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BIAX:
A Computer Program for the Analysis of Reinforced Concrete Sections

BY

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ABSTRACT

A program developed for use on MS–DOS personal computers for the analysis of reinforced concrete sections is presented. The capabilities of the program include the calculation of section properties, interaction diagrams, or moment–curvature relations. The interaction diagrams and moment–curvature relations can be computed for either uniaxial or biaxial loading. The CAL/SAP library of subroutines was used to provide a user friendly program environment.

ACKNOWLEDGEMENTS

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The writer would like to thank the numerous graduate students at the University of California at Berkeley that provided valuable suggestions that assisted in the development of the program. Professor E. L. Wilson is acknowledged for development of the CAL/SAP library of subroutines that made the task of creating a user friendly program considerably easier.

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INTRODUCTION

1.1 Introduction

A general purpose computer program to evaluate uniaxial and biaxial strength and deformation characteristics of reinforced concrete (R.C.) sections is described. The program was developed for use on MS–DOS personal computers and has been used extensively at the University of California for both research and teaching purposes. Although other programs are available for this purpose [NISEE (1987)], many have limitations (such as uniaxial loading), are not available for personal computers, or are cumbersome to use.

1.2 Program Capabilites

The program computes strength and deformation characterisitcs based on the assumption that plane sections remain plane after the application of loading. Based on this assumption, the program can be used to compute strength or moment–curvature relations for uniaxial or biaxial monotonic loading of reinforced concrete sections. The strength can be computed for a single loading case, or interaction diagrams can be generated (e.g. $P - M_{xx}$, $P - M_{yy}$, or $M_{xx} - M_{yy}$).

Nonlinear material models are used for both the reinforcing steel and the concrete. The model for the stress–strain behavior of the reinforcing steel is versatile, allowing relations that closely approximate experimentally observed behavior. Models for the concrete stress–strain behavior include the modified Kent and Park [Park et al. (1982)], and Sheikh and Uzumeri (1982) relations. The relationship suggested by Vecchio and Collins (1986) is used to describe the stress–strain relation for concrete in tension. Presently, the program allows two stress–strain diagrams for concrete (unconfined and confined), and four relations for reinforcing steel.

The R.C. section is described as a combination of rectangular subsections; therefore, the program allows easy generation of T, L, or barbell shaped sections. The program user specifies a mesh for each subsection. An iterative procedure (simple bisection algorithm) is used to obtain a solution for the prescribed problem.

1.3 Report Outline

The program manual is presented in the following section. Pertinant notes are included to facilitate user understanding. Appendices are included to detail the material and section modeling capabilities of the program, and present applications and examples.

REFERENCES

Hognestad, E. (1951),"A Study of Combined Bending and Axial Load in Reinforced Concrete Members," University of Illinois Engineering Experimental Station, Bulletin Series No. 399, November 1951, 128 pp.

NISEE: National Information Service for Earthquake Engineering (1987),"Computer Software for Earthquake Engineeing," Earthquake Engineering Research Center, University of California at Berkeley, June 1987.

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BIAX

USERS MANUAL

A Computer Program for the Analysis of Reinforced Concrete Sections

By: John W. Wallace

Disclaimer

Although extensive work has been carried out to verify the program results, the user is soley responsible for the accuracy of the results produced by the **BIAX** program.

Program Limitations

The user must create a input file to describe the R.C. section and the desired solution. Because storage limitations did not arise, minimal effort was placed on overall program efficiency. It is unlikely that the storage capacity of the program will be exceeded for most problems. Dynamic storage allocation can be implemented with program modifications, but is currently not available. The current fixed array dimensions are (selected so that program will run on system with 512k):

Number of Sections	100
Number of Elements	2000
Number of Reinforcing Bars	300

All calculations are done in double precision.

Program Input

The CAL/SAP library of subroutines [developed by E. L. Wilson at the University of California at Berkeley] is used to read the data from the input file. The subroutines allow the use of free-form input which facilitates the task of creating an input data file.

Future Program Development

The future development of the program will be directed towards providing interactive graphics, and options for nonlinear strain distributions, and reinforcement slip. A routine to assist in the creation of moment–rotation relations from moment–curvature relations is also being considered.

Program Execution

The program is executed by typing **BIAX**. The user is prompted for the name of the input file. The program prints information to the terminal screen concerning the program execution.

Several output files are created by the program (E12.6 format is generally used for the output files). They are:

(1)	filename.OUT	output file of program EXECUTION including calculated results
(2)	filename.DAT	file for PLOTTING column (1) X–Moment, M_{xx} column (2) Axial Load, P column (3) Y–Moment, M_{yy} column (4) Curvature, ϵ_c/d column (5) Maximum Steel tensile strain
(3)	filename.DBG	DEBUG file
(4)	conc.dat	CONCRETE material stress–strain
(5)	steel.dat	STEEL material stress–strain
(6)	confc.dat	CONFINED concrete element coordinates
(7)	sects.dat	steel bar locations for plotting check of input file
(8)	sectc.dat	concrete section corner locations for plotting check of input file

COMMENTS

By using sects.dat and sectc.dat the input file can be checked for errors by using any 2D-GRAPHICS program. When more than one rectangular section is defined a line will be drawn from the starting point of each section to the starting point of the next section. Ignore this line.

The program calculates section properties. Inertias (I_{xx}, I_{yy}, and I_{xy}) are calculated for both the neutral axis location and the global midpoint of all the sections defined. The moments are given about the midpoint because it is easy for the user to locate.

A batch file is provided to delete output files created by the **BIAX** program. Use the file **EAT.BAT** and the input filename to delete the files created by the program (execute by typing **EAT** followed by the filename, e.g. EAT EX1)

Program Input

The following several pages describe the input data file requirements for the **BIAX** program. The input file is separated into seven blocks. Separators are used within the input file to specify the location of the seven data blocks. The separators may appear in any order. The separators and the information obtained within each data block are described in the following table.

BLOCK	SEPARATOR	DESCRIPTION OF DATA BLOCK
(1)	SYSTEM	Data block to define global analysis parameters.
(2)	SECTION	Data block to define rectangular subsections that make up the R.C. section.
(3)	STEEL	Data block to define location, area, and type of steel reinforcing bars.
(4)	HOLES	Data block to define any holes (voids) that may exist in R.C. section.
(5)	CONFINED	Data block to define portions of the R.C. section that are confined.
(6)	PROPERTIES	Data block to define material properties for the reinforceing steel and concrete.
(7)	DATA	Data block to define the parameters for the solution or solutions desired.

NOTES: (1) For the analysis of a simple unconfined R.C. section, only data blocks (2), (3), (6), and (7) are required. All the parameters for the **SYSTEM** data block have default values, and therefore, this block is not required in this case.

(2) The only required data block is **SECTION**. If only this data block is specified, the program will compute the section properties (Area, Inertia, etc).

(3) In the CAL/SAP subroutines a colon is used to denote the end of data input for each line. Comment statements are allowed following the use of a colon.

(4) The following pages describe the input file requirements for each data block.

SYSTEM : --

Data block used to specify global analysis parameters.

Line 1	D=	i,j,k	i,j,k=0 no debug messages (default) i,j,k=1 debug messages given for different options within the program
	U=	1	Input specfied in data file (default)
		0	Interactive input
	T=	0	No generation of P–M surface (default)
		1	generation of P–M surface
		2	generation of p–m surface (dimensionless)
	R=	0	Area of bars specified (default)
		R	Where R= steel ratio for section
	S=	0	Automatic iteration (Default)
		1	Interactive iteration
	P=	0	(Default)
		1	Plot material stress–strain relations
	E=	0	Default
		1	Limit maximum concrete strain so rebar does not fracture
		2	Do not allow rebar to fracture
	TOL=	#	Tolerence of convergence to specified axial load [0.001]
	C=	0	If rebar is located within both confined and unconfined concrete then the program will search to determine type of concrete closest to each rebar (to subtract off concrete area taken up by steel).
		1	If all concrete at rebar is unconfined
		2	If all concrete at rebar is confined
	M=	0	Default
		1	Rotate entire section by 180 degrees For non–symmetric sections to change location of compression zone. See Fig. A.5 for the definition of the compression reference point.

SECTION : --

Data block used to specify R.C. section geometry and mesh.

Line 1 to NS		One line for each rectangular subsection defining the complete R.C. section. NS is the total number of sections
	i	Where i is the section # in sequential order (e.g. 1,2,3,etc)
	HI=	length of section in I–direction
	HJ=	length of section in J–direction
	N1=	# of elements in I–direction (Default = 1)
	N2=	# of elements in J–direction (Default = 1)
	X=	X Starting location for bottom left corner of rectangle
	Y=	Y Starting location for bottom left corner of rectangle
	A=	angle, Xr, Yr Angle = (0–360 degrees) to rotate about point Xr, Yr. A positve angle represents counterclockwise rotation). Xr,Yr = Point to rotate section about (default = 0,0). See note (1).
END SECTION WITH BLANK LINE		

NOTE: (1) By using the 'A=' option it is possible to create all sections in a global X, Y coordinate system, and rotate them to an arbitrary position. Slight overlapping of sections will occur at points where sections that are rotated are "attached" to sections that are not rotated. X_r and Y_r define global coordinates about which to rotate the section. The 'A=' option defaults to the previous specified value ('A=0,0,0' to stop section rotation).

STEEL : --

Data block used to specify reinforcing bar information.

Line 1 to END	nbar	Bar number
	X=	X–coordinate
	Y=	Y–coordinate
	A=	area of reinforcing bar
	T=	steel type (four types allowed)
	G=	i bar #, j bar #, bar increment # For linear generation of reinforcing bars between bars i and j, at the specified bar increment. For example, G=1,5,1 generates bars 2, 3, and 4 at equal increments (ΔX, ΔY) between bars 1 and 5.
	R=	angle, Xr, Yr Where: angle is the angle of rotation in degrees (0–360) and X_r, Y_r is the center of rotation. A positive angle corresponds to counterclockwise rotation. All subsequent bars will be rotated until 'R=0,0,0' is specified.
END SECTION WITH BLANK LINE		

NOTES: (1) nbar must begin each line

(2) scalar multiples can be used on any term except nbar, e.g. X=10*12 or X=25/12

(3) the default value for 'A' is the previously specified value.

(4) area of bar can be omitted if 'R=' is specified in **SYSTEM** data block.

(5) bar increment # defaults to [1]

(6) values for nbar need not be sequential or continous. This provides an easy means to add or delete bars without renumbering.

(7) When the 'R=' option is used, all rebar specified on subsequent lines will also be rotated. To deactivate this option use 'R=0,0,0'.

HOLES : --

Data block used to specify holes or voids in RC section.

Line 1 to end	i, j, inc	i	element # for first element
		j	element # for last element
		inc	element increment for generation (default=1)
OR	i, F=	i,inum,jnum,iinc,jinc	
		i	first element for frontal generation
		inum	number of elements in i–direction
		jnum	number of elements in j–direction
		iinc	element increment for i–direction
		jinc	element increment for j–direction
END SECTION WITH BLANK LINE			

`CONFINED : ---------------------------------------------------------------`

Data block used to specify location (elements) of confined concrete.

Line 1 to end	i, j, inc	i	element # for first element
		j	element # for last element
		inc	element increment for generation (default=1)
OR	i, F=	i,inum,jnum,iinc,jinc	
		i	first element for frontal generation
		inum	number of elements in i–direction
		jnum	number of elements in j–direction
		iinc	element increment for i–direction
		jinc	element increment for j–direction
END SECTION WITH BLANK LINE			

PROPERTIES : --

Data block used to specify material properties.

line 1		Unconfined concrete properties
	FC=	peak compressive stress
	E1=	strain at peak compressive stress
	E2=	E50u strain (Modified Kent–Park)
	FR=	tensile stress
line 2		Confined concrete properties (must be specified – See Note (1))
	FC=	peak compressive stress
	E1=	strain at peak compressive stress
	E2=	E50u+E50h strain (modified Kent–Park) or strain for 1/2 of drop from fcmax to fcmin from E1 (or E3 if specified)
	E3=	yield strain plateau (default = E1, no plateau)
	FR=	maximum tensile stress
	FM=	minimum compressive stress at high strain
line 3 to 7		reinforcement (steel) properties
	FY=	yield stress
	FU=	ultimate stress (def. = FY)
	FF=	failure stress (def. = FY)
	E1=	strain for onset of strain hardening (def. = 10 %)
	E2=	strain at stress FU (def. = 10 %)
	E3=	strain at stress FF (def. = 10 %)
	E=	modulus of elasticity
	ET=	initial modulus of elasticity for strain hardening region (def.= 0)
END SECTION WITH BLANK LINE		

NOTES: (1) A line to specify values for confined concrete is required; however, it may be a left blank when confined concrete is not required.

(2) The only values required for the reinforcing steel are the yield stress, and the initial modulus. If only these values are specified, an elasto–plastic steel stress–strain is assumed.

(3) The relation suggested by Vecchio and Collins [ACI Journal, Vol. 83 No. 2, March–April 1986.] is used to describe the stress–strain for concrete in tension.

DATA : --

Data block used to specify desired solution.

Line 1 to end	EC=	extreme fiber strain for concrete
	A=	neutral axis angle desired (defined from global X–axis)
	P=	axial load desired
	PHI=	phi factor to apply to produce design P–M interaction curve (default=1.0)
	N=	Number of points used to compute the P–M interaction diagram (default=11)
END SECTION WITH BLANK LINE		

NOTES: (1) this data block is not required when interactive input is specified.

(2) if generating P–M surface only 'EC=' and 'A=' need to be specified once, 'P=' is not required (and will be ignored if specified).

(3) If P–M surface is not being generated, use as many lines as necessary to define the desired solutions. For moment–curvature analyses specify as many values of extreme fiber compressive strain (monotonic) as desired.

(4) 'EC=' (compression reference point) is the point on the section furthest from the neutral axis (at angle specified). See Fig. A.5.

(5) For P $\leq$ 0.10, the Phi factor is determined by using linear interpolation between the specified phi factor and 0.9 (at P=0). [Note: P_b is not considered].

APPENDIX A

SECTION AND MATERIAL MODELING

Modeling capabilites for the materials and section geometry are described. Section definition is described first, followed by available material stress–strain relationships.

A.1 Reinforced Concrete Section Modeling

The modeling of rectangular reinforced concrete sections is accomplished by subdividing the section into elements. Figure A.1 presents a beam cross–section, and a possible mesh. The mesh of elements is defined by specifying the number of elements in each of the principal directions of the section. For more complicated sections, such as T–Beams or walls with boundary elements, several rectangular sections can be used to describe the element geometry (Fig. A.2). A reference point on each section (I=0,J=0) is used to define the starting location (X_s, Y_s) of each section (Fig. A.2) in the global (X,Y) coordinate system. The location of reinforcing is defined by specifying coordinates in the global coordinate system (X,Y).

A.2 Material Modeling

The program allows stress–strain curves for both unconfined and confined concrete. The concrete stress–strain behavior can be described by either the modified Kent and Park model [Park et al. (1982)], or the Sheikh and Uzumeri model (1982) (Fig. A.3). The initial portion of the stress–relation is described by a second–degree parabolic shape. The relation suggested by Hognestad (1951) is used in this program.

The stress–strain model for the reinforcing steel allows a bilinear curve, or the consideration of strain hardening effects (Fig. A.4). The strain hardening curve is defined by the initial slope of the stress–strain curve at the onset of strain hardening, the ultimate stress and strain, and the fracture stress and strain. The equations describing the relationship are based on the equation presented by Saenz (1964). Care must be exercised when using the strain hardening curve because the relationship used to produce the curve is sensitive. It is suggested to always plot the material stress–strain curves to ensure they are reasonable.

A.3 Solution Reference Angle

The solution is computed with respect to the global X–axis. Therefore, a user specified angle of zero (0.0) coincides with the global X–axis. Angles other than zero (0 to 90 degrees) are measured counterclockwise from the global X–axis (Fig. A.5).

A.4 Solution Reference Point

The analysis of the R.C. section is based on a user specified extreme fiber concrete compressive strain. The location of the compression reference point is determined by the program to be the point furthest on the defined section perpendicular to the defined orientation of the neutral axis in the positive Y direction (Fig. A.5).

A.5 Solution Scheme

The strain at the centerline of each element is computed from the reference point strain assuming plane sections remain plane after loading. The axial load is computed as the sum for all elements (the elements are defined by the specified mesh) of the element stress times the element area. The moments (X–direction and Y–direction) are computed as the product of the element axial force and the perpendicular distance to a line through the geometric centroid of the concrete section parallel to the specified orientation of the neutral axis.

The accuracy of a given solution is determined in part by the number of elements used to model a cross section. The user should verify that the mesh refinement is adequate.

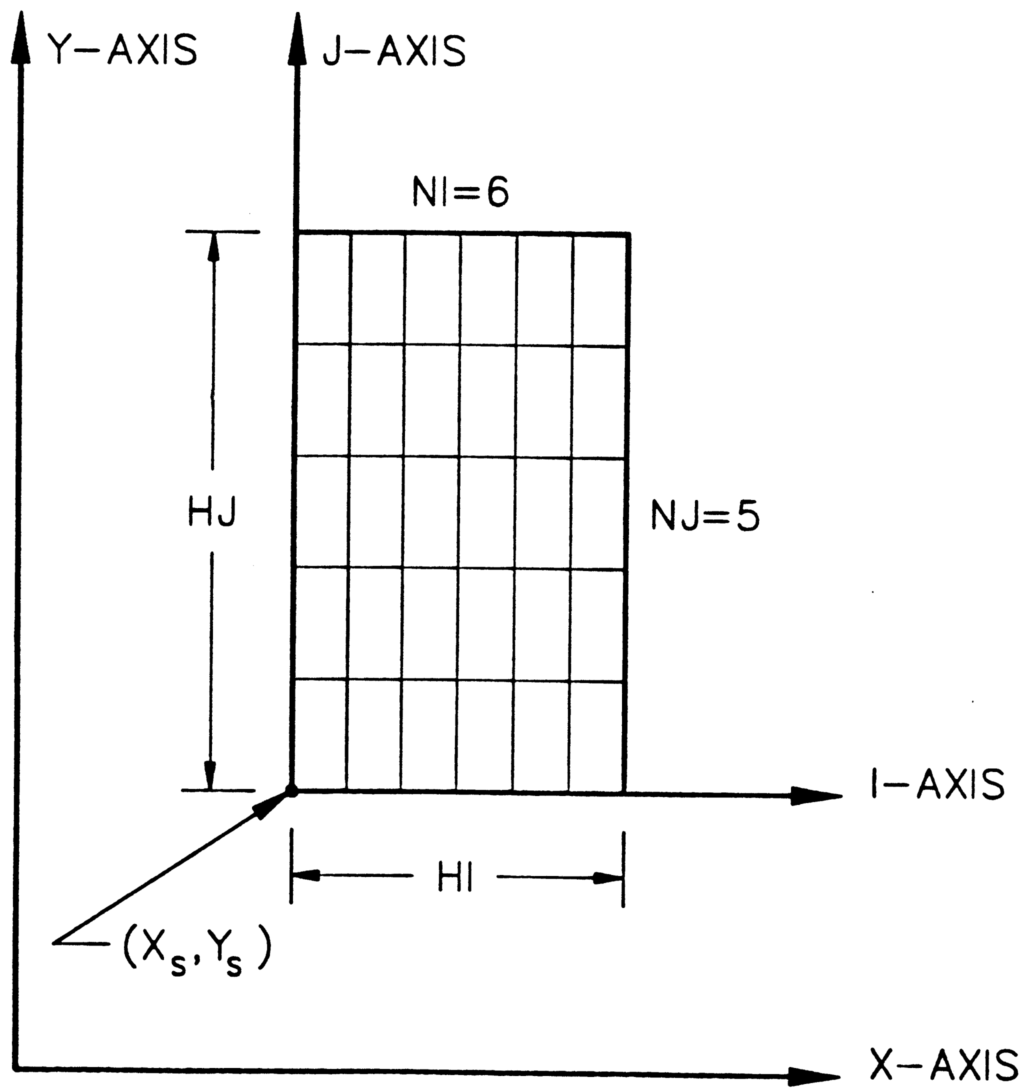

Fig. A.1 Beam Cross Section Modeling

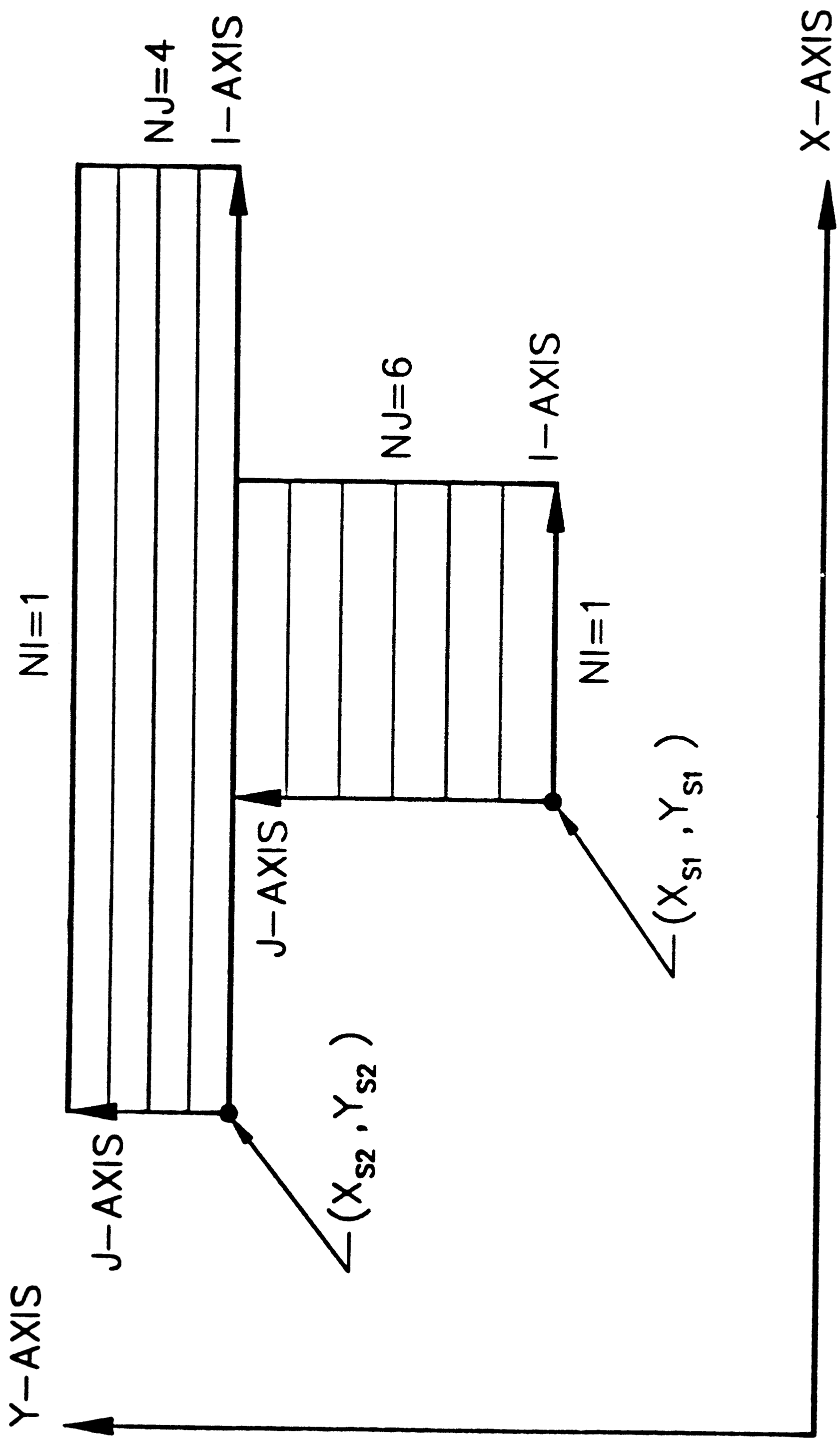

Fig. A.2 T–Beam Cross Section Modeling

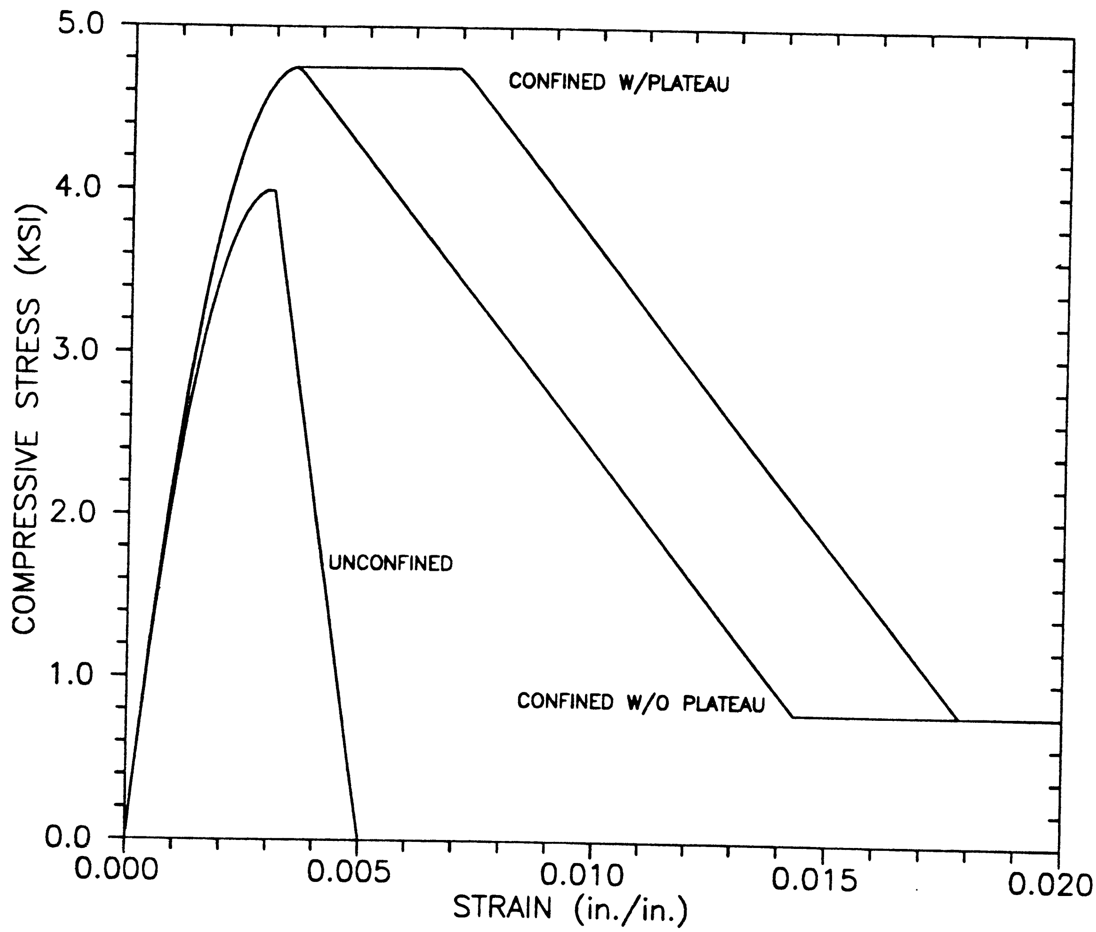

Fig. A.3 Concrete Stress–Strain Relations

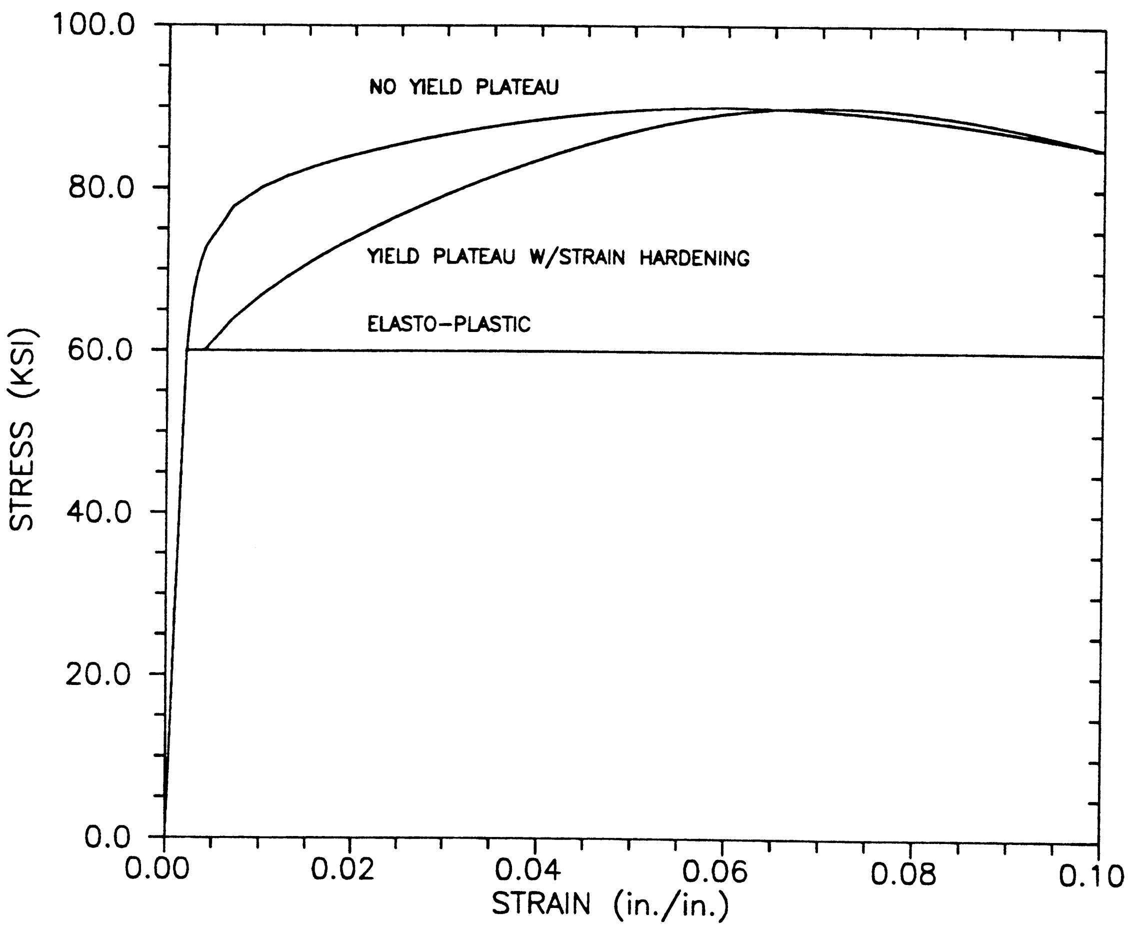

Fig. A.4 Steel Stress–Strain Relations

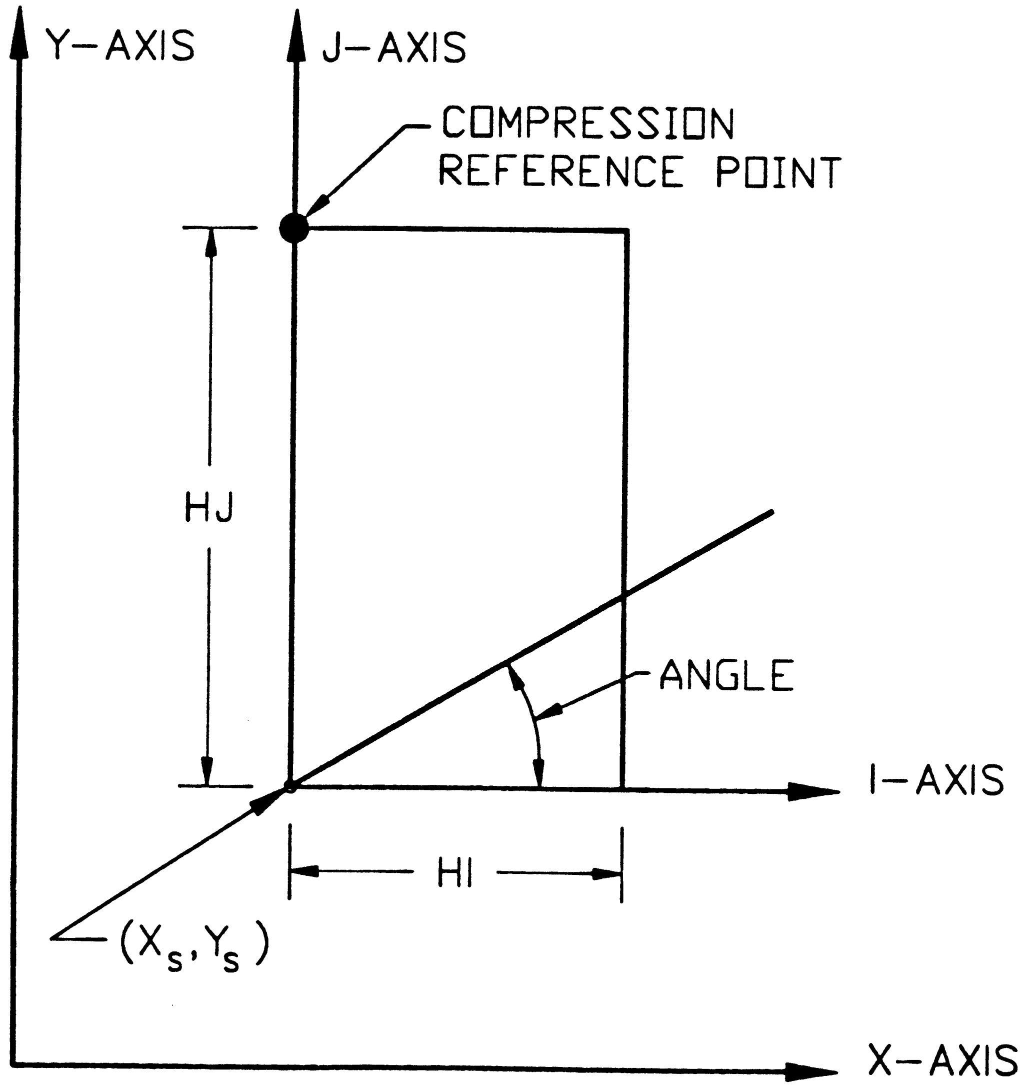

Fig. A.5 Solution Reference Parameters

APPENDIX B

EXAMPLES AND APPLICATIONS

Three examples are presented to facilitate program use and detail program applications. No detailed calculations were made to determine precise values for the material property variables. The intent of the examples is to detail program options.

Example 1: Compute the P–M interaction diagram for the section shown below. Grade 60 elasto-plastic steel and f'_c=4 ksi are used.

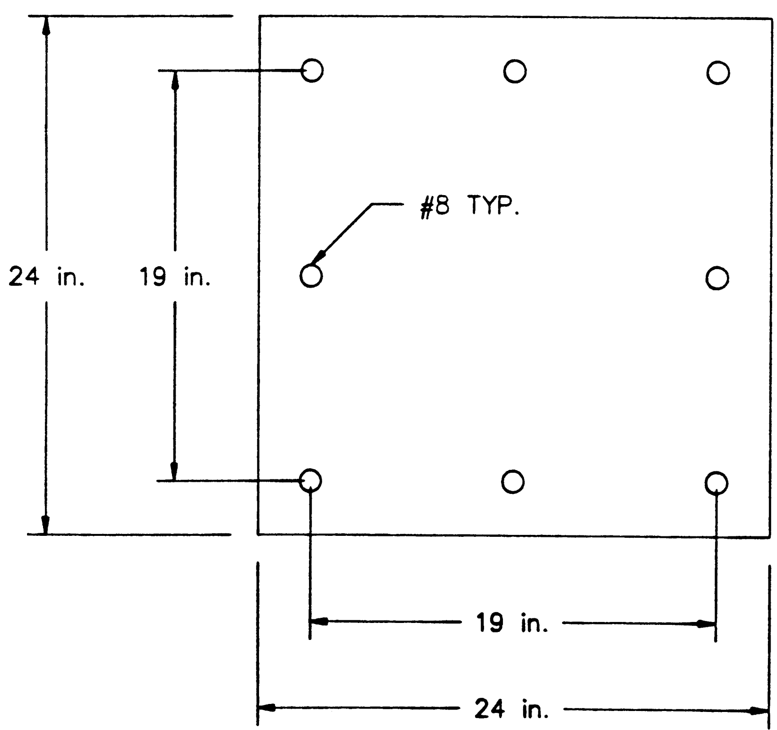

Fig. B.1 Example 1: Column Cross Section

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EXAMPLE 1 : -------------------------------------------------------------

Example 1: COLUMN w/ Unconfined Concrete
P-M Interaction Diagram  -  Based on Design Steel stress-strain


SYSTEM:
D=0,0,1  T=1  E=1  C=1  P=1  TOL=0.0001 : T=1 for P-M Diagram
:                                  P=1 to check stress-strain
:                                  C=1 all concrete is unconfined
:                                  E=1 do not allow any rebar to fracture
:
SECTION:
 1   HI= 24  HJ= 24  N1= 12  N2= 12  X= 0   Y= 0 :  24"x24" Column
:                                                  12x12 mesh
:
STEEL:
  1     X=   2.5  Y=   2.5  A=0.79 T= 1 :  Long. Steel Type
  3     X=  21.5  Y=   2.5  G= 1, 3     :  8 #8 Bars
  5     X=  21.5  Y=  21.5  G= 3, 5     :  2 in. clear cover to bars
  7     X=   2.5  Y=  21.5  G= 5, 7     :  assume #4 hoops
  8     X=   2.5  Y=  12                :
:
:
:
PROPERTY:
FC=4*0.85  E1=0.003  E2= 0.004  FR=0.4 : Tensile strength = 10% f'c
                                       : Blank line for confined concrete
FY=60  E3=0.120  E=29000               : Fracture of steel at 12% strain
:
:
DATA:
EC=0.003  A=0  N=20             : Moment about global X-axis for Ultimate
EC=0.003  A=0  N=20  PHI=0.70 : compressive strain of 0.003, with and
:                                 without capacity reduction factors
:
END
```

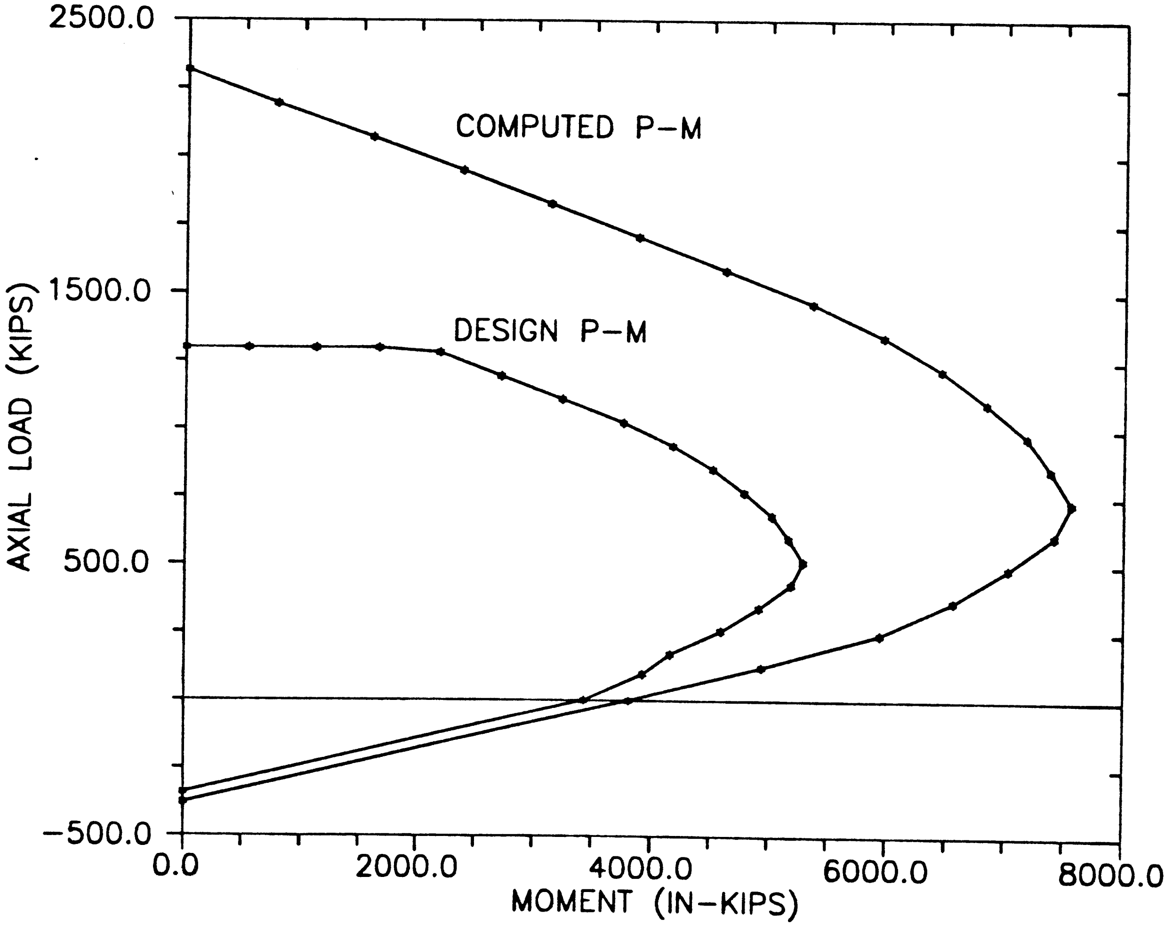

Fig. B.2 Example 1: Computed P–M Interaction Diagram

Example 2: Compute the Moment–Curvature diagram for the section shown below. The concrete is 4000 psi, and the reinforcing steel behavior is based on typical observed experimental relations for grade 60 steel.

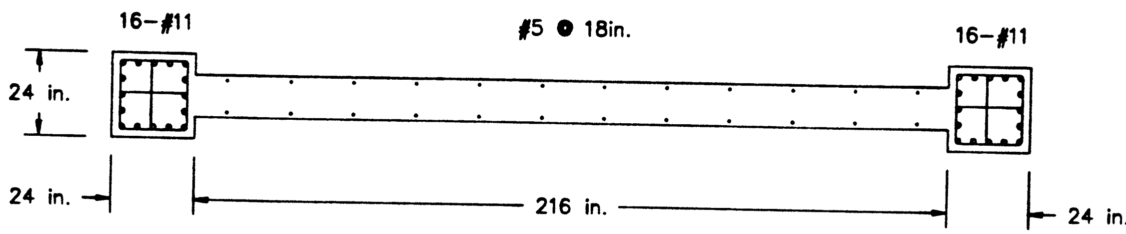

Fig. B.3 Example 2: Wall Cross Section

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EXAMPLE 2 : ----------------------------------------------------------

Example 2: Shear Wall w/ Confined Boundary Elements
Moment - Curvature Calculations for Probable Steel stress-strain
:
SYSTEM:
 T=0  E=0  P=1  TOL=0.0001 :
:
SECTION:
 1    HI= 24  HJ= 24  N1=  8  N2=  8  X= 0   Y=  0 : Boundary Element
 2    HI= 12  HJ=216  N1=  4  N2= 72  X= 6   Y= 24 : Web
 3    HI= 24  HJ= 24  N1=  8  N2=  8  X= 0   Y=240 : Boundary Element
:
CONFINED:
 10      F=  10, 6, 6,1, 8: BOUNDARY ELEMENT
 362     F= 362, 6, 6,1, 8:  "
:
STEEL:
  1     X=   3    Y=   3     A=1.56   T= 1 :  Boundary element steel
  5     X=  21    Y=   3     G= 1, 5  :       16 #11 Bars
  9     X=  21    Y=  21     G= 5, 9  :
 13     X=   3    Y=  21     G= 9,13  :
 16     X=   3    Y=    7.5  G=13,16  :
 17     X=   3    Y= 243              : Boundary element steel
 21     X=  21    Y= 243     G=17,21  :
 25     X=  21    Y= 261     G=21,25  :
 29     X=   3    Y= 261     G=25,29  :
 32     X=   3    Y= 246     G=29,32  :
 33     X=   8    Y=  33     A=0.31   : Web steel - #5 @ 18 in.
 44     X=   8    Y= 231     G=33,44  :
 45     X=  16    Y=  33              :
 56     X=  16    Y= 231     G=45,56  :
:
PROPERTY:
 FC=4  E1= 0.003   E2= 0.004   FR= .4
 FC=5  E1= 0.0035  E2= 0.01    FR= .4    FM= .80
 FY=65  FU=90   FF=85   E1=0.004  E2=0.08  E3=0.12  E=29000 ET=1500:
:
DATA:
 EC=0.0002  A= 0   P=1000 : Moment about global X-axis
 EC=0.0004  A= 0   P=1000
 EC=0.0006  A= 0   P=1000
 EC=0.0008  A= 0   P=1000
 EC=0.0010  A= 0   P=1000
 EC=0.0015  A= 0   P=1000
 EC=0.0020  A= 0   P=1000
 EC=0.0025  A= 0   P=1000
 EC=0.0030  A= 0   P=1000
 EC=0.0035  A= 0   P=1000
 EC=0.0040  A= 0   P=1000
 EC=0.0050  A= 0   P=1000
 EC=0.0060  A= 0   P=1000
 EC=0.0070  A= 0   P=1000
:
END
```

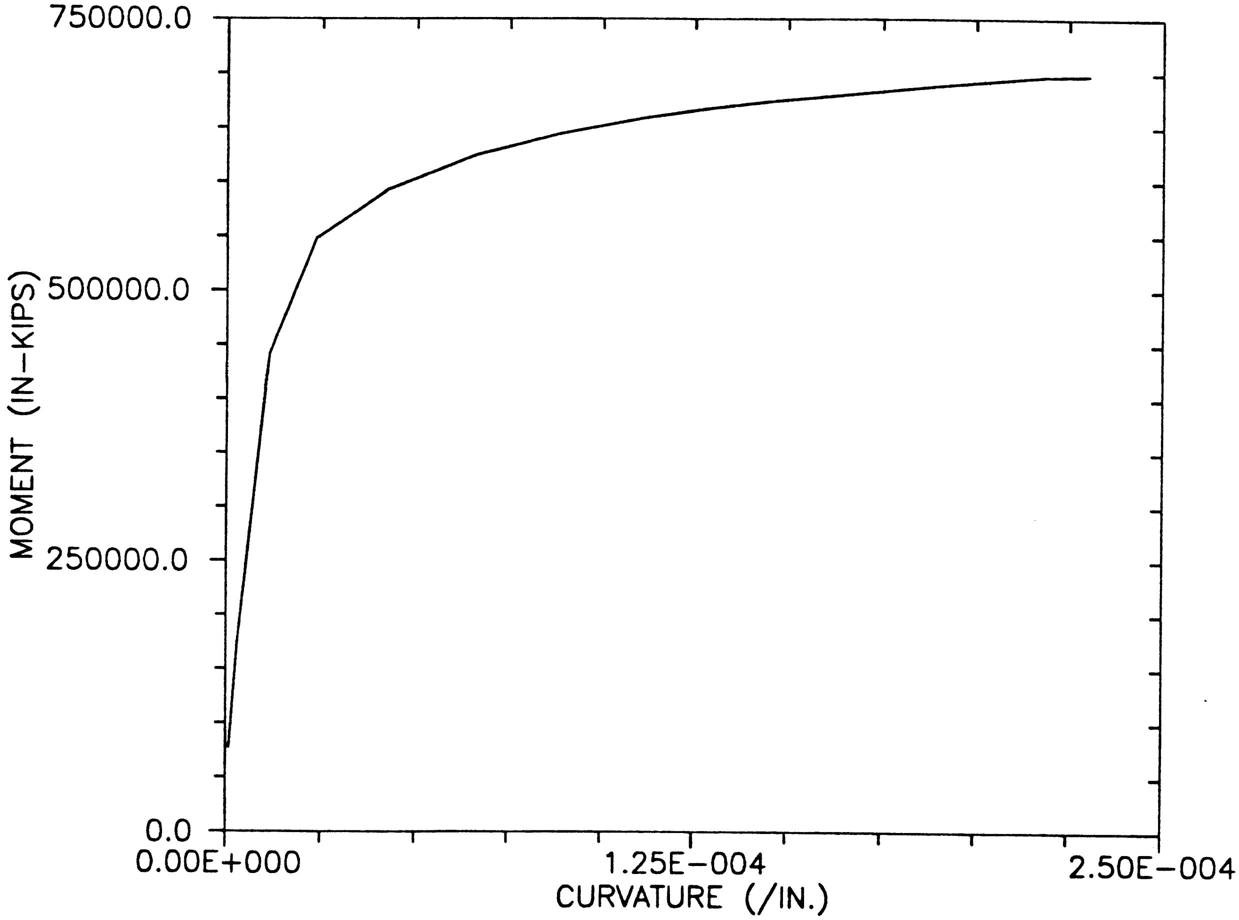

Fig. B.4 Example 2: Computed Moment–Curvature Relation

Example 3: Compute the P–M interaction diagram for the section shown below. The concrete is 4000 psi, and grade 60 reinforcing is used.

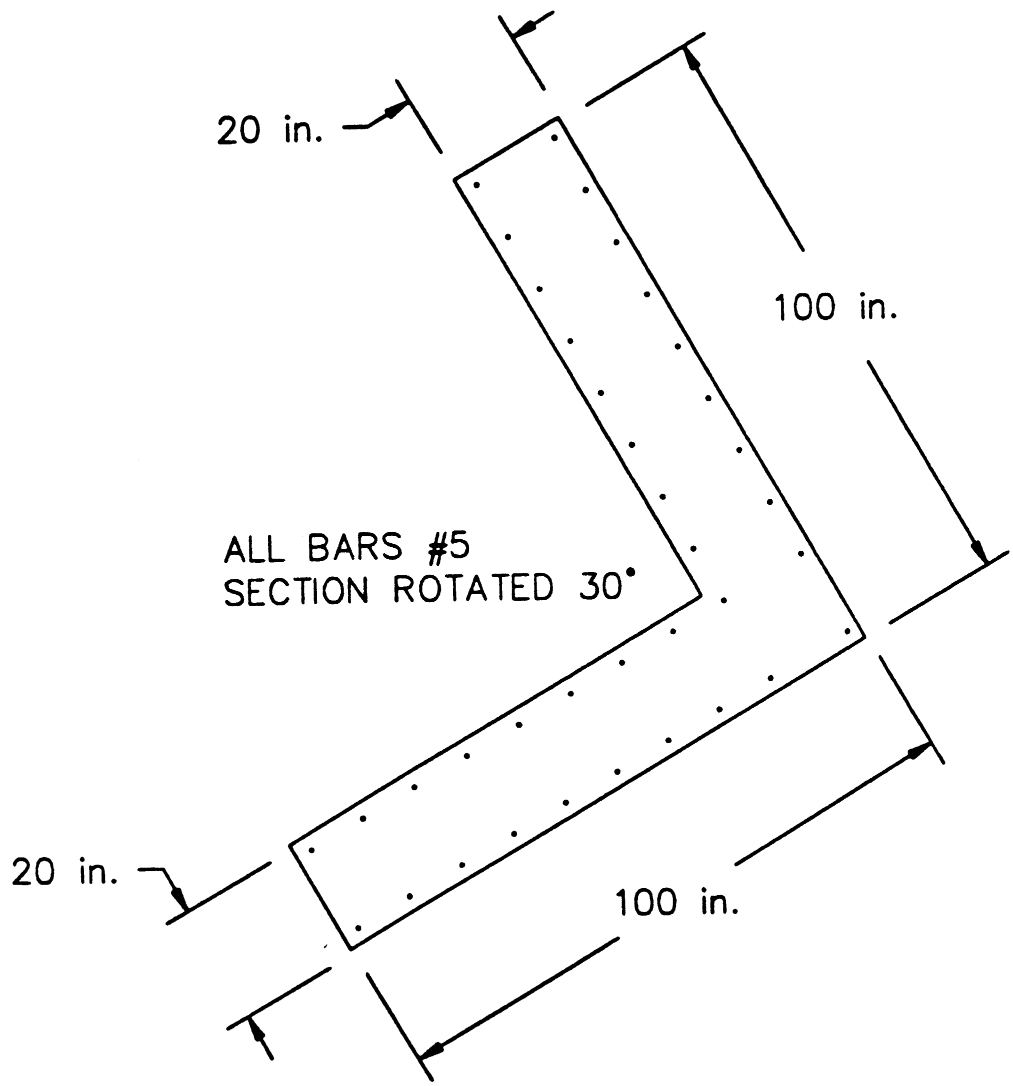

Fig. B.5 Example 3: Wall Cross Section

```
EXAMPLE 3 : ------------------------------------------------------------

Example 3: L - Section Rotated 30 degree  - Unconfined Concrete
P-M Interaction Surface
:
:
SYSTEM:
 T=1  E=0  C=1  P=1  M=0  TOL=0.0001 :
:
:
SECTION:
 1   HI=100  HJ= 20  N1= 50  N2= 10  X= 0   Y=  0  A=30,0,10:
 2   HI= 20  HJ= 80  N1= 10  N2= 40  X=80   Y= 20  A=30,0,10:
:
STEEL:
  1    X=   2    Y=   2     A=0.31   R=30,0,10: Rotate all steel
  9    X=  82    Y=   2     G= 1, 9  :
 10    X=  98    Y=   2              :
 11    X=  98    Y=  18              :
 19    X=  98    Y=  98     G=11,19  :
 20    X=   2    Y=  18              :
 29    X=  82    Y=  18     G=20,29  :
 37    X=  82    Y=  98     G=29,37  :
:
PROPERTY:
 FC=4  E1= 0.0030  E2= 0.004   FR= .4
 FC=5  E1= 0.0035  E2= 0.01    FR= .4       FM= .80
 FY=70   FU=110  FF=105  E1=0.005  E2=0.070  E3=0.10 E=29000 ET=1500:
:
DATA:
 EC=0.003   A=90          : Moment about y-axis
:
END
```

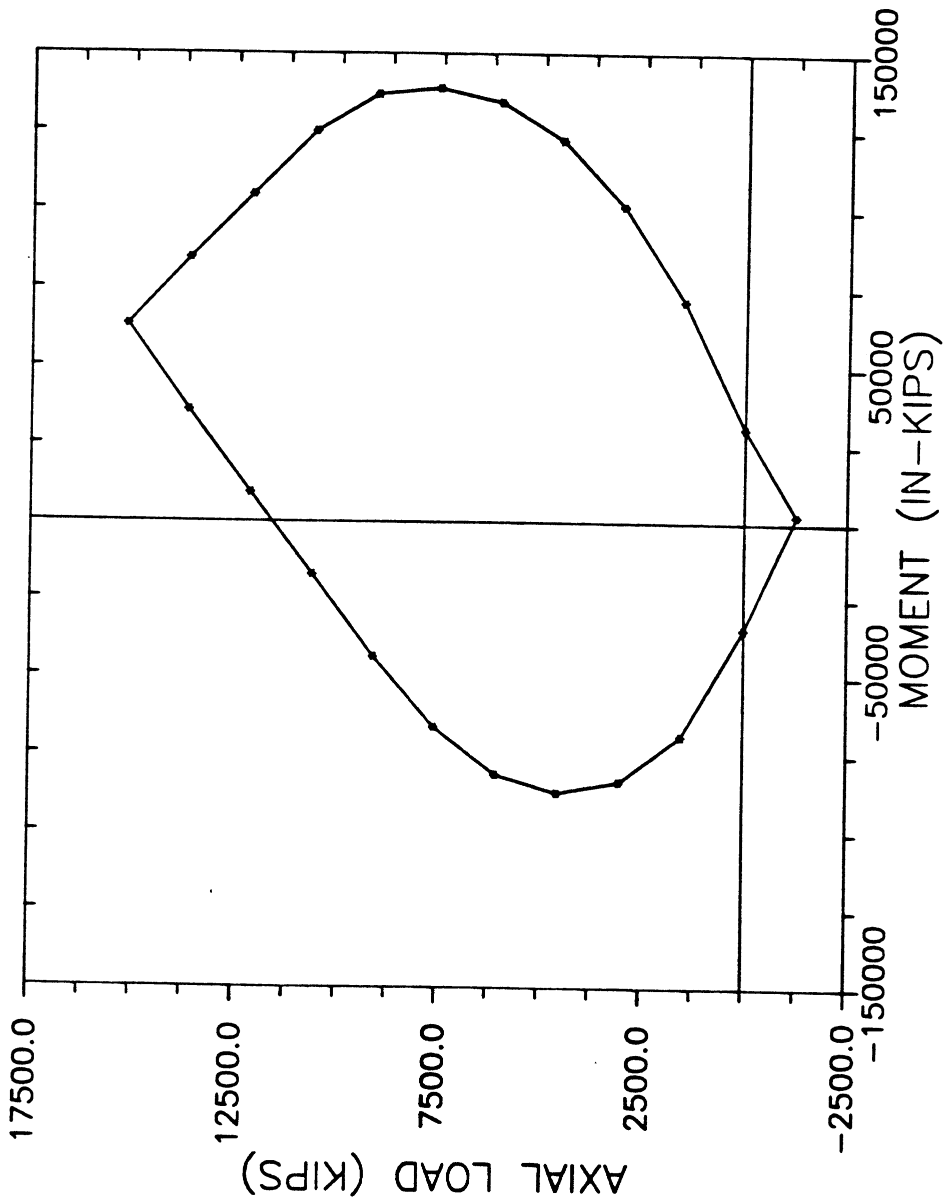

Fig. B.6 Example 3: Computed P–M Interaction Diagram

APPENDIX C

CONCRETE STRESS-STRAIN RELATIONS

C.1 Modified Kent–Park [Park et al. (1982)]

The following equations are used to describe the stress–strain relations of confined and unconfined concrete (See Fig. C.1)

$$f_c = kf'_c\left[\frac{2\epsilon_c}{\epsilon_o k} - \left(\frac{\epsilon_c}{\epsilon_o k}\right)^2\right] \qquad \epsilon_c \leq k\epsilon_o \qquad \text{(C.1.a)}$$

$$f_c = kf'_c\left[1 - Z_m\left(\epsilon_c - \epsilon_o k\right)\right] \geq 0.2kf'_c \qquad \epsilon_c > k\epsilon_o \qquad \text{(C.1.b)}$$

$$k = 1 + \frac{\rho f_{yh}}{f'_c} \qquad \text{(C.2)}$$

$$Z_m = \frac{0.5}{\epsilon_{50u} + \epsilon_{50h} - \epsilon_o k} \qquad \text{(C.3)}$$

$$\epsilon_{50u} = \frac{3 + \epsilon_o f'_c}{f'_c - 1000} \qquad \text{(C.4)}$$

$$\epsilon_{50h} = 0.75\rho\sqrt{h/s} \qquad \text{(C.5)}$$

where f_c is the longitudinal concrete stress, ϵ_c is the longitudinal concrete strain, f_{yh} is the yield stress for the hoop reinforcement, h is the width of the concrete core measured to the outside of the hoops, s is the center-to-center spacing of the hoops, and ρ is the ratio of the volume of hoop reinforcement to volume of concrete core measured to the outside of the hoops. Units of psi are used for stress, and ϵ_o is typically assumed to be 0.002.

C.2 Sheikh and Uzumeri (1982)

The following equations are used to describe the stress–strain relation for confined concrete (See Fig. C.2) for a square column with uniformly distributed longitudinal reinforcement

$$K_s = 1.0 + \frac{2.73B^2}{P_{occ}}\left[\left(1 - \frac{nC^2}{5.5B^2}\right)\left(1 - \frac{s}{2B}\right)^2\right]\sqrt{p_s f_s'} \qquad \text{(C.6)}$$

where f_s' is in kips per square inch and P_{occ} is in kips.

ϵ_{s1} is the minimum concrete strain corresponding to the maximum concrete stress.

$$\epsilon_{s1} = 0.55 K_s f_c' \text{ x } 10^{-6} \qquad \text{(C.7)}$$

ϵ_{s2} is the maximum concrete strain corresponding to the maximum concrete stress.

$$\frac{\epsilon_{s2}}{\epsilon_{oo}} = 1 + \frac{0.81}{C}\left[1 - 5.0\left(\frac{s}{B}\right)^2\right]\frac{\rho_s f_s'}{\sqrt{f_c'}} \qquad \text{(C.8)}$$

The slope Z of the unloading is similar to that used for the modified Kent–Park relations.

$$Z = \frac{0.5}{0.75\rho_s\sqrt{\frac{B}{s}}} \qquad \text{(C.9)}$$

The strain value corresponding to 0.85 of the maximum concrete stress is calculated as

$$\epsilon_{85} = \frac{0.15}{Z} + \epsilon_{s2} \;=\; 0.225\rho_s\sqrt{\frac{B}{s}} + \epsilon_{s2} \qquad \text{(C.10)}$$

In equations C.6 to C.10, B is the center-to-center distance of the perimeter hoops (to define the confined core), C is the center-to-center spacing of the longitudinal reinforcing bars, n is the number of longitudinal reinforcing bars (in Eq. C.6, the quantity nC^2 assumes equal spacing of longitudinal reinforcement), P_{occ} is $0.85 f_c' A_{core}$, s is the spacing of the hoops, ρ_s is the ratio of the volume of hoop reinforcement to volume of concrete core, and f_s is the yield stress of the hoops. Units of ksi are used for stress in the above equations. A value of 0.002 is typically assumed for ϵ_{oo}. The minimum stress at high strains can be taken as $0.3K_s f_c'$.

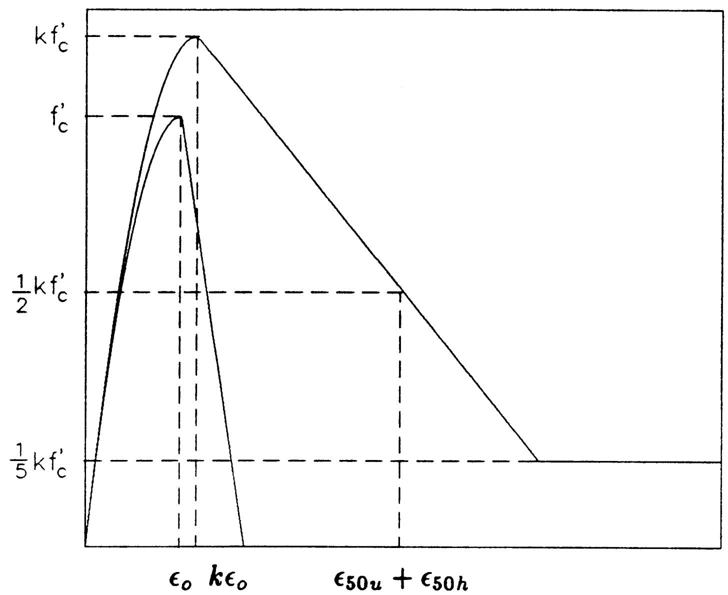

Fig. C.1 Modified Kent–Park Stress–Strain Relations

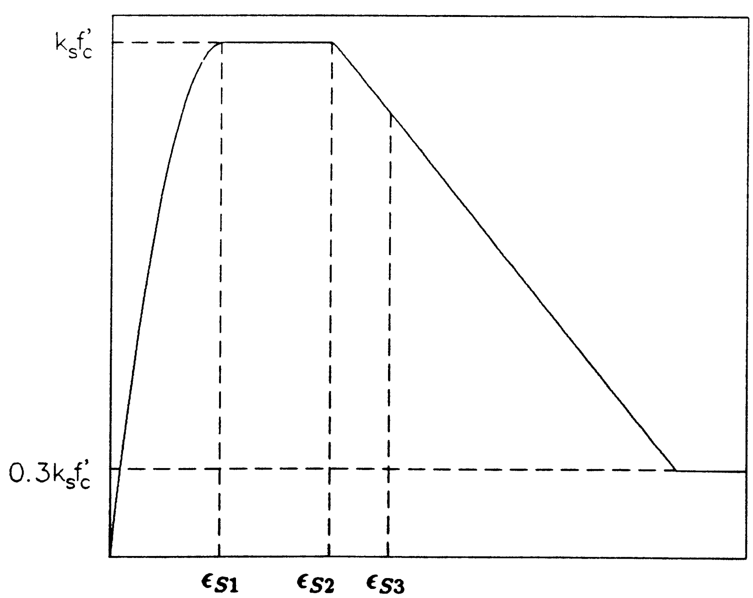

Fig. C.2 Sheikh and Uzumeri Stress–Strain Relation