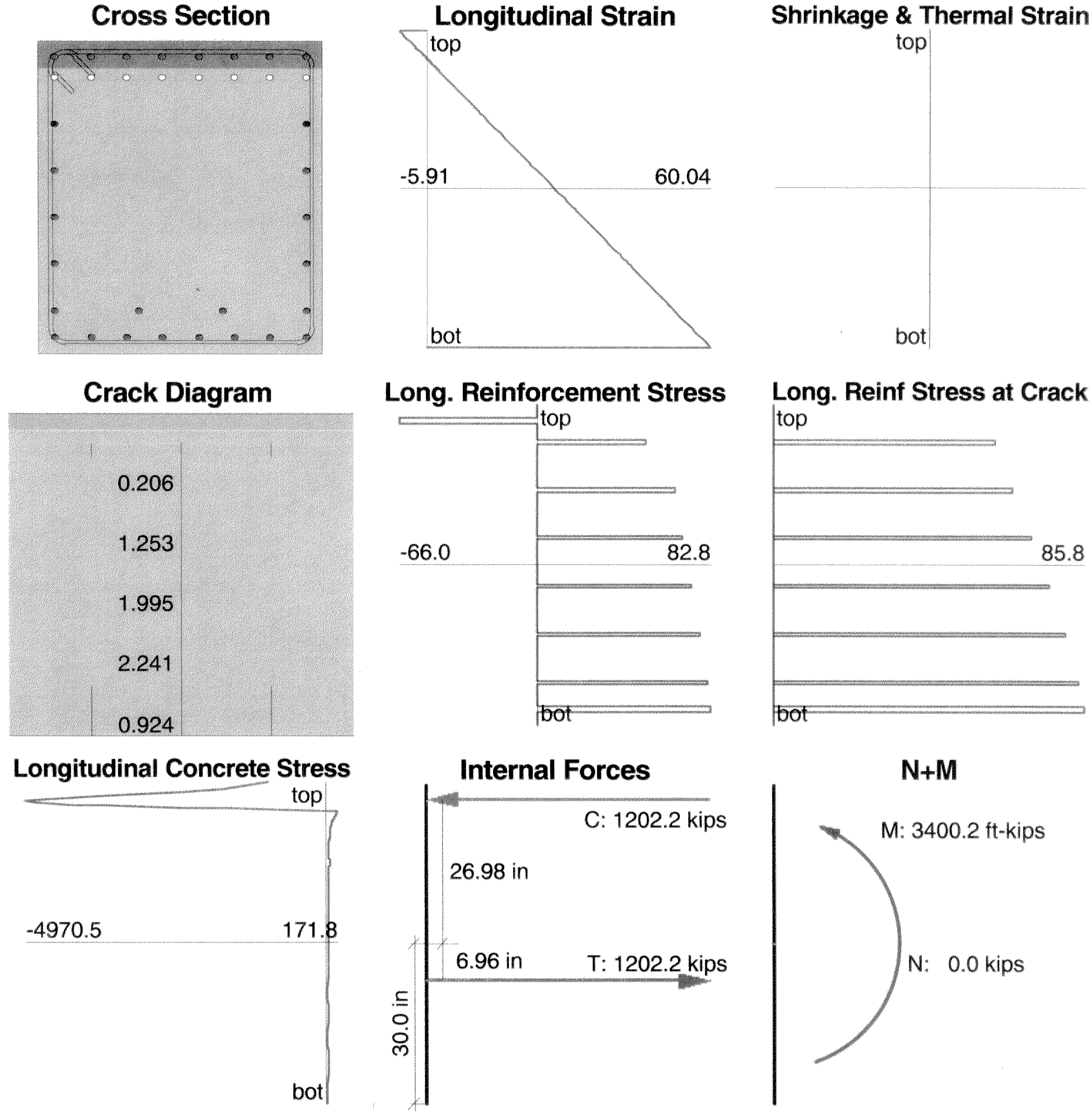
ϕ = 1099.20 rad/10^6 in

γ_{xy}(avg) = 0.00 ms

Axial Load = 0.0 kips

Moment:= 3400.2 ft-kips

Shear = 0.0 kips



6

INITIAL STIFFNESS VALUES:

$P = (380 + 51)(4)/3 = 575^{K}/\text{COL}$ — SUPERSTRUCT.

$3.375 \times 45\text{FT}/3 = 51^{K}/\text{COL}$ — CAP WT.

$1.440 \times 21.5\text{FT}/2 = 15^{K}/\text{COL}$ — 1/2 COL. WT.

641 KIPS

$\phi_y = 0.000168\ \text{IN}^{-1}$ — PAGE 7

$M_p = 34{,}800\ \text{IN}\cdot\text{K}$ — PAGE 9

$$(EI) = \frac{M_p}{\phi_y} = \frac{34{,}800}{.000168} = 207{,}142{,}857\ \text{K}\cdot\text{IN}^2$$

$$K_i = \frac{12 \times EI}{(21.5 \times 12)^3} = 145\ \text{K/IN/COLUMN}$$

APPROXIMATE YIELD DISPLACEMENT

$$\Delta_y \approx V_p/(3 \times K_i)$$

$$V_p\ (21.5 \times 12/2) \cong 34{,}800 \times 3$$

$$V_p \cong 809\ \text{KIPS/BENT}$$

$$\Delta_y \approx \frac{809}{3 \times 145} \Rightarrow \boxed{\Delta_y \approx 1.86''}$$

PLASTIC HINGE LENGTH: — 4.11.6

$$L_p = 0.08L + 0.15 f_{ye} d_{bl} \geq 0.3 f_{ye} d_{bl}$$

L = LENGTH OF COLUMN FROM M_{MAX} TO CONTRA-FLEXURE = 129" — PAGE 11

$f_{ye} = 66\ \text{KSI}$ — PAGE 2

d_{bl} = DIAMETER OF LONGITUDINAL REBAR IN COLUMN = 1"

$$L_p = 0.08 \times 129 + 0.15 \times 66 \times 1$$
$$= 10.32'' + 9.9''$$
$$= 20.22'' > .3 \times 66 \times 1 = 19.8''$$

$$\boxed{L_p = 20.22''}$$

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COUNTY: CROSSING: NOTES

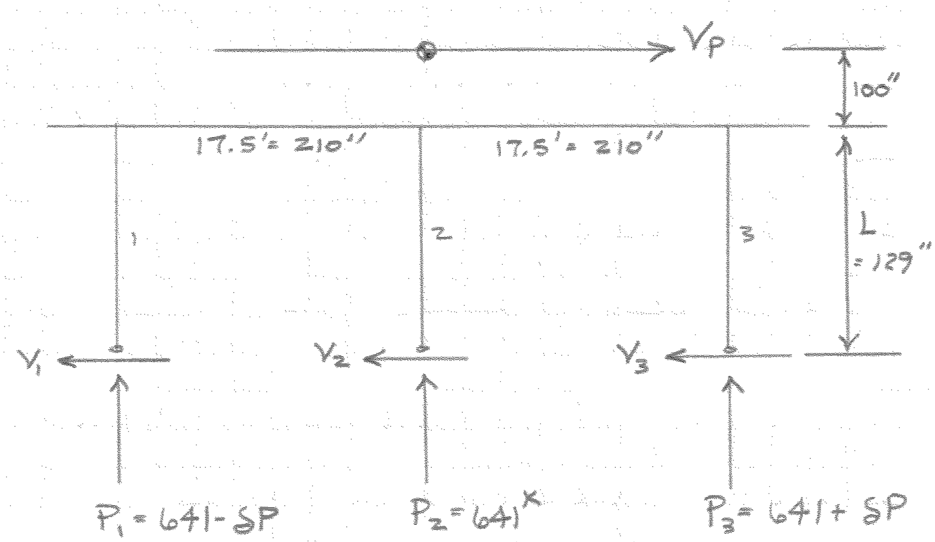
DEFLECTION EQUATIONS

$$\Delta_y = \phi_y L^2/3$$

$$\Delta_p = (\phi_u - \phi_y)(L_p)(L - L_p/2)$$

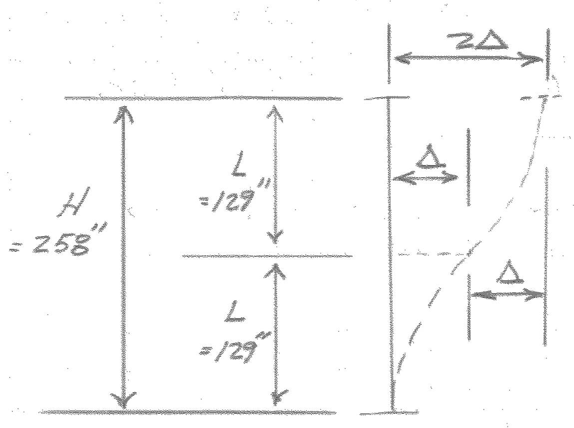
$$\Delta_u = \Delta_y + \Delta_p$$

NOTE THAT THESE EQUATIONS GIVE THE DISPLACEMENT BETWEEN POINTS OF ZERO-MOMENT AND MAXIMUM MOMENT IN THE COLUMN, NOT NECESSARILY THE DISPLACEMENT BETWEEN THE TOP AND BOTTOM OF THE COLUMN.



$$V_P\,(229") = \delta P(210)(2)$$

$$\delta P = 0.545\,V_P$$



SLIDES 7-12 & 7-13 OF "SEISMIC DESIGN & RETROFIT OF HIGHWAY BRIDGES" PARTICIPANT WB, IMBSEN & ASSOC., APRIL 2002.

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COUNTY: CROSSING: NOTES

OBSERVE, ON PAGE 8, THAT A LINEAR RELATIONSHIP BETWEEN AXIAL LOAD, P, AND PLASTIC MOMENT, M_p, IS NOT AN UNREASONABLE ASSUMPTION.

THUS, THE GAIN IN M_p AT THE "LEEWARD" COLUMN WILL BE VERY NEARLY OFFSET BY AN EQUAL LOSS IN M_p AT THE WINDWARD COLUMN.

PLASTIC SHEAR CALCULATION WILL THUS BE BASED ON $3 \times M_{p2}$

$M_{p2} = M_p$ @ 641^K AXIAL LOAD

$= 34,681$ IN·KIPS — PAGE 9

$3M_{p2} = 104,044$ IN·KIPS

$$V_p = V_1 + V_2 + V_3 \cong \frac{3M_{p2}}{L}$$

$V_p = 104,044$ IN·K / 129 IN

$\Rightarrow$ **$V_p = 806$ KIPS**

$SP = 0.545 \times 806 = 440$ KIPS

$P_1 = 641 - 440 = 201^K \rightarrow M_{p1} = 31,522$

$P_2 = 641 \rightarrow M_{p2} = 34,681$

$P_3 = 641 + 440 = 1,081 \rightarrow M_{p3} = 37,840$

$V_1 = 31,522/129 = 244$ KIPS

$V_2 = 34,681/129 = 269$ KIPS

$V_3 = 37,840/129 = 293$ KIPS

$\Sigma V = 806^K = V_p$ CHECKS

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COUNTY: CROSSING: NOTES

$M_{OT} = V_p (100 + 129)$

$= 806 (229) = \underline{184,574 \text{ IN}\cdot\text{K}}$

$M_{RES} = (P_3 - P_1)(210)$

$= (1,081 - 201)(210)$

$= \underline{184,800 \text{ IN}\cdot\text{K}}$

$\approx M_{RES}$ (WITHIN 0.12%) CHECKS

AN ITERATIVE PROCEDURE WILL BE USED TO LOCATE THE SHEAR CAUSING THE FIRST HINGE AND THE LOCATION OF THE FIRST HINGE.

SECOND-ORDER EFFECTS WILL BE INCLUDED AS DESCRIBED ON PAGE 3:

STEP 1. ASSUME A VALUE OF V_{TOTAL}

STEP 2. COMPUTE $P_1 = 641 - .545\, V_{TOTAL}$ — PAGE 18

$P_2 = 641$

$P_3 = 641 + .545\, V_{TOTAL}$

STEP 3. COMPUTE:

$(EI)_{EFF\text{-}i} = 112,952 P_i + 137,819,293 - P_i (258)^2/12$

$i = 1, 2, 3$

STEP 4. COMPUTE $\Delta_2 = \dfrac{\frac{1}{2} V_{TOTAL} (258)^3}{[3 (EI)_{EFF\text{-}2}](12)}$

STEP 5. COMPUTE $V_i = \dfrac{(EI)_{EFF\cdot i} \times V_{TOTAL}}{(EI)_{EFF\text{-}1} + (EI)_{EFF\text{-}2} + (EI)_{EFF\text{-}3}}$

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COUNTY: CROSSING: NOTES

STEP 6. COMPUTE:

$$M_{pi} = 30{,}079 + 7.18\,P_i$$

$$i = 1, 2, 3$$

STEP 7. COMPUTE:

$$M_i = V_i\,(129'') + P_i\,(\Delta_2)$$

$$i = 1, 2, 3$$

STEP 8. COMPUTE:

$$\left(\frac{M_i}{M_{pi}}\right) \qquad i = 1, 2, 3$$

STEP 9. IF THE $MAX\left(\frac{M_i}{M_{pi}}\right) = 1.000$,

THE SOLUTION HAS CONVERGED AND THE COLUMN WITH THE VALUE OF 1.000 IS THE LOCATION OF THE HINGE.

OTHERWISE, START OVER WITH A NEW VALUE OF

$$(V_{TOTAL})_{NEW} = \frac{(V_{TOTAL})_{OLD}}{MAX\left(\frac{M_i}{M_{pi}}\right)}$$

THIS WAS DONE WITH AN INITIAL V_{TOTAL} = 806 KIPS. THE SEQUENCE OF ITERATIONS IS SHOWN ON PAGES 22-25.

NOTE: Δ_2 IS THE DEFLECTION BETWEEN POINT OF ZERO MOMENT (MID-HEIGHT) AND MAXIMUM MOMENT. TOTAL DISPLACEMENT = $2 \times \Delta_2$

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Assumed
V_{TOTAL} = 806 kips

Δ_2 = 0.93 inches

P_1 = 202
P_2 = 641
P_3 = 1,080

$(EI)_{EFF-1}$	159,486,104	0.257
$(EI)_{EFF-2}$	206,665,898	0.333
$(EI)_{EFF-3}$	253,845,692	0.409
$(EI)_{EFF-TOT}$	619,997,694	1.000

V_1 =	207
V_2 =	269
V_3 =	330
V_{TOTAL} =	806

Column	M_p, in-kips	M, in-kips	M/M_P
1	31,529	26,934	0.854
2	34,688	35,254	1.016
3	37,846	43,575	1.151

Revised V_{TOTAL} = 700

Assumed V_{TOTAL} =	700	kips
Δ_2 =	0.81	inches
P_1 =	260	
P_2 =	641	
P_3 =	1,023	

$(EI)_{EFF-1}$	165,690,891	0.267
$(EI)_{EFF-2}$	206,665,898	0.333
$(EI)_{EFF-3}$	247,640,906	0.399
$(EI)_{EFF-TOT}$	619,997,694	1.000

V_1 =	187
V_2 =	233
V_3 =	280
V_{TOTAL} =	700

Column	M_p, in-kips	M, in-kips	M/M_P
1	31,945	24,342	0.762
2	34,688	30,618	0.883
3	37,431	36,894	0.986

Revised V_{TOTAL} = 710

Assumed V_{TOTAL} =	710	kips
Δ_2 =	0.82	inches
P_1 =	254	
P_2 =	641	
P_3 =	1,028	

$(EI)_{EFF-1}$	165,105,533	0.266
$(EI)_{EFF-2}$	206,665,898	0.333
$(EI)_{EFF-3}$	248,226,263	0.400
$(EI)_{EFF-TOT}$	619,997,694	1.000

V_1 =	189
V_2 =	237
V_3 =	284
V_{TOTAL} =	710

Column	M_p, in-kips	M, in-kips	M/M_P
1	31,906	24,599	0.771
2	34,688	31,055	0.895
3	37,470	37,512	1.001

Revised V_{TOTAL} = 709

Assumed V_{TOTAL} =	709	kips	
Δ_2 =	0.82	inches	TOTAL $\delta = 2 \times 0.82 = 1.64''$
P_1 =	255		
P_2 =	641		
P_3 =	1,027		

$(EI)_{EFF-1}$	165,164,069	0.266
$(EI)_{EFF-2}$	206,665,898	0.333
$(EI)_{EFF-3}$	248,167,727	0.400
$(EI)_{EFF-TOT}$	619,997,694	1.000

V_1 =	189
V_2 =	236
V_3 =	284
V_{TOTAL} =	709

Column	M_p, in-kips	M, in-kips	M/M_P
1	31,910	24,573	0.770
2	34,688	31,012	0.894
3	37,466	37,450	1.000

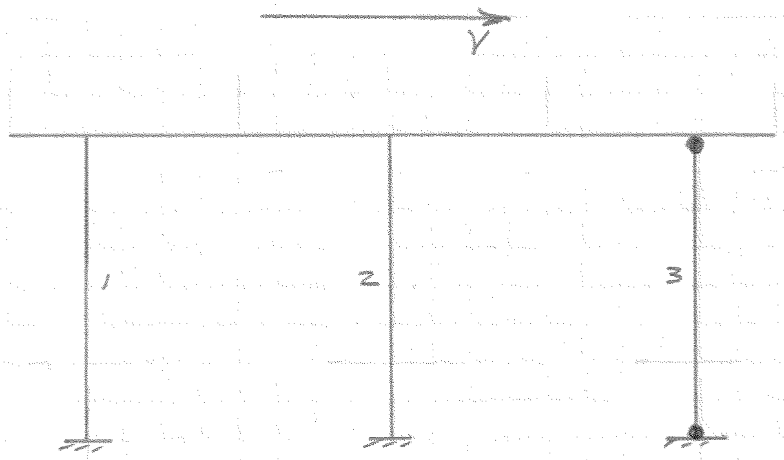
Revised V_{TOTAL} = 709

THUS, THE 1ST PLASTIC HINGE FORMS AT COLUMN #3 WHEN THE TOTAL SHEAR ON THE BENT IS 709 KIPS.

THE YIELD DISPLACEMENT IS 1.64''

COUNTY: CROSSING: NOTES

ONCE THE HINGES FORM IN COLUMN 3:



INITIAL VALUES FOR THIS PHASE:

M_1 = 24,573 IN·K M_{p1} = 31,910 IN·K

P_1 = 255 KIPS

V_1 = 189 KIPS

ϕ_1 = 0.000145 IN^{-1} (= $\phi_{y1} \times M_1 / M_{p1}$)

ϕ_{y1} = 0.000188 IN^{-1} (FROM P. 7)

ϕ_{u1} = 0.00163 IN^{-1} (FROM P. 8)

PAGE 25

M_2 = 31,012 IN·K M_{p2} = 34,688 IN·K

P_2 = 641 KIPS

V_2 = 236 KIPS

ϕ_2 = 0.000153 IN^{-1} (= $\phi_{y2} \times M_2 / M_{p2}$)

ϕ_{y2} = 0.000171 IN^{-1} (FROM P. 7)

ϕ_{u2} = 0.00149 IN^{-1} (FROM P. 8)

M_3 = M_p = 37,450 IN·KIPS

P_3 = 1,027 KIPS

V_3 = 284 KIPS

ϕ_3 = ϕ_{y3} = 0.000154 IN^{-1} (FROM P. 7)

ϕ_{u3} = 0.00135 (FROM P. 8)

Δ = 0.82"

V = 709 KIPS

NOTE THAT $P_1 + P_2 + P_3$ MUST STILL ADD UP TO 3 × 641 = 1,923 KIPS

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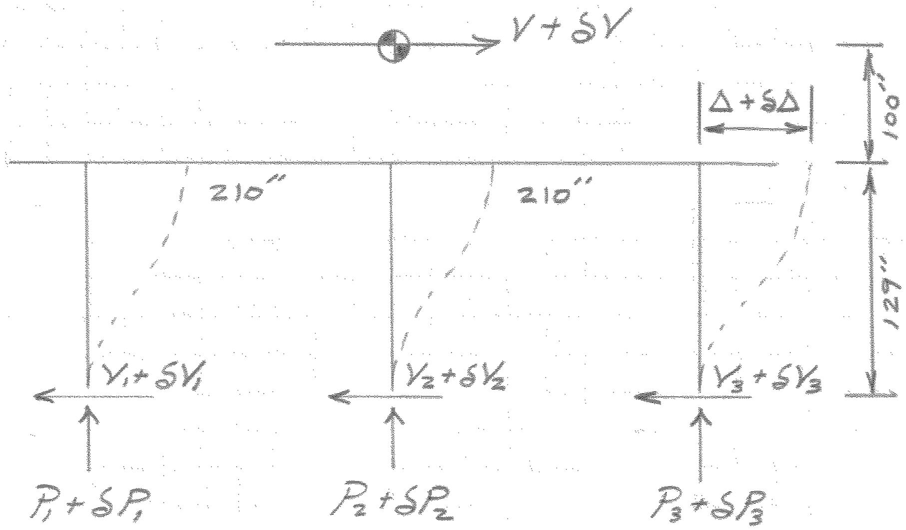

1. ASSUME A VALUE FOR $\delta\Delta$

2. ASSUME A VALUE FOR δV_3
(IT WILL BE NEGATIVE)

3. $(P_3 + \delta P_3) = \dfrac{M_{P3} - (V_3 + \delta V_3)(129)}{\Delta + \delta\Delta}$

4. $(P_1 + \delta P_1 + P_2 + \delta P_2) = 1{,}923 - (P_3 + \delta P_3)$

5. $(P_{1-2})_{AVG} = \frac{1}{2}(P_1 + \delta P_1 + P_2 + \delta P_2)$

6. $(EI)_{EFF\text{-}TOTAL}$

$$[137{,}819{,}293 + 112{,}952\,(P_{1-2})_{AVG}] \times 2 - \frac{1{,}923 \times 258^2}{12}$$

7. $\delta V = \dfrac{12\,(EI)_{EFF\text{-}TOTAL}\,(\delta\Delta)}{(258)^3}$

8. SUM MOMENTS ABOUT COL. 2 CONTRAFLEX.

$$(P_1 + \delta P_1) = \frac{-(V + \delta V)(229) + (P_3 + \delta P_3)(210)}{210}$$

9. $P_2 + \delta P_2 = (P_1 + \delta P_1 + P_2 + \delta P_2) - (P_1 + \delta P_1)$

10. CALCULATE $(EI)_{EFF\text{-}1}$
$(EI)_{EFF\text{-}2}$
USING $(P_1 + \delta P_1)$ & $(P_2 + \delta P_2)$ IN THE EQUATION IN STEP 6.

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11. CALCULATE :

$$V_1 + \delta V_1 = \frac{12\,(EI)_{EFF\cdot 1}\,(\delta\Delta)}{(258)^3} + V_1$$

$$V_2 + \delta V_2 = \frac{12\,(EI)_{EFF\cdot 2}\,(\delta\Delta)}{(258)^3} + V_2$$

12. $(EI)_{EFF\text{-}3} = -\,(P_3 + \delta P_3)(258)^2/12$

$$\delta V_3 = \frac{12\,(EI)_{EFF\cdot 3}\,(\delta\Delta)}{(258)^3}$$

IF THIS $\delta V_3 = \delta V_3$ ASSUMED IN STEP 2, PROCEED TO STEP 13. OTHERWISE, REVISE δV_3 & RETURN TO STEP 3.

13. CALCULATE

$$M_1 = (V_1 + \delta V_1)(129) + (P_1 + \delta P_1)(\Delta + \delta\Delta)$$

$$M_2 = (V_2 + \delta V_2)(129) + (P_2 + \delta P_2)(\Delta + \delta\Delta)$$

$$M_{P1} = 30{,}079 + 7.18\,(P_1 + \Delta P_1)$$

$$M_{P2} = 30{,}079 + 7.18\,(P_2 + \Delta P_2)$$

IF $X = MAX\,(M_i/M_{Pi},\ i = 1,2) = 1.00$, CONVERGENCE REACHED.

OTHERWISE REVISE $\delta\Delta$:

$$(\Delta + \delta\Delta)_{NEW} = \frac{(\Delta + \delta\Delta)_{OLD}}{X}$$

& RETURN TO STEP 2.

ITERATION WAS CARRIED OUT. RESULTS ARE SHOWN ON PAGE 29.

$V + \delta V = 782$ KIPS

$\Delta + \delta\Delta = 1.09''$

TOTAL DISPLACEMENT WHEN HINGE FORMS IN COLUMN 2 IS $2 \times 1.09 = 2.18''$.

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PHASE II: After hinges form in column #3

Initial conditions:

Column	M, in-k	P, kips	V, kips	ϕ, in^{-1}
1	24573	255	189	0.000145
2	31012	641	236	0.000153
3	37450	1027	284	0.000154
Δ =	0.82	inches		
V =	709	kips	ΣFy =	1,923

Assumed $\delta\Delta$ = 0.27 inches

Assumed ΔV_3 =	-0.90	kips
$V_3+\delta V_3$ =	283.11	kips
$P_3+\delta P_3$ =	852.71	kips
$P_1+\delta P_1+P_2+\delta P_2$ =	1,070.29	kips
$(P_{1-2})_{AVG}$ =	535.14	kips
$(EI)_{EFF-TOT}$ =	385,862,987	kip-in^2
δV =	72.80	kips
$V+\delta V$ =	781.80	kips
$V_1+\delta V_1+V_2+\delta V_2$ =	498.69	kips
$P_1+\delta P_1$ =	0.18	kips
$P_2+\delta P_2$ =	1,070.11	kips
$(EI)_{EFF1}$ =	137,838,517	kip-in^2
$(EI)_{EFF2}$ =	252,754,458	kip-in^2
$(EI)_{EFF3}$ =	-4,729,988	kip-in^2
	385,862,987	kip-in^2
$V_1+\delta V_1$=	215.00	kips
$V_2+\delta V_2$ =	283.69	kips
$V_3+\delta V_3$ =	283.11	kips
	781.80	kips

$\Delta + \delta\Delta = 0.82 + 0.27$
$= 1.09''$

$M_1+\delta M_1$=	27,736	M_{P1} =	30,080	0.922
$M_2+\delta M_2$ =	37,762	M_{P2} =	37,762	1.000
$M_3+\delta M_3$ =	37,450			

ROTATION OF PLASTIC HINGE AT COLUMN 3:

$\theta_{P3} = 0.27''/129'' = 0.00209$ RADIANS

FROM TIME HINGE FORMS IN COLUMN 3 TO TIME HINGE FORMS IN COLUMN 2.

COUNTY:	CROSSING:	NOTES

FOR THE FINAL PHASE, WE WILL ASSUME THE ENTIRE INCREMENTAL SHEAR, δV, IS TAKEN BY THE ONLY REMAINING COLUMN WITHOUT PLASTIC HINGES, COLUMN 1.

INITIAL CONDITIONS FOR PHASE III:

$V = 782\ KIPS \quad \Delta = 1.09''$

$V_1 = 215\ KIPS \quad V_2 = 284\ KIPS \quad V_3 = 283\ KIPS$
$P_1 = 0\ KIPS \quad P_2 = 1{,}070\ KIPS \quad P_3 = 853\ KIPS$
$M_1 = 27{,}736\ IN \cdot K$
$M_{p1} = 30{,}080\ IN \cdot K$

$$\delta V = \frac{30{,}080 - 27{,}736}{129} = 18.2\ KIPS$$

$$(EI)_{EFF\text{-}TOTAL} = 137{,}819{,}293 + 112{,}952\,(0) - \frac{1923 \times 258^2}{12}$$

$$= 127{,}152{,}412\ K \cdot IN^2$$

$$\delta\Delta = \frac{18.2\,(258)^3}{12 \times 127{,}152{,}412} = 0.20''$$

$\Delta = 1.09 + 0.20 = 1.29''$
$V = 782 + 18 = 800\ KIPS$

TOTAL DISPLACEMENT $= 2 \times 1.29'' = 2.58''$

$\theta_{p3} = 0.00209 + 0.2/129$
$= 0.00364$ RADIANS

PAGE 29

THERE IS NO LONGER AN EXPLICIT CHECK OF ROTATION CAPACITY OF PLASTIC HINGES. RATHER, THE LOCAL DUCTILITY DEMAND IS COMPUTED.

$$\mu_D = 1 + \frac{\Delta_{pd}}{\Delta_y} \quad \text{(SECT. 4.9)}$$

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COUNTY: CROSSING: NOTES

HINGE ROTATION WILL BE TRACKED ANYWAY.

ONCE THE FINAL COLUMN HAS HINGED, THE BENT WILL DISPLACE UNDER CONSTANT SHEAR UNTIL THE ULTIMATE CURVATURE IS REACHED IN COLUMN 3, WHICH WAS THE FIRST COLUMN TO HINGE.

$\phi_{u3} = 0.00135\ IN^{-1}$ PAGE 26
$\phi_{y3} = 0.000154\ IN^{-1}$

$\Delta_p = (\phi_u - \phi_y)(L_p)(L - L_p/2)$ PAGE 18

$L_p = 20.22''$ PAGE 17
$L = 129''$ PAGE 18

$\Delta_p = (0.00135 - 0.000154)(20.22)(129 - 10.11)$

$\Delta_p = 2.875''$ $\Delta_{TOT} = 0.82 + 2.875 = 3.695''$

SUMMARY:

STATE	V	Δ	2Δ	COMMENT
1	709^K	0.82"	1.64"	COLUMN 3 HINGES
2	782^K	1.09"	2.18"	COLUMN 2 HINGES
3	800^K	1.29"	2.58"	COLUMN 1 HINGES
4	800^K	3.70"	7.39"	COLLAPSE

TOTAL REQ'D ROTATION OF PLASTIC HINGES AT COLUMN 3, θ_{pd}:

$$\theta_{pd} = (3.70 - 0.82)/129''$$

$$\theta_{pd} = 0.0223 \text{ RADIANS}$$

ROTATION CAPACITY OF PLASTIC HINGE:

$$\theta_{pc} = \phi_u \times L_p = 0.00135 \times 20.22'' = 0.0273 \text{ RADIANS} > 0.0223,\ OK$$

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DT-1420 (Structures Design Form 3)

COUNTY: CROSSING: NOTES

Δ_{pd} = PLASTIC DISPLACEMENT DEMAND
= ELASTIC DISPLACEMEN FROM SEISAB
$- \Delta_y$

SEISAB BENT DISPLACEMENT = 2.93"

$$\Delta_{pd} = 2.93\left(\tfrac{1}{2}\right) - 0.82$$

$$\Delta_{pd} = 0.65''$$

PLASTIC DISPLACEMENT CAPACITY

$$\Delta_{pc} = 2.875''$$

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SEC. 4.9

$$\mu_D = 1 + \frac{\Delta_{pd}}{\Delta_y} = 1 + \frac{0.65}{0.82} = 1.79$$

$1.79 < 8$, OK

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CHECK | DATE

COUNTY: CROSSING: | NOTES

IF WE HAD ASSUMED ALL HINGES FORM SIMULTANEOUSLY IN ALL COLUMNS:

USE $P_{AVG} = 641^K$

$(EI)_{EFF\text{-}AVG} = 137,819,293 + 112,952(641) - \frac{641(258)^2}{12}$ — PAGES 3,10

$= 206,665,898 \; K \cdot IN^2$

$(M_P)_{AVG} = 30,079 + 7.18(641)$ — PAGE 9

$= 34,681 \; IN \cdot K$

$(\phi_y)_{AVG} = 0.000199 - 4.42 \times 10^{-8}(641)$ — PAGE 7

$= 0.000171 \; IN^{-1}$

$(\phi_u)_{AVG} = 0.00173 - 3.7 \times 10^{-7}(641)$ — PAGE 8

$= 0.00149 \; IN^{-1}$

$M_{P2} = V_2(H/2) + P_2(d_y)$

$= (V_p/3)(129) + 641(d_y)$

$d_y = \frac{V_p(258)^3}{3(12)(206,665,898)} = \frac{V_p}{433.2}$

$V_p\frac{(129)}{3} + 641\left(\frac{V_p}{433.2}\right) = 34,681$

$\Rightarrow$ $V_p = 780$ KIPS

$d_y = 1.80''$

$\Delta_p = (0.00149 - 0.000171)(20.22)(129 - 10.11) = 3.17''$ — PAGES 17,18

$\Delta_y = d_y/2 = 0.9''$

$\Delta_u = 0.9 + 3.17 = 4.07''$

$d_u = 2\Delta_u = 8.14''$

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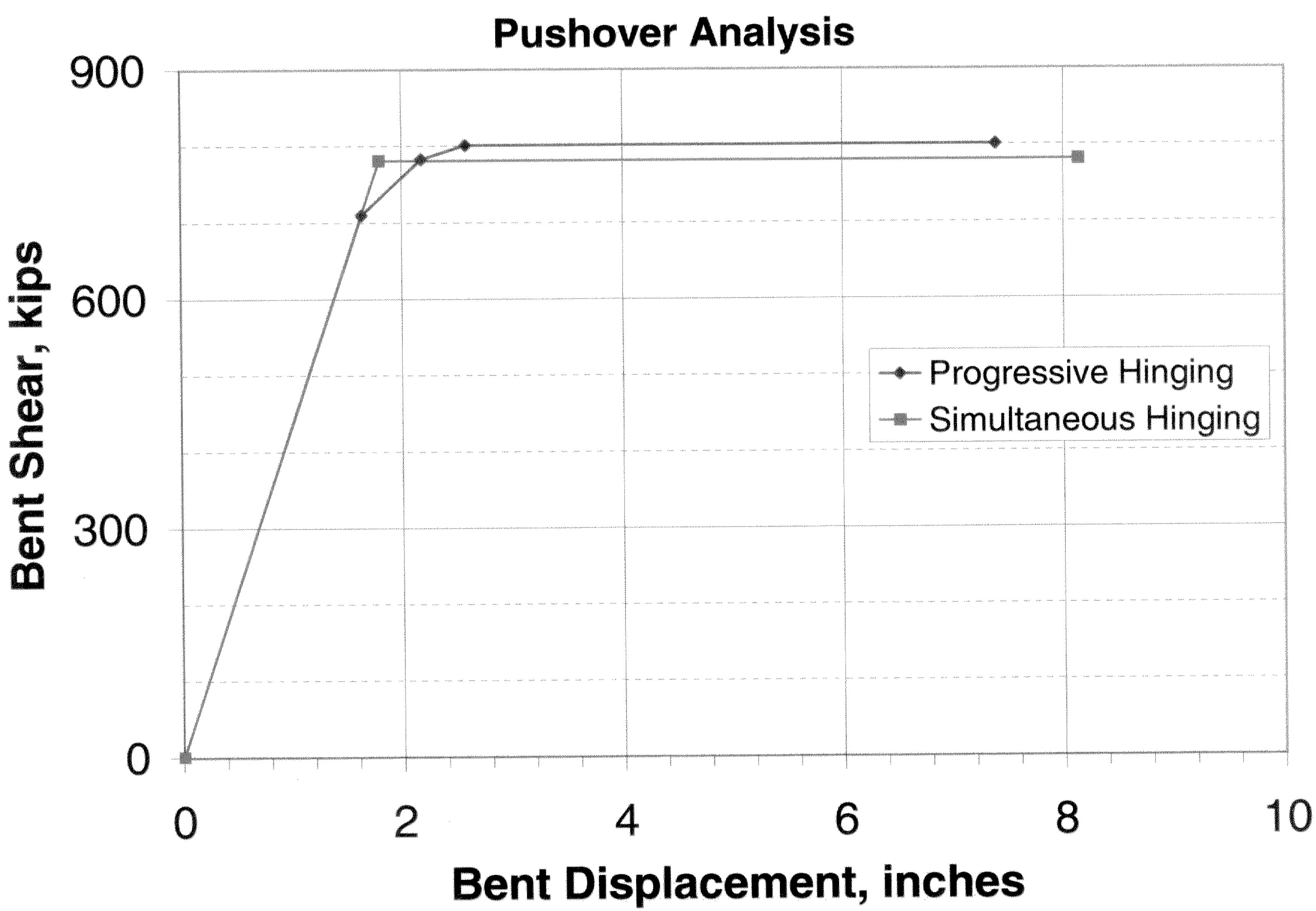
Pushover Analysis
900
600
300
0
Bent Shear, kips
0
2
4
6
8
10
Bent Displacement, inches
Progressive Hinging
Simultaneous Hinging