ANALYSIS OF A TENSION SPLICE BY FINITE ELEMENT TECHNIQUES

by

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Master of Science in Engineering
in the
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YOUNGSTOWN STATE UNIVERSITY

August 1973

ABSTRACT

ANALYSIS OF A TENSION SPLICE BY FINITE ELEMENT TECHNIQUES

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The purpose of this thesis was to analyze a tension splice connection used in the bottom chord of long roof truss. Using finite element techniques and the STRUDL-II program, analytical results were obtained and then verified experimentally. Test specimens were strain gaged at points of maximum stress, as obtained from analytical results, and then tested to a maximum load of 70,000 lbs. Based on the experimental verification of the analytical results, the correct analytical procedure or modeling technique was obtained and thereby enabling the analyst to determine the load capacity of the splice connection.

ACKNOWLEDGEMENT

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The author also wishes to thank his review committee Dr. Paul X. Bellini and Dr. Michael K. Householder for their time and valuable suggestions in the development of this work.

Finally, greatful appreciation extended to Mr. Mike J. Repetski for his assistance in the laboratory and to Mrs. Sally Bartlett for typing this thesis. Special thanks goes out to my brother, Dr. S. K. Sekaran and his wife Dr. Kamalesh Sekaran for their encouragement and financial support during the study when it was most needed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

CHAPTER I

INTRODUCTION

The objective of this thesis was to analyze the reliability of a tension splice connection used in the bottom chord of long roof trusses, i.e. spans over 40 feet. Figures 1.1 and 1.2 show the pertinent details of a general truss and the corresponding splice. The analysis was accomplished using finite element techniques and the STRUDL-II* program. This type of splice is utilized primarily for ease in shop fabrication and for ease during field erection.

A problem arises due to the fact that the force in the chord does not act at the center of gravity of the splice plate and hence, the splice plate is subjected to considerable bending due to the resulting eccentric loading. It was required, therefore, to determine the corresponding stress levels and distribution, and to determine structural adequacy of the splice.

The following steps were used in this study:

1. Analysis of the splice plate using finite element techniques by means of the STRUDL-II program.
2. Verification of the analytical results by experimentation.

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*See Appendix A.

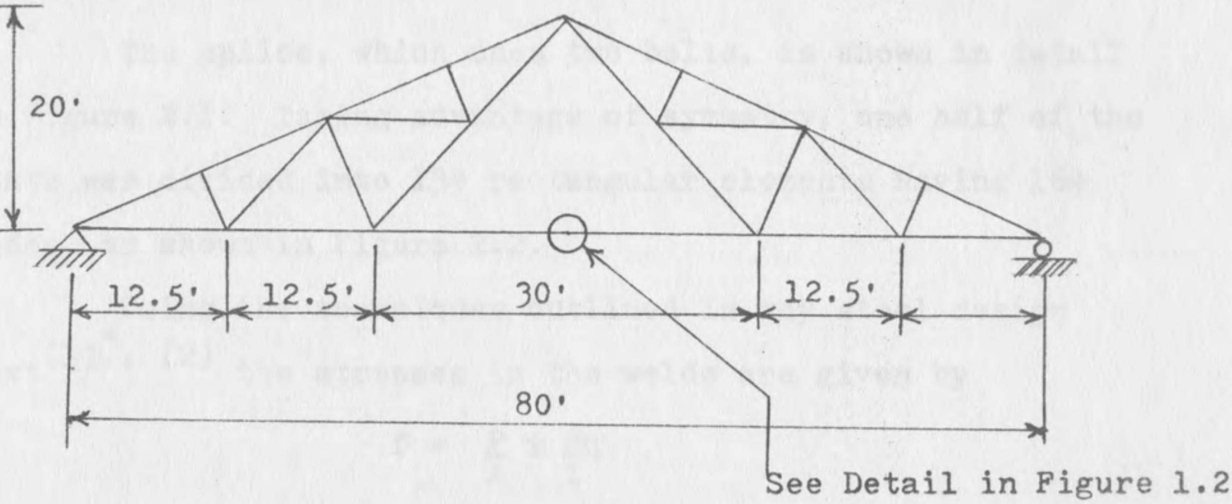


Figure 1.1 GENERAL TRUSS

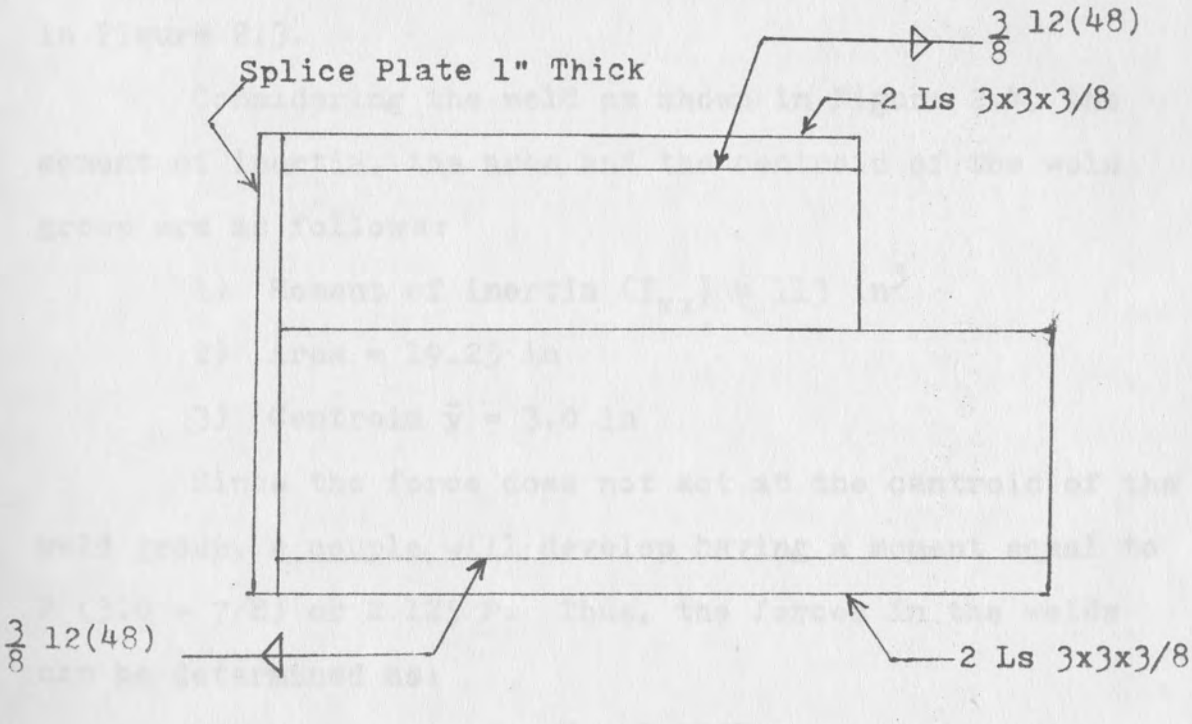


Figure 1.2 SPLICE CONNECTION

CHAPTER II

ANALYTICAL PROCEDURE

The splice, which uses two bolts, is shown in detail in Figure 2.1. Taking advantage of symmetry, one half of the plate was divided into 134 rectangular elements having 164 nodes, as shown in Figure 2.2.

Using the techniques outlined in any steel design text[(1)*], [(2)] the stresses in the welds are given by

$$f = \frac{P}{A} \pm \frac{Mc}{I}$$

in which the welds are treated as lines having no width. These weld forces can be distributed to the nodes as shown in Figure 2.3.

Considering the weld as shown in Figure 2.4, the moment of inertia, the area, and the centroid of the weld group are as follows:

1) Moment of inertia (I_{xx}) = 113 in^3
2) Area = 19.25 in
3) Centroid $\bar{y}$ = 3.0 in

Since the force does not act at the centroid of the weld group, a couple will develop having a moment equal to P (3.0 - 7/8) or 2.125 P. Thus, the forces in the welds can be determined as:

$$F = \frac{P}{A} \pm 2.125P \frac{y}{I}$$

*Number in parenthesis indicates reference cited.

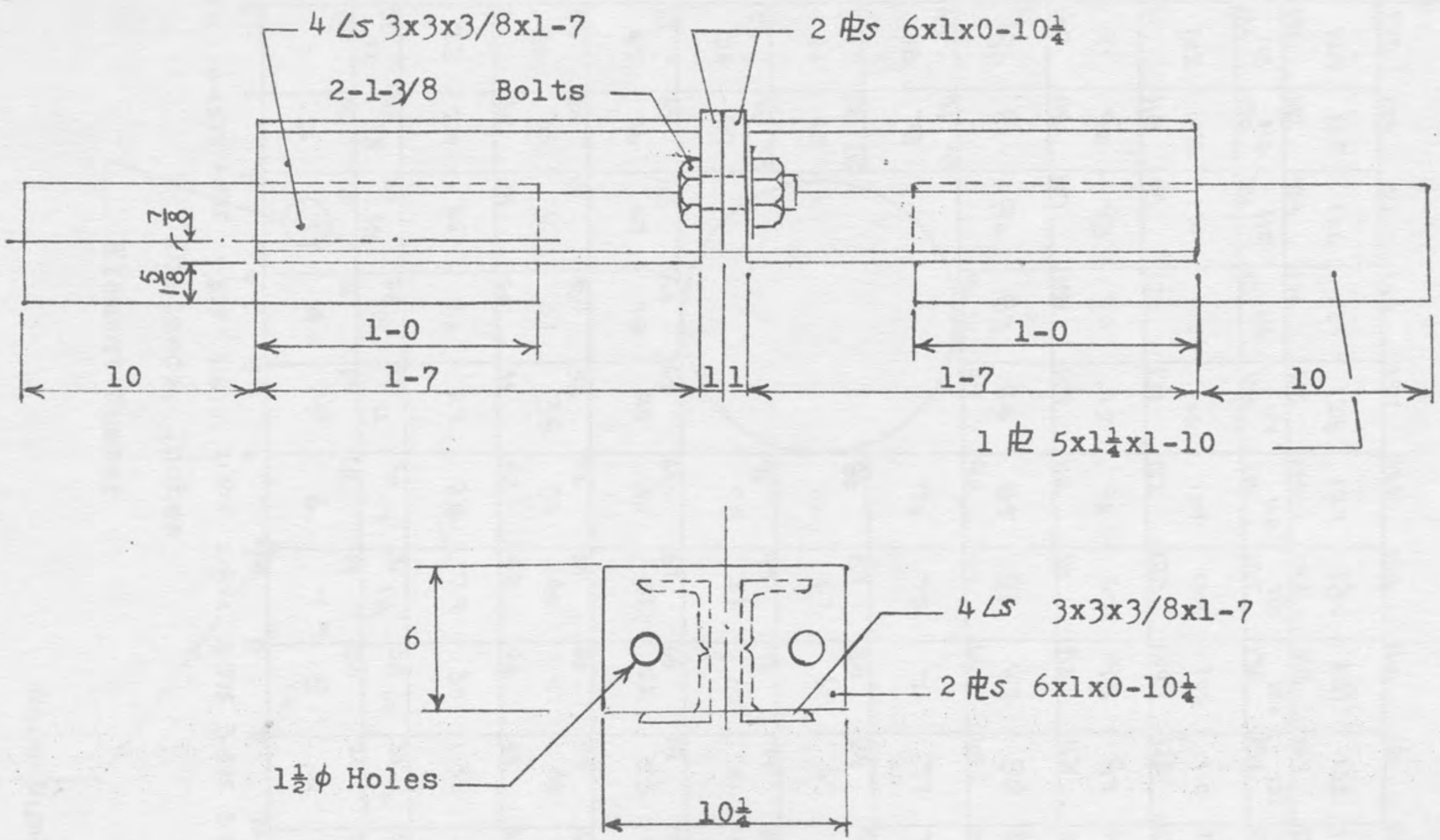


Figure 2.1 DETAILS OF SPECIMEN

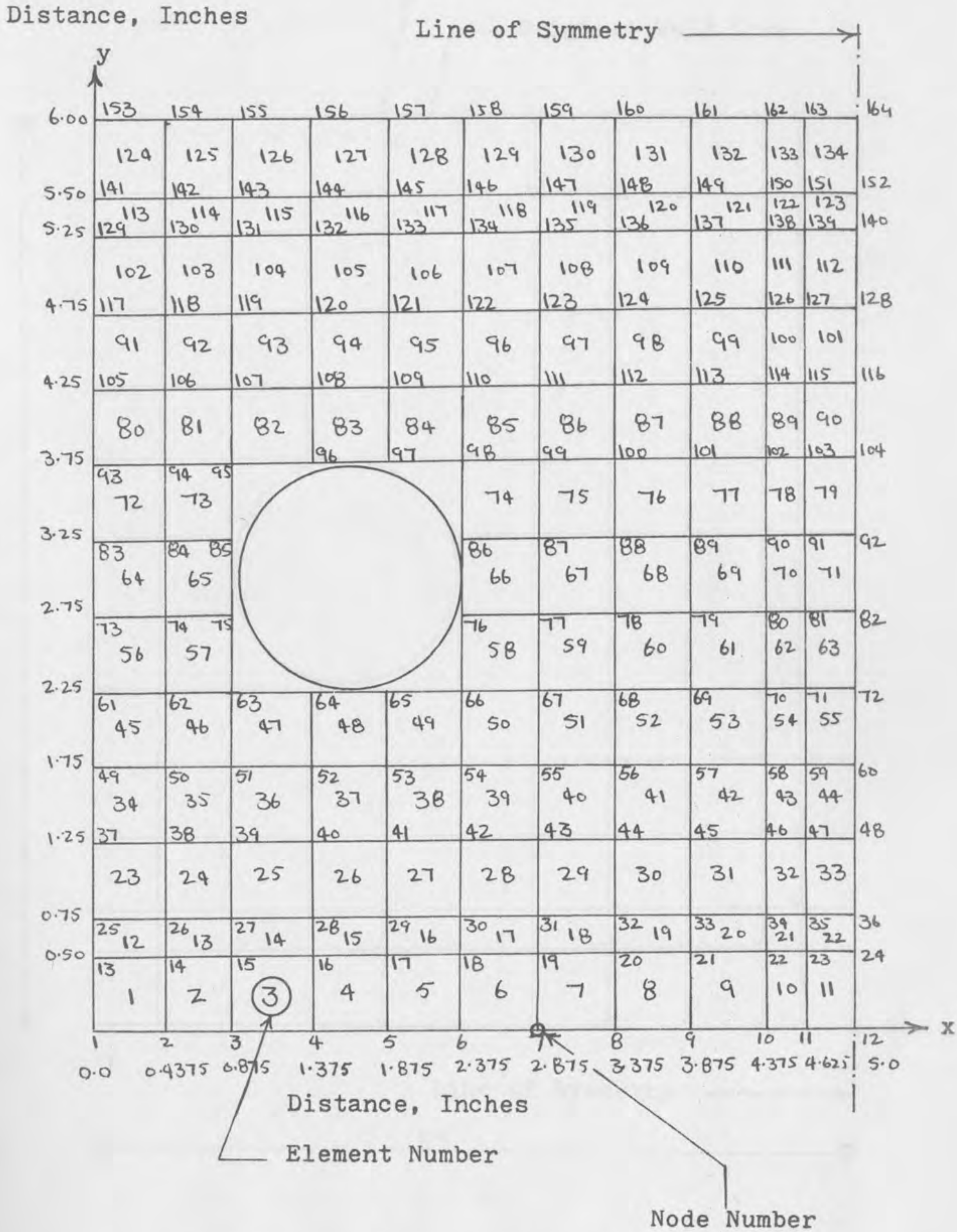


Figure 2.2 TYPICAL ELEMENT ARRANGEMENT

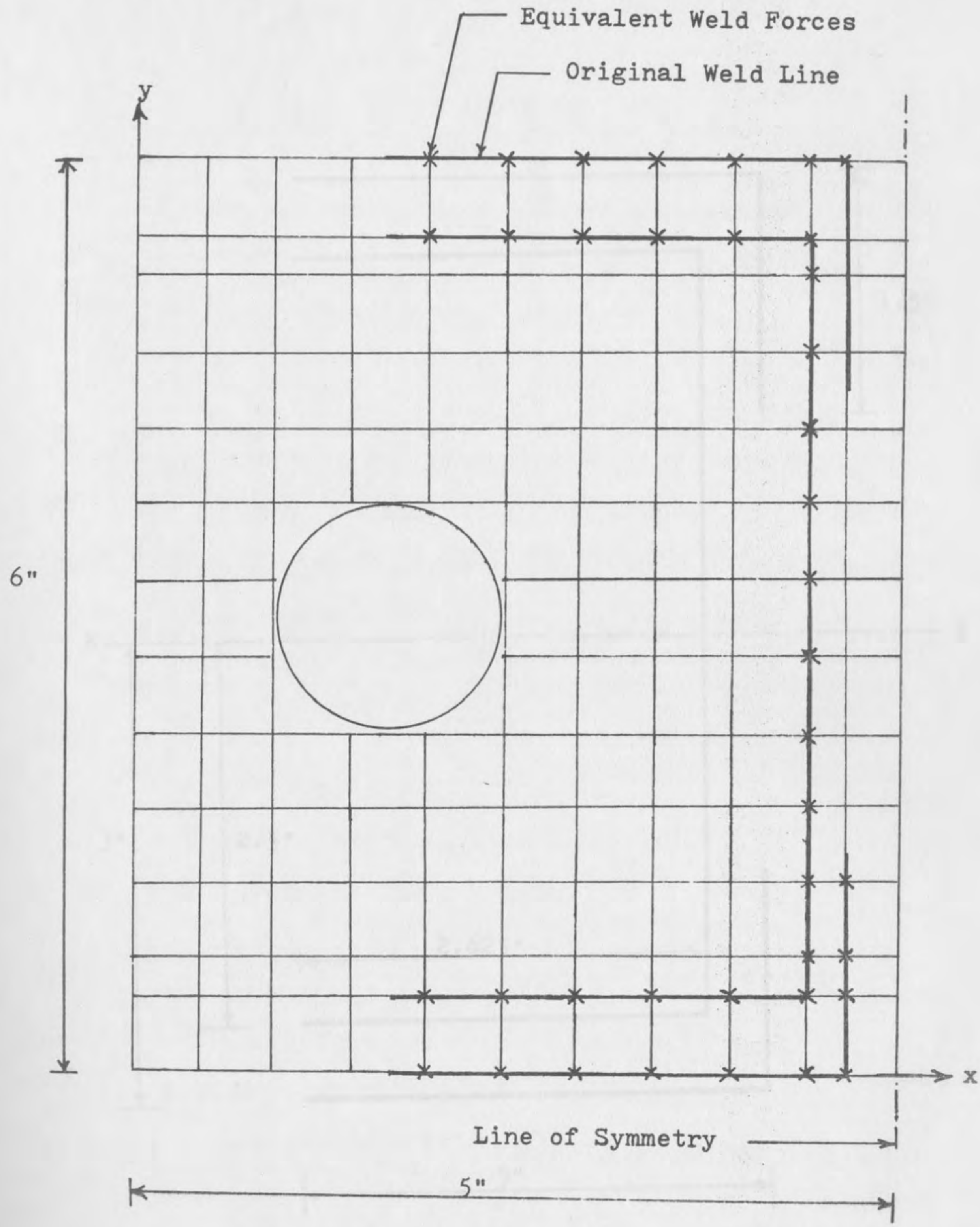


Figure 2.3 DISTRIBUTION OF WELD FORCES

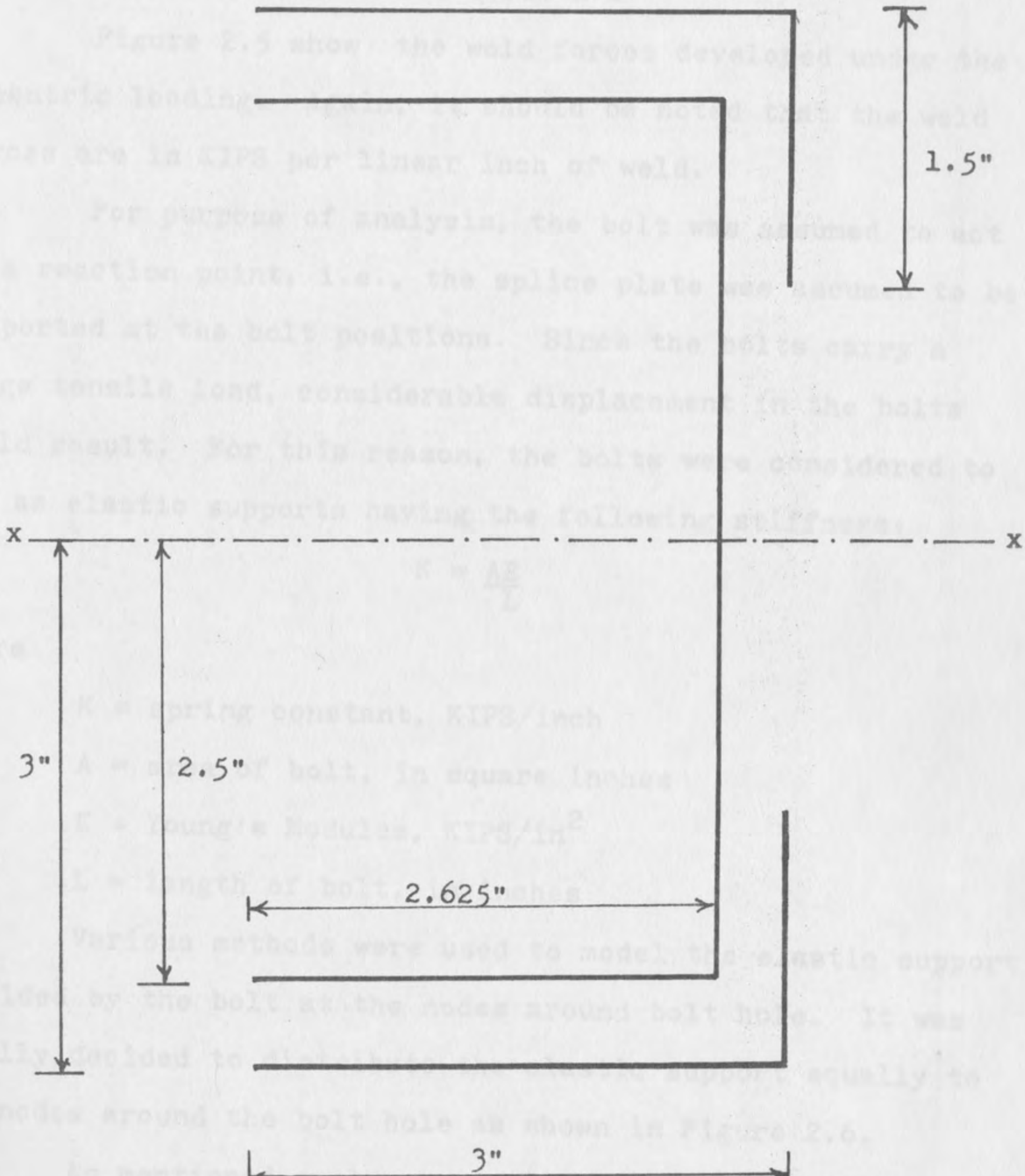


Figure 2.4 WELD LINE REPRESENTATION

where F = force per linear inch of weld

P = applied load in KIPS

y = distance from centroid in inches

I = moment of inertia about x-x

Figure 2.5 show the weld forces developed under the eccentric loading. Again, it should be noted that the weld forces are in KIPS per linear inch of weld.

For purpose of analysis, the bolt was assumed to act as a reaction point, i.e., the splice plate was assumed to be supported at the bolt positions. Since the bolts carry a large tensile load, considerable displacement in the bolts could result. For this reason, the bolts were considered to act as elastic supports having the following stiffness:

$$K = \frac{AE}{L}$$

where

K = spring constant, KIPS/inch

A = area of bolt, in square inches

E = Young's Modulus, KIPS/in^2

L = length of bolt, in inches

Various methods were used to model the elastic support provided by the bolt at the nodes around bolt hole. It was finally decided to distribute the elastic support equally to all nodes around the bolt hole as shown in Figure 2.6.

As mentioned early, one half of the plate was analyzed due to symmetry. This helped to save computer time. However, care must be taken at the line of symmetry. The support

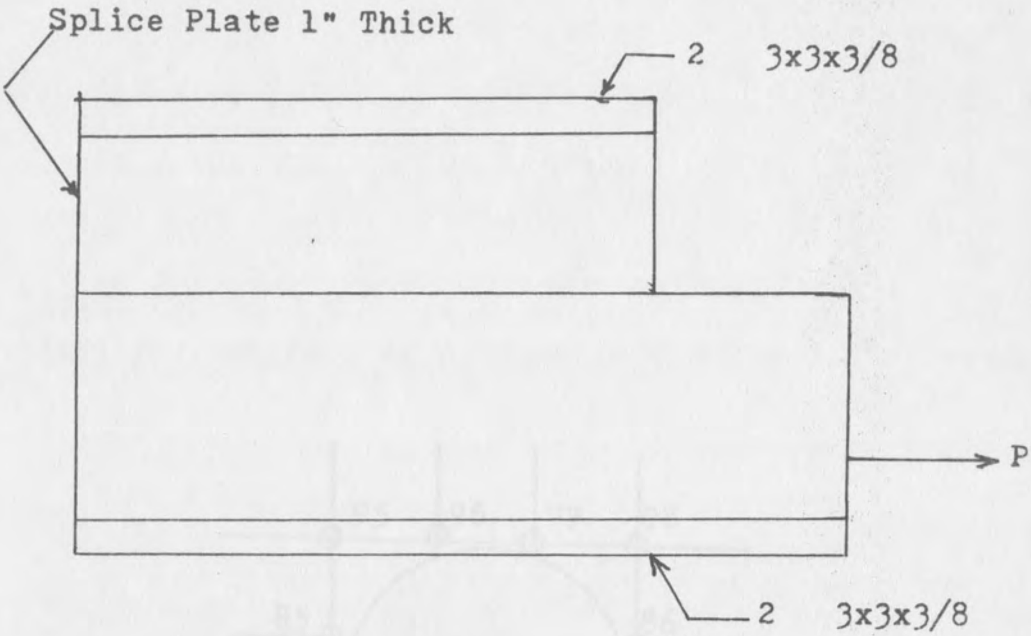


Figure 2.5a

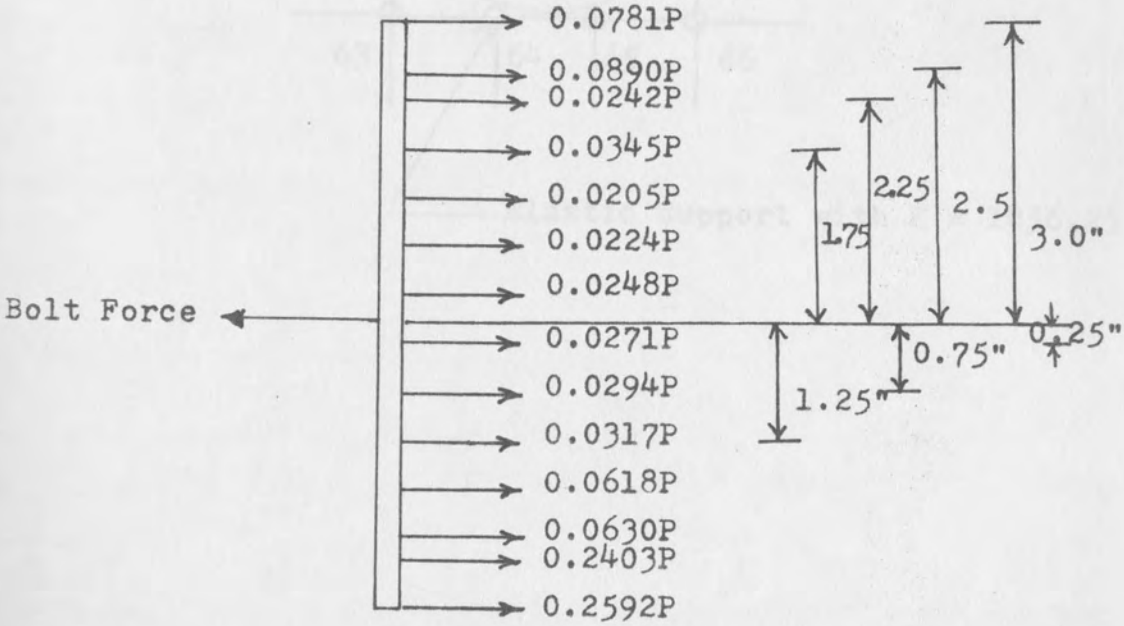


Figure 2.5b

Figure 2.5 FREE BODY DIAGRAM OF SPLICE PLATE

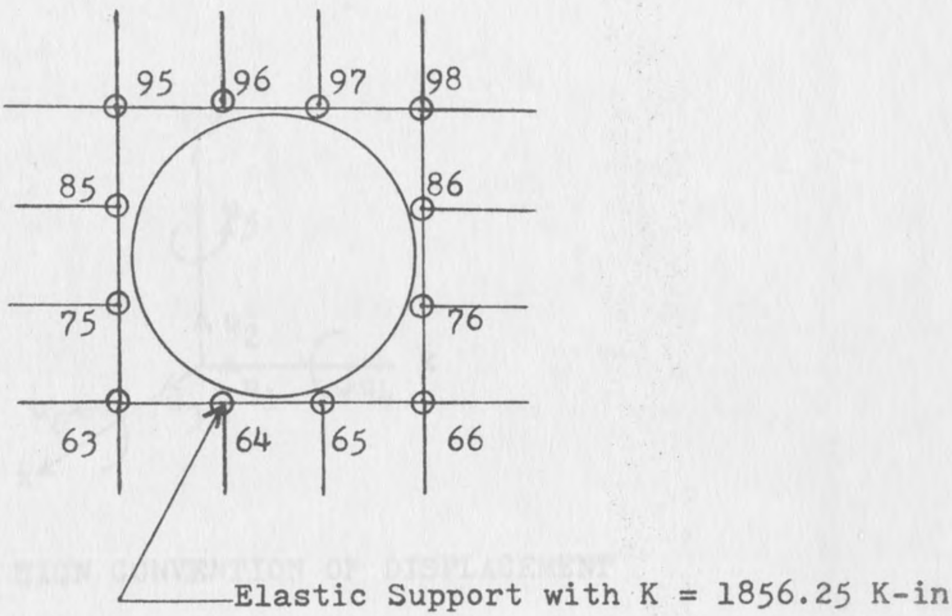


Figure 2.6 ELASTIC SUPPORT DISTRIBUTION

conditions along the line of symmetry differ from the original plate conditions. The nodes must be treated as supports and the appropriate releases must be made.[3] In order to model the nodes along the line of symmetry, force in the z direction and the moment y should be released. (see Figure 2.7 and 2.8) There are no rotations about the x axis along the line of symmetry and no releases need be made in that direction.

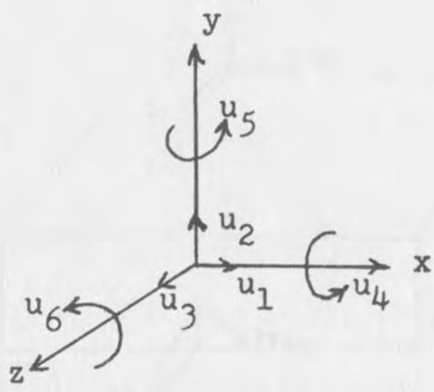


Figure 2.7 SIGN CONVENTION OF DISPLACEMENT

The following four cases were considered for the analysis:

Case I: In this case, the boundary conditions around the plate exterior edges were assumed as free edges. The weld forces were taken to act as shown in Figure 2.9. The bolt was assumed to provide equal elastic support at all nodes on the bolt hole,

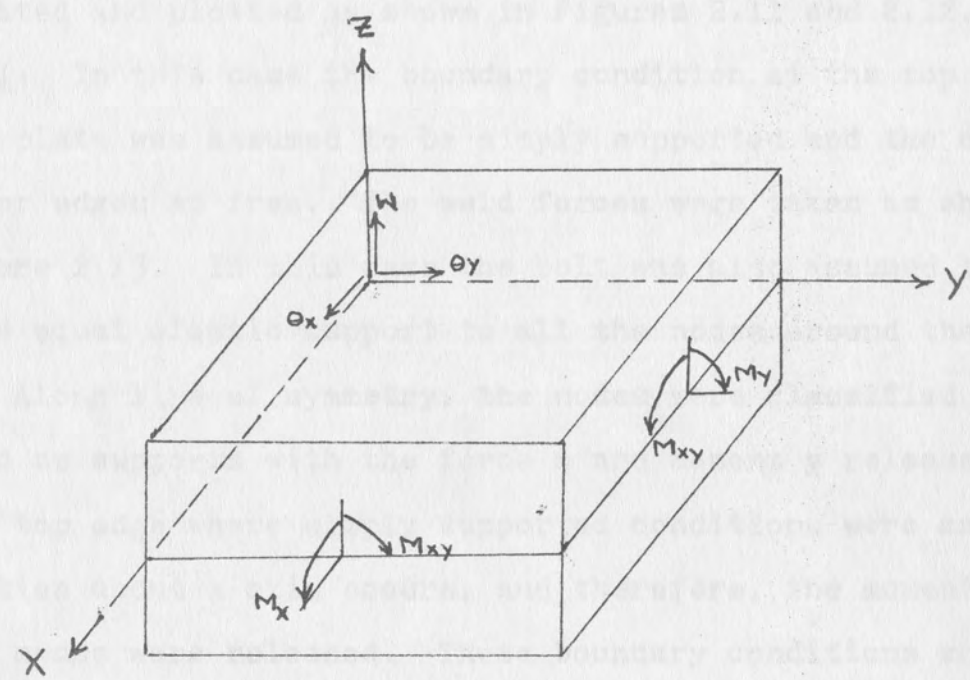


Figure 2.8 SIGN CONVENTION OF STRESS

i.e., node 63 to 66, 75, 76, 85, 86, 95 to 98 as shown in Figure 2.9. Along the line of symmetry, the nodes were classified and treated as supports and the appropriate releases, i.e., force z and moment y, were accomplished. Typical portions of input and output of the STRUDL program are presented in Figure 2.10. From the output, the stresses were calculated and plotted as shown in Figures 2.11 and 2.12.

Case II: In this case the boundary condition at the top edge of the plate was assumed to be simply supported and the other exterior edges as free. The weld forces were taken as shown in Figure 2.13. In this case the bolt was also assumed to provide equal elastic support to all the nodes around the bolt hole. Along line of symmetry, the nodes were classified and treated as supports with the force z and moment y released. At the top edge where simply supported conditions were assumed, a rotation about x axis occurs, and therefore, the moment x at all nodes were released. These boundary conditions and the applied forces are shown in Figure 2.13. Using these boundary conditions and forces, the stiffness analysis was made. Typical portions of input and output of the STRUDL program are presented in Figure 2.14. From the output, the stresses were calculated and plotted as shown in Figures 2.15 and 2.16.

Case III: In this case, the adjacent splice plate was assumed to provide simple support up to 0.5 inch from the top edge. All other exterior edges were considered free. The weld forces were unchanged and the elastic support provided by the bolt was unaltered. As before, the force z and moment y were released along line of symmetry. At the simply supported support, i.e., those near the top edge of the plate, moment x was released at all nodes. The boundary conditions and forces acting are shown in Figure 2.17. Typical portions of input and output of the STRUDL program are presented in Figure 2.18. The results are plotted as shown in Figures 2.19 and 2.20.

Case IV: Same as Case III except that the adjacent splice plate was assumed to provide simple support down to 0.75 inch from the top edge of the plate. The boundary conditions and forces acting are shown in Figure 2.21. Typical portions of input and output of the STRUDL program are presented in Figure 2.22. The results are plotted as shown in Figures 2.23 and 2.24.

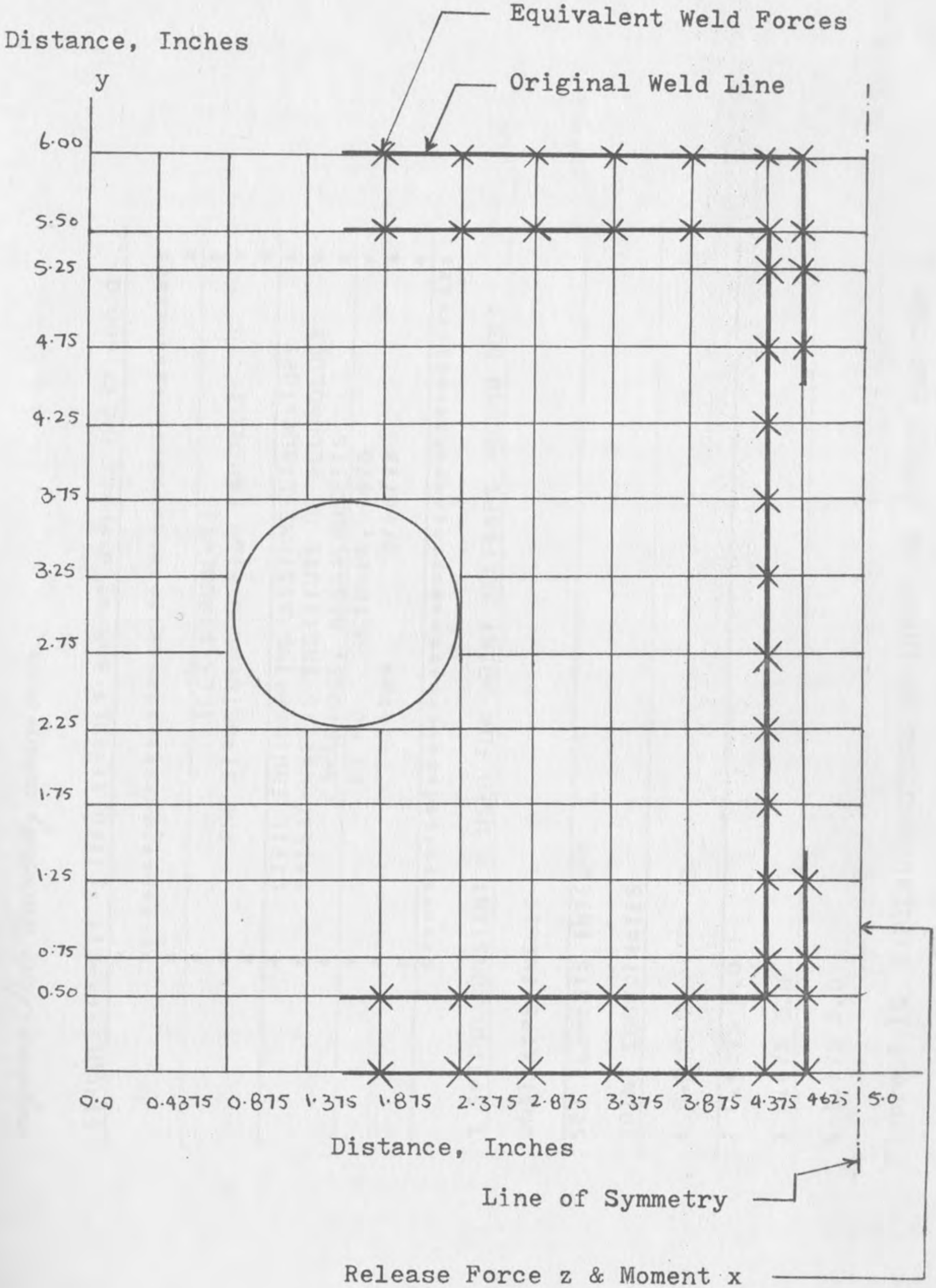


Figure 2.9 DETAILS OF CASE I

ungstown State University COMPUTER CENTER

```
STRUDL 'PB-S1' 'FIXED AT BOLT AND WELD FORCE ONLY' 40000

          ********************************************
          *                                          *
          *             ICES STRUDL-II               *
          *       THE STRUCTURAL DESIGN LANGUAGE     *
          *                                          *
          *     CIVIL ENGINEERING SYSTEMS LABORATORY *
          *    MASSACHUSETTS INSTITUTE OF TECHNOLOGY *
          *         CAMBRIDGE, MASSACHUSETTS         *
          *          V2 MO    OCTOBER, 1970          *
          *           3:26:14       3/16/73          *
          *                                          *
          ********************************************

$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT

UNIT KIPS INCHES

SET ELEMENTS INTEGER

JOINT COORDINATES

1 0.0 0.0

2 0.4375 0.0

3 0.875 0.0

4 1.375 0.0
```

Figure 2.10 TYPICAL PORTIONS OF INPUT AND OUTPUT FOR CASE I

Node Number

x Coordinate

y Coordinate

Support Condition

65 1.875 2.25 S	119 0.875 4.75	164 5.0 6.0
66 2.375 2.25 S	120 1.375 4.75	TYPE PLATE BENDIN
67 2.875 2.25	121 1.875 4.75	ELEMENT INCIDENCE
68 3.375 2.25	122 2.375 4.75	1 1 2 14 13
69 3.875 2.25	123 2.875 4.75	2 2 3 15 14
70 4.375 2.25	124 3.375 4.75	3 3 4 16 15
71 4.625 2.25	125 3.875 4.75	4 4 5 17 16
72 5.0 2.25 S	126 4.375 4.75	5 5 6 18 17
73 0.0 2.75	127 4.625 4.75	6 6 7 19 18
74 0.4375 2.75	128 5.0 4.75 S	7 7 8 20 19
75 0.875 2.75 S	129 0.0 5.25	8 8 9 21 20
76 2.375 2.75 S	130 0.4375 5.25	9 9 10 22 21
77 2.875 2.75	131 0.875 5.25	10 10 11 23 22
78 3.375 2.75	132 1.375 5.25	11 11 12 24 23
79 3.875 2.75	133 1.875 5.25	12 13 14 26 25
80 4.375 2.75	134 2.375 5.25	13 14 15 27 26
81 4.625 2.75	135 2.875 5.25	14 15 16 28 27
82 5.0 2.75 S	136 3.375 5.25	15 16 17 29 28
83 0.0 3.25	137 3.875 5.25	16 17 18 30 29
84 0.4375 3.25	138 4.375 5.25	17 18 19 31 30
85 0.875 3.25 S	139 4.625 5.25	18 19 20 32 31

Figure 2.10 (Cont'd)

```
ELEMENT PROPERTIES
1 TO 134 TYPE 'BPR' THICKNESS 1.0
CONSTANTS
E 30000. ALL
POISSON 0.3 ALL
$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT
JOINT RELEASES
12 24 36 48 60 72 82 92 104 116 128 140 152 FORCE Z MOMENT X
63 TO 66 75 76 85 86 95 TO 98 KFZ 1856.25
$ WELD FORCE ONLY
LOADING 1 'WELD FORCE AT JOINTS'
JOINT LOADS
157 TO 161 FORCE Z 0.298
162 FORCE Z 0.223
163 FORCE Z 0.242
145 TO 148 FORCE Z 0.374
149 FORCE Z 0.280
150 FORCE Z 0.189
151 FORCE Z 0.263
139 FORCE Z 0.304
127 FORCE Z 0.416
138 FORCE Z 0.304
23 FORCE Z 0.939
11 FORCE Z 0.731
10 FORCE Z 0.75
5 TO 9 FORCE Z 1.0
STIFFNESS ANALYSIS
OUTPUT DECIMAL 4
LIST DISPLACEMENT STRESSES ALL
```

Figure 2.10 (Cont'd)

```
***************************
*RESULTS OF LATEST ANALYSES*
***************************


PROBLEM - PB-S1     TITLE - FIXED AT BOLT AND WELD FORCE ONLY

ACTIVE UNITS  INCH KIP  RAD  DEGF SEC

ACTIVE STRUCTURE TYPE  PLATE   BENDING

ACTIVE COORDINATE AXES  X Y

LOADING - 1              WELD FORCE AT JOINTS

ELEMENT STRESSES

ELEMENT


1        NODE  1       MXX   0.156908E 00   MYY   0.155180E 00   MXY   0.374752E 00
1        NODE  2       MXX  -0.109111E 01   MYY  -0.473726E-01   MXY   0.716039E 00
1        NODE  14      MXX  -0.710599E 00   MYY  -0.123618E 01   MXY   0.965951E 00
1        NODE  13      MXX  -0.424106E-01   MYY  -0.143242E 01   MXY   0.624663E 00

2        NODE  2       MXX  -0.104802E 01   MYY  -0.344272E-01   MXY   0.722757E 00
2        NODE  3       MXX  -0.166704E 01   MYY  -0.163928E-01   MXY   0.116106E 01
2        NODE  15      MXX  -0.137926E 01   MYY  -0.114972E 01   MXY   0.137680E 01
2        NODE  14      MXX  -0.736257E 00   MYY  -0.124389E 01   MXY   0.938498E 00
```

Figure 2.10 (Cont'd)

RESULTANT JOINT DISPLACEMENTS - FREE JOINTS

JOINT		X DISP.	Y DISP.	Z DISP.	X ROT.	Y ROT.
		/-------DISPLACEMENT			-------ROTATION----	
1	GLOBAL			0.0026	-0.0017	-0.0014
2	GLOBAL			0.0032	-0.0018	-0.0014
3	GLOBAL			0.0039	-0.0020	-0.0017
4	GLOBAL			0.0048	-0.0024	-0.0020
5	GLOBAL			0.0059	-0.0028	-0.0023
6	GLOBAL			0.0071	-0.0033	-0.0025
7	GLOBAL			0.0084	-0.0036	-0.0025
8	GLOBAL			0.0096	-0.0039	-0.0023
9	GLOBAL			0.0106	-0.0041	-0.0018
10	GLOBAL			0.0114	-0.0043	-0.0011
11	GLOBAL			0.0116	-0.0043	-0.0006
13	GLOBAL			0.0018	-0.0015	-0.0012
14	GLOBAL			0.0023	-0.0017	-0.0012
15	GLOBAL			0.0029	-0.0020	-0.0014
16	GLOBAL			0.0036	-0.0024	-0.0016
17	GLOBAL			0.0045	-0.0028	-0.0019
18	GLOBAL			0.0055	-0.0032	-0.0021
19	GLOBAL			0.0066	-0.0036	-0.0022

Figure 2.10 (Cont'd)

Distance, Inches

Distance, Inches	0.4375	0.875	1.375	1.875	2.375	2.875	3.375	3.875	4.375	4.625	5.0
5.50–6.00	0.24	0.18	0.0	0.0	-1.50	-2.94	-1.26	-1.92	-3.96	-6.4	-5.58
5.25–5.50	0.72	0.48	0.18	-0.54	-2.64	-6.54	-4.08	-4.20	-7.86	-12.9	-9.72
4.75–5.25	1.14	1.02	0.72	0.0	-1.20	-2.64	-3.42	-4.80	-6.12	-7.0	-7.44
4.25–4.75	1.68	1.80	2.16	2.28	1.62	0.12	-2.10	-4.26	-5.34	-5.7	-6.12
3.75–4.25	1.38	2.40	3.96	5.82	9.0	3.48	-4.02	-4.44	-6.48	-6.9	-7.26
3.25–3.75	0.66	0.36				-5.28	-8.04	-8.70	-9.18	-9.3	-9.60
2.75–3.25	0.24	0.90				-9.90	-13.86	-13.74	-12.72	-11.8	-11.88
2.25–2.75	-2.16	-22.38				-20.52	-14.22	-19.20	-15.60	-13.8	-13.44
1.75–2.25	-10.80	-18.24	-33.60	-44.88	-61.92	-56.40	-27.66	-21.12	-15.72	-13.4	-12.64
1.25–1.75	-17.04	-19.62	-24.0	-29.10	-30.60	-27.42	-22.50	-16.92	-12.36	-9.9	-9.36
0.75–1.25	-14.04	-14.16	-15.0	-15.60	-15.0	-13.86	-12.06	-9.66	-6.72	-4.8	-4.62
0.50–0.75	-9.90	-9.00	-8.46	-7.56	-6.48	-5.64	-4.92	-3.96	-2.46	-1.20	-1.02
0.0–0.50	-3.84	-3.66	-3.30	-2.70	-2.04	-1.68	-1.38	-1.02	-0.48	0.0	-0.06

Distance, Inches

Figure 2.11 STRESS (σ_{yy}) FOR CASE I, KSI

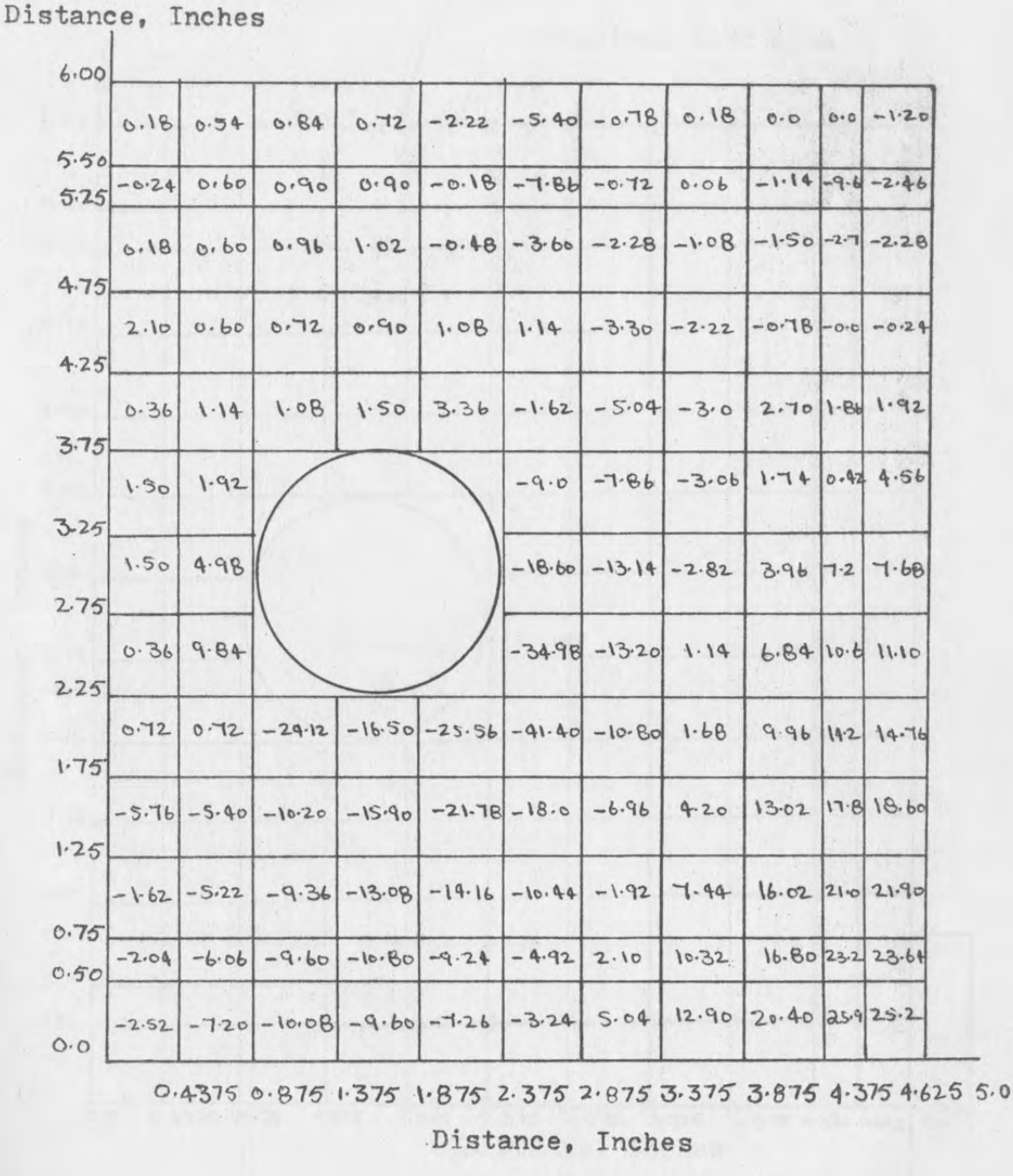


Figure 2.12 STRESS (σ_{xx}) FOR CASE I, KSI

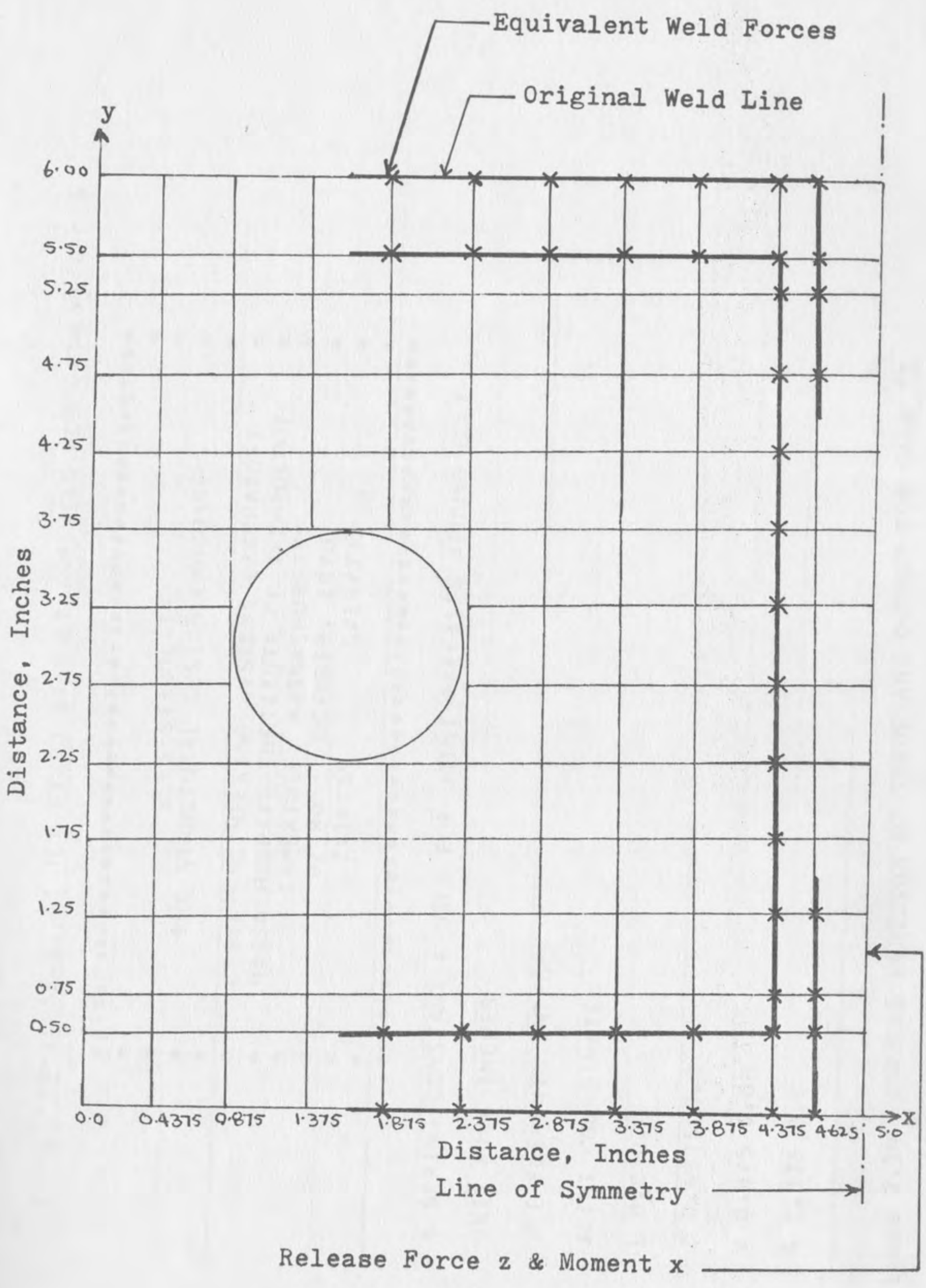


Figure 2.13 DETAILS OF CASE II

```
STRUDL 'PB-3' 'S.S. AT TOP FIXED AT BOLT AND WELD FORCE ONLY' 40000

           ****************************************************
           *                                                  *
           *                 ICES STRUDL-II                   *
           *         THE STRUCTURAL DESIGN LANGUAGE           *
           *                                                  *
           *      CIVIL ENGINEERING SYSTEMS LABORATORY        *
           *      MASSACHUSETTS INSTITUTE OF TECHNOLOGY       *
           *           CAMBRIDGE, MASSACHUSETTS               *
           *            V2 M0     OCTOBER, 1970               *
           *             7:14:59         5/19/73              *
           *                                                  *
           ****************************************************

$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT

UNIT KIPS INCHES

SET ELEMENTS INTEGER

JOINT COORDINATES

1 0.0 0.0

2 0.4375 0.0

3 0.875 0.0

4 1.375 0.0
```

Figure 2.14 TYPICAL PORTIONS OF INPUT AND OUTPUT FOR CASE II

Node Number
x Coordinate
y Coordinate
Support Condition

```
86 2.375 3.25 S
87 2.875 3.25
88 3.375 3.25
89 3.875 3.25
90 4.375 3.25
91 4.625 3.25
92 5.0 3.25 S
93 0.0 3.75
94 0.4375 3.75
95 0.875 3.75 S
96 1.375 3.75 S
97 1.875 3.75 S
98 2.375 3.75 S
99 2.875 3.75
100 3.375 3.75
101 3.875 3.75
102 4.375 3.75
103 4.625 3.75
104 5.0 3.75 S
105 0.0 4.25
106 0.4375 4.25
119 0.875 4.75
120 1.375 4.75
121 1.875 4.75
122 2.375 4.75
123 2.875 4.75
124 3.375 4.75
125 3.875 4.75
126 4.375 4.75
127 4.625 4.75
128 5.0 4.75 S
129 0.0 5.25
130 0.4375 5.25
131 0.875 5.25
132 1.375 5.25
133 1.875 5.25
134 2.375 5.25
135 2.875 5.25
136 3.375 5.25
137 3.875 5.25
138 4.375 5.25
139 4.625 5.25
164 5.0 6.0 S
TYPE PLATE BENDING.
ELEMENT INCIDENCES
1 1 2 14 13
2 2 3 15 14
3 3 4 16 15
4 4 5 17 16
5 5 6 18 17
6 6 7 19 18
7 7 8 20 19
8 8 9 21 20
9 9 10 22 21
10 10 11 23 22
11 11 12 24 23
12 13 14 26 25
13 14 15 27 26
14 15 16 28 27
15 16 17 29 28
16 17 18 30 29
17 18 19 31 30
18 19 20 32 31
```

Figure 2.14 (Cont'd)

```
ELEMENT PROPERTIES
1 TO 134 TYPE 'BPR' THICKNESS 1.0
CONSTANTS
E 30000. ALL
POISSON 0.3 ALL
$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT
JOINT RELEASES
12 24 36 48 60 72 82 92 104 116 128 140 152 FORCE Z MOMENT X
63 TO 66 75 76 85 86 95 TO 98 KFZ 1856.25
153 TO 164 MOMENT X
$ WELD FORCE ONLY
LOADING 1 'WELD FORCE AT JOINTS'
JOINT LOADS
157 TO 161 FORCE Z 0.298
162 FORCE Z 0.223
163 FORCE Z 0.242
```

```
46 FORCE Z 0.662
34 FORCE Z 0.678
22 FORCE Z 0.689
21 FORCE Z 0.693
17 TO 20 FORCE Z 0.924
47 FORCE Z 0.882
35 FORCE Z 0.899
23 FORCE Z 0.939
11 FORCE Z 0.731
10 FORCE Z 0.75
5 TO 9 FORCE Z 1.0
STIFFNESS ANALYSIS
OUTPUT DECIMAL 4
LIST DISPLACEMENT STRESSES ALL
```

Figure 2.14 (Cont'd)

```
*****************************
*RESULTS OF LATEST ANALYSES*
*****************************
```

PROBLEM - PB-3   TITLE - S.S. AT TOP FIXED AT BOLT AND WELD FORCE ONLY

ACTIVE UNITS INCH KIP RAD DEGF SEC

ACTIVE STRUCTURE TYPE PLATE BENDING

ACTIVE COORDINATE AXES X Y

LOADING - 1   WELD FORCE AT JOINTS

ELEMENT STRESSES

ELEMENT							
1	NODE 1	MXX	0.156867E 00	MYY	0.155308E 00	MXY	0.374903E 00
1	NODE 2	MXX	-0.109173E 01	MYY	-0.474143E-01	MXY	0.716101E 00
1	NODE 14	MXX	-0.711491E 00	MYY	-0.123595E 01	MXY	0.966268E 00
1	NODE 13	MXX	-0.424299E-01	MYY	-0.143250E 01	MXY	0.625070E 00
2	NODE 2	MXX	-0.104870E 01	MYY	-0.344770E-01	MXY	0.722841E 00
2	NODE 3	MXX	-0.166799E 01	MYY	-0.164089E-01	MXY	0.116088E 01
2	NODE 15	MXX	-0.138059E 01	MYY	-0.114943E 01	MXY	0.137676E 01
2	NODE 14	MXX	-0.737178E 00	MYY	-0.124368E 01	MXY	0.938721E 00

Figure 2.14 (Cont'd)

LOADING - 1 WELD FORCE AT JOINTS

RESULTANT JOINT DISPLACEMENTS - SUPPORTS

JOINT		/------------------DISPLACEMENT			------------	-ROTATION-
		X DISP.	Y DISP.	Z DISP.	JT.	Y ROT.
12	GLOBAL			0.0116	-0.0043	0.0
24	GLOBAL			0.0095	-0.0041	0.0
36	GLOBAL			0.0085	-0.0039	0.0
48	GLOBAL			0.0067	-0.0036	0.0
60	GLOBAL			0.0050	-0.0031	0.0
63	GLOBAL			0.0006	0.0	0.0
64	GLOBAL			0.0008	0.0	0.0
65	GLOBAL			0.0010	0.0	0.0
66	GLOBAL			0.0012	0.0	0.0
72	GLOBAL			0.0036	-0.0025	0.0
75	GLOBAL			0.0005	0.0	0.0
76	GLOBAL			0.0009	0.0	0.0
82	GLOBAL			0.0025	-0.0019	0.0
85	GLOBAL			0.0004	0.0	0.0
86	GLOBAL			0.0007	0.0	0.0
92	GLOBAL			0.0017	-0.0014	0.0
95	GLOBAL			0.0004	0.0	0.0
96	GLOBAL			0.0004	0.0	0.0
97	GLOBAL			0.0004	0.0	0.0
98	GLOBAL			0.0005	0.0	0.0
104	GLOBAL			0.0010	-0.0011	0.0
116	GLOBAL			0.0006	-0.0008	0.0
128	GLOBAL			0.0003	-0.0005	0.0
140	GLOBAL			0.0001	-0.0003	0.0
141	GLOBAL			0.0	-0.0001	0.0
142	GLOBAL			0.0	-0.0001	0.0
143	GLOBAL			0.0	-0.0001	0.0

Figure 2.14 (Cont'd)

Distance, Inches	0.4375	0.875	1.375	1.875	2.375	2.875	3.375	3.875	4.375	4.625	5.0
6.00 – 5.50	0.42	0.36	0.12	-0.18	-1.14	-3.42	-3.30	-2.04	-4.80	-7.9	-5.84
5.50 – 5.25	1.14	0.98	5.70	-0.24	-2.58	-6.60	-4.26	-4.38	-8.22	-13.2	-10.92
5.25 – 4.75	1.86	1.68	1.32	0.42	-1.02	-2.64	-3.54	-4.38	-6.36	-7.7	-8.04
4.75 – 4.25	2.76	2.82	3.06	3.06	1.98	0.24	-2.10	-4.38	-5.62	-5.8	-6.42
4.25 – 3.75	2.52	4.08	5.70	6.66	9.84	3.54	-4.20	-5.40	-6.60	-7.1	-7.38
3.75 – 3.25	1.50	0.90				-6.0	-8.16	-8.76	-9.30	-9.4	-9.60
3.25 – 2.75	0.66	1.08				-8.10	-13.86	-13.74	-12.78	-12.0	-11.94
2.75 – 2.25	-1.98	-1.68				-20.58	-23.82	-19.20	-15.60	-13.8	-11.64
2.25 – 1.75	-16.80	-18.30	-33.60	-45.00	-61.86	-56.34	-27.66	-21.12	-15.66	-13.7	-12.84
1.75 – 1.25	-17.04	-19.62	-24.0	-29.10	-30.54	-27.42	-22.50	-16.92	-12.36	-9.9	-9.36
1.25 – 0.75	-14.04	-14.16	-15.0	-15.60	-15.12	-13.80	-12.06	-9.60	-6.72	-4.8	-4.32
0.75 – 0.50	-9.90	-9.00	-8.46	-7.56	-6.48	-5.64	-4.92	-3.96	-2.40	-1.2	-1.14
0.50 – 0.0	-3.84	-3.66	-3.30	-2.70	-2.04	-1.68	-1.38	-1.02	-0.54	0.0	-0.06

Distance, Inches

Figure 2.15 STRESS (σ_{yy}) FOR CASE II, KSI

Distance, Inches

6.00, 5.50, 5.25, 4.75, 4.25, 3.75, 3.25, 2.75, 2.25, 1.75, 1.25, 0.75, 0.50, 0.00

0.4375	0.875	1.375	1.875	2.375	2.875	3.375	3.875	4.375	4.625	5.0
0.06	0.18	0.30	0.48	0.78	-4.20	0.66	0.12	0.54	-7.1	-0.72
-0.12	0.47	0.72	1.14	0.60	-6.48	0.0	0.12	-1.86	-9.6	-2.28
-0.24	-0.66	1.08	1.32	0.12	-2.54	-1.74	-0.96	-1.86	-3.0	-2.28
0.30	0.96	1.32	1.32	1.64	-0.66	-2.94	-2.10	-0.89	-0.2	-0.66
0.48	1.98	1.74	3.72	3.60	-1.50	-4.86	-2.76	0.18	1.64	1.64
0.96	2.40				-9.18	-8.40	-3.12	1.74	4.1	4.64
1.56	5.04				-18.36	-11.64	-2.82	3.90	7.1	7.56
1.56	9.84				-34.92	-13.26	-1.20	6.84	10.5	11.10
-0.66	-3.84	-12.0	-16.50	-25.50	-41.16	-10.80	-1.32	9.96	14.1	14.76
-0.84	-5.40	-11.16	-15.72	-21.90	-18.24	-7.20	4.14	13.02	17.7	18.48
-1.62	-5.22	-9.72	-13.08	-14.16	-10.62	-1.92	4.44	14.82	21.1	21.90
-2.16	-6.06	-9.60	-10.80	-9.24	-4.92	2.10	10.26	18.30	23.2	23.8
-2.52	-7.20	-10.20	-9.66	-6.36	-3.18	5.04	12.84	20.40	24.9	25.20

Distance, Inches

Figure 2.16 STRESS (σ_{xx}) FOR CASE II, KSI

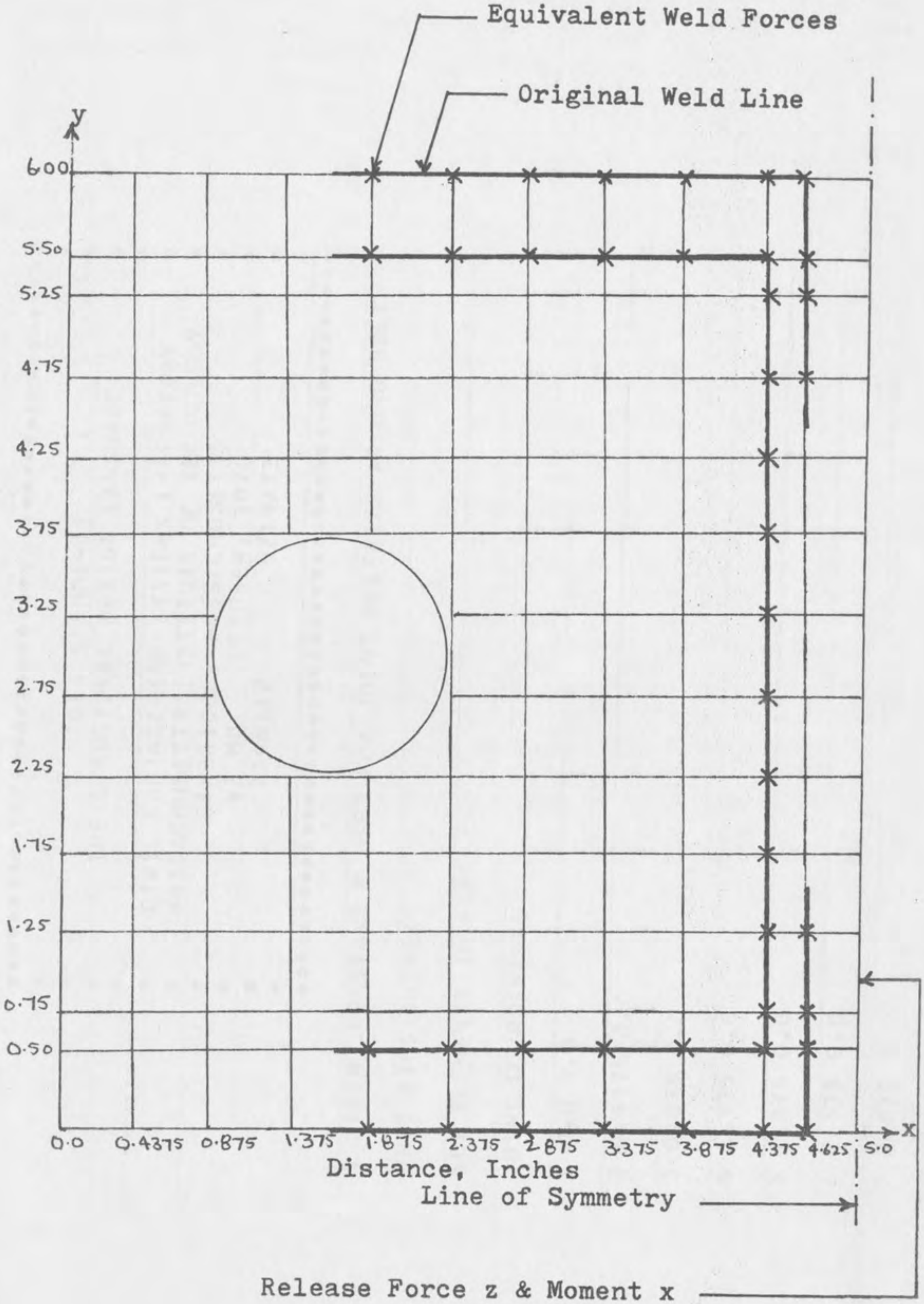


Figure 2.17 DETAILS OF CASE III

```
STRUDL 'PB-SS' 'S.S. UPTO .5 INCH FROM TOP AND WELD FORCE

          **************************************************
          *                                                *
          *                 ICES STRUDL-II                 *
          *          THE STRUCTURAL DESIGN LANGUAGE        *
          *                                                *
          *       CIVIL ENGINEERING SYSTEMS LABORATORY     *
          *       MASSACHUSETTS INSTITUTE OF TECHNOLOGY    *
          *            CAMBRIDGE, MASSACHUSETTS            *
          *              V2 MO    OCTOBER, 1970            *
          *              7:46:12         5/19/73           *
          *                                                *
          **************************************************

$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT

UNIT KIPS INCHES

SET ELEMENTS INTEGER

JOINT COORDINATES

1 0.0 0.0

2 0.4375 0.0

3 0.875 0.0

4 1.375 0.0

5 1.875 0.0

6 2.375 0.0

7 2.875 0.0

8 3.375 0.0
```

Figure 2.18 TYPICAL PORTIONS OF INPUT AND OUTPUT FOR CASE III

Node Number
x Coordinate
y Coordinate

```
53 1.875 1.75
54 2.375 1.75
55 2.875 1.75
56 3.375 1.75
57 3.875 1.75
58 4.375 1.75
59 4.625 1.75
60 5.0 1.75 S
61 0.0 2.25
62 0.4375 2.25
63 0.875 2.25 S
64 1.375 2.25 S
65 1.875 2.25 S
66 2.375 2.25 S
67 2.875 2.25
68 3.375 2.25
69 3.875 2.25
70 4.375 2.25
71 4.625 2.25
72 5.0 2.25 S
73 0.0 2.75
131 0.875 5.25
132 1.375 5.25
133 1.875 5.25
134 2.375 5.25
135 2.875 5.25
136 3.375 5.25
137 3.875 5.25
138 4.375 5.25
139 4.625 5.25
140 5.0 5.25 S
141 0.0 5.50 S
142 0.4375 5.50 S
143 0.875 5.50 S
144 1.375 5.50 S
145 1.875 5.50 S
146 2.375 5.50 S
147 2.875 5.50 S
148 3.375 5.50 S
149 3.875 5.50 S
150 4.375 5.50 S
151 4.625 5.50 S
164 5.0 6.0 S
TYPE PLATE BENDING
ELEMENT INCIDENCES
1 1 2 14 13
2 2 3 15 14
3 3 4 16 15
4 4 5 17 16
5 5 6 18 17
6 6 7 19 18
7 7 8 20 19
8 8 9 21 20
9 9 10 22 21
10 10 11 23 22
11 11 12 24 23
12 13 14 26 25
13 14 15 27 26
14 15 16 28 27
15 16 17 29 28
16 17 18 30 29
17 18 19 31 30
18 19 20 32 31
```

Figure 2.18 (Cont'd)

```
ELEMENT PROPERTIES
1 TO 134 TYPE 'BPR' THICKNESS 1.0
CONSTANTS
E 30000. ALL
POISSON 0.3 ALL
$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT
JOINT RELEASES
12 24 36 48 60 72 82 92 104 116 128 140 152 FORCE Z MOMENT X
63 TO 66 75 76 85 86 95 TO 98 KFZ 1856.25
141 TO 151 153 TO 164 MOMENT X
$ WELD FORCE ONLY
LOADING 1 'WELD FORCE AT JOINTS'
JOINT LOADS
157 TO 161 FORCE Z 0.298
162 FORCE Z 0.223
163 FORCE Z 0.242

46 FORCE Z 0.662
34 FORCE Z 0.678
22 FORCE Z 0.689
21 FORCE Z 0.693
17 TO 20 FORCE Z 0.924
47 FORCE Z 0.882
35 FORCE Z 0.899
23 FORCE Z 0.939
11 FORCE Z 0.731
10 FORCE Z 0.75
5 TO 9 FORCE Z 1.0
STIFFNESS ANALYSIS
OUTPUT DECIMAL 4
LIST DISPLACEMENT STRESSES ALL
```

Figure 2.18 (Cont'd)

```
******************************
*RESULTS OF LATEST ANALYSES*
******************************
```

PROBLEM - PB-SS   TITLE - S.S. UPTO .5 INCH FROM TOP AND WELD FORCE ONLY

ACTIVE UNITS INCH KIP RAD DEGF SEC

ACTIVE STRUCTURE TYPE PLATE BENDING

ACTIVE COORDINATE AXES X Y

LOADING - 1   WELD FORCE AT JOINTS

ELEMENT STRESSES

ELEMENT

1	NODE	1	MXX	0.156827E 00	MYY	0.155561E 00	MXY	0.375128E 00
1	NODE	2	MXX	-0.109293E 01	MYY	-0.474492E-01	MXY	0.716049E 00
1	NODE	14	MXX	-0.713166E 00	MYY	-0.123512E 01	MXY	0.966595E 00
1	NODE	13	MXX	-0.424836E-01	MYY	-0.143199E 01	MXY	0.625674E 00
2	NODE	2	MXX	-0.104992E 01	MYY	-0.345649E-01	MXY	0.722821E 00
2	NODE	3	MXX	-0.167029E 01	MYY	-0.165100E-01	MXY	0.116037E 01
2	NODE	15	MXX	-0.138330E 01	MYY	-0.114877E 01	MXY	0.137643E 01
2	NODE	14	MXX	-0.738931E 00	MYY	-0.124283E 01	MXY	0.938879E 00

Figure 2.18 (Cont'd)

LOADING - 1 WELD FORCE AT JOINTS

RESULTANT JOINT DISPLACEMENTS - SUPPORTS

JOINT		/---------------DISPLACEMENT---------------//--- X DISP.	Y DISP.	Z DISP.	X ROT.
12	GLOBAL			0.0117	-0.0043
24	GLOBAL			0.0096	-0.0040
36	GLOBAL			0.0086	-0.0039
48	GLOBAL			0.0067	-0.0035
60	GLOBAL			0.0051	-0.0031
63	GLOBAL			0.0007	0.0
64	GLOBAL			0.0009	0.0
65	GLOBAL			0.0011	0.0
66	GLOBAL			0.0013	0.0
72	GLOBAL			0.0037	-0.0025
75	GLOBAL			0.0006	0.0
76	GLOBAL			0.0010	0.0
82	GLOBAL			0.0026	-0.0019
85	GLOBAL			0.0006	0.0
86	GLOBAL			0.0008	0.0
92	GLOBAL			0.0018	-0.0014
95	GLOBAL			0.0005	0.0
96	GLOBAL			0.0005	0.0
97	GLOBAL			0.0006	0.0
98	GLOBAL			0.0006	0.0
104	GLOBAL			0.0011	-0.0011
116	GLOBAL			0.0007	-0.0008
128	GLOBAL			0.0003	-0.0006
140	GLOBAL			0.0001	-0.0003
152	GLOBAL			0.0000	-0.0002
153	GLOBAL			0.0	-0.0003
154	GLOBAL			0.0	-0.0003

Figure 2.18 (Cont'd)

Distance, Inches	0.4375	0.875	1.375	1.875	2.375	2.875	3.375	3.875	4.375	4.625	5.0
6.00–5.50	-3.12	-3.78	-4.20	-4.44	-4.80	-4.98	-4.64	-3.00	-5.46	-8.1	-5.76
5.50–5.25	-5.52	-6.42	-7.14	-7.68	-7.26	-6.72	-7.92	-7.92	-9.18	-10.2	-10.44
5.25–4.75	-2.94	-3.06	3.30	-3.66	-4.02	-3.90	-5.22	-6.36	-7.14	-7.2	-7.7
4.75–4.25	1.02	1.26	1.74	2.22	0.96	-0.78	-3.0	-5.04	-6.12	-6.0	-6.84
4.25–3.75	2.58	5.70	6.66	7.02	-10.80	3.78	-4.44	-5.82	-7.02	-7.2	-7.56
3.75–3.25	2.22	1.44				-5.46	-8.40	-9.0	-9.6	-6.9	-9.84
3.25–2.75	1.32	1.50				-9.78	-13.80	-13.80	-12.50	-12.0	-12.12
2.75–2.25	-1.44	1.98				-29.28	-27.84	-19.14	-15.60	-13.8	-12.9
2.25–1.75	-10.38	-18.24	-33.72	-45.0	-62.04	-56.40	-27.60	-15.06	-15.66	-13.2	-13.6
1.75–1.25	-16.92	-19.56	-24.0	-29.22	-30.60	-27.42	-22.50	-16.92	-15.36	-8.4	-9.36
1.25–0.75	-13.98	-14.16	-15.0	-15.06	-15.12	-13.80	-12.06	-9.60	-6.90	-4.2	-5.8
0.75–0.50	-9.90	-9.0	-8.4	-7.56	-6.48	-5.64	-4.92	-3.96	-2.40	-1.2	-1.02
0.50–0.00	-3.84	-3.66	-3.30	-2.40	-2.14	-1.68	-1.38	-1.08	-0.48	0.0	-0.6

Distance, Inches

Figure 2.19 STRESS (σ_{yy}) FOR CASE III, KSI

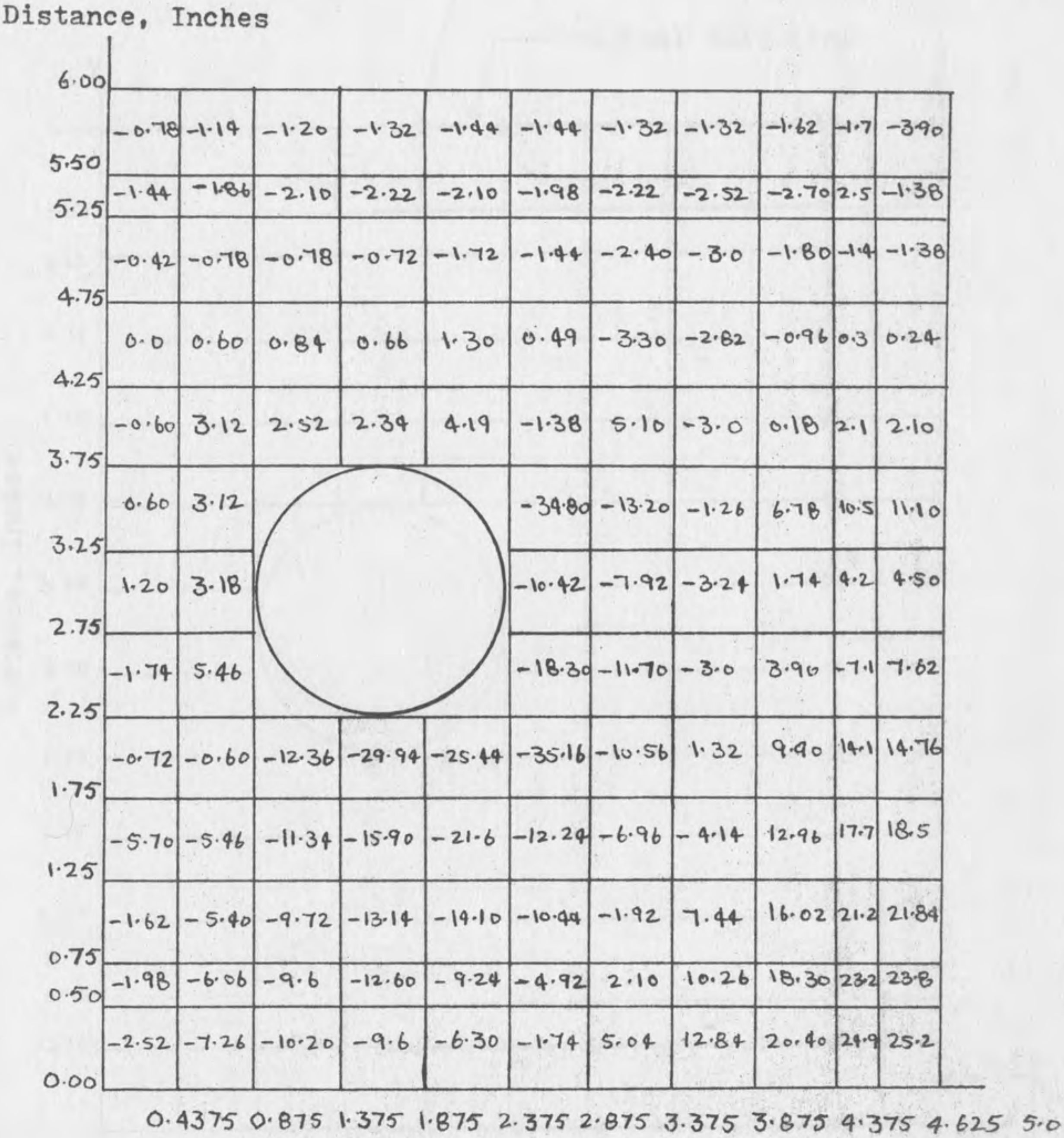


Figure 2.20 STRESS (σ_{xx}) FOR CASE III, KSI

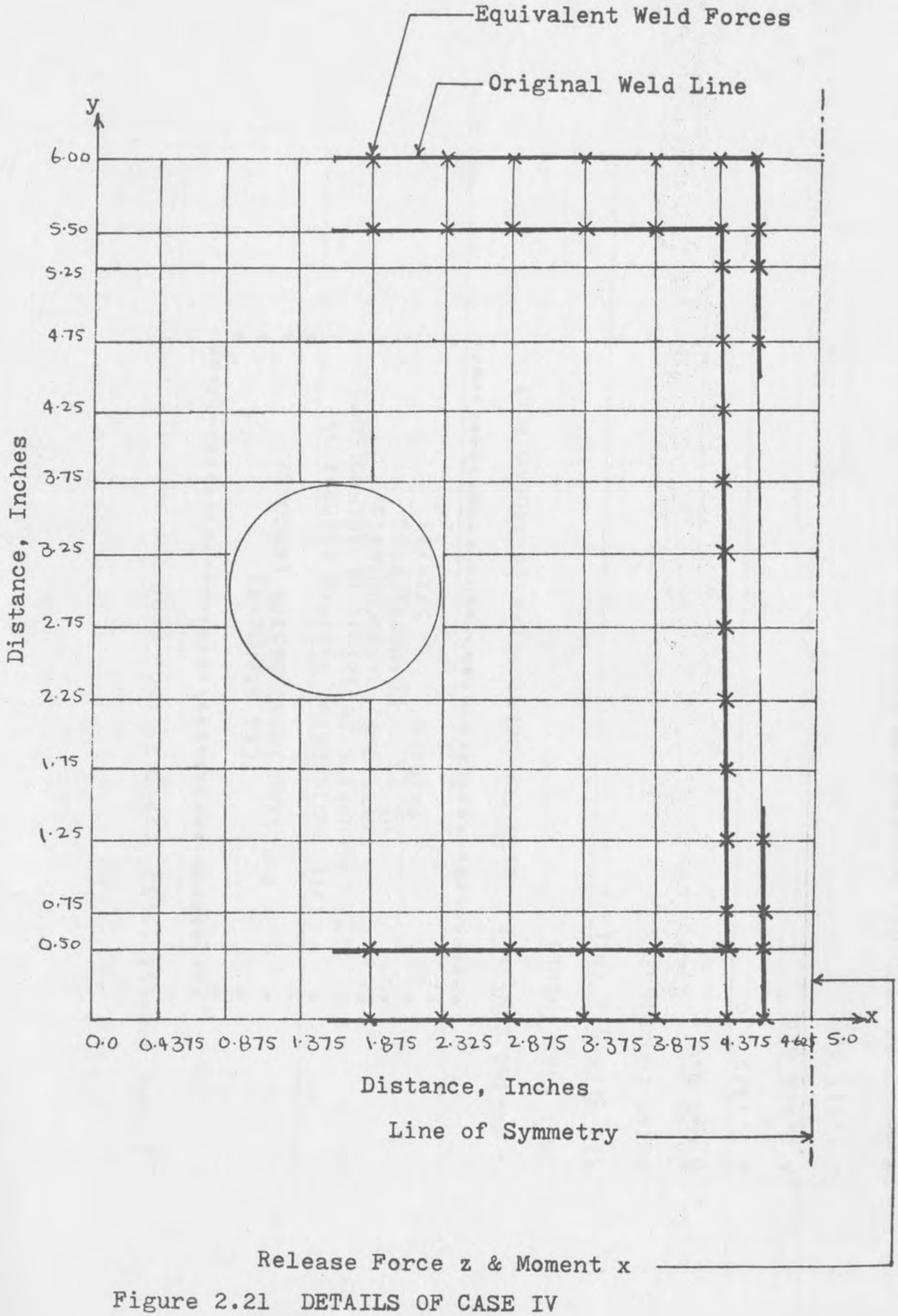


Figure 2.21 DETAILS OF CASE IV

```
STRUDL 'PB-SS' 'S.S. UPTP 0.75 INCH FROM TOP AND WELD FORCE ONLY' 40000

                   *******************************************
                   *                                         *
                   *             ICES STRUDL-II              *
                   *       THE STRUCTURAL DESIGN LANGUAGE    *
                   *                                         *
                   *    CIVIL ENGINEERING SYSTEMS LABORATORY *
                   *    MASSACHUSETTS INSTITUTE OF TECHNOLOGY*
                   *         CAMBRIDGE, MASSACHUSETTS        *
                   *          V2 M0    OCTOBER, 1970         *
                   *          9:10:04        5/19/73         *
                   *                                         *
                   *******************************************

$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT

UNIT KIPS INCHES

SET ELEMENTS INTEGER

JOINT COORDINATES

1 0.0 0.0

2 0.4375 0.0

3 0.875 0.0

4 1.375 0.0
```

Figure 2.22 TYPICAL PORTIONS OF INPUT AND OUTPUT FOR CASE IV

Node Number — x coordinate — y Coordinate — Support Condition

86 2.375 3.25 S	131 0.875 5.25 S	164 5.0 6.0 S
87 2.875 3.25	132 1.375 5.25 S	TYPE PLATE BENDING
88 3.375 3.25	133 1.875 5.25 S	ELEMENT INCIDENCES
89 3.875 3.25	134 2.375 5.25 S	1 1 2 14 13
90 4.375 3.25	135 2.875 5.25 S	2 2 3 15 14
91 4.625 3.25	136 3.375 5.25 S	3 3 4 16 15
92 5.0 3.25 S	137 3.875 5.25 S	4 4 5 17 16
93 0.0 3.75	138 4.375 5.25 S	5 5 6 18 17
94 0.4375 3.75	139 4.625 5.25 S	6 6 7 19 18
95 0.875 3.75 S	140 5.0 5.25 S	7 7 8 20 19
96 1.375 3.75 S	141 0.0 5.50 S	8 8 9 21 20
97 1.875 3.75 S	142 0.4375 5.50 S	9 9 10 22 21
98 2.375 3.75 S	143 0.875 5.50 S	10 10 11 23 22
99 2.875 3.75	144 1.375 5.50 S	11 11 12 24 23
100 3.375 3.75	145 1.875 5.50 S	12 13 14 26 25
101 3.875 3.75	146 2.375 5.50 S	13 14 15 27 26
102 4.375 3.75	147 2.875 5.50 S	14 15 16 28 27
103 4.625 3.75	148 3.375 5.50 S	15 16 17 29 28
104 5.0 3.75 S	149 3.875 5.50 S	16 17 18 30 29
105 0.0 4.25	150 4.375 5.50 S	17 18 19 31 30
106 0.4375 4.25	151 4.625 5.50 S	18 19 20 32 31

Figure 2.22 (Cont'd)

```
ELEMENT PROPERTIES
1 TO 134 TYPE 'BPR' THICKNESS 1.0
CONSTANTS
E 30000. ALL
POISSON 0.3 ALL
$ SPRING CONSTANT K USED FOR JOINT RELEASES AROUND BOLT
JOINT RELEASES
12 24 36 48 60 72 82 92 104 116 128 140 152 FORCE Z MOMENT X
63 TO 66 75 76 85 86 95 TO 98 KFZ 1856.25
129 TO 139 141 TO 151 153 TO 164 MOMENT X
$ WELD FORCE ONLY
LOADING 1 'WELD FORCE AT JOINTS'
JOINT LOADS
157 TO 161 FORCE Z 0.298
162 FORCE Z 0.223
163 FORCE Z 0.242

145 TO 148 FORCE Z 0.374
149 FORCE Z 0.280
150 FORCE Z 0.189
151 FORCE Z 0.263
139 FORCE Z 0.304
127 FORCE Z 0.416
138 FORCE Z 0.304
23 FORCE Z 0.939
11 FORCE Z 0.731
10 FORCE Z 0.75
5 TO 9 FORCE Z 1.0
STIFFNESS ANALYSIS
OUTPUT DECIMAL 4
LIST DISPLACEMENT STRESSES ALL
```

Figure 2.22 (Cont'd)

```
****************************
*RESULTS OF LATEST ANALYSES*
****************************

 PROBLEM - PR-SS      TITLE - S.S. UPTP 0.75 INCH FROM TOP AND WELD FORCE ONLY

 ACTIVE UNITS  INCH KIP  RAD  DEGF SEC

 ACTIVE STRUCTURE TYPE  PLATE   BENDING

 ACTIVE COORDINATE AXES  X Y

LOADING - 1               WELD FORCE AT JOINTS

ELEMENT STRESSES

ELEMENT

1          NODE  1      MXX    0.156914E 00    MYY    0.155382E 00    MXY    0.375073E 00
1          NODE  2      MXX   -0.109206E 01    MYY   -0.475093E-01    MXY    0.716191E 00
1          NODE  14     MXX   -0.712002E 00    MYY   -0.123609E 01    MXY    0.966395E 00
1          NODE  13     MXX   -0.425264E-01    MYY   -0.143266E 01    MXY    0.625277E 00

2          NODE  2      MXX   -0.104899E 01    MYY   -0.345786E-01    MXY    0.723068E 00
2          NODE  3      MXX   -0.166798E 01    MYY   -0.165288E-01    MXY    0.116100E 01
2          NODE  15     MXX   -0.138073E 01    MYY   -0.115013E 01    MXY    0.137653E 01
2          NODE  14     MXX   -0.737824E 00    MYY   -0.124385E 01    MXY    0.938598E 00
```

Figure 2.22 (Cont'd)

LOADING - 1 WELD FORCE AT JOINTS

RESULTANT JOINT DISPLACEMENTS - SUPPORTS

JOINT		DISPLACEMENT			ROTATION	
		X DISP.	Y DISP.	Z DISP.	X ROT.	Y ROT.
12	GLOBAL			0.0115	-0.0043	0.0
24	GLOBAL			0.0094	-0.0041	0.0
36	GLOBAL			0.0084	-0.0039	0.0
48	GLOBAL			0.0065	-0.0036	0.0
60	GLOBAL			0.0049	-0.0031	0.0
63	GLOBAL			0.0006	0.0	0.0
64	GLOBAL			0.0007	0.0	0.0
65	GLOBAL			0.0009	0.0	0.0
66	GLOBAL			0.0011	0.0	0.0
72	GLOBAL			0.0035	-0.0025	0.0
75	GLOBAL			0.0004	0.0	0.0
76	GLOBAL			0.0008	0.0	0.0
82	GLOBAL			0.0024	-0.0020	0.0
85	GLOBAL			0.0004	0.0	0.0
86	GLOBAL			0.0006	0.0	0.0
92	GLOBAL			0.0015	-0.0015	0.0
95	GLOBAL			0.0003	0.0	0.0
96	GLOBAL			0.0003	0.0	0.0
97	GLOBAL			0.0003	0.0	0.0
98	GLOBAL			0.0004	0.0	0.0
104	GLOBAL			0.0009	-0.0011	0.0
116	GLOBAL			0.0004	-0.0007	0.0
128	GLOBAL			0.0001	-0.0004	0.0
129	GLOBAL			0.0	-0.0000	
130	GLOBAL			0.0	-0.0000	
131	GLOBAL			0.0		
132	GLOBAL			0.0		

Figure 2.22 (Cont'd)

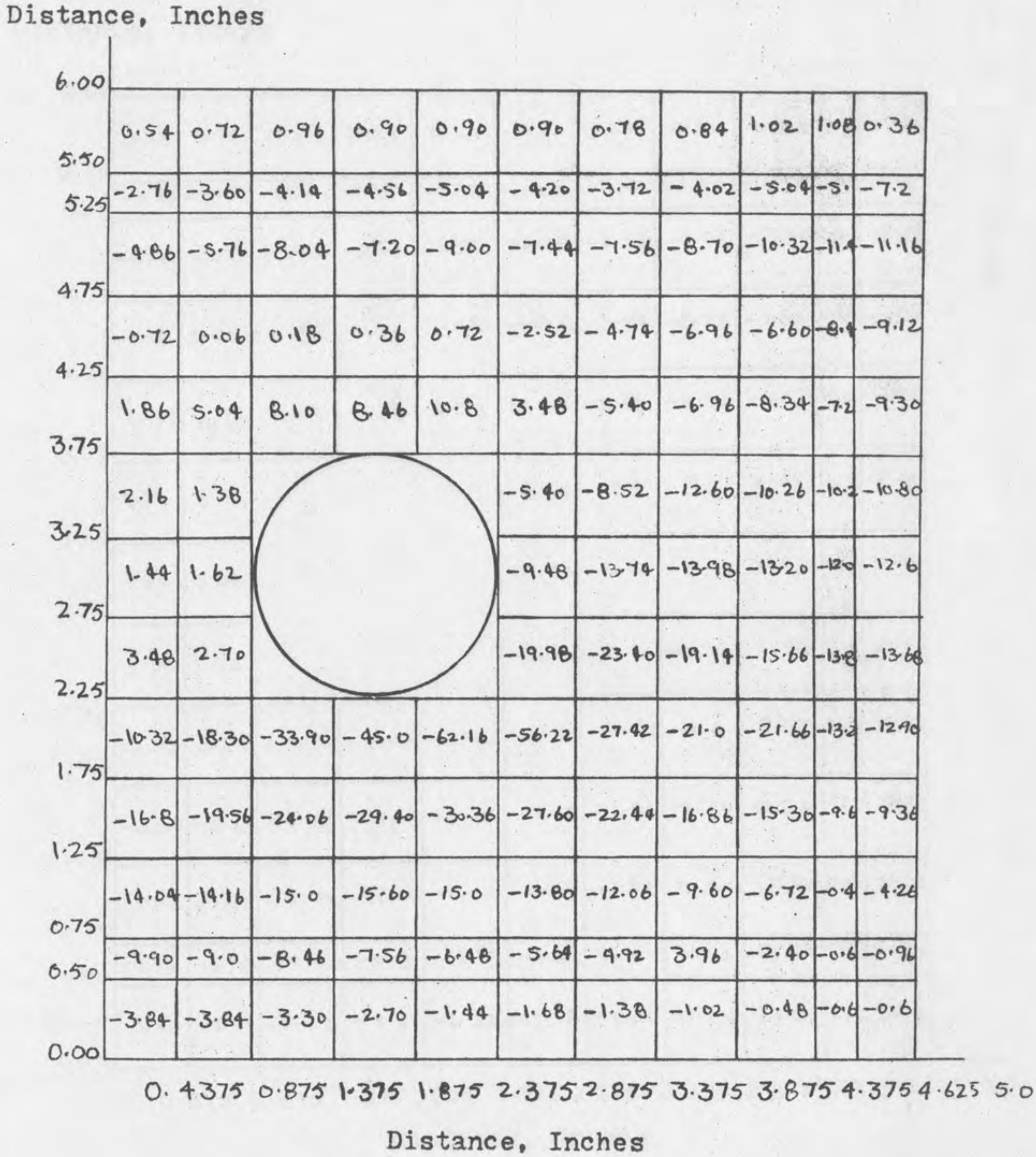


Figure 2.23 STRESS (σ_{yy}) FOR CASE IV, KSI

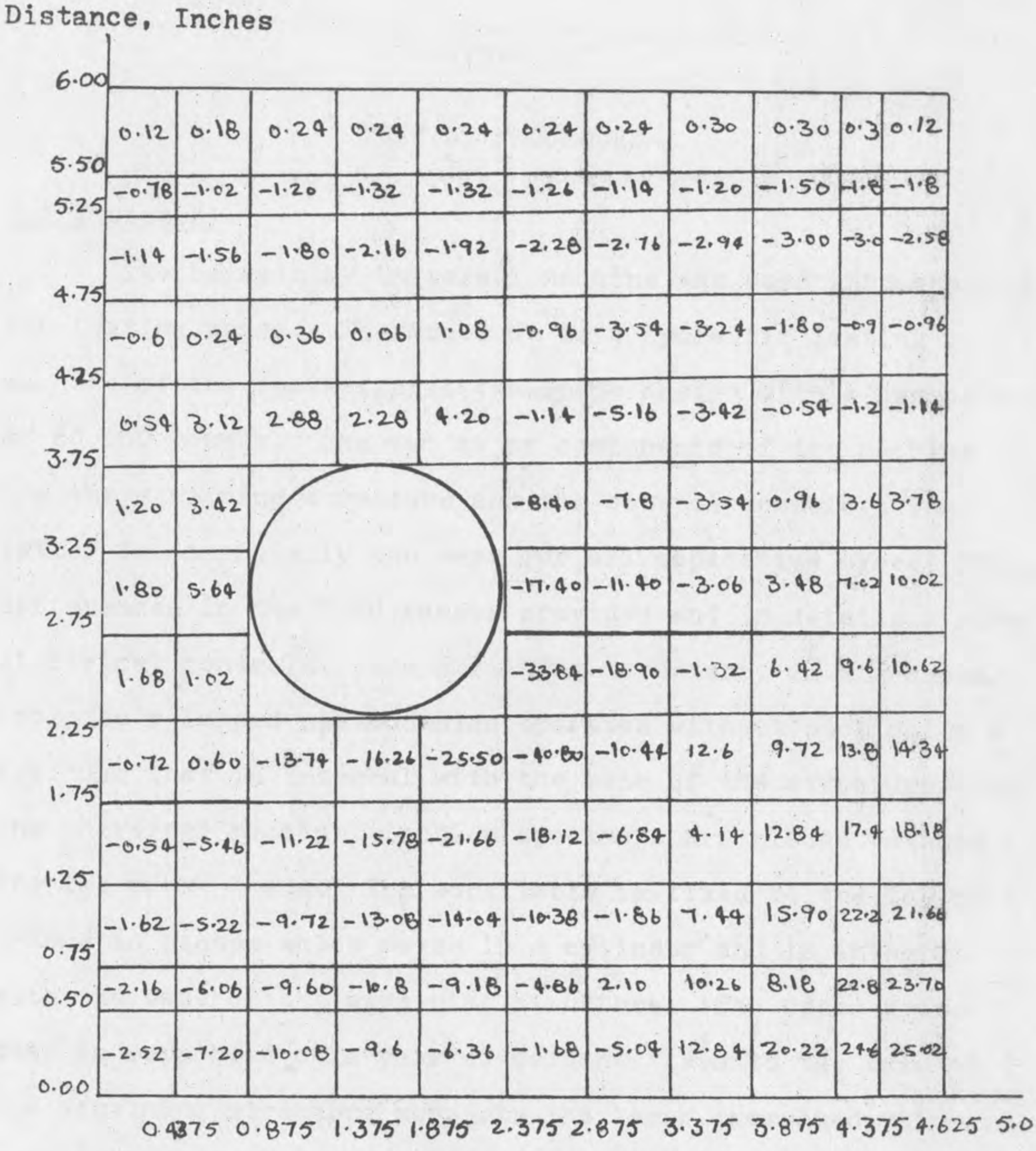


Figure 2.24 STRESS (σ_{xx}) FOR CASE IV, KSI

CHAPTER III

TESTING PROCEDURE

3.1 Equipment:

The Baldwin HV Universal machine was used throughout the testing phase. The Model HV is a hydraulic testing machine of the conventional two-space design with a capacity of 60,000 pounds. The two major components of the machine are the straining structure and the control console. The latter is essentially the same for all capacities except for differences in the load ranges provided and in details of the electrical controls. The straining structure, in all cases, includes a lapped piston which operates without packing in a cylinder that is integral with the base of the structure. In the universal machine, tension specimens are placed between the two cross heads. The work table is fixed to the top of a hydraulic piston which moves in a cylinder and is integral with the base of the straining structure. The upper cross-head is supported on a pair of columns fixed to the base of the straining structure supports the lower crosshead which is vertically adjustable. Each crosshead contains a tapered grip jaw pocket located on the vertical axis of the load-apply cylinder and piston. Upper movement of the hydraulic piston applies load to a tension specimen supported between the cross-heads. Pressure to move the piston in the cylinder is produced by a motor-driven hydraulic pump whose output passes through suitable control valves.

For the strain measurements, the BSG-6 Switch Balance and the BAM-1 Bridge Amplifier were used. The strain gages selected were SR-4, type AFX-7, 90° rosette with a gage factor of $1.97 \pm 2\%$. Up to six channels of the strain gages were individually connected to the inputs of the BSG-6 enabling any individual channel to be prebalanced and switched into the single channel instrumentation, i.e., the BAM-1 Bridge Amplifier.

The strain gages were placed at the locations on the splice plate shown in Figure 3.1. These points were selected from the points of maximum stress as obtained from the analysis portion of the study. It was hoped that the gage positions selected would yield a maximum and minimum stress distribution across the plate.

3.2 Test Procedure:

Using the standard bonding techniques, the strain gages were bonded on the prepared surfaces of the splice plates. The specimens were clamped between the two cross-heads of the testing machine by tapered, grip jaw pockets as shown in Figures 3.2 to 3.4. The load was increased gradually in increments of 2,500 pounds. The strains were recorded at every load increment. The stresses were calculated at each gage position using the following procedure:

$$\sigma_{xx} = \frac{E}{1-\mu^2}(\epsilon_{xx} + \mu\epsilon_{yy})$$

$$\sigma_{yy} = \frac{E}{1-\mu^2}(\epsilon_{yy} + \mu\epsilon_{xx})$$

where

σ_{xx} = stress produced in x-direction, KIPS/in^2

σ_{yy} = stress produced in y-direction, KIPS/in^2

E = Young's modulus, 30,000 KIPS/in^2

μ = Poisson's ratio, 0.3

ϵ_{xx} = strain in x-direction, micro in/in

ϵ_{yy} = strain in y-direction, micro in/in

Figure 3.1 STRAIN GAGES ON TEST SPECIMEN

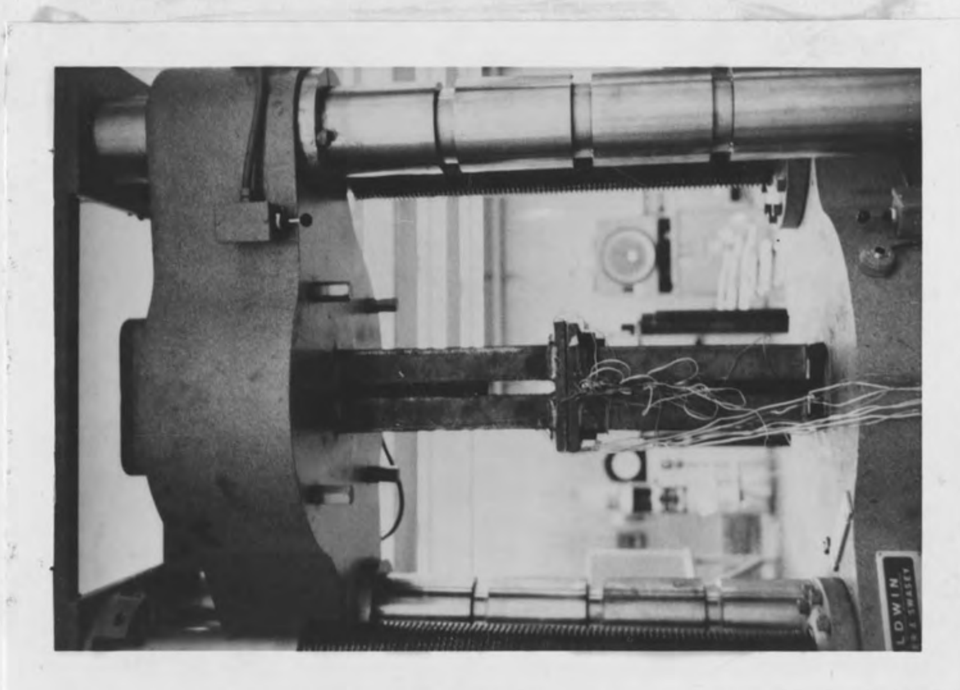


Figure 3.2 SPECIMEN IN THE TESTING MACHINE

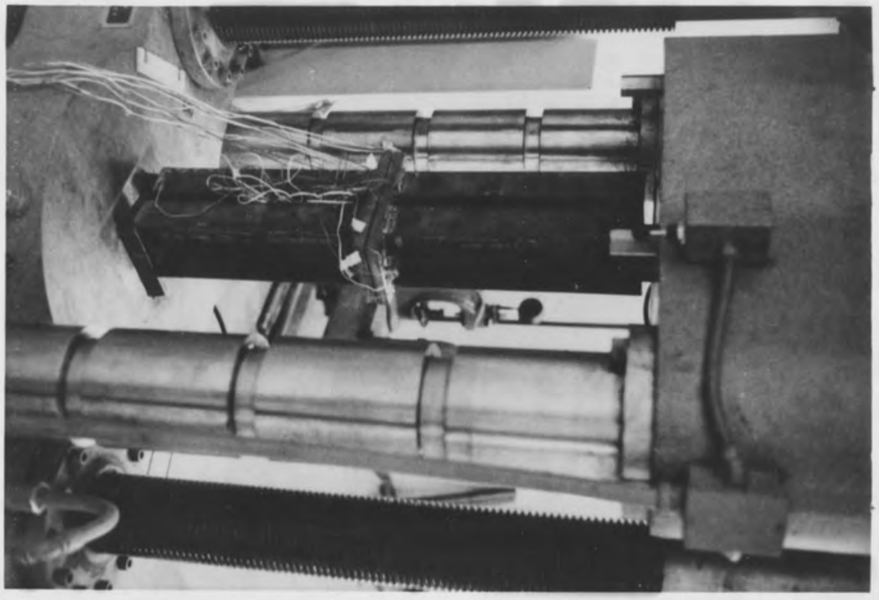


Figure 3.3 SPECIMEN IN THE TESTING MACHINE

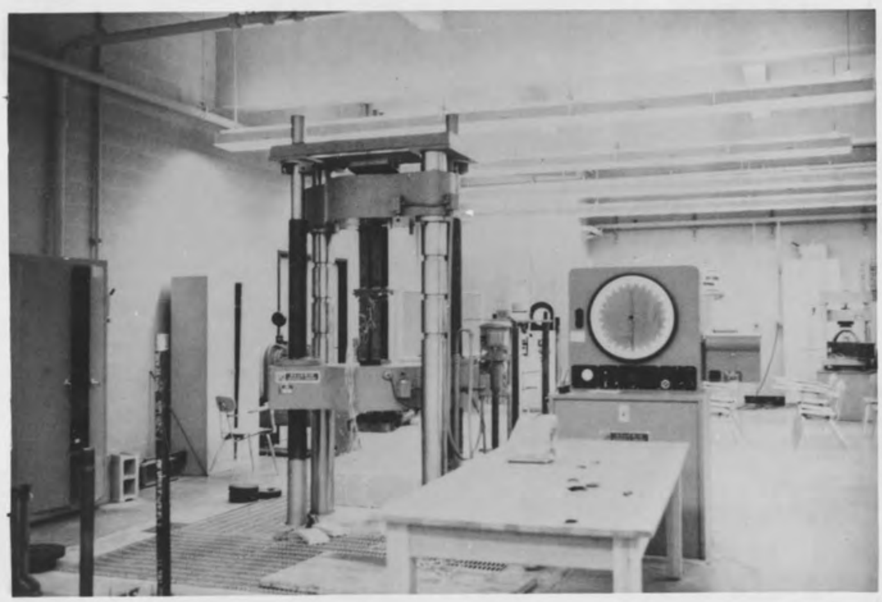


Figure 3.4 TEST SETUP

CHAPTER IV

TEST RESULTS

The strain gage locations used are shown in Figure 4.1. Tables 4.1 through 4.2 inclusive tabulate the recorded strain and corresponding applied loads.

Figures 4.2 through 4.11 show the load vs. strain curves for gage locations 1 to 5. Tables 4.3 and 4.4 tabulates the stresses for gage locations 1 to 5. The tabulated stresses were obtained from recorded strain values as follows:

$$\sigma_{xx} = \frac{E}{1-\mu^2} (\epsilon_{xx} + \mu \epsilon_{yy})$$

$$\sigma_{yy} = \frac{E}{1-\mu^2} (\epsilon_{yy} + \mu \epsilon_{xx})$$

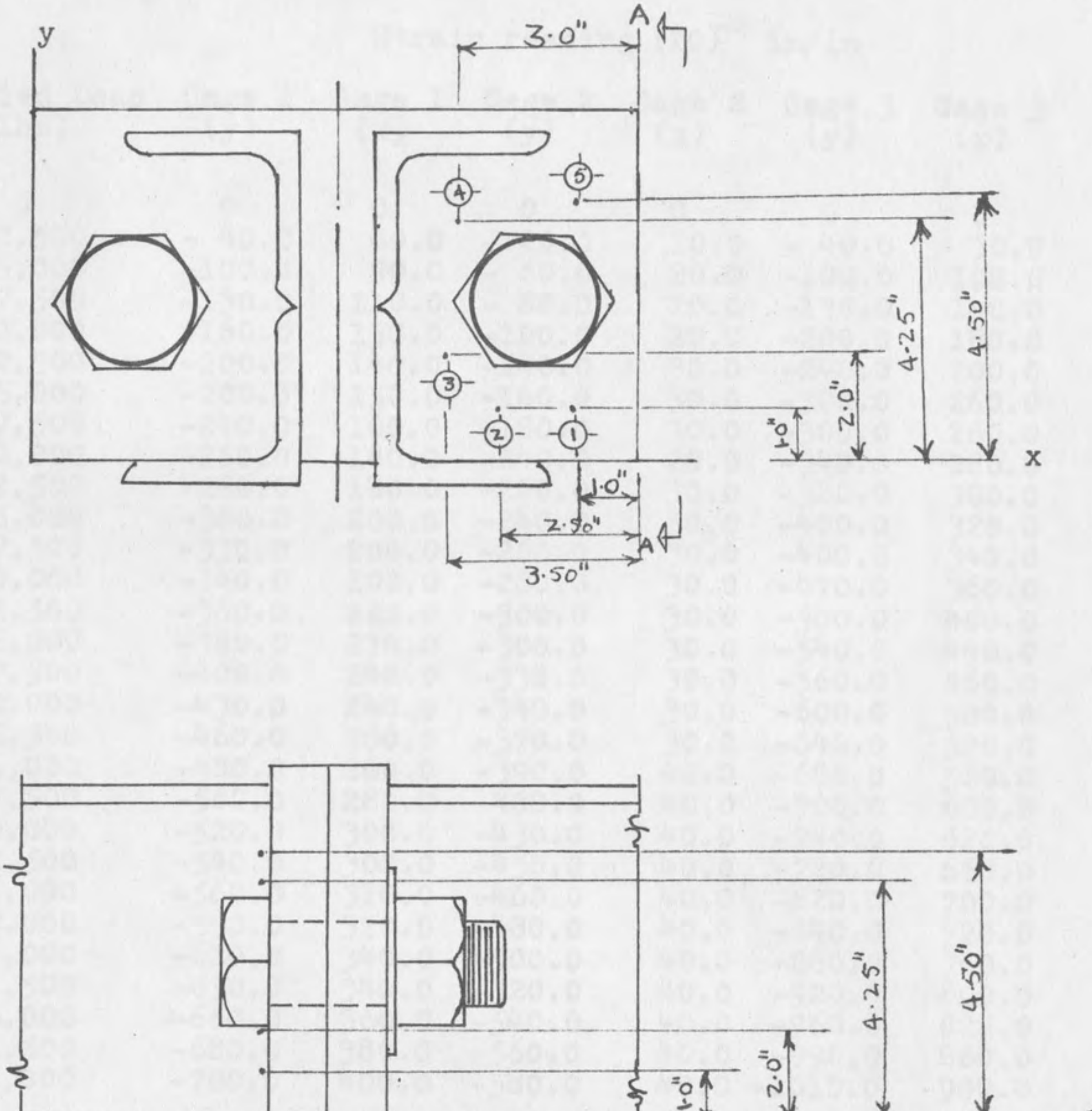
where

E = Young's modulus, 30,000 KIPS/in^2

μ = Poisson's ratio, 0.3

ϵ_{xx} = measured strain in x-direction, $(10)^{-6}$ in/in

ϵ_{yy} = measured strain in y-direction, $(10)^{-6}$ in/in



VIEW A-A

○ Gage No. and position

-⊕- Projections indicate direction of strain measurement.

Figure 4.1 STRAIN GAGE LOCATIONS OF SPECIMEN

TABLE 4.1

RECORDED TEST RESULTS FOR TEST SPECIMEN

	Strain reading $(10)^{-6}$ in/in					
Applied Load (lbs)	Gage 1 (y)	Gage 1 (x)	Gage 2 (y)	Gage 2 (x)	Gage 3 (y)	Gage 3 (x)
0	0	0	0	0	0	0
2,500	- 40.0	40.0	- 20.0	10.0	- 40.0	30.0
5,000	-100.0	90.0	- 60.0	20.0	-100.0	100.0
7,500	-130.0	110.0	- 80.0	20.0	-130.0	140.0
10,000	-160.0	130.0	-100.0	20.0	-200.0	180.0
12,500	-200.0	140.0	-140.0	30.0	-240.0	200.0
15,000	-200.0	150.0	-160.0	30.0	-300.0	260.0
17,500	-240.0	160.0	-180.0	30.0	-300.0	260.0
20,000	-260.0	180.0	-240.0	20.0	-340.0	280.0
22,500	-280.0	180.0	-220.0	30.0	-380.0	300.0
25,000	-300.0	200.0	-240.0	30.0	-400.0	320.0
27,500	-330.0	200.0	-260.0	30.0	-400.0	340.0
30,000	-340.0	200.0	-280.0	30.0	-470.0	380.0
32,500	-360.0	210.0	-300.0	30.0	-500.0	400.0
35,000	-380.0	220.0	-300.0	30.0	-540.0	440.0
37,500	-400.0	240.0	-330.0	30.0	-560.0	460.0
40,000	-430.0	240.0	-340.0	30.0	-600.0	500.0
42,500	-460.0	260.0	-370.0	30.0	-640.0	520.0
45,000	-480.0	260.0	-390.0	40.0	-680.0	560.0
47,500	-500.0	280.0	-400.0	40.0	-700.0	600.0
50,000	-520.0	300.0	-430.0	40.0	-740.0	620.0
52,500	-540.0	300.0	-450.0	40.0	-780.0	660.0
55,000	-560.0	310.0	-460.0	40.0	-820.0	700.0
57,000	-590.0	320.0	-480.0	40.0	-840.0	720.0
60,000	-610.0	340.0	-500.0	40.0	-880.0	760.0
62,500	-630.0	340.0	-520.0	40.0	-920.0	800.0
65,000	-660.0	360.0	-540.0	40.0	-960.0	820.0
67,500	-680.0	380.0	-560.0	40.0	-990.0	860.0
70,000	-700.0	400.0	-580.0	40.0	-1010.0	900.0

TABLE 4.2

RECORDED TEST RESULTS FOR TEST SPECIMEN

Applied Load (lbs)	Strain reading $(10)^{-6}$in/in Gage 4 (y)	Gage 4 (x)	Gage 5 (y)	Gage 5 (x)
0	0	0	0	0
2,500	- 20.0	10.0	- 20.0	10.0
5,000	- 20.0	30.0	- 40.0	20.0
7,500	- 20.0	40.0	- 60.0	40.0
10,000	- 40.0	40.0	- 60.0	40.0
12,500	- 50.0	40.0	- 70.0	60.0
15,000	- 60.0	40.0	- 80.0	60.0
17,500	- 60.0	30.0	- 80.0	70.0
20,000	- 60.0	20.0	- 90.0	80.0
22,500	- 80.0	20.0	-100.0	100.0
25,000	-100.0	20.0	-100.0	100.0
27,500	-100.0	0.0	-100.0	100.0
30,000	-110.0	0.0	-100.0	110.0
32,500	-120.0	-10.0	-100.0	110.0
35,000	-120.0	-20.0	-100.0	120.0
37,500	-130.0	-20.0	-110.0	120.0
40,000	-140.0	-20.0	-110.0	130.0
42,500	-150.0	-20.0	-110.0	140.0
45,000	-160.0	-20.0	-110.0	140.0
47,500	-160.0	-20.0	-120.0	140.0
50,000	-170.0	-20.0	-120.0	140.0
52,500	-180.0	-20.0	-120.0	140.0
55,000	-190.0	-20.0	-120.0	140.0
57,500	-200.0	-20.0	-130.0	140.0
60,000	-200.0	-20.0	-120.0	140.0
62,500	-210.0	-20.0	-130.0	140.0
65,000	-220.0	-20.0	-130.0	140.0
67,500	-220.0	-20.0	-130.0	140.0
70,000	-230.0	-20.0	-130.0	140.0

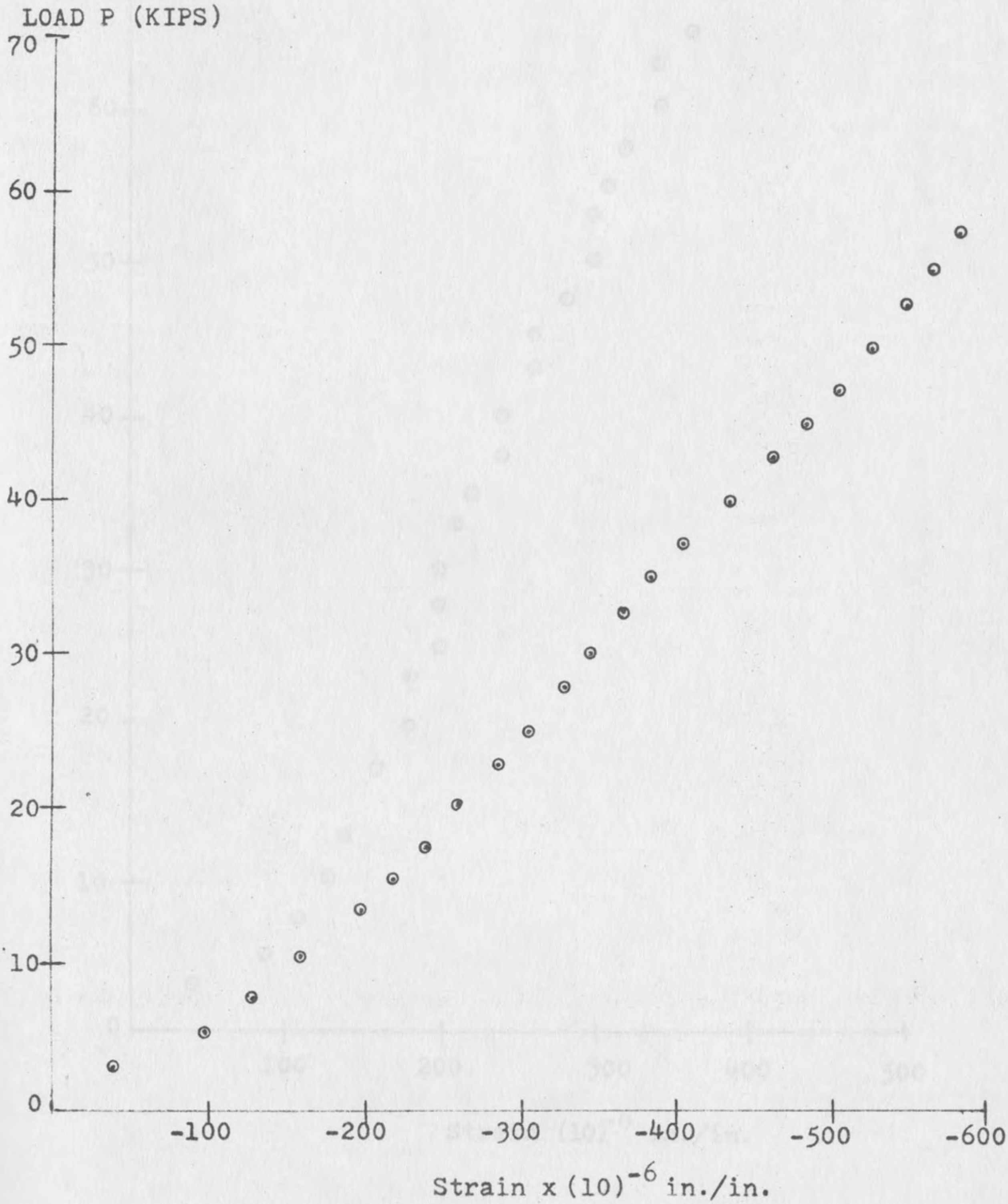


Figure 4.2 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 1 (y Direction)

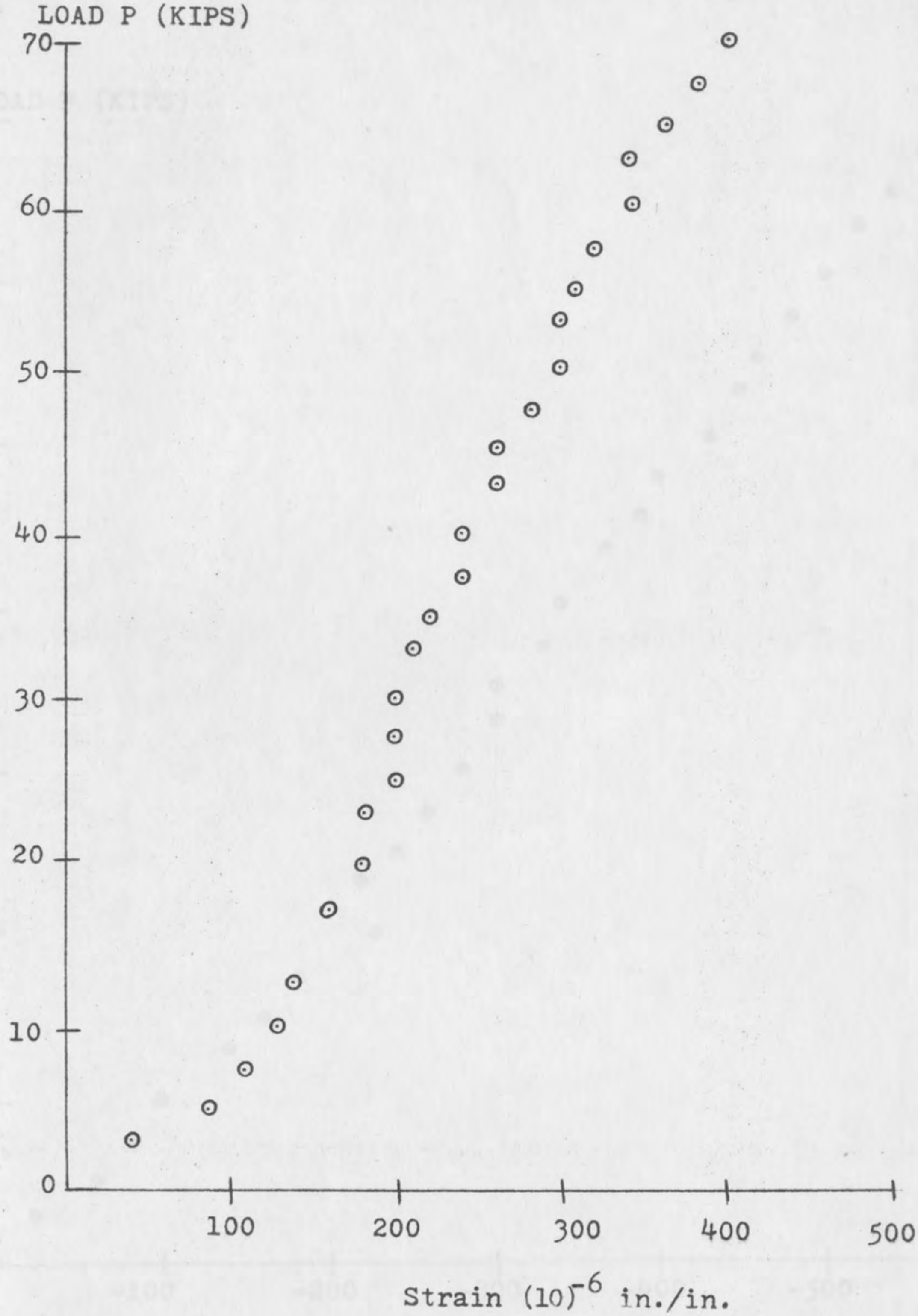


Figure 4.3 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 1 (x Direction)

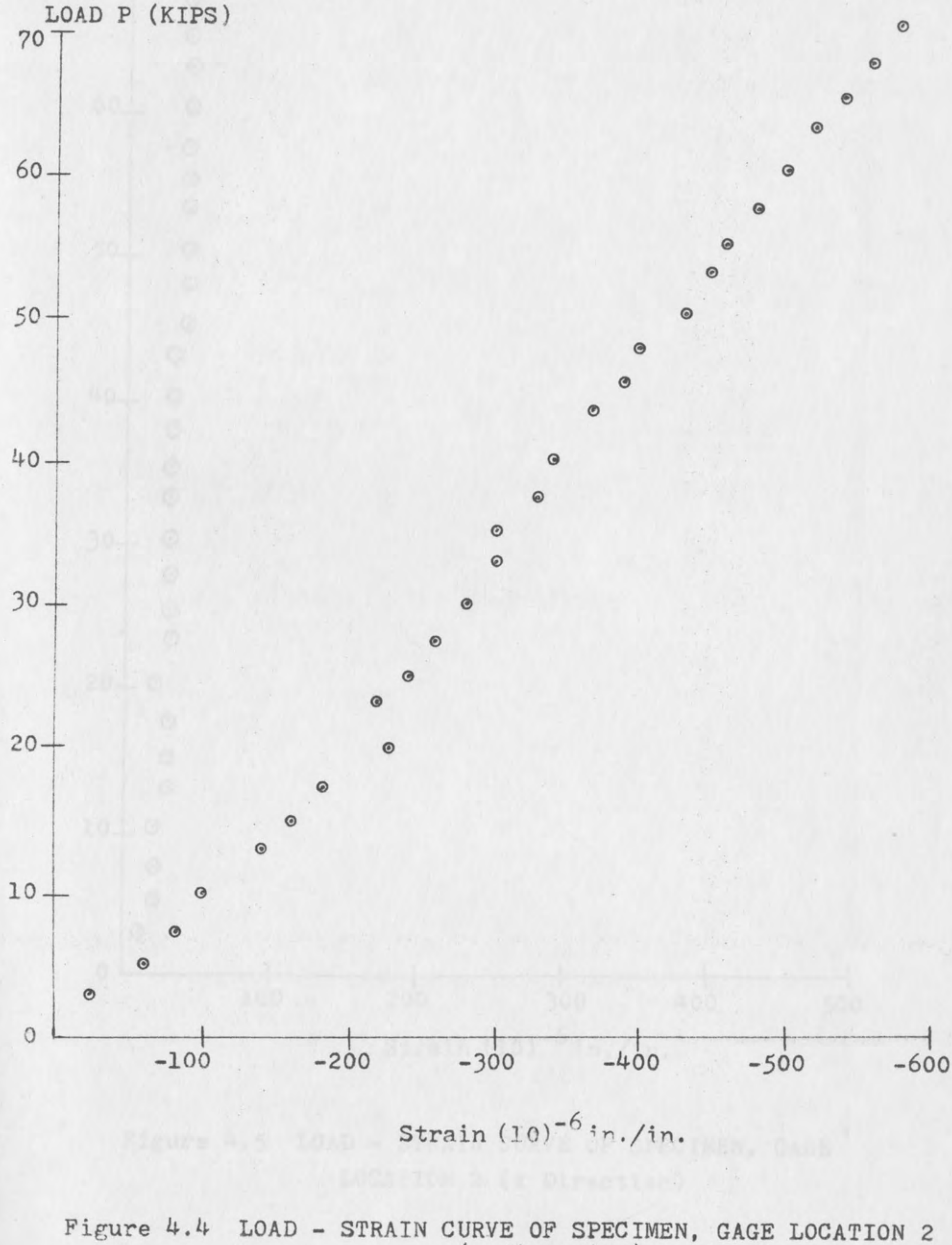


Figure 4.4 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 2 (y direction)

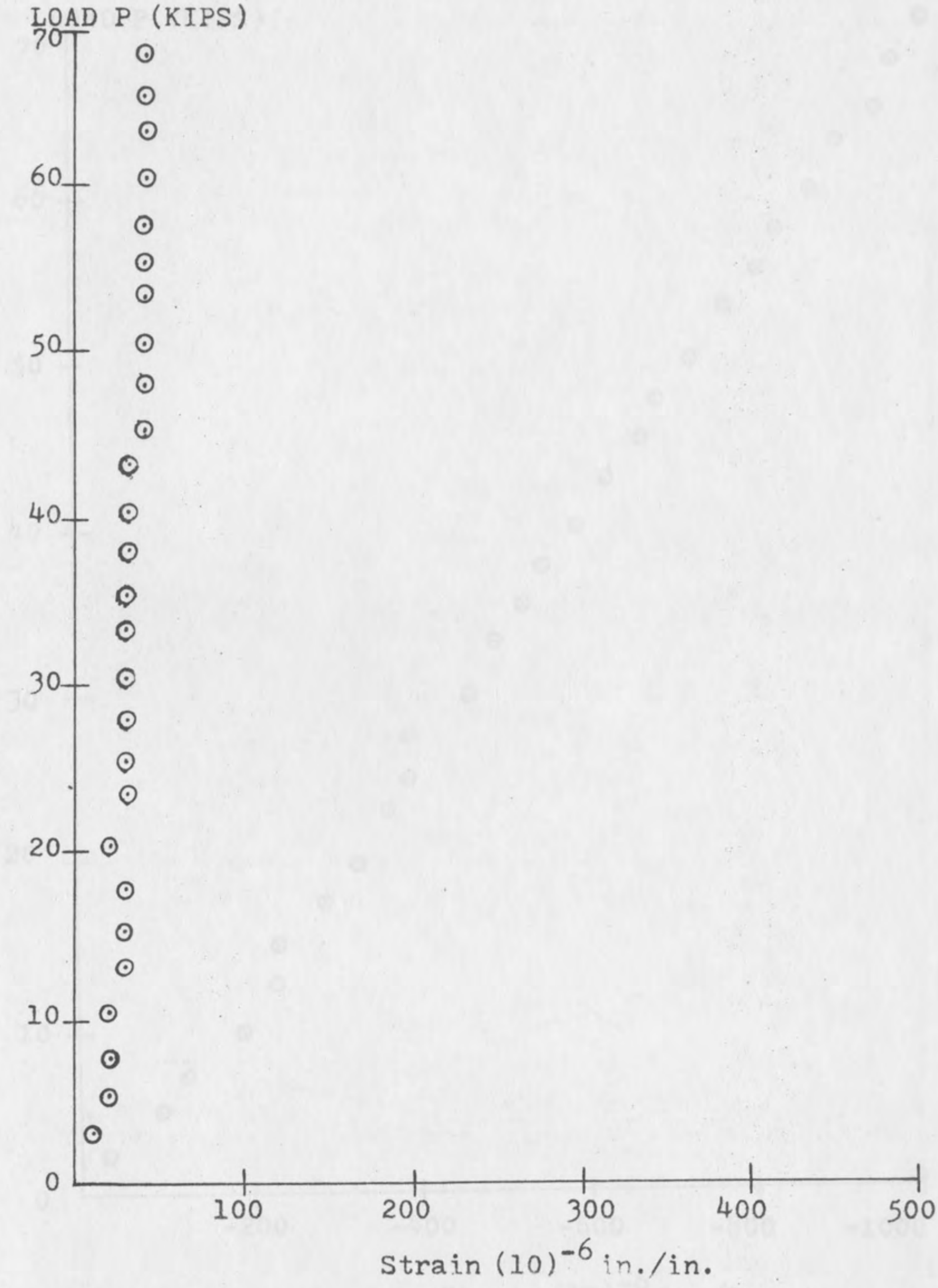


Figure 4.5 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 2 (x Direction)

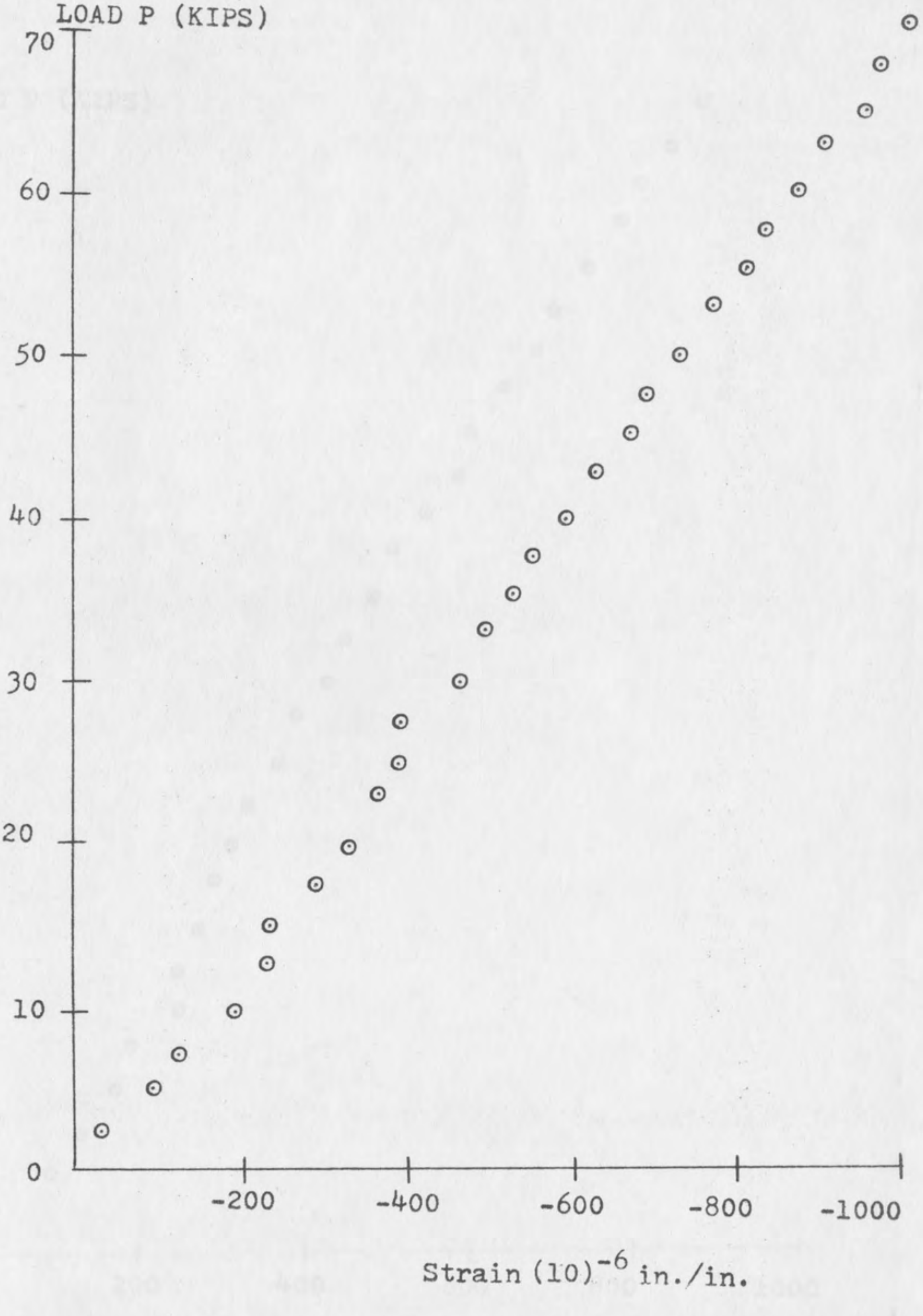


Figure 4.6 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 3 (y direction)

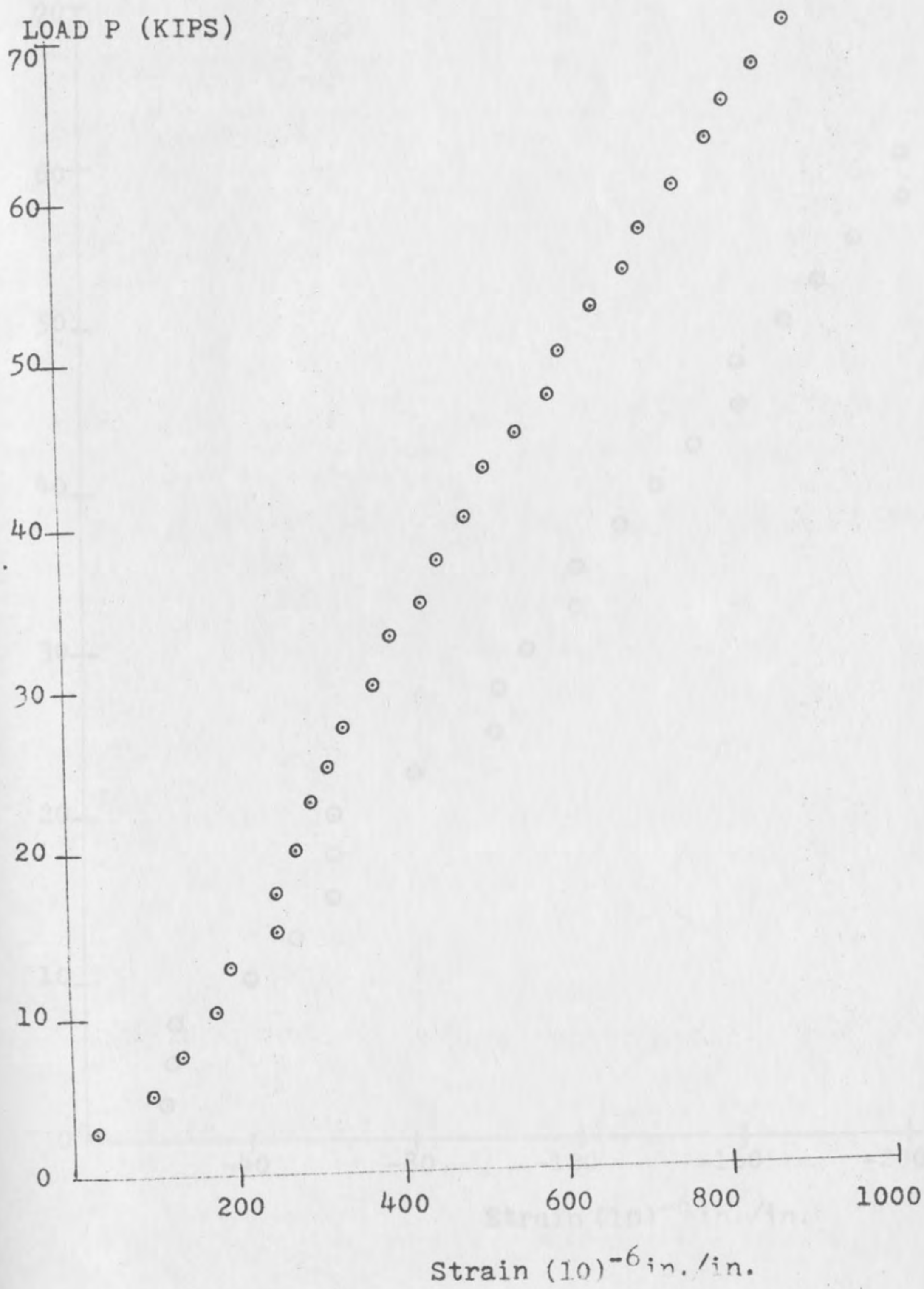


Figure 4.7 LOAD - STRAIN CURVE OF SPECIMEN GAGE LOCATION 3 (x direction)

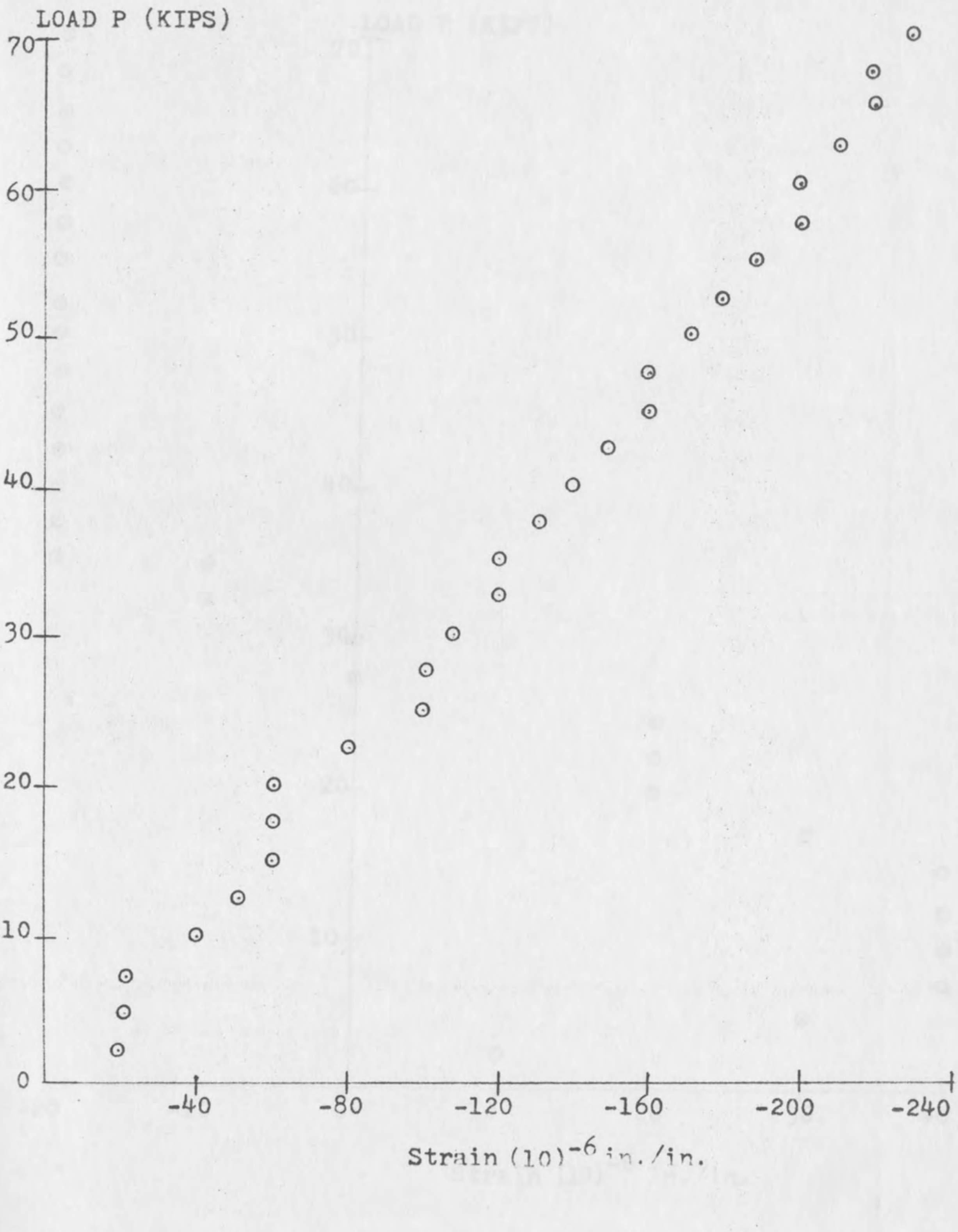


Figure 4.8 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 4 (y direction)

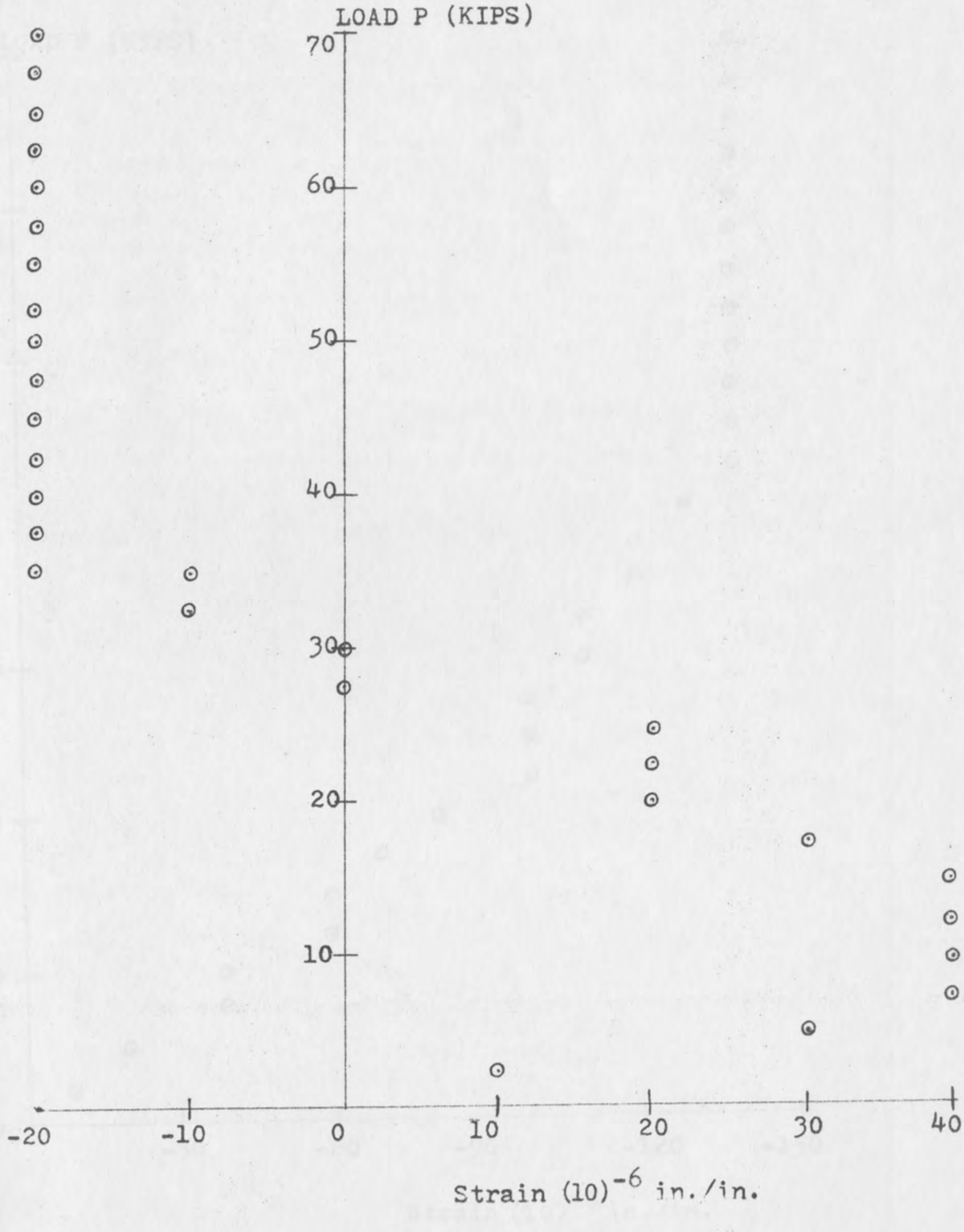


Figure 4.9 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 4 (x direction)

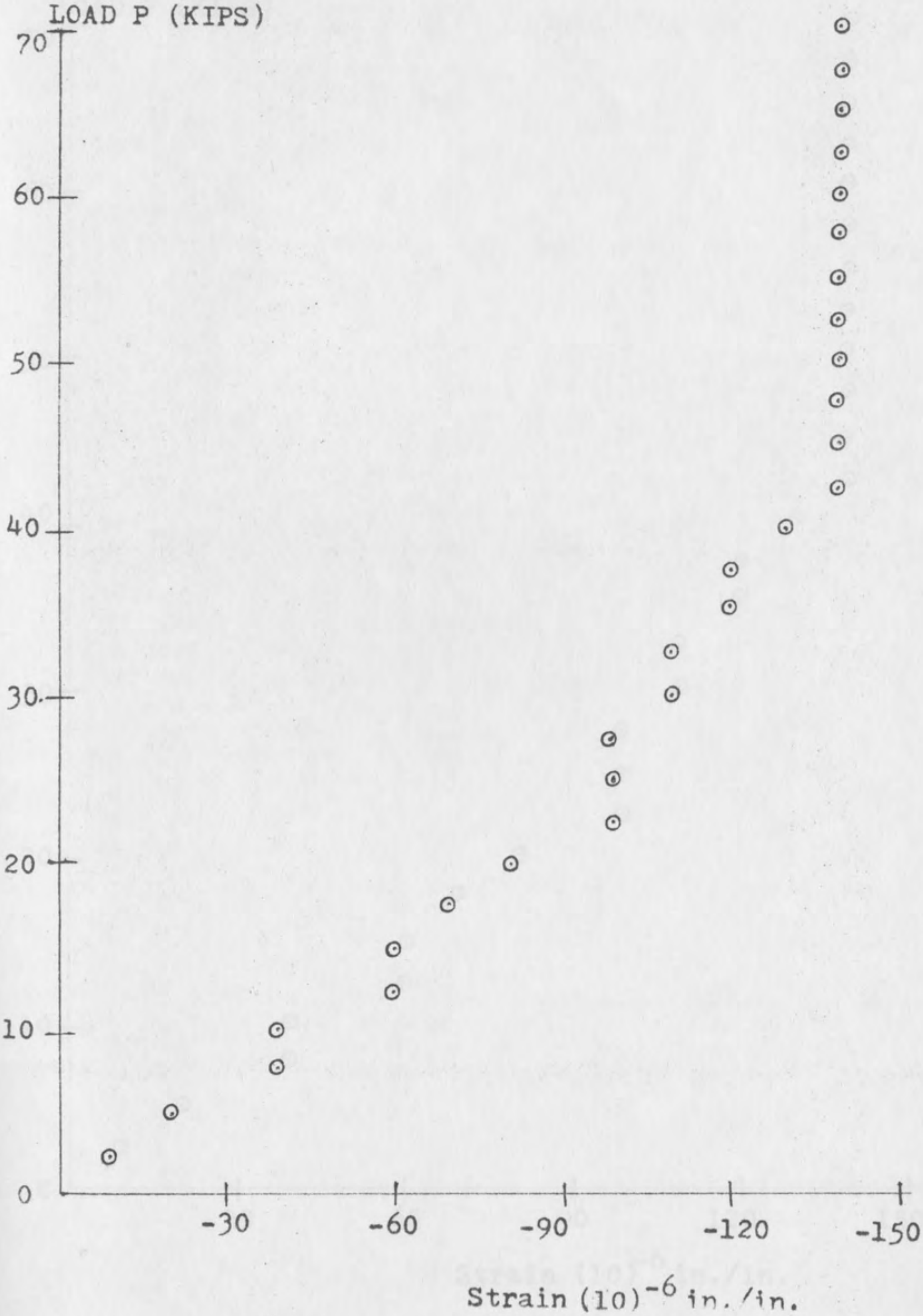


Figure 4.10 LOAD - STRAIN CURVE OF SPECIMEN, GAGE LOCATION 5 (y direction)

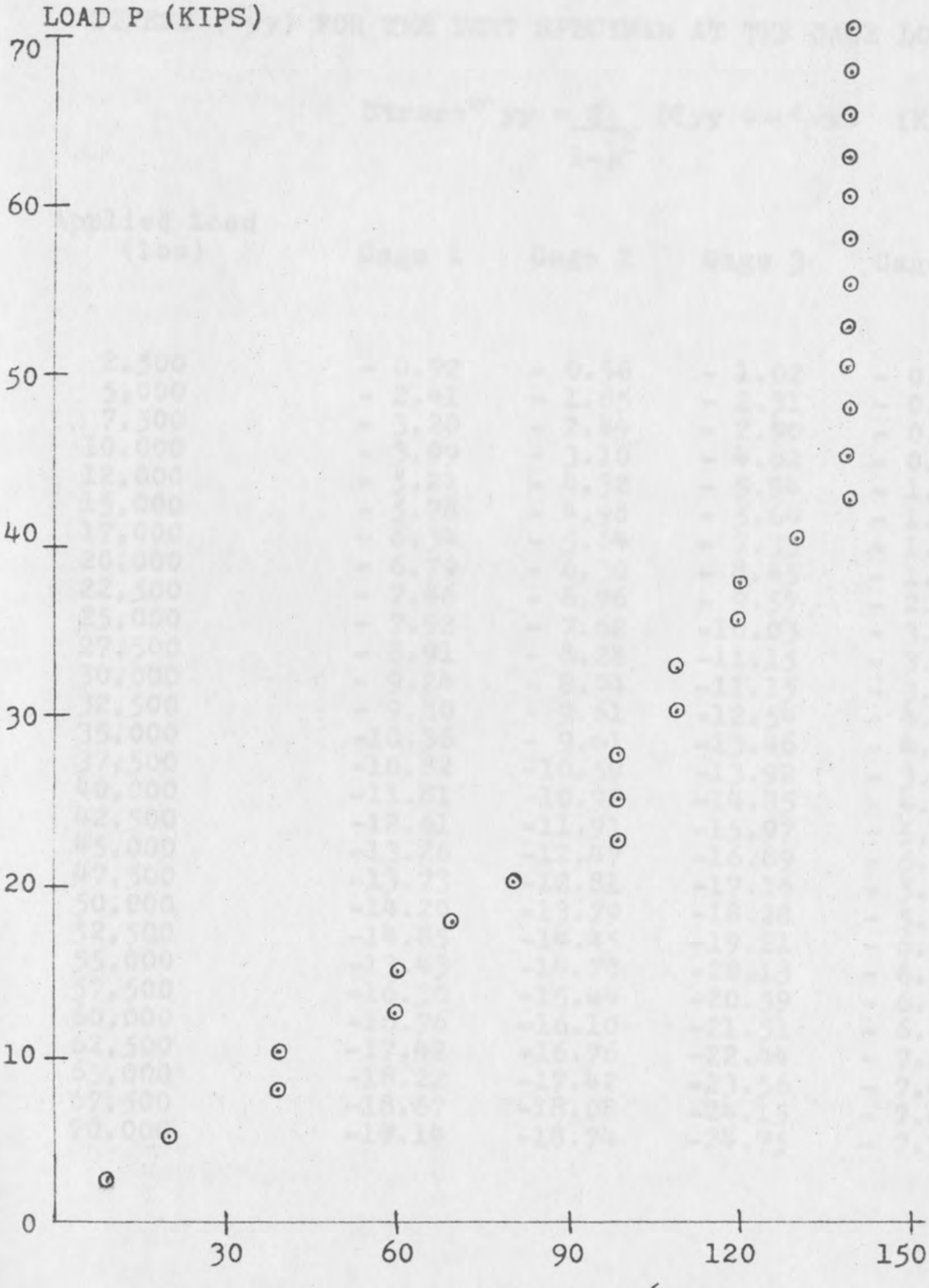


Figure 4.11 LOAD - STRAIN CURVE OF SPECIMEN GAGE LOCATION 5 (x direction)

TABLE 4.3

STRESS (σ_{yy}) FOR THE TEST SPECIMEN AT THE GAGE LOCATIONS

$$\text{Stress } \sigma_{yy} = \frac{E}{1-\mu^2} (\epsilon_{yy} + \mu \epsilon_{xx}) \quad \text{(KSI)}$$

Applied Load (lbs)	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5
2,500	- 0.92	- 0.56	- 1.02	- 0.56	-0.56
5,000	- 2.41	- 1.85	- 2.31	- 0.36	-1.18
7,500	- 3.20	- 2.44	- 2.90	- 0.36	-1.58
10,000	- 3.99	- 3.10	- 4.82	- 0.92	-1.58
12,000	- 5.21	- 4.32	- 5.94	- 1.25	-1.71
15,000	- 5.78	- 4.98	- 5.64	- 1.58	-2.04
17,000	- 6.34	- 5.64	- 7.33	- 1.38	-2.27
20,000	- 6.79	- 6.30	- 8.45	- 1.78	-2.27
22,500	- 7.46	- 6.96	- 9.57	- 2.44	-2.31
25,000	- 7.92	- 7.62	-10.03	- 3.10	-2.31
27,500	- 8.91	- 8.28	-11.15	- 3.30	-2.31
30,000	- 9.24	- 8.94	-11.15	- 3.60	-2.21
32,500	- 9.80	- 9.61	-12.54	- 4.05	-2.21
35,000	-10.36	- 9.61	-13.46	- 4.15	-2.11
37,500	-10.82	-10.59	-13.92	- 3.38	-2.44
40,000	-11.81	-10.92	-14.85	- 4.82	-2.34
42,500	-12.61	-11.91	-15.97	- 5.14	-2.24
45,000	-13.26	-12.47	-16.89	- 5.47	-2.24
47,500	-13.73	-12.81	-17.16	- 5.47	-2.57
50,000	-14.20	-13.79	-18.28	- 5.80	-2.57
52,500	-14.85	-14.45	-19.21	- 6.13	-2.57
55,000	-13.43	-14.78	-20.13	- 6.47	-2.57
57,500	-16.30	-15.44	-20.59	- 6.79	-2.90
60,000	-16.76	-16.10	-21.51	- 6.79	-2.57
62,500	-17.42	-16.76	-22.44	- 7.12	-2.90
65,000	-18.22	-17.42	-23.56	- 7.45	-2.90
67,500	-18.67	-18.08	-24.15	- 7.45	-2.90
70,000	-19.14	-18.74	-24.75	- 7.78	-2.90

TABLE 4.4

STRESS (σ_{xx}) FOR THE TEST SPECIMEN AT THE GAGE LOCATIONS

$$\text{Stress } (\sigma_{xx}) = \frac{E}{1-\mu^2} (\epsilon_{xx} + \mu\epsilon_{yy}) \text{ KSI}$$

Applied Load (lbs)	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5
2,500	0.924	0.132	0.594	0.132	0.132
5,000	1.98	0.066	2.31	0.792	0.264
7,500	2.34	-0.132	3.33	1.122	0.726
10,000	2.706	-0.33	3.960	0.924	0.726
12,500	2.640	-0.396	4.22	0.825	1.287
15,000	2.772	-0.594	5.214	0.726	1.188
17,500	2.904	-0.792	5.610	0.396	1.518
20,000	3.366	-0.990	5.874	0.066	1.749
22,500	3.630	-1.386	6.138	-0.132	2.310
25,000	3.630	-1.386	6.60	-0.33	2.310
27,500	3.33	-1.584	6.864	-0.99	2.310
30,000	3.23	-1.782	7.887	-1.089	2.640
32,500	3.366	-1.980	8.250	-1.518	2.640
35,000	3.498	-1.980	9.174	-1.848	2.970
37,500	3.960	-2.277	9.636	-1.947	2.871
40,000	3.762	-2.376	10.56	-2.046	3.201
42,500	4.026	-2.640	10.824	-2.145	3.531
45,000	3.828	-2.541	11.748	-2.244	3.531
57,500	4.290	-2.640	12.87	-2.244	3.432
50,000	4.75	-3.267	13.13	-2.343	3.432
52,500	4.554	-3.135	14.058	-2.442	3.432
55,000	4.686	-3.234	14.982	-2.541	3.432
57,500	4.719	-3.430	15.440	-2.640	3.333
60,000	5.181	-3.630	16.368	-2.640	3.430
62,500	4.983	-3.828	17.29	-2.739	3.333
65,000	5.346	-4.02	17.55	-2.83	3.333
67,500	5.808	-4.224	18.57	-2.838	3.333
70,000	6.270	-4.422	19.602	-3.03	3.333

CHAPTER V

COMPARISON OF RESULTS

When comparing the analytical results and the experimental results, some flexibility was incorporated. From Figure 2.11, 2.12, 2.15, 2.16, 2.19, 2.20, 2.23 and 2.24, it can be seen that the stress at some locations is quite sensitive to small movements, i.e. from one element to another. Since it is difficult to physically place the strain gages at the exact anticipated positions, and orientations, there can exist some discrepancy between the actual gage locations and the analytical positions. In order to account for this differences, as well as any other introduced errors that might have been realized during testing, a comparison between the analytical results and the test results was made using a 1/2 inch radius around the theoretical gage location. In other words the best analytical results within a radius of 1/2 inch was taken for comparison with the experimentally obtained results.

Tables 5.1 to 5.4 tabulate the experimental and analytical results for the support cases described earlier in Chapter II. Also, the corresponding coordinates of the measured or computed stresses are tabulated.

In order further to determinate which support condition, i.e. Case I through Case IV, best models the actual conditions, the displaced shape of the plate was examined using the analytical results. The displacements in the z direction were obtained from the STRUDL output for the support conditions described earlier in Chapter II. These displacements plotted and are shown in Figures 5.1 through 5.4 inclusive. It was hoped that the computed deformed shapes of the plate could be compared to that obtained in earlier tests [4] as shown in Figure 5.5. The displacements along different sections of the plate were drawn and are shown in Figures 5.6 to 5.25. The support conditions assumed in Case IV best describes the actual displacements. (see Figures 5.21 to 5.25) This can be explained as follows, the assumed simply supported condition across the top portion of the plate allows no displacement up to 1 inch from the top of plate as the load is initially applied. In the other support cases the plate tend to displace at the top edge which is not the actual case as can be seen in Figure 5.5. Since the plates initially support one another there must be no displacement at top edge to small loads. Thus, can be said that the Case IV best represents this actual problem. Also, referring to Tables 5.1 and 5.2 the calculated stress at the various gage locations for Case IV is close to experimental stress.

TABLE 5.1

Experimental Stress σ_{yy}			Analytical Results - Stress σ_{yy} (KSI)				
Gage Location	Coordinate	Stress (σ_{yy}) KSI	Coordinate	Case I	Case II	Case III	Case IV
1	(2.50, 1.0)	-14.20	(2.0, 1.0)	-12.48	-12.48	-12.48	-12.48
2	(4.0, 1.0)	-13.79	(4.50, 1.0)	-14.10	-14.10	-14.10	-14.10
3	(1.50, 2.0)	-18.28	(1.0, 1.75)	-16.50	-16.50	-16.98	-16.48
4	(2.0, 4.25)	- 5.80	(1.50, 4.25)	- 4.32	- 4.86	- 5.40	- 6.26
5	(4.0, 4.50)	- 2.57	(3.50, 4.50)	2.22	3.06	1.98	0.27

TABLE 5.2

Experimental Stress σ_{xx}			Analytical Results - Stress σ_{xx} (KSI)				
Gage Location	Coordinate	Stress (σ_{xx}) KSI	Coordinate	Case I	Case II	Case III	Case IV
1	(2.50, 1.0)	4.75	(2.0, 1.0)	- 4.02	- 4.08	- 4.02	- 3.96
2	(4.0, 1.0)	- 3.26	(4.50, 1.0)	- 4.92	- 4.32	- 4.44	- 4.32
3	(1.50, 2.0)	13.13	(1.0, 1.75)	11.46	11.46	11.46	11.46
4	(4.0, 4.50)	- 2.34	(1.50, 4.25)	- 2.58	- 2.40	- 2.88	- 3.30
5	(4.0, 4.50)	3.43	(3.50, 4.75)	0.78	1.32	0.72	0.18

TABLE 5.3

Experimental Stress σ_{yy}			Analytical Results - Stress σ_{yy} (KSI)				
Gage Location	Coordinate	Stress (σ_{yy}) KSI	Coordinate	Case I	Case II	Case III	Case IV
1	(2.50, 1.0)	-14.20	(2.50, 1.0)	-14.10	-14.10	-14.10	-13.73
2	(4.0, 1.0)	-13.79	(4.0, 1.0)	-14.76	-14.76	-14.76	-14.79
3	(1.50, 2.0)	-18.28	(1.50, 2.0)	-22.74	-22.74	-22.74	-22.56
4	(2.0, 4.25)	- 5.80	(2.0, 4.25)	- 3.75	- 3.16	- 3.74	- 5.11
5	(4.0, 4.50)	- 2.57	(4.0, 4.50)	2.08	3.04	1.46	0.03

TABLE 5.4

Experimental Stress σ_{xx}			Analytical Results - Stress σ_{xx} (KSI)				
Gage Location	Coordinate	Stress (σ_{xx}) KSI	Coordinate	Case I	Case II	Case III	Case IV
1	(2.50, 1.0)	4.75	(2.50, 1.0)	-11.40	-11.40	-11.40	-12.42
2	(4.0, 1.0)	- 2.94	(4.0, 1.0)	- 8.55	- 8.64	- 8.58	- 8.98
3	(1.50, 2.0)	13.13	(1.50, 2.0)	1.62	- 4.02	- 6.66	- 7.80
4	(2.0, 4.25)	- 2.34	(2.0, 4.25)	- 4.17	- 3.97	- 4.26	- 4.38
5	(4.0, 4.50)	3.43	(4.0, 4.50)	0.85	1.25	0.78	0.31

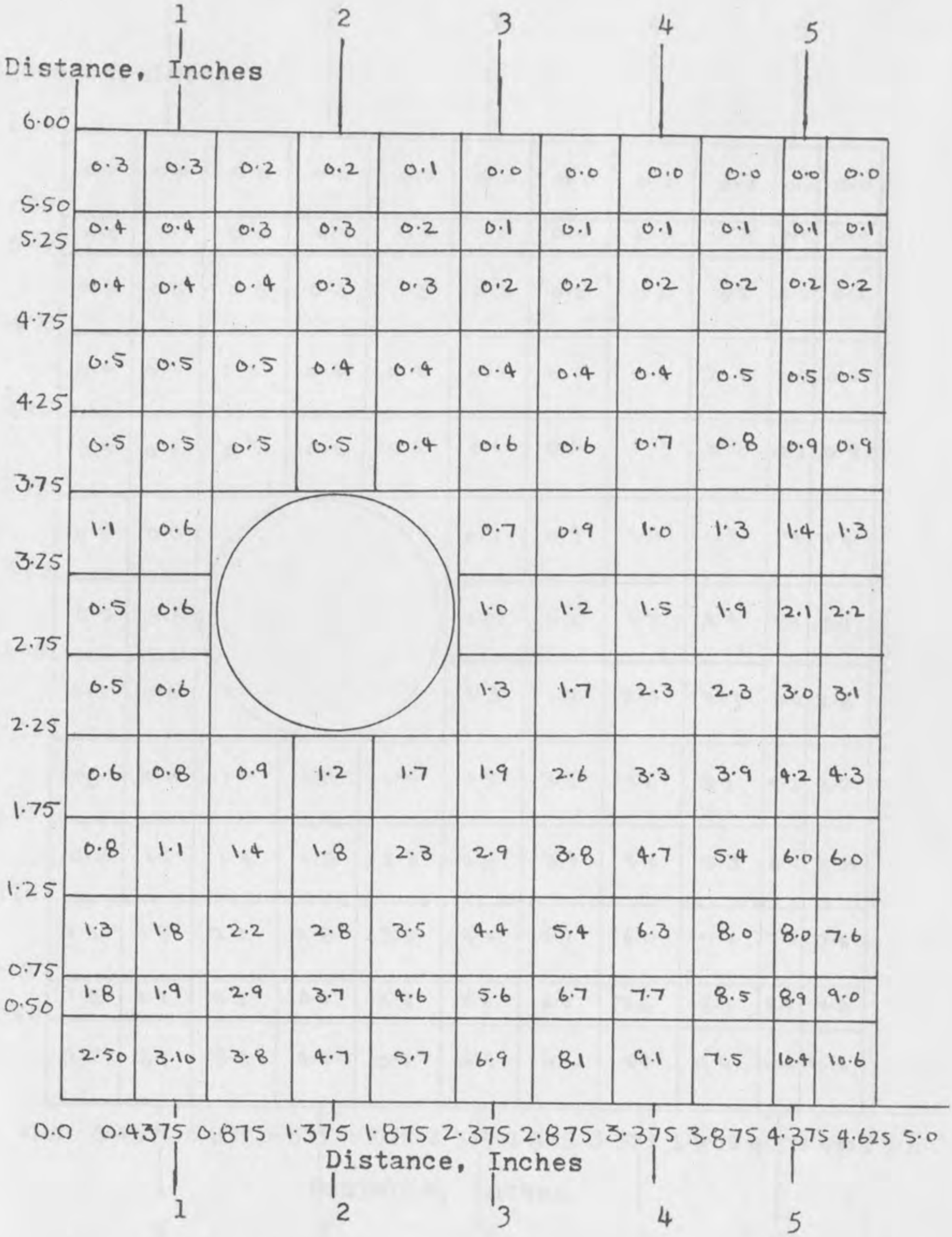


Figure 5.1 COMPUTED DISPLACEMENTS IN INCHES x 10^{-3} FOR CASE I

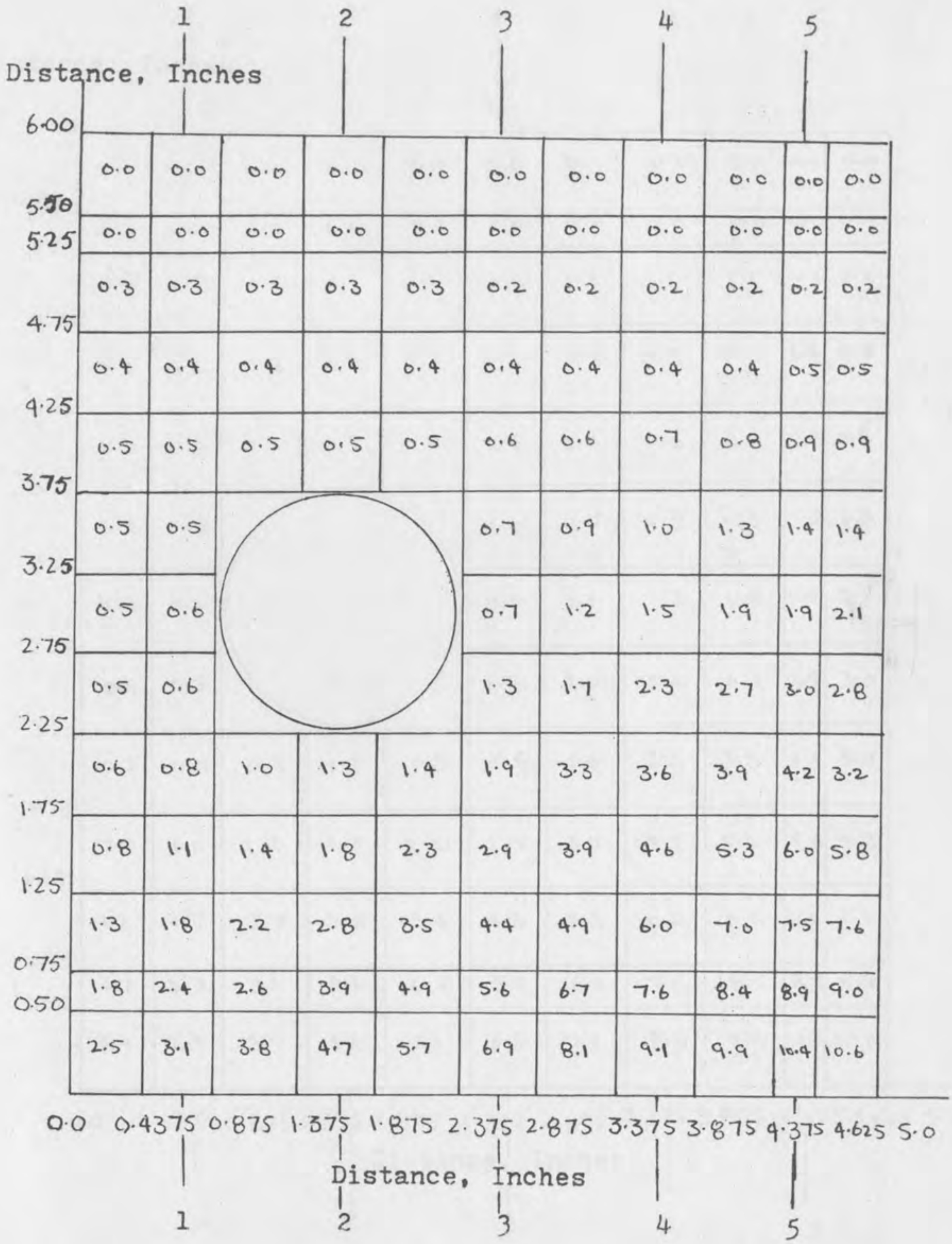


Figure 5.2 COMPUTED DISPLACEMENTS IN INCHES x 10^{-3} FOR CASE II

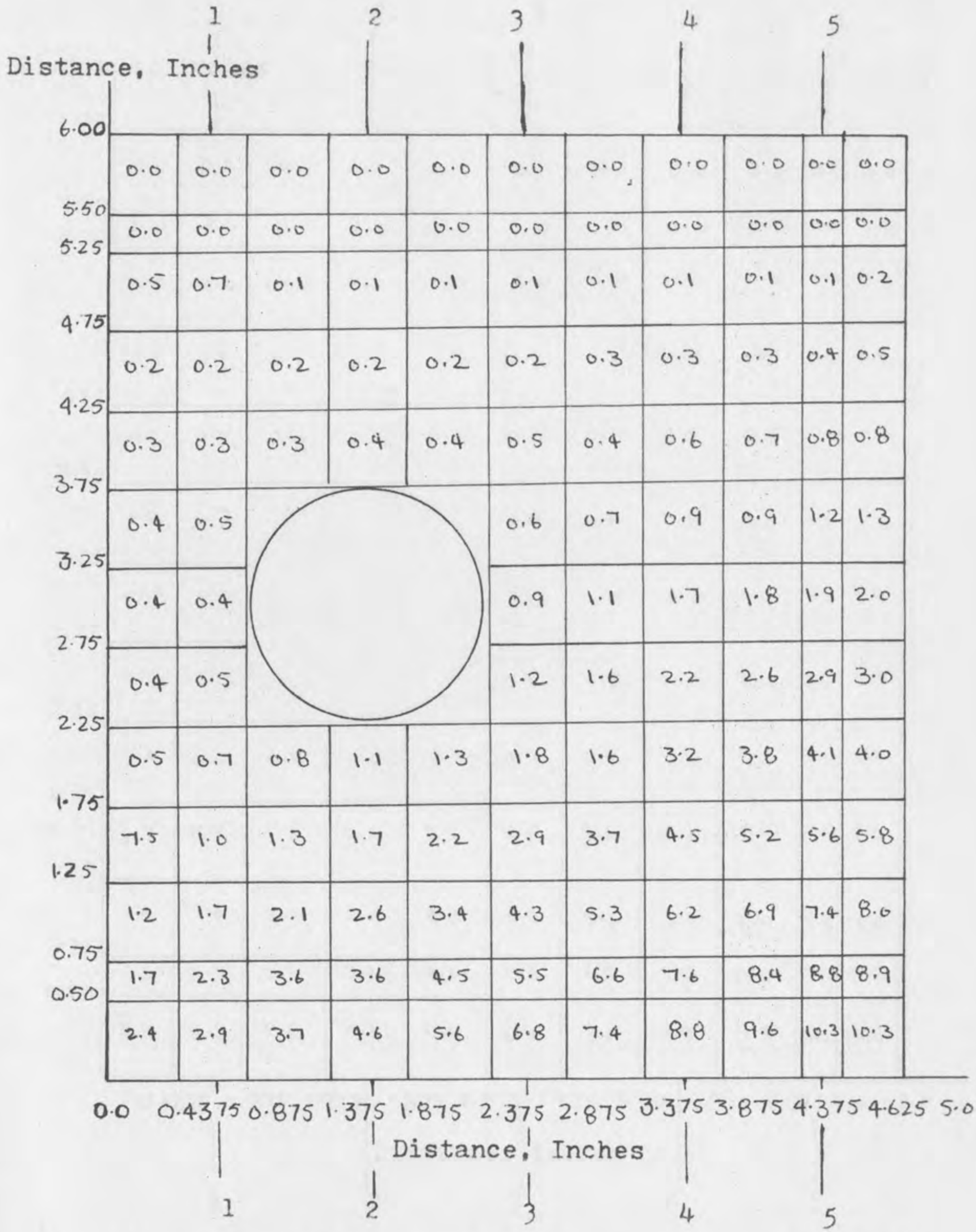


Figure 5.3 COMPUTED DISPLACEMENTS IN INCHES x 10^{-3}
FOR CASE III

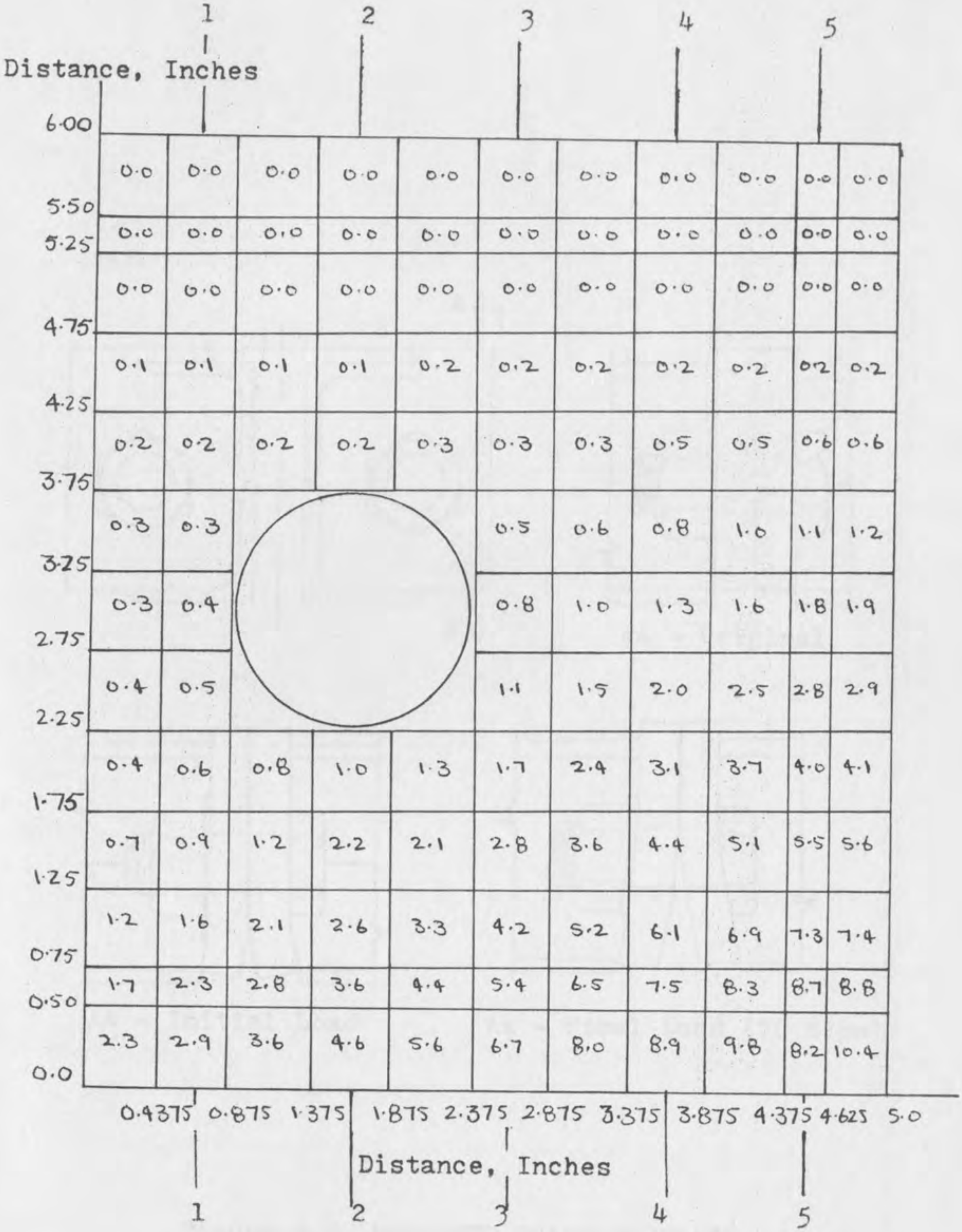


Figure 5.4 COMPUTED DISPLACEMENTS IN INCHES x 10^{-3} FOR CASE IV

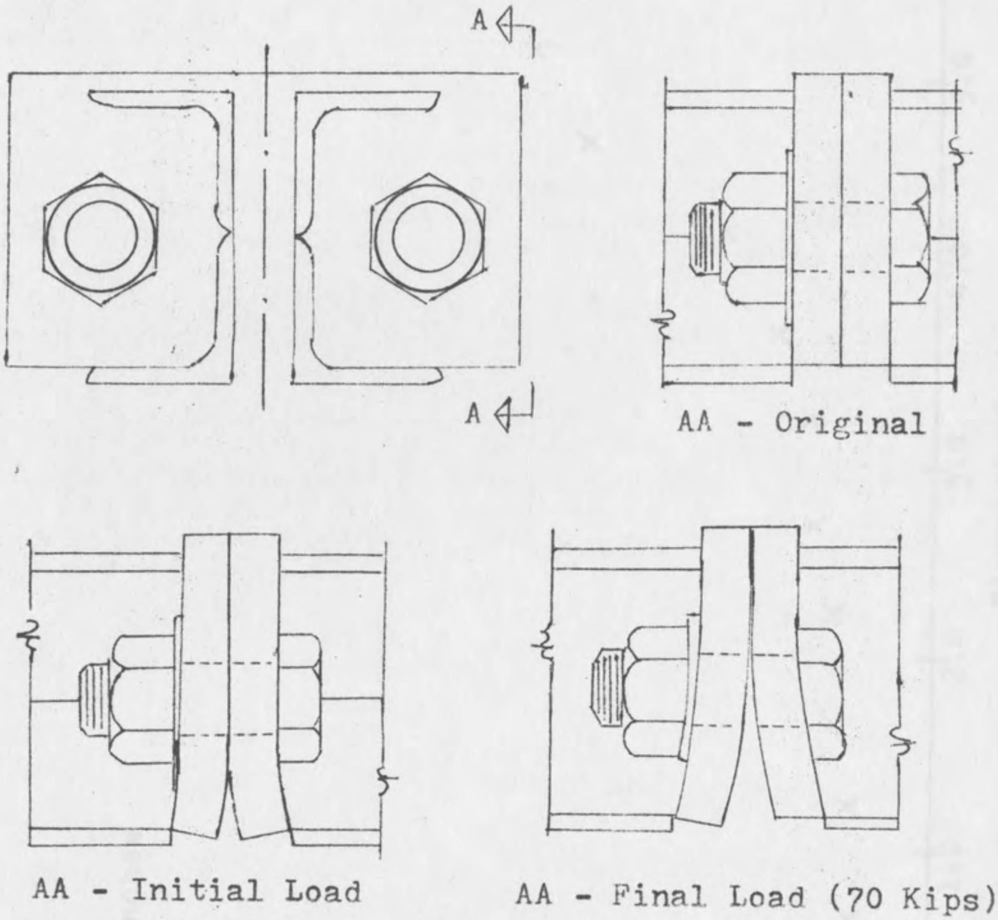


Figure 5.5 DEFORMED SHAPE OF PLATE

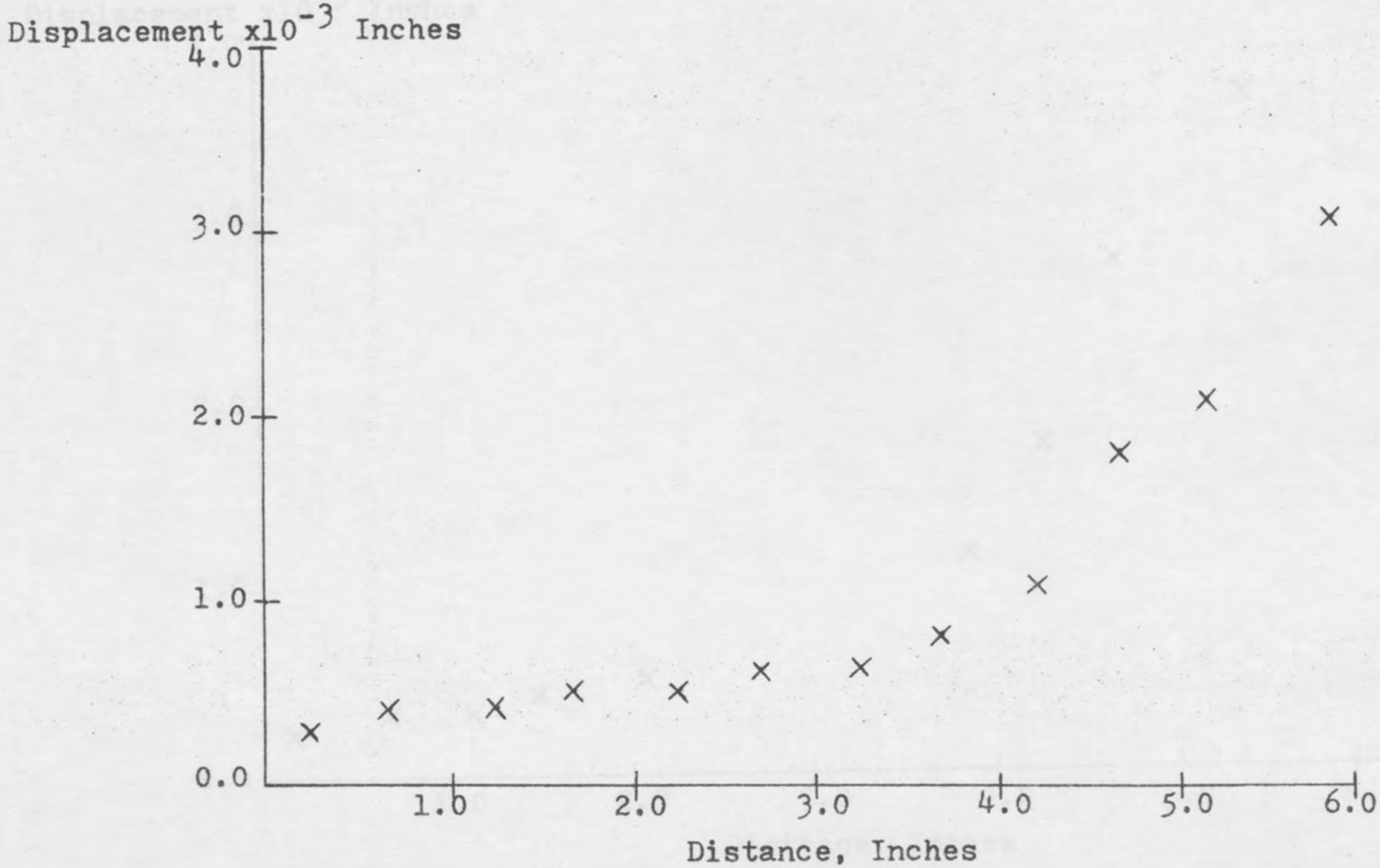


Figure 5.6 DISPLACEMENT IN INCHES AT SECTION 1-1 FOR CASE I

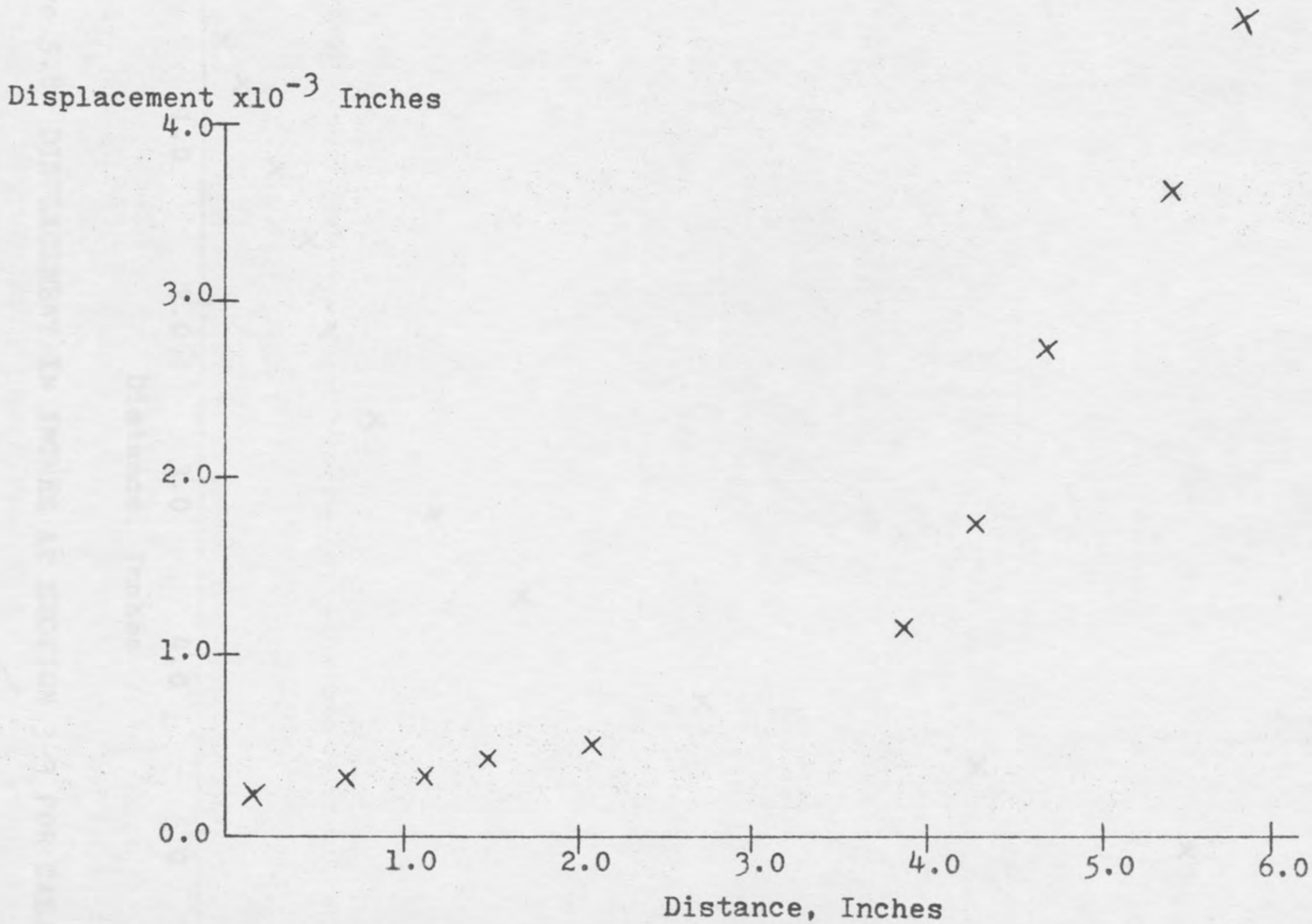


Figure 5.7 DISPLACEMENT IN INCHES AT SECTION 2-2 FOR CASE I

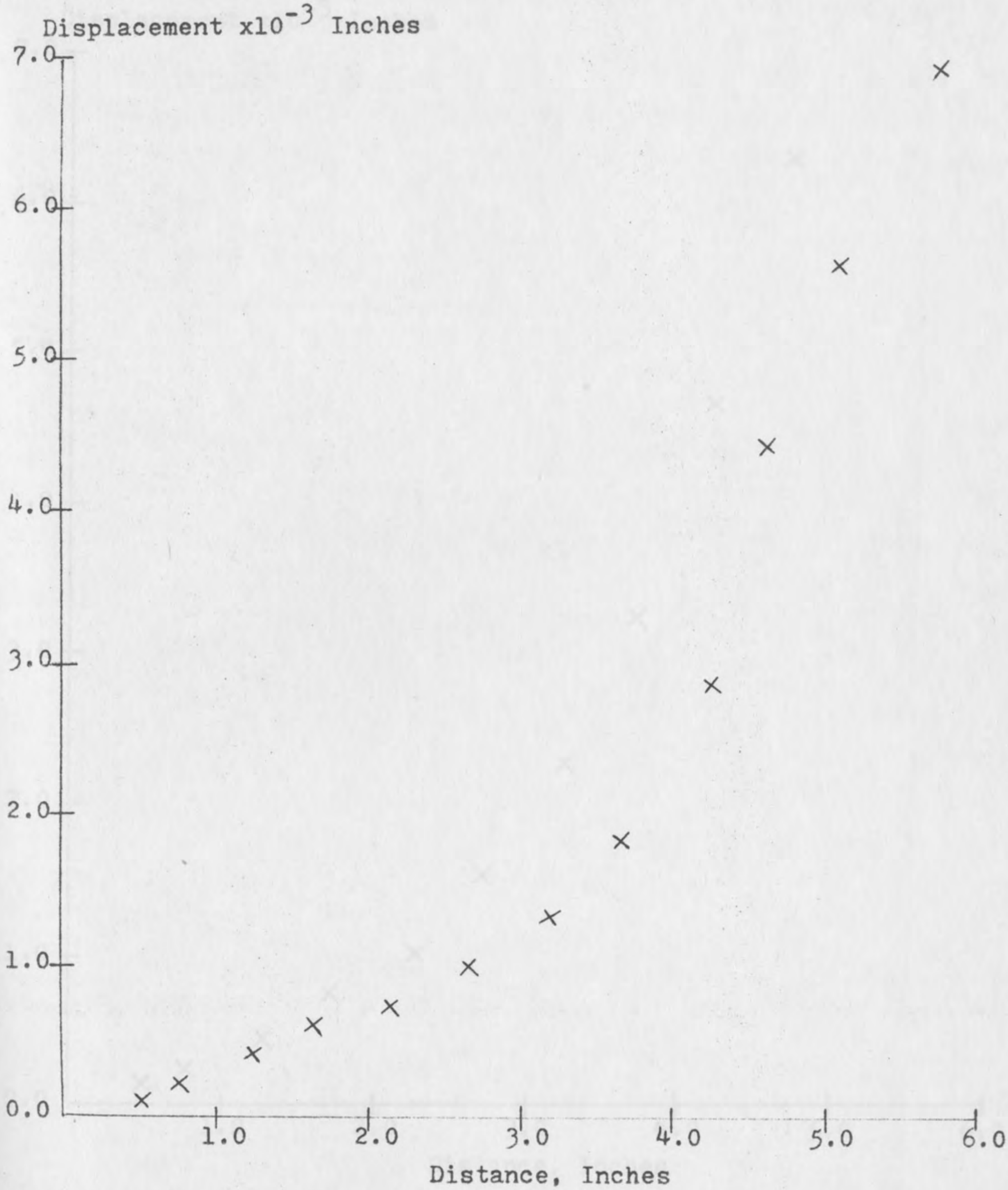


Figure 5.8 DISPLACEMENT IN INCHES AT SECTION 3-3 FOR CASE I

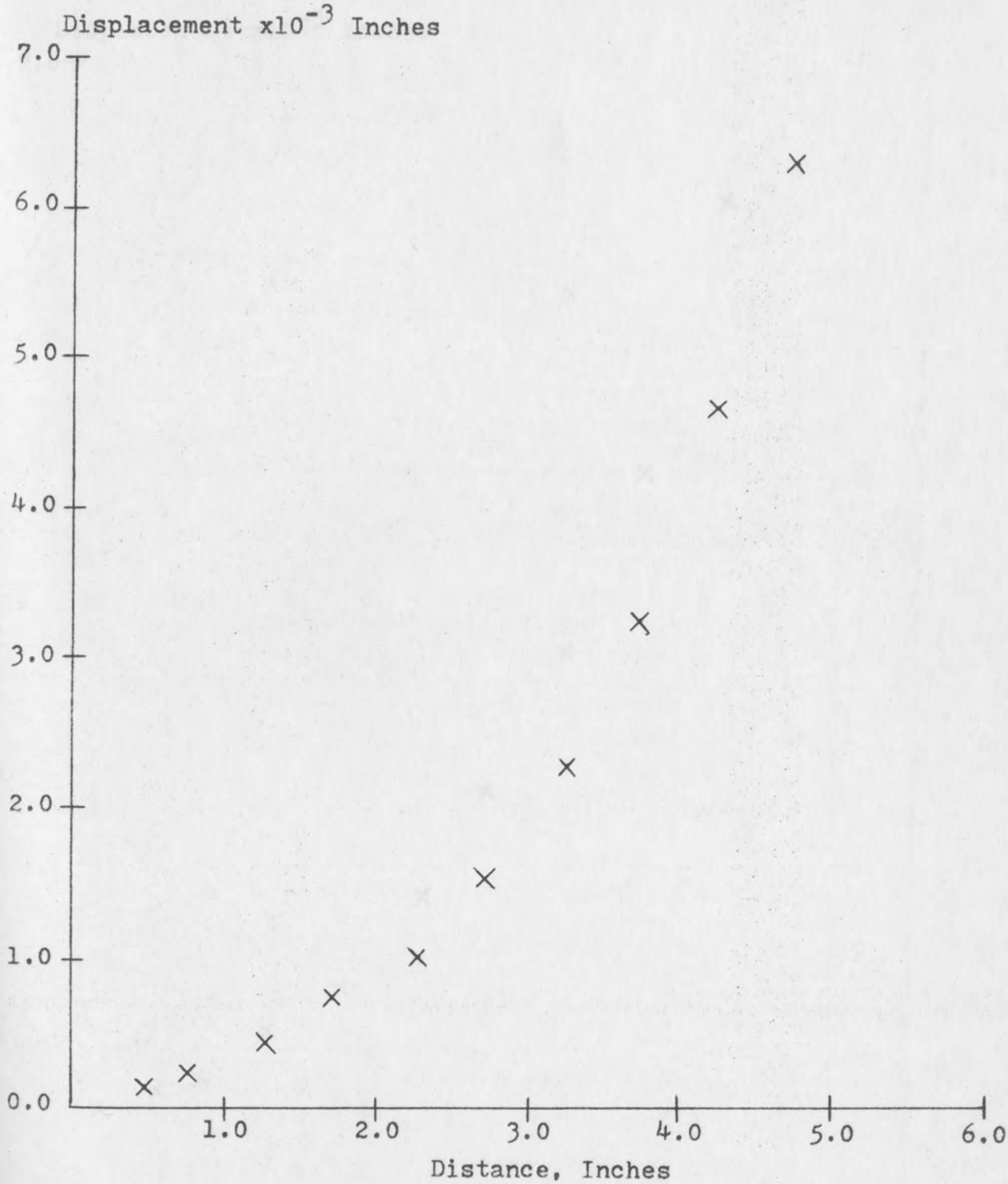


Figure 5.9 DISPLACEMENT IN INCHES AT SECTION 4-4 FOR CASE I

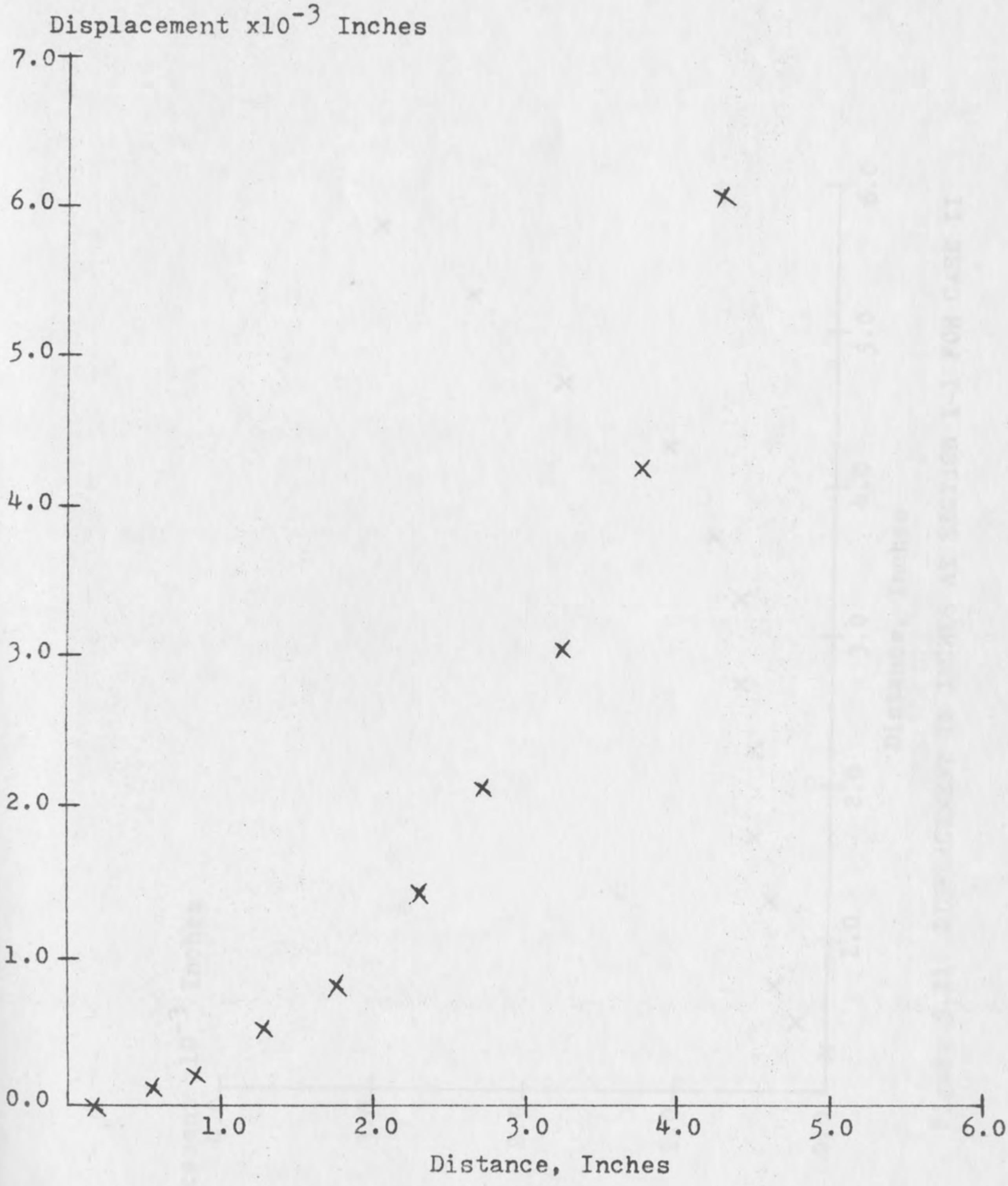


Figure 5.10 DISPLACEMENT IN INCHES AT SECTION 5-5 FOR CASE I

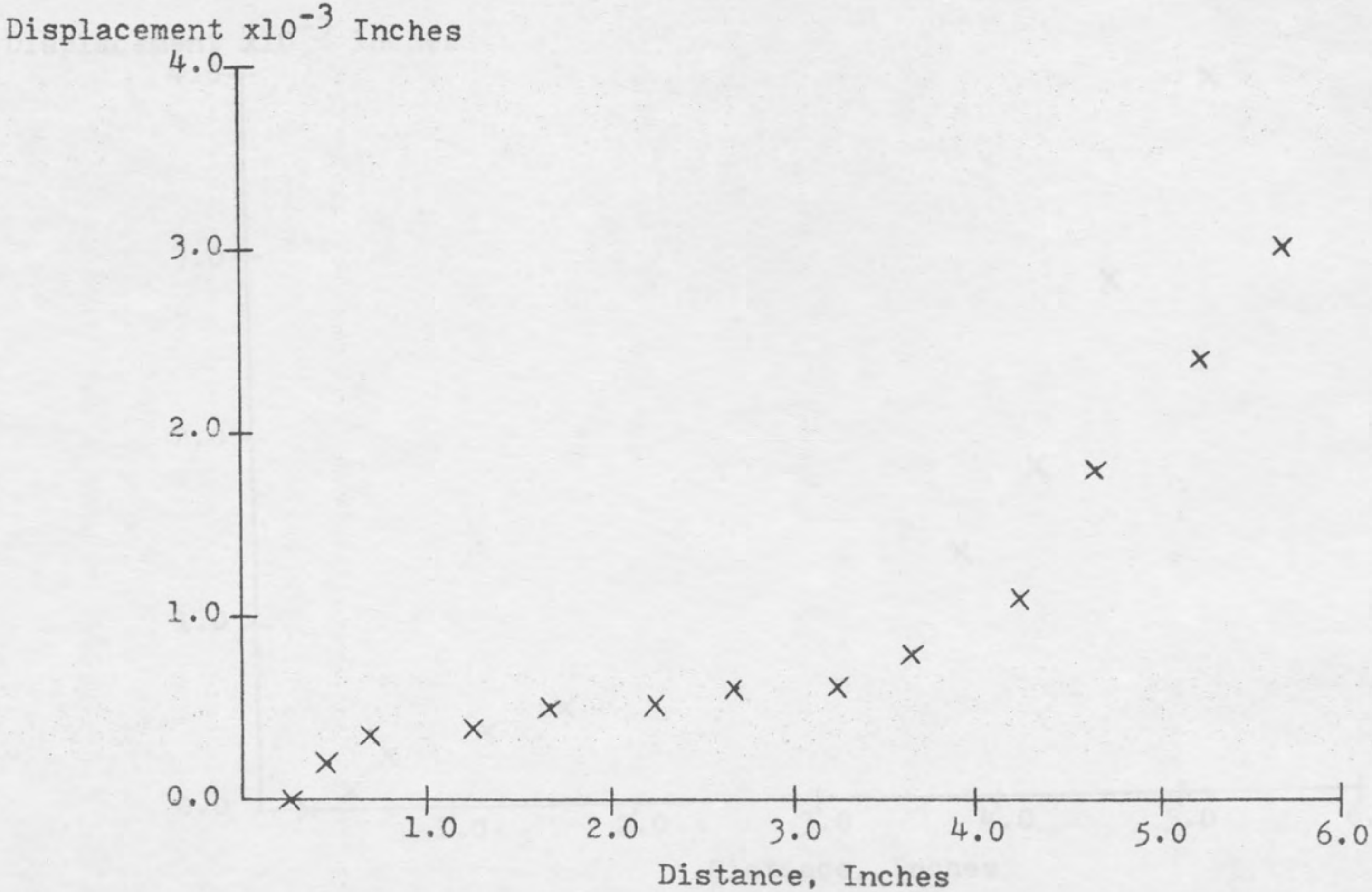


Figure 5.11 DISPLACEMENT IN INCHES AT SECTION 1-1 FOR CASE II

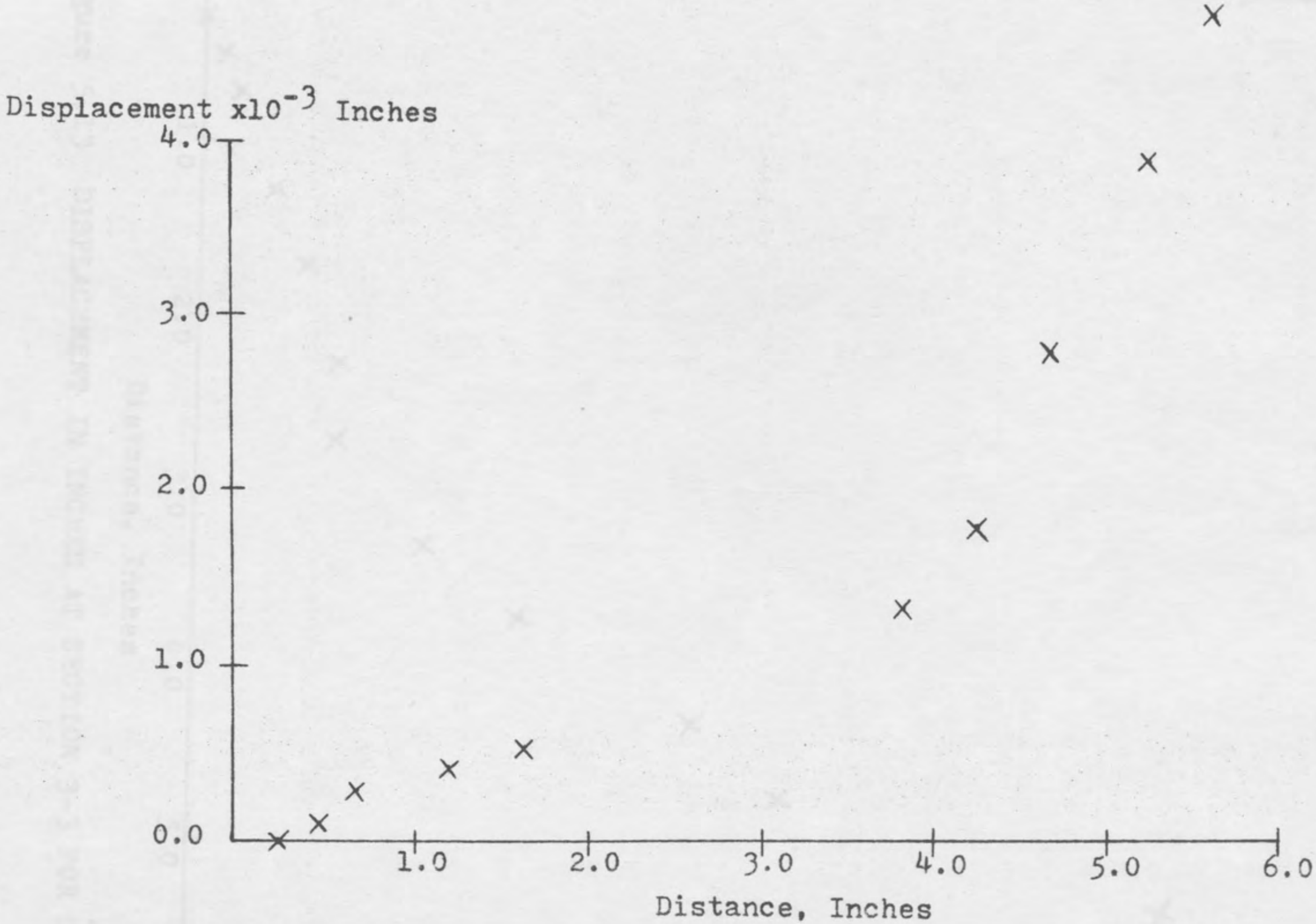


Figure 5.12 DISPLACEMENT IN INCHES AT SECTION 2-2 FOR CASE II

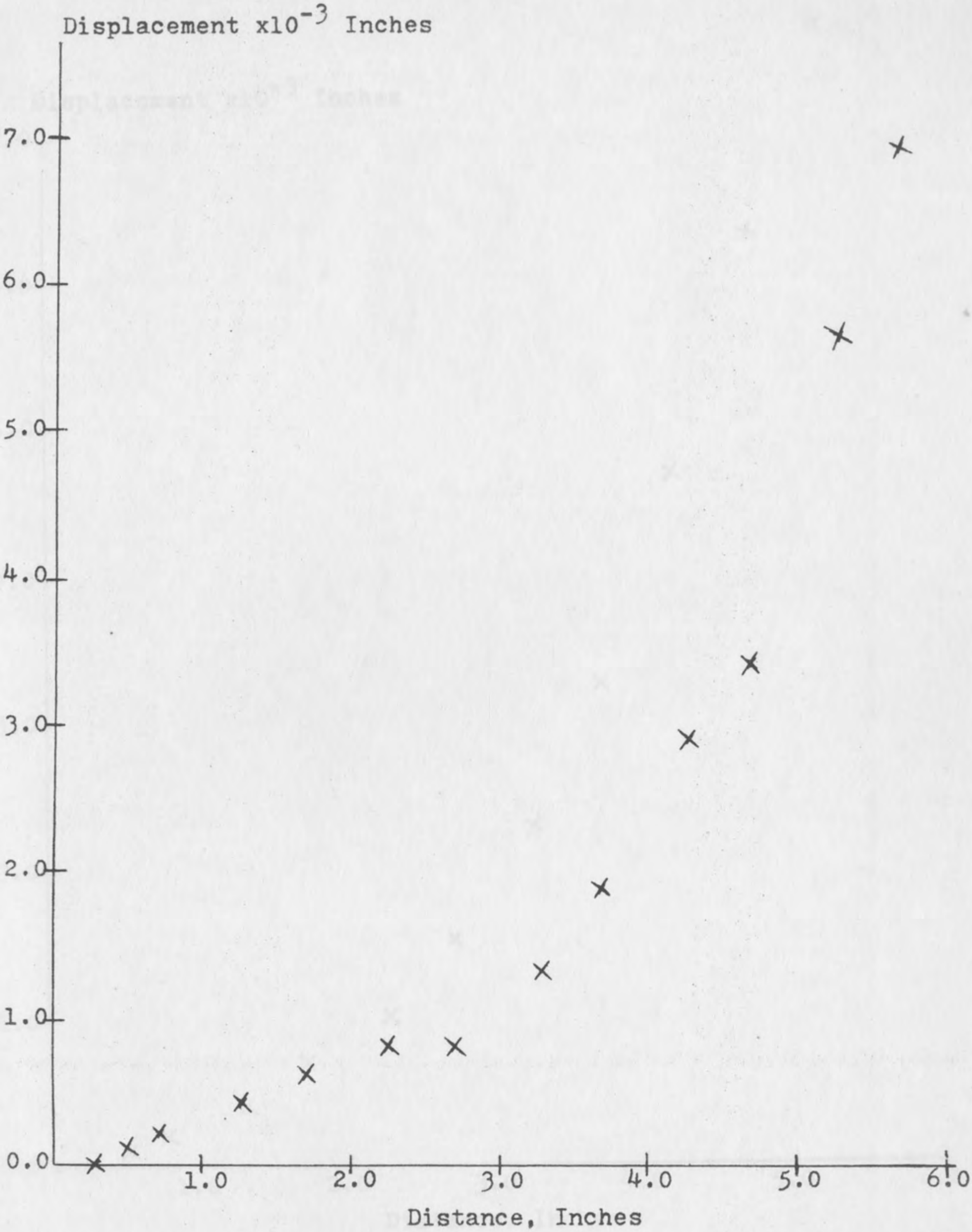


Figure 5.13 DISPLACEMENT IN INCHES AT SECTION 3-3 FOR CASE II

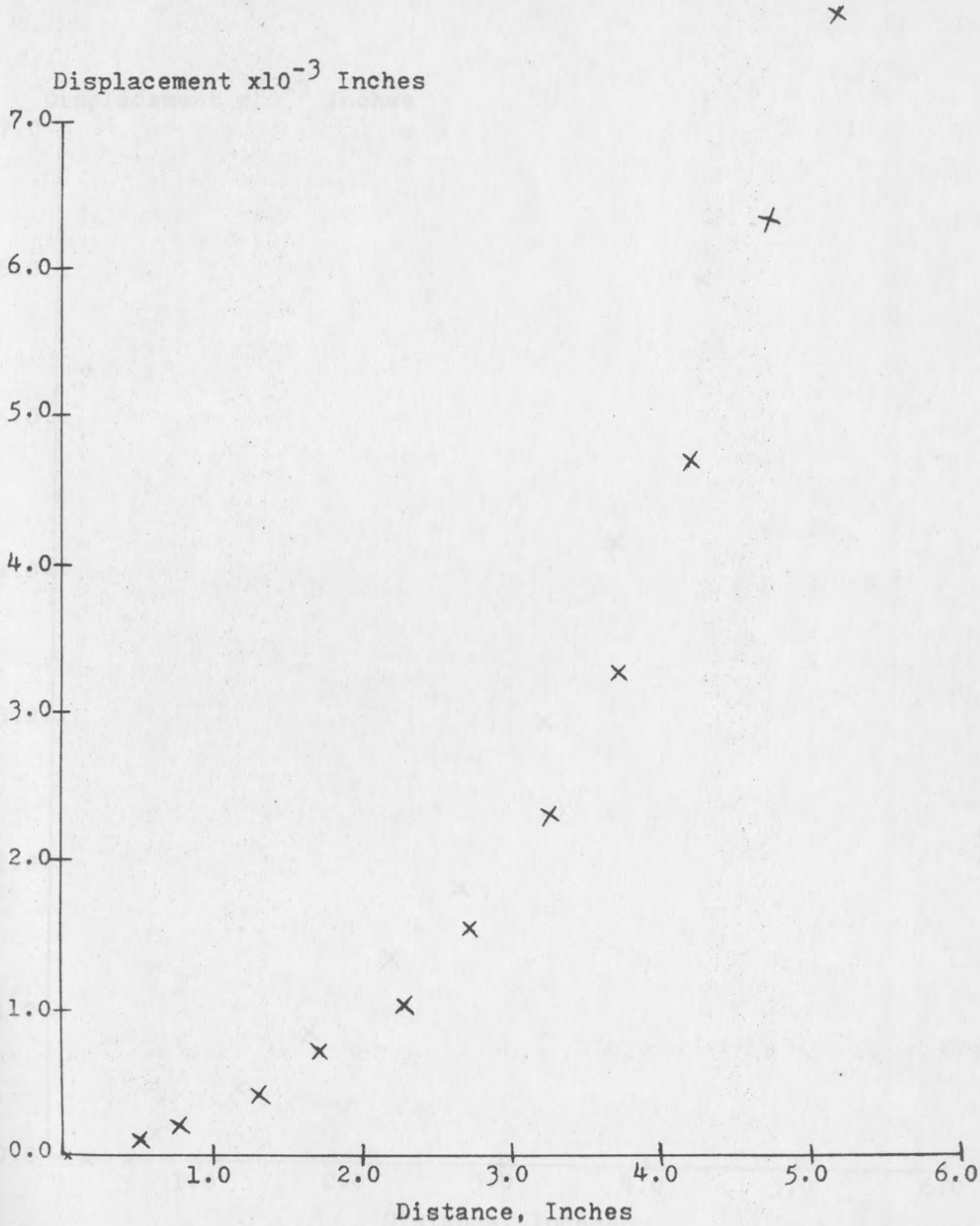


Figure 5.14 DISPLACEMENT IN INCHES AT SECTION 4-4 FOR CASE II

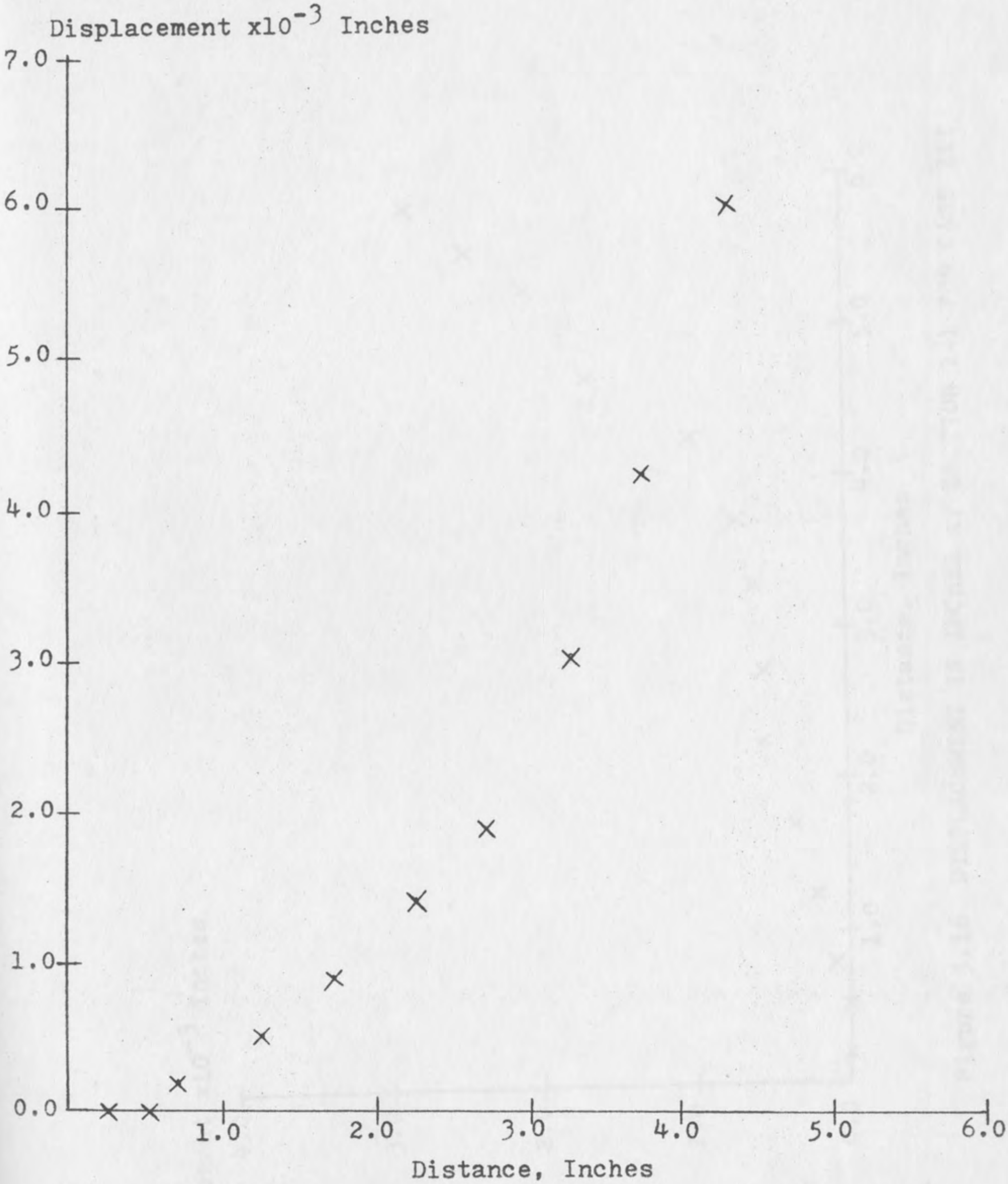


Figure 5.15 DISPLACEMENT IN INCHES AT SECTION 5-5 FOR CASE II

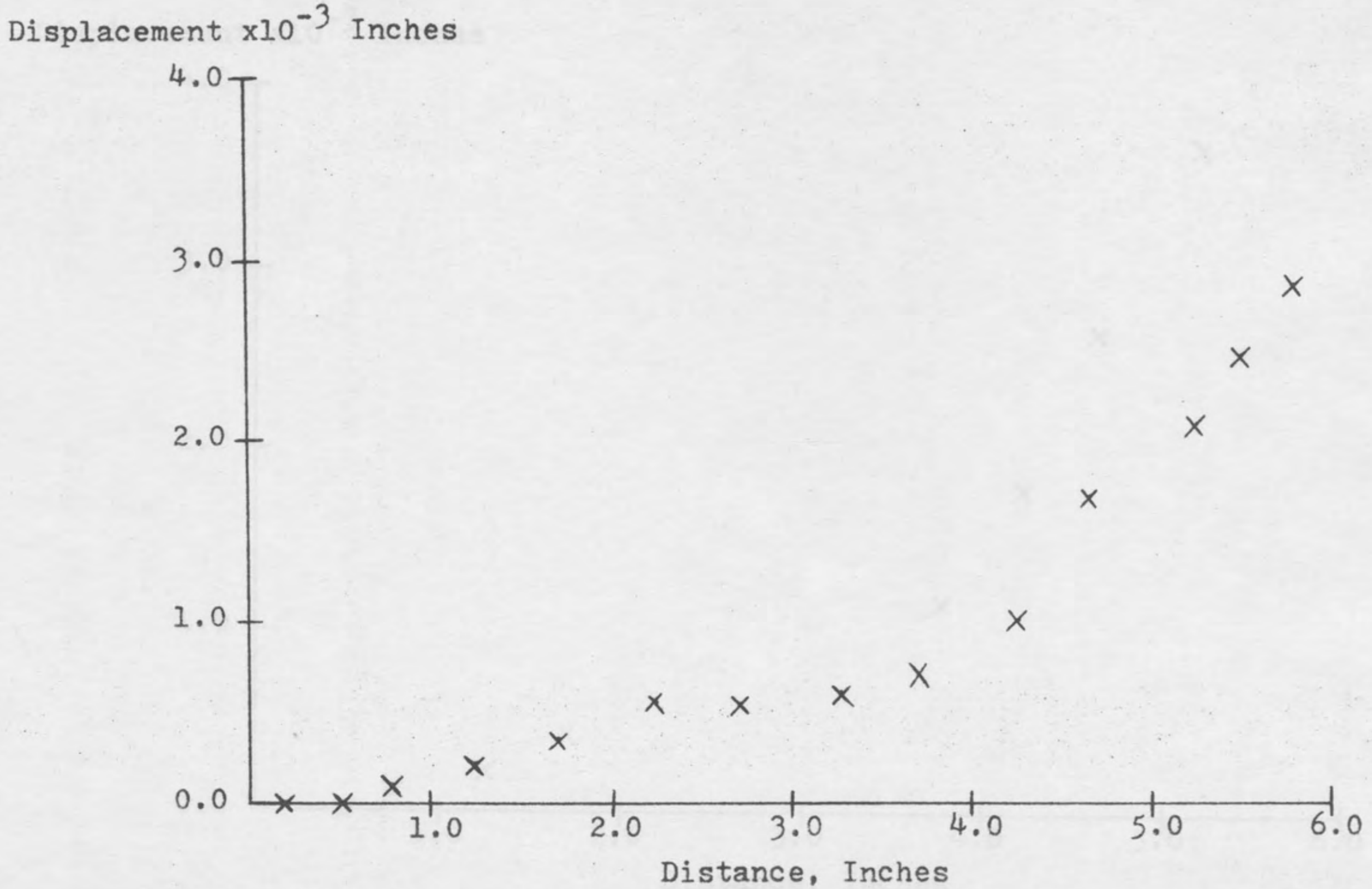


Figure 5.16 DISPLACEMENT IN INCHES AT SECTION 1-1 FOR CASE III

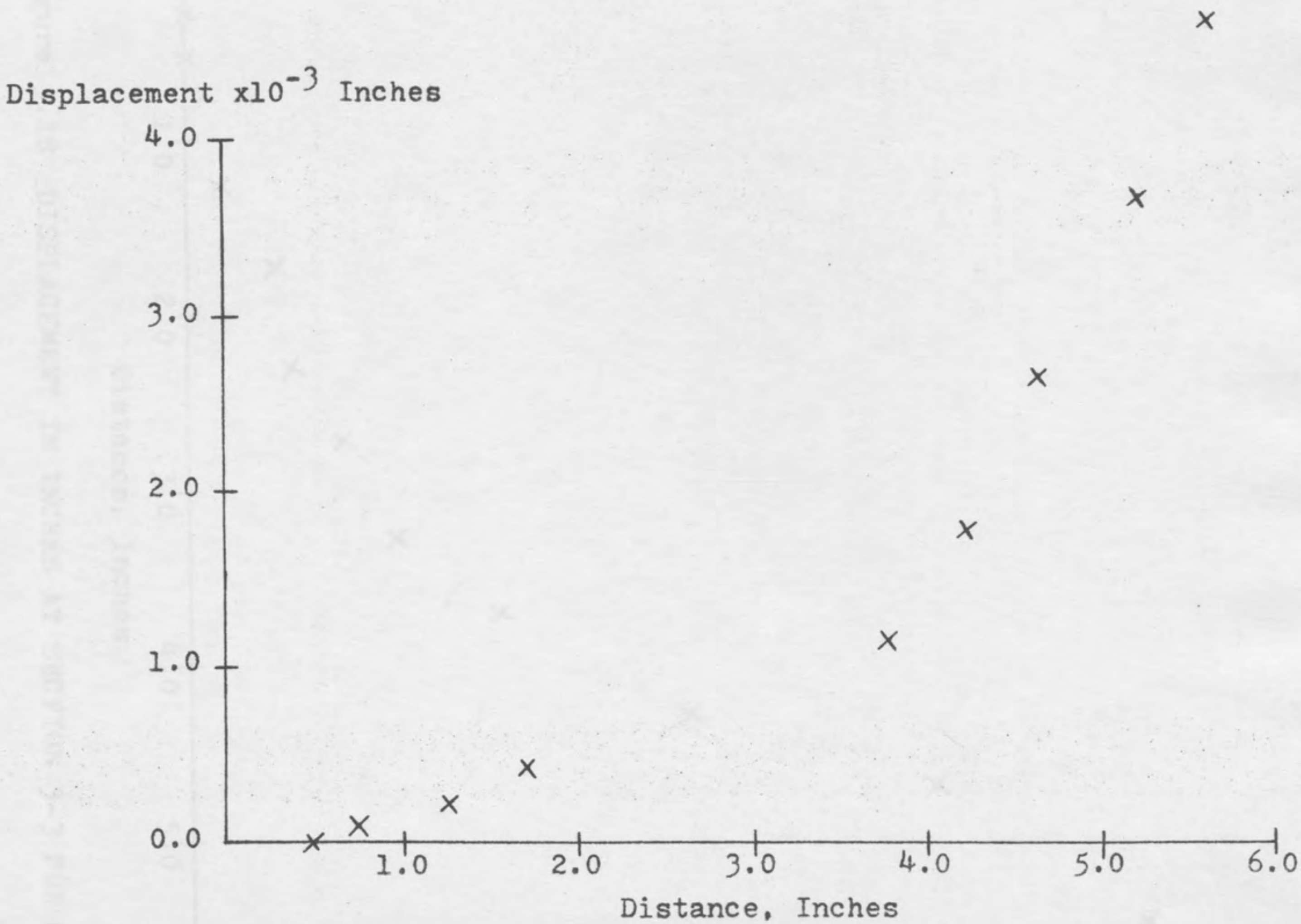


Figure 5.17 DISPLACEMENT IN INCHES AT SECTION 2-2 FOR CASE III

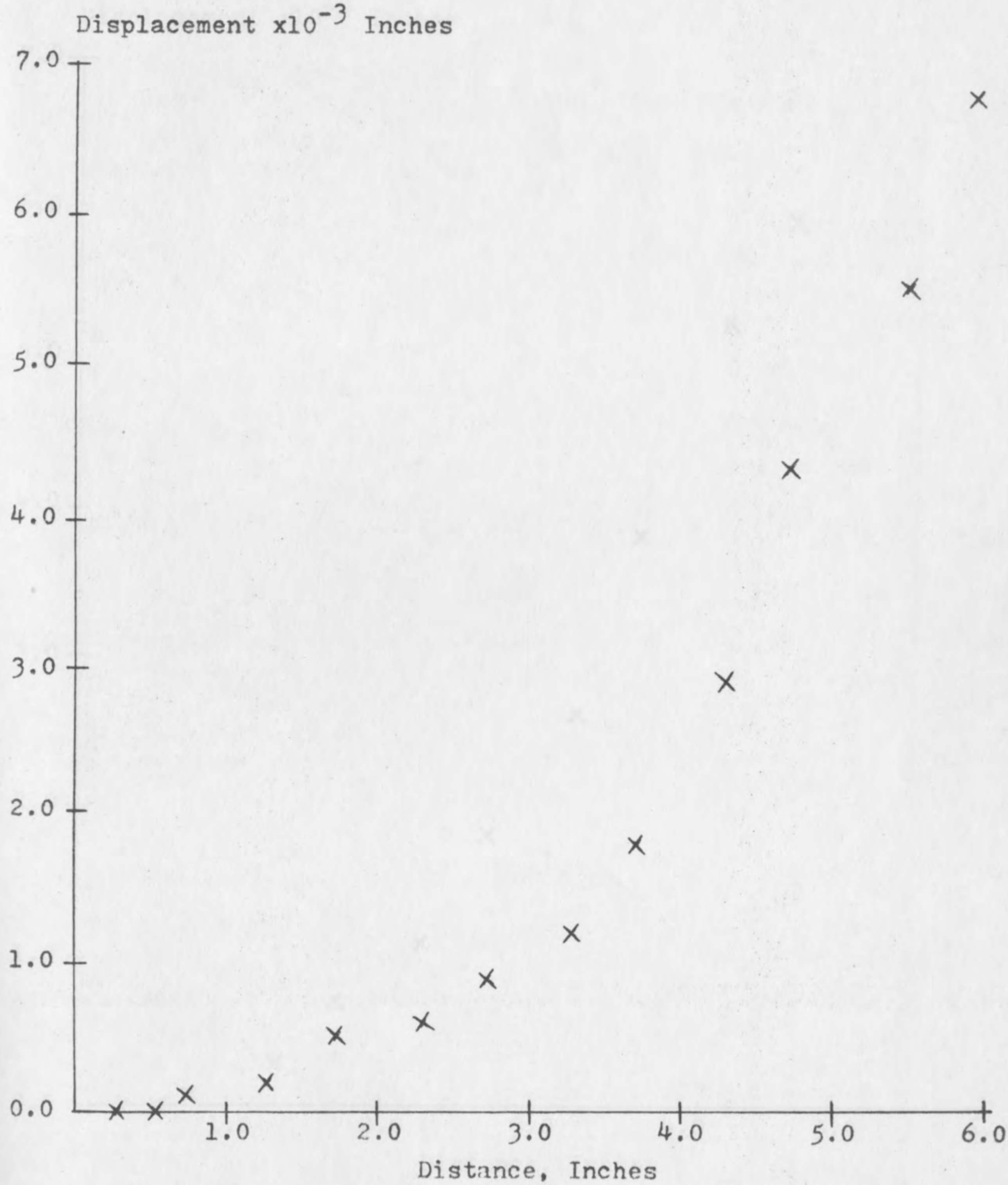


Figure 5.18 DISPLACEMENT IN INCHES AT SECTION 3-3 FOR CASE III

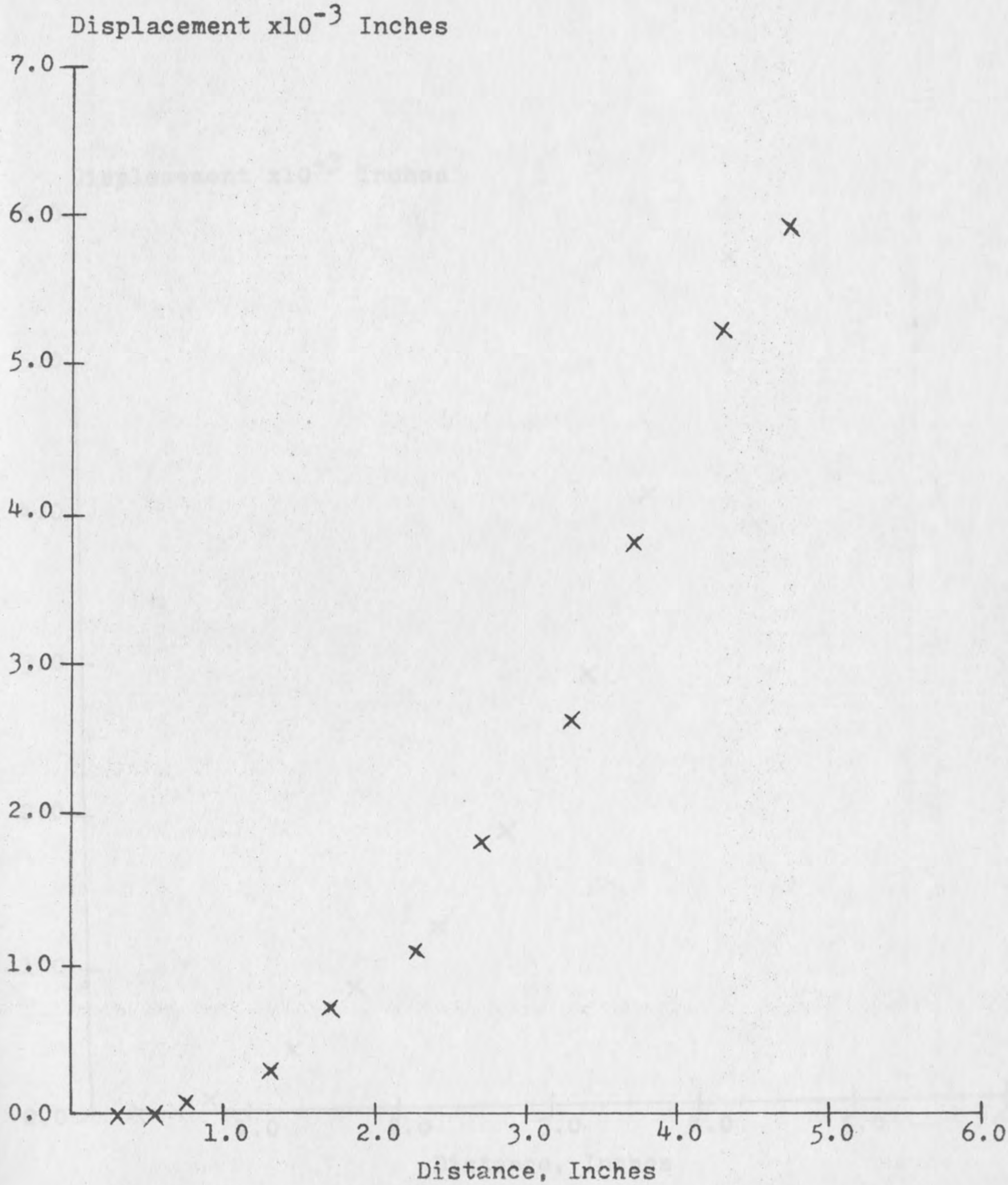


Figure 5.19 DISPLACEMENT IN INCHES AT SECTION 4-4 FOR CASE III

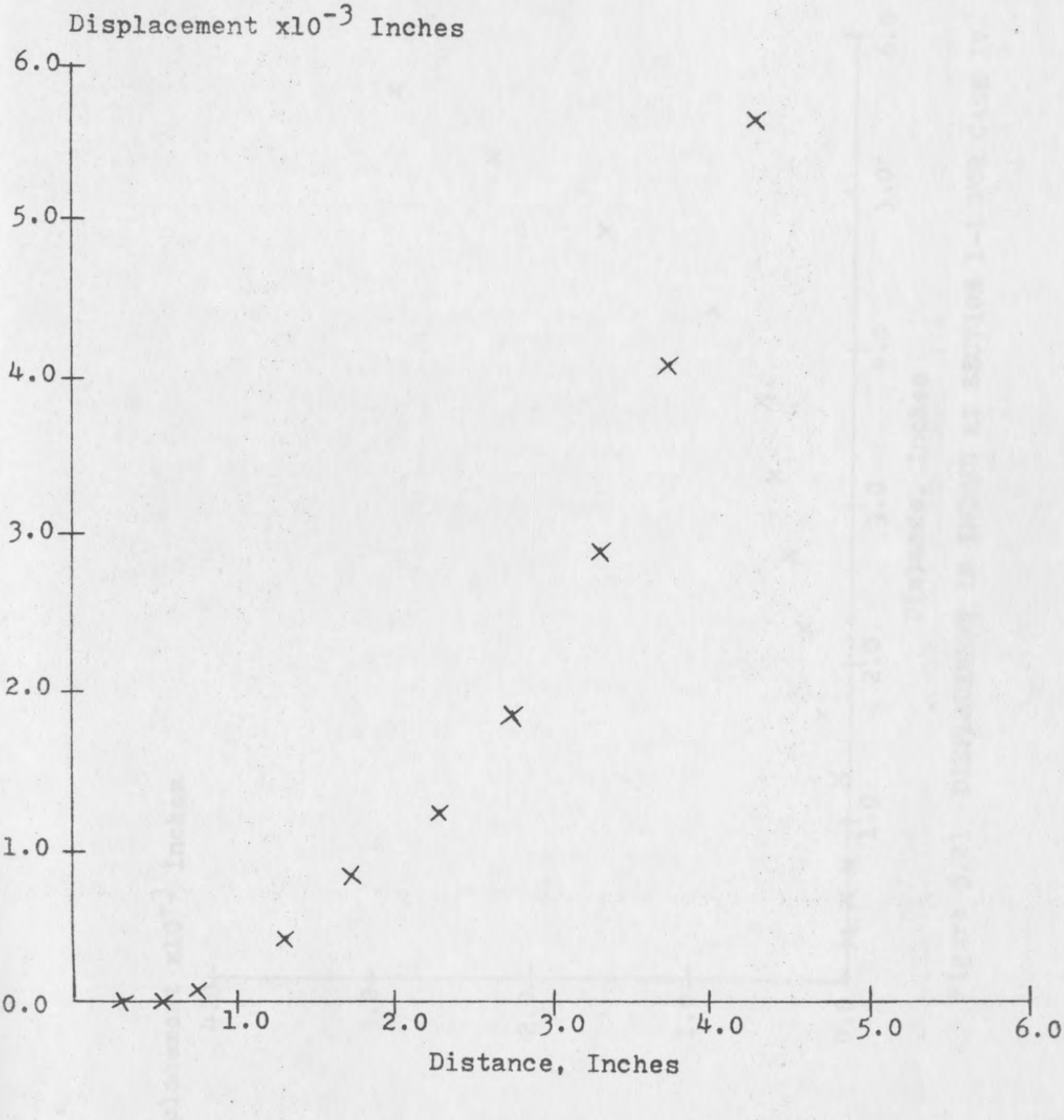


Figure 5.20 DISPLACEMENT IN INCHES AT SECTION 5-5 FOR CASE III

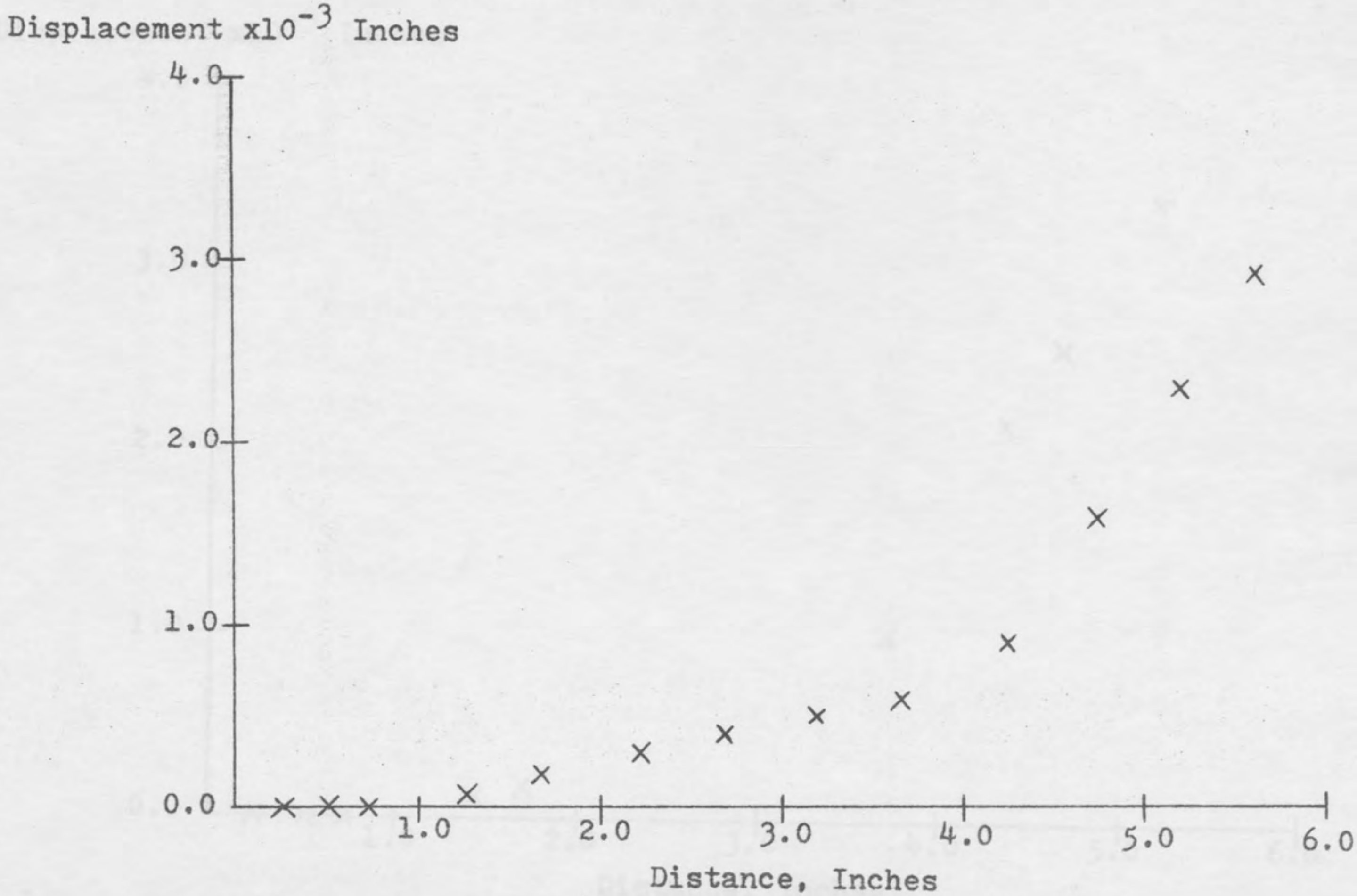


Figure 5.21 DISPLACEMENT IN INCHES AT SECTION 1-1 FOR CASE IV

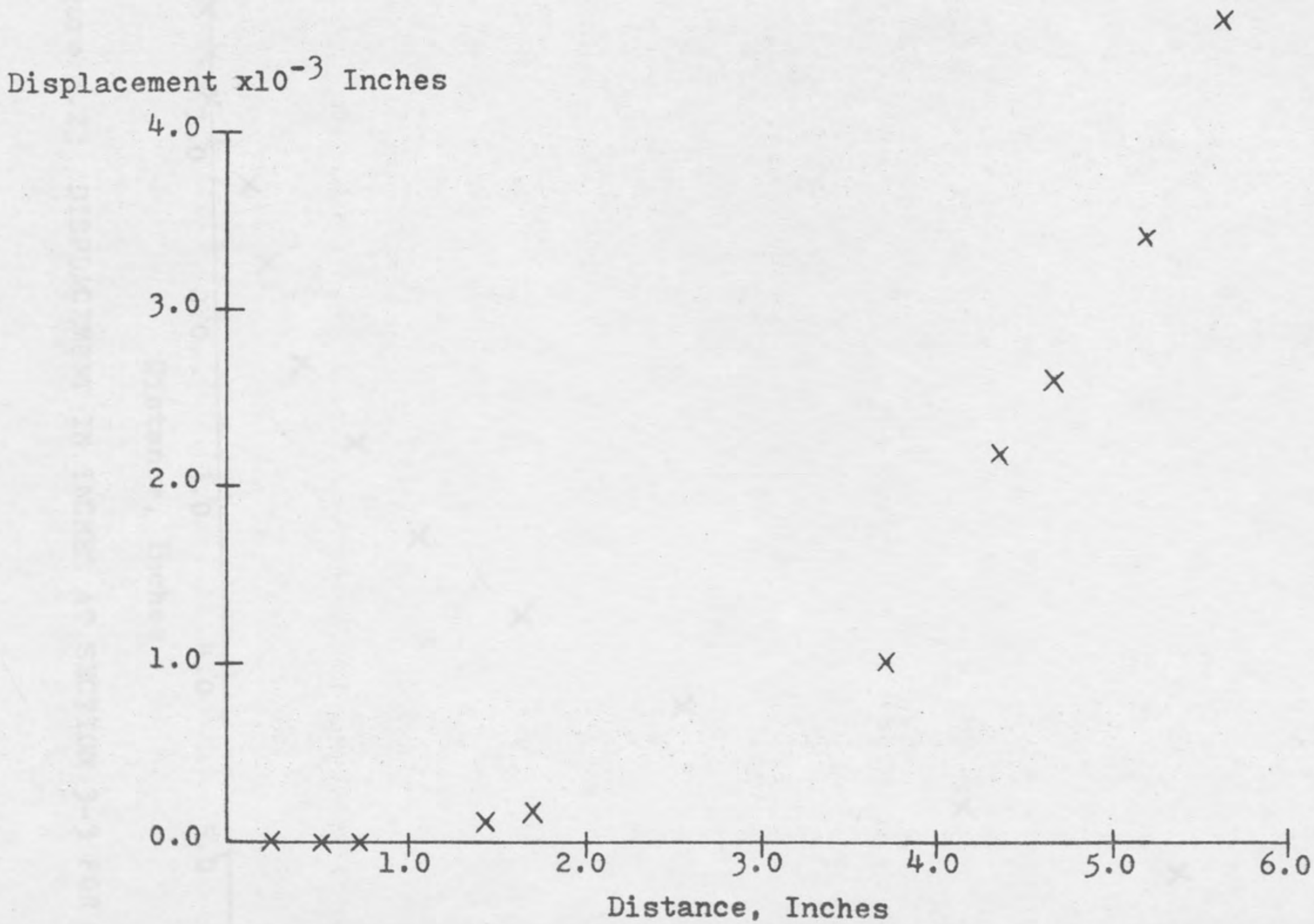


Figure 5.22 DISPLACEMENT IN INCHES AT SECTION 2-2 FOR CASE IV

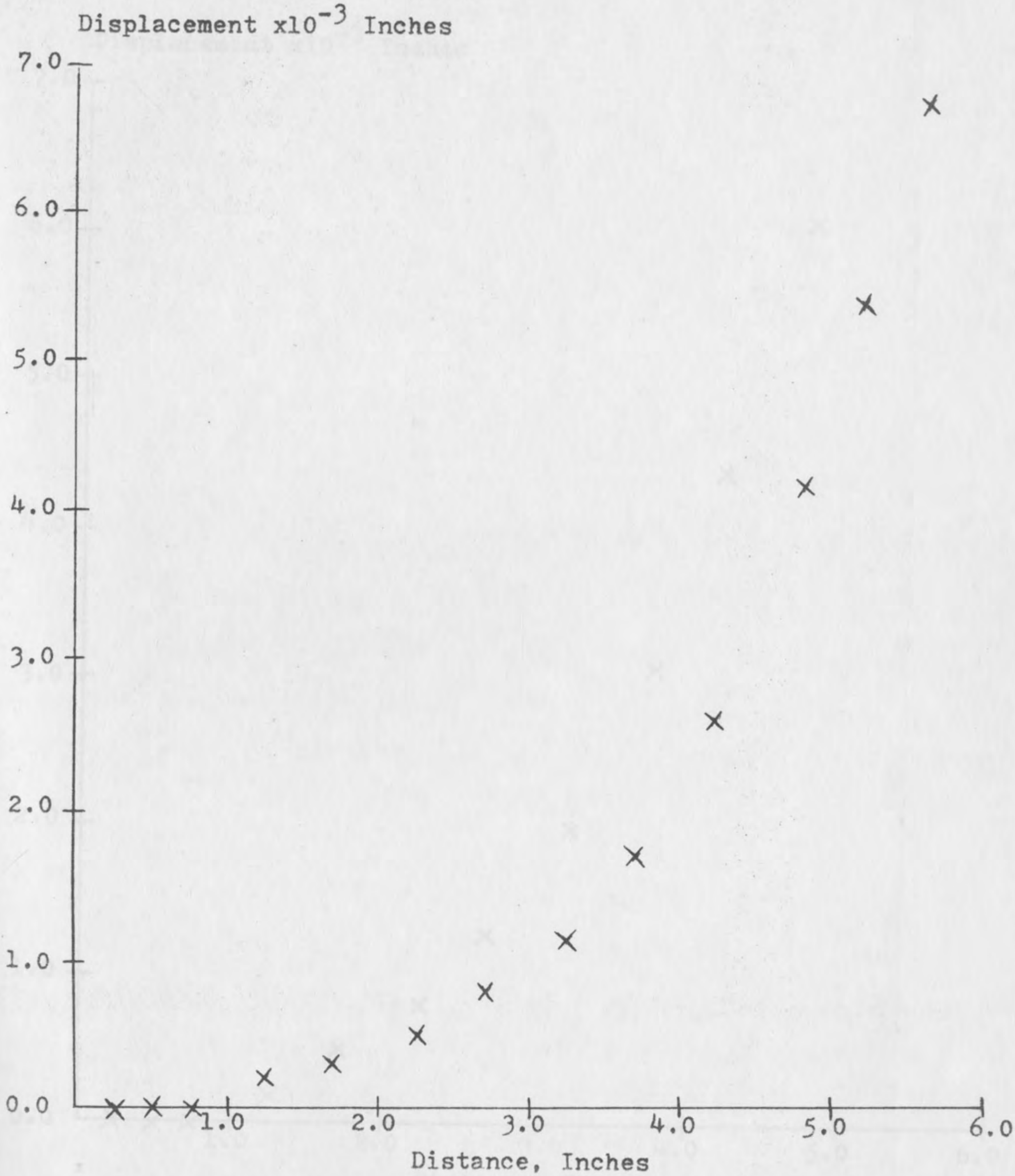


Figure 5.23 DISPLACEMENT IN INCHES AT SECTION 3-3 FOR CASE IV

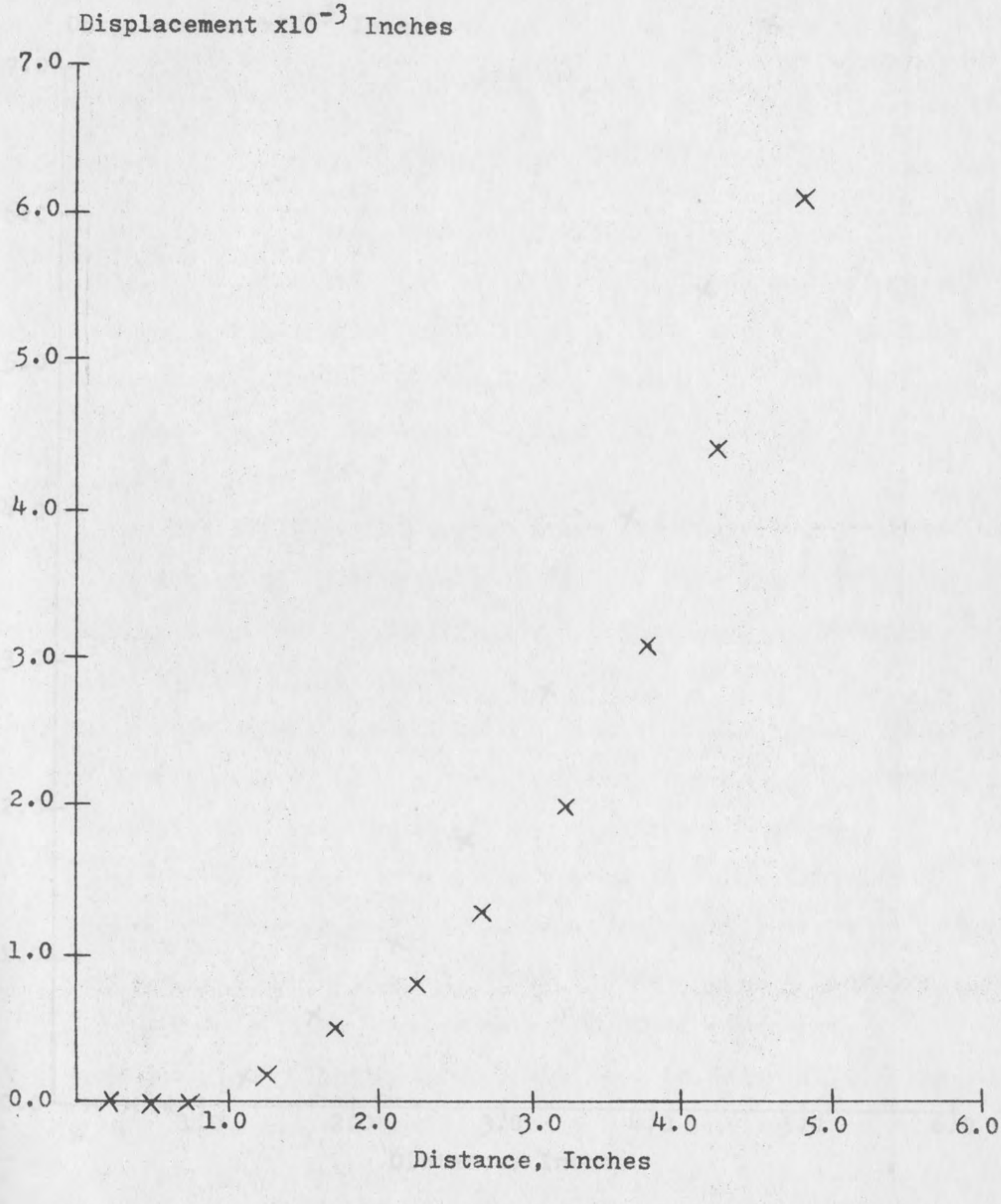


Figure 5.24 DISPLACEMENT IN INCHES AT SECTION 4-4 FOR CASE IV

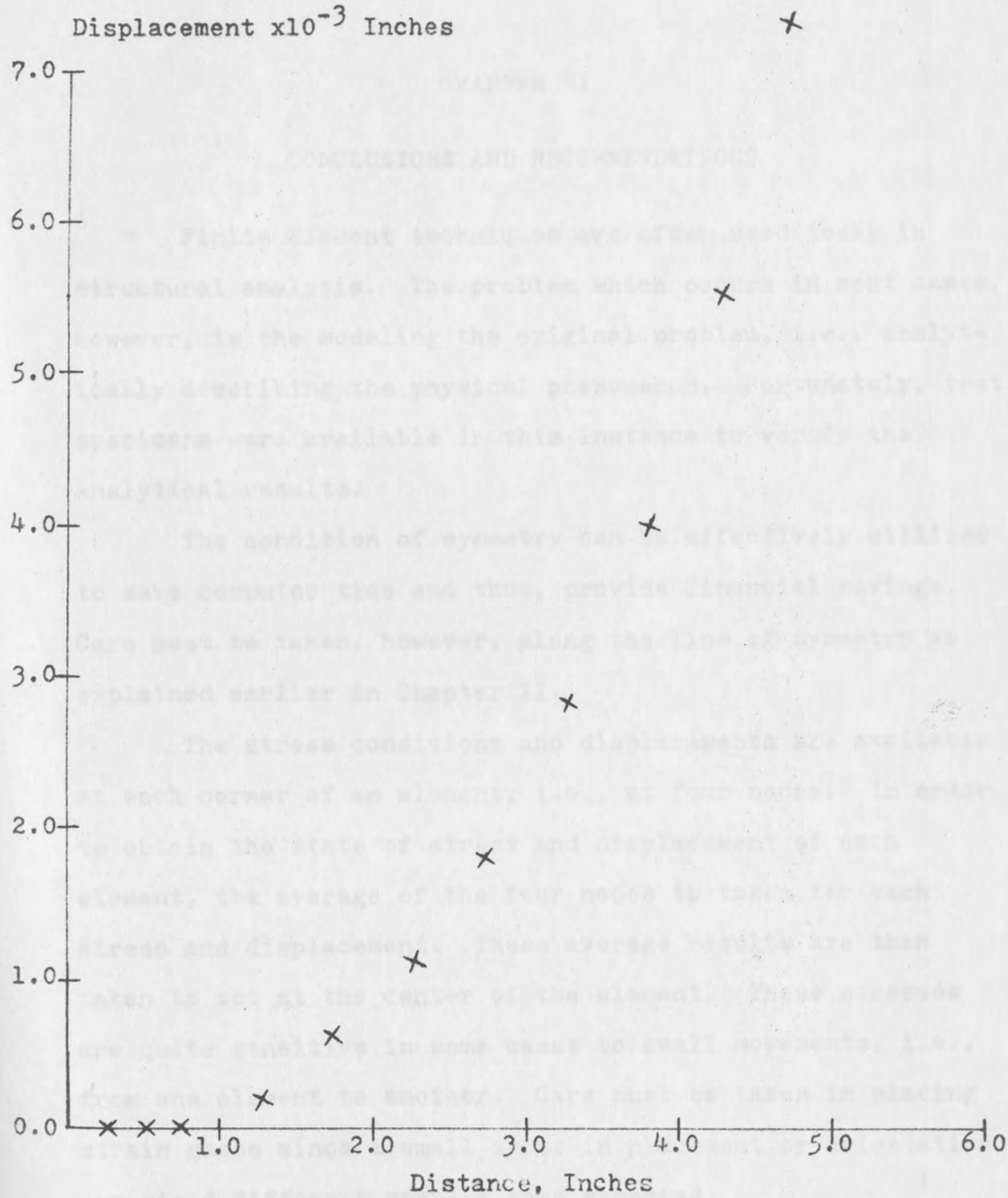


Figure 5.25 DISPLACEMENT IN INCHES AT SECTION 5-5 FOR CASE IV

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Finite Element techniques are often used today in structural analysis. The problem which occurs in most cases, however, is the modeling the original problem, i.e., analytically describing the physical phenomenon. Fortunately, test specimens were available in this instance to verify the analytical results.

The condition of symmetry can be effectively utilized to save computer time and thus, provide financial savings. Care must be taken, however, along the line of symmetry as explained earlier in Chapter II.

The stress conditions and displacements are available at each corner of an element, i.e., at four nodes. In order to obtain the state of stress and displacement of each element, the average of the four nodes is taken for each stress and displacement. These average results are then taken to act at the center of the element. These stresses are quite sensitive in some cases to small movements, i.e., from one element to another. Care must be taken in placing strain gages since a small error in placement or orientation can yield different results than expected.

It was extremely difficult to model this particular problem for the STRUDL-II program as evidenced by the several support cases used in this study. Because of the many support conditions tried and due to the speed and use of the computer, sufficiently accurate results were obtained in this instance. For problems of this nature, i.e., physical conditions which are difficult at best to model analytically, it is recommended that the analytical results not be taken at face value but rather only after experimental testing through full scale specimens or models.

It is recommended that this problem be further investigated using many more strain gage locations. Gage locations were limited in this study primarily due to lack of proper funding for the study.

APPENDIX A

This Appendix is presented to provide the reader, who may be unfamiliar with the STRUDL-II program, with an opportunity to become oriented to its use, application, and results. Furthermore several numerical examples are presented to demonstrate how various support conditions can be successfully modeled.

The following STRUDL commands were used in the STRUDL-II program.[(5), (6)]

1. Problem Initiation Statement: This must be the first command in a finite element job. (only the control card will precede this command)

General Form: STRUDL 'a_1' ('title')

'a_1' is the problem identifier or name. As an alphanumeric element, it must be enclosed in single quotes. It is limited in length to 8 characters.

'Title' is an arbitary problem title of up to 64 characters, including blanks. It must be enclosed in single quotes.

2. Dimensional Units For Input And Output: The units statement is used to define the dimensional units of input data which follows in subsequent requested output. Any number of units statements may be used in a problem.

3. Identification Mode Command: Set element command is optional. If used, it must appear before any member, joint loading condition names are used. The integer identification

mode is provided to make implementation of efficiency considerations easier.

4. Joint Coordinate Command: This command is used to describe the geometry of the structures. Any coordinate not given is taken as zero. The status of a joint is represented either as free or support. A support joint is assumed fixed against motion, except as modified by the release command. A free joint has no external displacement constraints acting upon it. If not specified, free is assumed.

5. Structural Type Command: It specifies the type of structure used for analysis. This statement must appear before each and every element incidences command.

6. Element Commands: The element incidences define the problem topology, or connectivity.

Tabular Form Element Incidences

$$\begin{bmatrix} i_1 \\ 'a_1' \end{bmatrix}$$

Elements:

i_1 - integer element identifier

$'a_1'$ - alphanumeric element identifier

6a. Element Properties Command: The element properties may be input in a variety of forms. The type of properties specified depends on the problem and element type. For the analysis type 'BPR' is used. 'BPR' is a rectangular element with four nodal points, the corner points. The thickness used was 1.0 inch.

7. Specification Of Member Constants:

General Form: Constants (constant description)

$$\text{Constant Description} = \begin{bmatrix} E \\ G \\ \text{Poisson} \end{bmatrix}$$

E refers to Young's modulus for members

G refers to the Shear Modulus for members

Poisson refers to Poisson's Ratio

8. Joint Release Command: Unless qualified by releases, Strudl assumes all support joints to be rigidly supported according to the structural type. A support joint in a frame or grid, unless released, allows no displacement or rotation. The displacement directions are shown in Figure A.1.

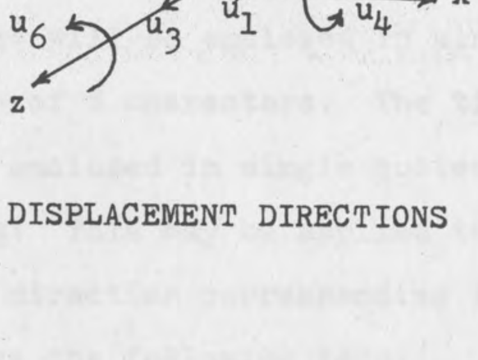


Figure A.1 DISPLACEMENT DIRECTIONS

The released displacement components are specified with the joint release command. Joint releases specify conditions on joints only. They specify the fixity of the joint to the support. If a joint is elastically supported in any direction, the joint is initially specified as a support joint and the elastic stiffness coefficient in the desired direction is given using the joint release command. To allow displacement in the desired direction, the force in that direction is released in this command. To allow rotation in the desired direction, the moment in that direction is released using joint release command.

9. Specification Of Structural Loading: The STRUDL language contains three types of statements for the specification of loads: Loading Condition Identifiers, Joint Load Statement, and Member Load Statements.

9a. Loading Condition Identifier: Loading Command
Loading (NAME) ('TITLE')

This command identifies the loading condition to which the loads listed below it apply. The name may be either an integer or an alphanumeric identifier. If alphanumeric, the name will be enclosed in single quotes and have a maximum length of 8 characters. The title is optional and if used must be enclosed in single quotes.

9b. Joint Loads: This may be applied to free joints or at supports in the direction corresponding to a joint release. This command take the following form:

Joint Loads

(Joint Name) Force (Direction Of Force) (Magnitude Of Force)

The joint name may be the name of a single node corresponding to the point of application of the given force or may be a list of joints which are to be loaded with forces of the same magnitude and direction. For Plate Bending problems, force must be in the z direction.

10. Analysis Command: The Stiffness Analysis command is used to execute a Finite Element analysis of a discretized structure. This command may be given any number of times during a problem. The form of the command is Stiffness Analysis.

As this is an execution command all the data required for an analysis must appear before the command.

11. List Command: To obtain the results of a finite element analysis it is necessary to use the list command. The nodal displacements and stresses are available as output. It is possible to obtain the results for all the nodes and elements or any subset of the complete set of nodes and elements. The stress quantities are positive as shown in Figure A.2. The form of command is List Displacements Stresses All.

EXAMPLE 1

Consider a square plate simply supported on all four sides and subjected to a uniform distributed loading of q intensity as shown in Figure A.3. The material can be assumed to be isotropic. Using symmetry conditions, only one quarter of the plate will be used for the STRUDL analysis as shown in

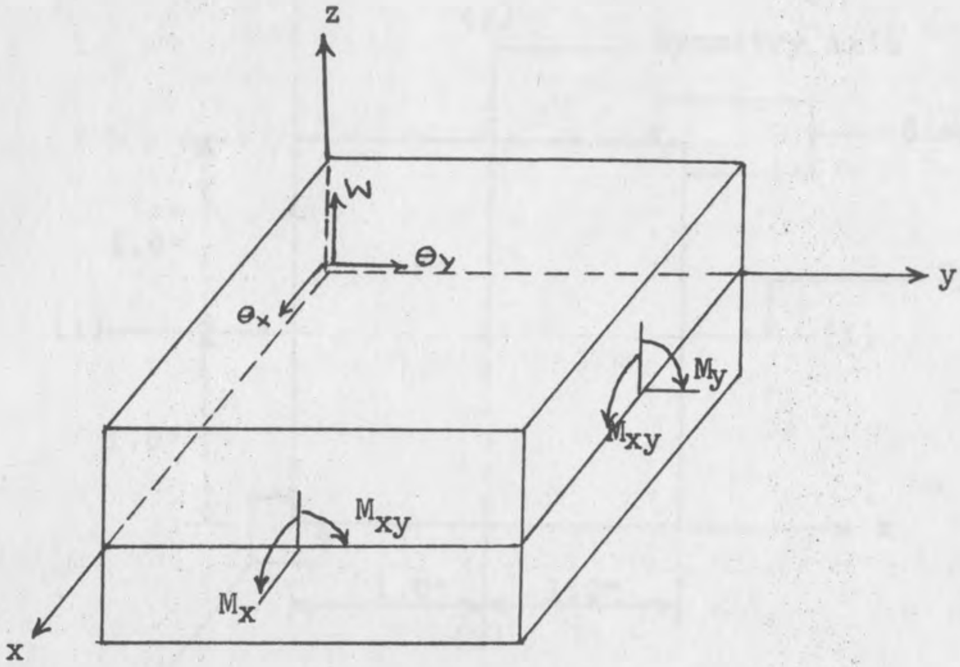


Figure A.2 SIGN CONVENTION OF STRESS

Figure A.4.

The input and output of the strudl program for Example 1 are shown in tables A.1 and A.2. As can be seen in Figure A.4, nodes 1 to 9, except 5, were treated as supports, i.e., restraining the translation and rotation normal to the boundary. Along the symmetry axis 1-1 (see Figure A.3) there is a translation and normal rotation, therefore, W and θ_y must be released. The corresponding STRUDL statement is Joint Release 8 FORCE Z MOMENT Y

Along the symmetry axis 2-2 (see Figure A.3) there is a translation (W) and normal rotation (θ_x) about Z and X axes

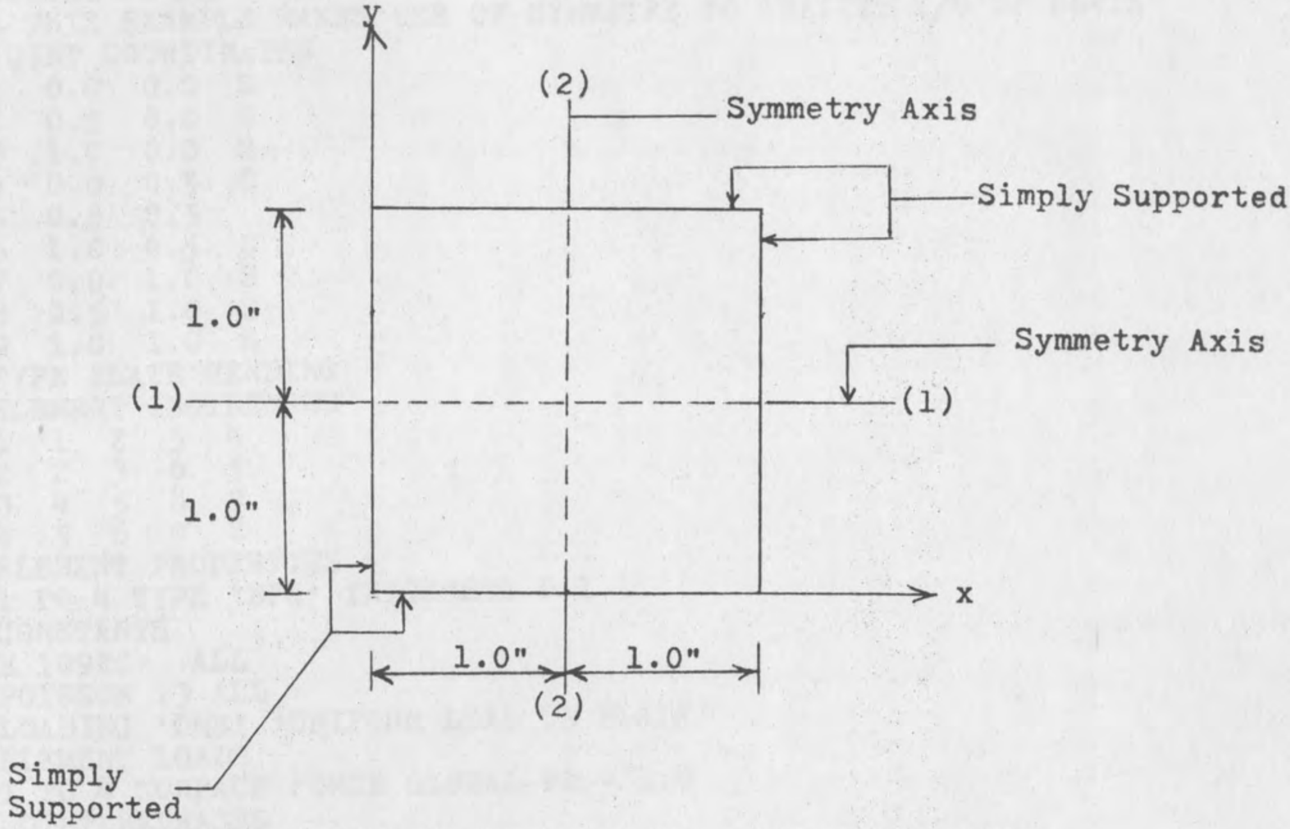


Figure A.3 SQUARE PLATE ALL SIDES SIMPLY SUPPORTED

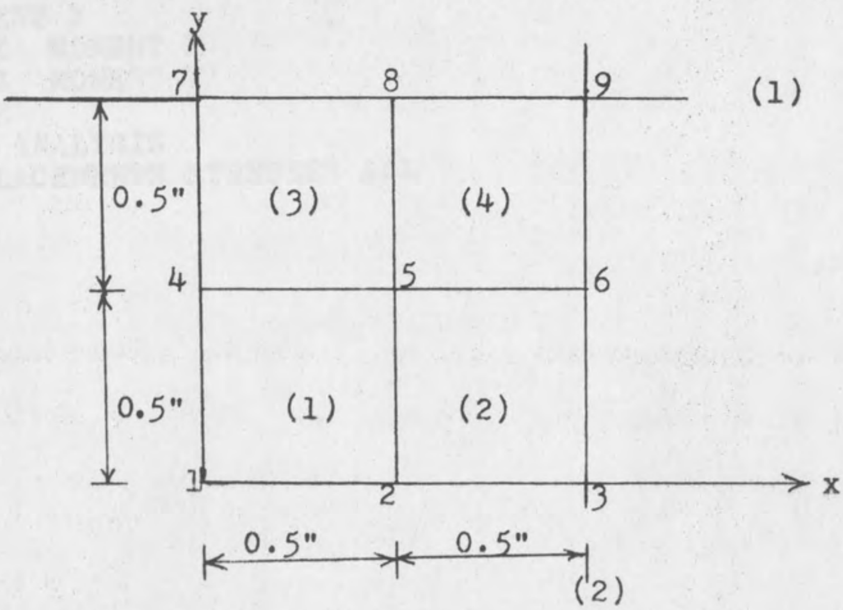


Figure A.4 1/4 OF SQUARE PLATE FOR STRUDL ANALYSIS

TABLE A.1

```
STRUDL 'EX-1' 'ALL SIDES SIMPLY SUPPORTED' 40000
$ THIS EXAMPLE MAKES USE OF SYMMETRY TO ANALYZE 1/4 OF PLATE
JOINT COORDINATES
1  0.0  0.0  S
2  0.5  0.0  S
3  1.0  0.0  S
4  0.0  0.5  S
5  0.5  0.5
6  1.0  0.5  S
7  0.0  1.0  S
8  0.5  1.0  S
9  1.0  1.0  S
TYPE PLATE BENDING
ELEMENT INCIDENCES
1  1  2  5  4
2  2  3  6  5
3  4  5  8  7
4  5  6  9  8
ELEMENT PROPERTIES
1 TO 4 TYPE 'BPR' THICKNESS 0.1
CONSTANTS
E 10920.  ALL
POISSON .3 ALL
LOADING 'ONE' 'UNIFORM LOAD ON PLATE'
ELEMENT LOADS
1 TO 4 SURFACE FORCE GLOBAL PZ - 1.0
JOINT RELEASES
2  3  MOMENT X
4  7  MOMENT Y
6  FORCE Z  MOMENT X
8  FORCE Z  MOMENT Y
9  FORCE Z
STIFFNESS ANALYSIS
LIST DISPLACEMENTS STRESSES ALL
FINISH
```

TABLE A.2

PROBLEM - EX-1 ALL SIDES SIMPLY SUPPORTED

Resultant Joint Displacements			
Joint	Z Displacement	X Rotation	Y Rotation
1	0.0	0.0	0.0
2	0.0	-0.0848	0.0
3	0.0	-0.1149	0.0
4	0.0	0.0	0.0848
5	-0.0364	-0.0538	0.0538
6	-0.0501	-0.0748	0.0
7	0.0	0.0	0.1149
8	-0.0501	0.0	0.0748
9	-0.0692	0.0	0.0

ELEMENT STRESSES				
Element	Node No.	M_{xx}	M_{yy}	M_{xy}
1	1	0.0	0.0	0.1356
1	2	-0.0060	-0.0201	0.0921
1	5	-0.1350	-0.1350	0.0487
1	4	-0.0201	-0.6058	0.0921
2	2	-0.0060	-0.0201	0.0791
2	3	-0.0048	-0.0163	0.0038
2	6	-0.1564	-0.1781	-0.0089
2	5	-0.1332	-0.1345	0.0664
3	4	-0.0202	-0.0060	0.0792
3	5	-0.1345	-0.1333	0.0664
3	8	-0.1781	-0.1564	-0.0089
3	7	-0.0163	-0.0048	0.0038
4	5	-0.1327	-0.1327	0.0434
4	6	-0.1547	-0.1726	0.0140
4	9	-0.2086	-0.2086	-0.1531
4	8	-0.1726	-0.1547	0.1405

respectively. Since node 6 along 2-2 was restrained before, it must also be released using the joint release command as follows 6 FORCE Z MOMENT X.

As explained previously, if there is a translation, a rotation, or both about any axes, (translation about Z axis, rotations about X or Y axis) the corresponding release must be made using the release command.

The analytical solution to Example 1 is available in Timoshenko.[7] The maximum deflection occurs at the center of the plate and is given by

$$_{max} = (0.00406) \frac{q\ a^4}{D_B} \qquad 1.1$$

where

q = Intensity of load, Kips

a = Length of side of plate, inches

D_B = Flexural rigidity, Kip - inches

The deflection using equation 1.1 is 0.06496 inch and by the STRUDL analysis, 0.06925 inch. The difference is very small.

<u>EXAMPLE 2</u>

Consider a square plate with one side fixed and other sides free as shown in Figure A.5. Two point loads act as shown in Figure A.5. Taking advantage of symmetry, one half of the plate will be considered in the STRUDL analysis as pictured in Figure A.6. The input and output for STRUDL program for Example 2 are presented in Tables A.3 and A.4. Along the line of symmetry, the translations and rotations

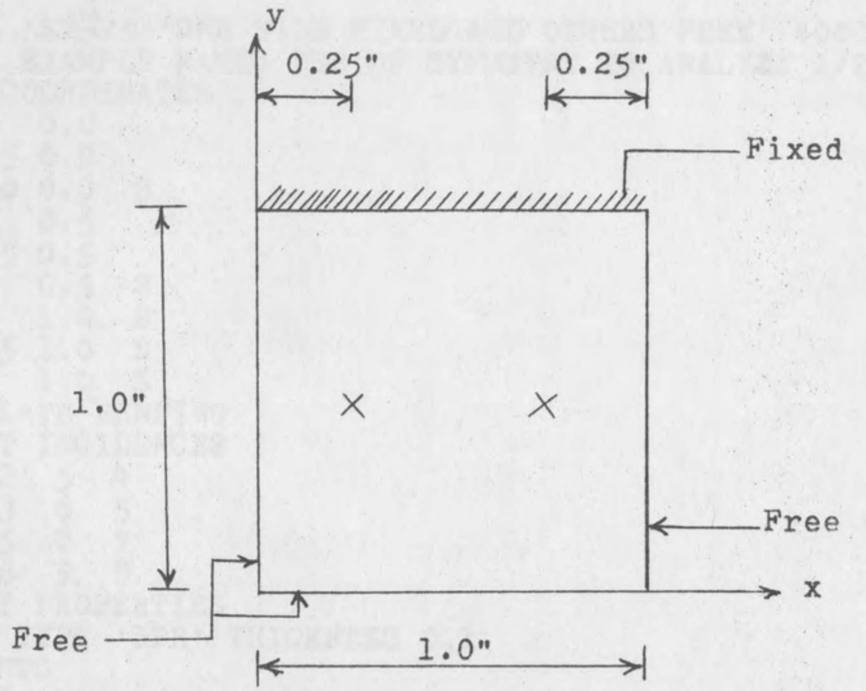


Figure A.5 PLATE FIXED AT TOP AND OTHER SIDES FREE

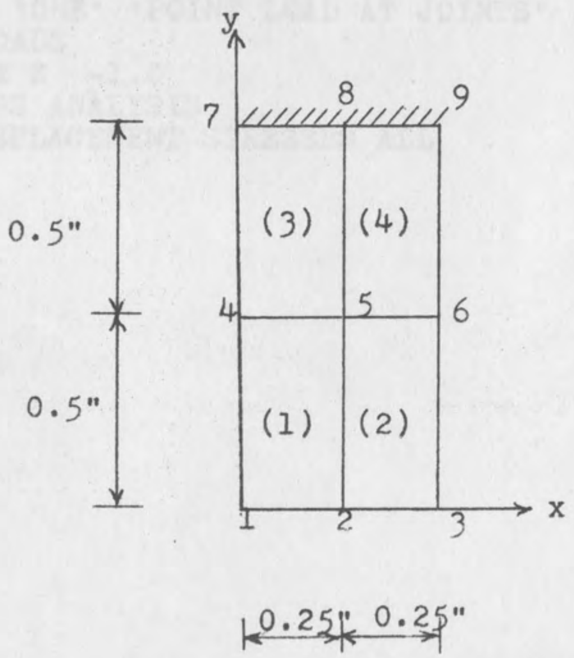


Figure A.6 1/2 OF PLATE FOR STRUDL ANALYSIS

TABLE A.3

```
STRUDL 'EX-2' 'ONE SIDE FIXED AND OTHERS FREE' 40000
$ THIS EXAMPLE MAKES USE OF SYMMETRY TO ANALYZE 1/2 OF PLATE
JOINT COORDINATES
1  0.0  0.0
2  0.25 0.0
3  0.50 0.0  S
4  0.0  0.5
5  0.25 0.5
6  0.5  0.5  S
7  0.0  1.0  S
8  0.25 1.0  S
9  0.5  1.0  S
TYPE PLATE BENDING
ELEMENT INCIDENCES
1  1  2  5  4
2  2  3  6  5
3  4  5  8  7
4  5  6  9  8
ELEMENT PROPERTIES
1 TO 4 TYPE 'BPR' THICKNESS 0.1
CONSTANTS
E 30000 ALL
POISSON 0.3 ALL
JOINT RELEASES
3  6  FORCE Z  MOMENT X
LOADING 'ONE' 'POINT LOAD AT JOINTS'
JOINT LOADS
5  FORCE Z  -1.0
STIFFNESS ANALYSIS
LIST DISPLACEMENT STRESSES ALL
```

TABLE A.4

PROBLEM - EX-2 ONE SIDE FIXED AND OTHERS FREE

Resultant Joint Displacements			
Joint	Z Displacement	X Rotation	Y Rotation
1	-0.0770	0.0972	0.0039
2	-0.0781	0.0949	0.0042
3	-0.0788	0.0960	0.0
4	-0.0289	0.0918	0.0140
5	-0.0312	0.0932	0.0038
6	-0.0313	0.0941	0.0
7	0.0	0.0	0.0
8	0.0	0.0	0.0
9	0.0	0.0	0.0

ELEMENT STRESSES				
Element	Node No.	M_{xx}	M_{yy}	M_{xy}
1	1	0.0235	-0.0157	0.0383
1	2	-0.0202	0.0097	-0.0017
1	5	-0.1300	-0.0374	-0.0301
1	4	-0.0673	0.0568	0.0098
2	2	-0.0076	0.0135	-0.0015
2	3	-0.0752	-0.0075	-0.0002
2	6	+0.0559	0.0206	0.0009
2	5	-0.1395	-0.0402	-0.0003
3	4	-0.0594	0.0834	-0.0291
3	5	-0.1338	-0.0498	0.0099
3	8	0.3104	1.0349	0.0206
3	7	0.2693	0.8976	-0.0184
4	5	-0.1432	-0.0527	-0.0204
4	6	0.0554	0.0189	-0.0055
4	9	0.3096	1.0321	0.0017
4	8	0.3104	1.0349	-0.0135

about Z and X axis were released respectively.

EXAMPLE 3

Consider the same boundary conditions as in Example 2. The whole plate will now be analyzed as shown in Figure A.7. There are no releases made, since the support allows no translation or rotation. The input and output of the STRUDL program are presented in Tables A.5 and A.6. The results for Example 2 and Example 3 are tabulated in Tables A.7 and A.8 for ease of comparison. These tables show no differences, and thus, symmetry conditions can be effectively used, and can save computer time.

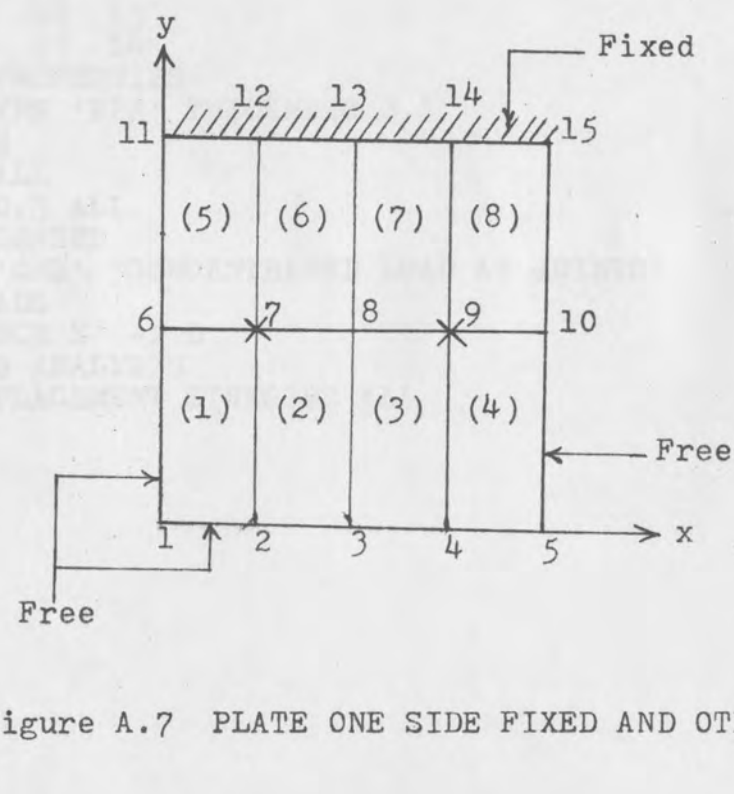


Figure A.7 PLATE ONE SIDE FIXED AND OTHERS FREE

TABLE A.5

```
STRUDL 'EX-3' 'ONE SIDE FIXED AND OTHERS FREE' 40000
JOINT COORDINATES
 1  0.00  0.0
 2  0.25  0.0
 3  0.50  0.0
 4  0.75  0.0
 5  1.00  0.0
 6  0.0   0.5
 7  0.25  0.5
 8  0.5   0.5
 9  0.75  0.5
10  1.0   0.5
11  0.0   1.0  S
12  0.25  1.0  S
13  0.5   1.0  S
14  0.75  1.0  S
15  1.0   1.0  S
TYPE PLATE BENDING
ELEMENT INCIDENCES
1  1  2   7   6
2  2  3   8   7
3  3  4   9   8
4  4  5  10   9
5  6  7  12  11
6  7  8  13  12
7  8  9  14  13
8  9  10  15  14
ELEMENT PROPERTIES
1 TO 8 TYPE 'BPR' THICKNESS 0.1
CONSTANTS
E 30000 ALL
POISSON 0.3 ALL
JOINT RELEASES
LOADING 'ONE' 'CONCENTRATED LOAD AT JOINTS'
JOINT LOADS
7 9 FORCE Z  -1.0
STIFFNESS ANALYSIS
LIST DISPLACEMENT STRESSES ALL
FINISH
```

TABLE A.6

PROBLEM - EX-3 ONE SIDE FIXED AND OTHERS FREE

Resultant Joint Displacements			
Joint	Z Displacement	X Rotation	Y Rotation
1	-0.0770	0.0972	0.0039
2	-0.0781	0.0949	0.0042
3	-0.0788	0.0960	0.0
4	-0.0781	0.0949	-0.0042
5	-0.0770	0.0972	-0.0039
6	-0.0289	0.0918	0.0140
7	-0.0312	0.0932	0.0038
8	-0.0313	0.0941	0.0
9	-0.0312	0.0932	-0.0038
10	-0.0289	0.0918	-0.1404
11	0.0	0.0	0.0
12	0.0	0.0	0.0
13	0.0	0.0	0.0
14	0.0	0.0	0.0
15	0.0	0.0	0.0

ELEMENT STRESSES				
Element	Node No.	M_{xx}	M_{yy}	M_{xy}
1	1	0.0235	-0.0157	0.0383
1	2	-0.0202	0.0097	-0.0017
1	7	-0.1300	-0.0374	-0.0301
1	6	-0.0673	0.0568	0.0098
2	2	-0.0076	0.0135	-0.0015
2	3	-0.0752	-0.0074	-0.0002
2	8	0.0559	0.0206	0.0009
2	7	-0.1395	-0.0402	-0.0003
3	3	-0.0752	-0.0074	0.0002
3	4	-0.0076	0.0134	0.0015
3	9	-0.1395	-0.0402	0.0003
3	8	0.0559	0.0206	-0.0009
4	4	-0.0202	0.0097	0.0017
4	5	0.0235	-0.0157	-0.0383
4	10	-0.0673	0.0568	-0.0098
4	9	-0.1300	-0.0374	0.0301

TABLE A.6 Continued

ELEMENT STRESSES				
Element	Node No.	M_{xx}	M_{yy}	M_{xy}
5	6	-0.0594	0.0834	-0.0291
5	7	-0.1338	-0.0498	0.0099
5	12	0.3104	1.0349	0.0206
5	11	0.2692	0.8976	-0.01844
6	7	-0.1432	-0.0527	-0.0204
6	8	0.0554	0.0189	-0.0055
6	13	0.0309	1.0321	0.0017
6	12	0.3104	1.0349	-0.0131
7	8	0.0554	0.0189	0.0055
7	9	-0.1432	-0.0527	0.0204
7	14	0.3104	1.0349	0.0131
7	13	0.3096	1.0321	-0.0017
8	9	-0.1338	-0.0498	-0.0099
8	10	-0.0594	0.0834	0.0291
8	15	0.2693	0.8976	0.0184
8	14	0.3104	1.0349	-0.0206

TABLE A-7

Results of Example 2 (use of symmtry)				Results of Example 3			
Node No.	Displacement	Rotation-x	Rotation-y	Node No.	Displacement	Rotation-x	Rotation-y
1	-0.0770	0.0972	0.0039	1	-0.0770	0.0972	0.0039
2	-0.0781	0.0949	0.0042	2	-0.0781	0.0949	0.0042
3	-0.0788	0.0960	0.0	3	-0.0788	0.0960	0.0
4	-0.02891	0.0918	0.0140	6	-0.0289	0.0918	0.0140
5	-0.0312	0.0932	0.0038	7	-0.0312	0.0932	0.0038
6	-0.0313	0.0960	0.0	8	-0.0313	0.0941	0.0
7	0.0	0.0	0.0	11	0.0	0.0	0.0
8	0.0	0.0	0.0	12	0.0	0.0	0.0
9	0.0	0.0	0.0	13	0.0	0.0	0.0

TABLE A-8

Results of Example 2 (use of symmtry)			Example 3		
Element No.	Stress (σ_{xx}) KSi	Stress (σ_{yy}) KSi	Element No.	Stress (σ_{xx}) KSi	Stress (σ_{yy}) KSi
1	-0.294	0.0198	1	-0.294	0.0198
2	-0.2406	0.0204	2	-0.2406	0.0204
3	0.5796	2.94	5	0.5796	2.94
4	0.7968	3.06	6	0.7968	3.06

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