A COMPUTER GRAPHIC TECHNIQUE FOR

STRUCTURAL ANALYSIS

By

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STRUCTURAL ANALYSIS

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PREFACE

At the beginning of my second year as a graduate student at

Oklahoma State University I became intrigued by a relatively new

technology called computer graphics. As to what triggered this intrigue,

I am not sure, but the momentum that it started has yet to dissipate.

Thus far, it has done nothing but open many new areas of interest for me.

My own experience in using computers had begun about four years

earlier in the area of structural analysis, but I had little opportunity

to use any form of computer graphics at that time. This was not sur-

prising since the computer graphic capabilities at OSU were limited to

a 13" Cal Comp plotter which was driven by an IBM 1620. Nevertheless

I later became interested in learning about computer graphics and I

began producing simple drawings on the Cal Comp plotter. I was fortunate

at this time to have available as background knowledge the work of

Mr. Phil Hendren. Mr. Hendren while working in the department of

Architecture at OSU, had used the same equipment to do some work in the

area of computer drawn perspectives. Even though Mr. Hendren was no

longer at OSU he had published a paper which I found useful in my initial

efforts. These efforts were mainly directed toward trying to create a

series of perspective drawings of a building or group of buildings.

Once this was accomplished I had hoped to make an animated movie which

would give the impression of moving through a space. This could be

accomplished by photographing each drawing the computer produced.

At the beginning of the second semester I was given the task of becoming familiar with a "canned" computer program which used another form of computer graphics. This particular program was called SYMAP and used a printer rather than a plotter to display the results of the program graphically. All my work with SYMAP was directed toward the production of maps to display such things as population densities, income levels in a particular area and many other types of similar data. Even though I spent the whole semester with this program and though it could have great potential for urban designers, I didn't realize its potential in structura analysis until a year later when I was again working with the program.

By the end of the second semester I realized that the IBM 1620 and the 13" plotter were not going to be capable of producing the type of computer drawings I was seeking. By chance I was fortunate enough to find both the equipment and the financial support to continue my work at the University of Florida. By working for the Bureau of Research in the College of Architecture and Fine Arts as a research faculty member I was able to carry on my work and also use the computer facilities at the University. The equipment they had at that time was an IBM 360/65 and a 563 Cal Comp 30" plotter. These were much nicer tools to work with and did a lot to spur my efforts.

I continued my work with the plotter, and I also once again began to work with the SYMAP program. This time I was simply showing other people how to use the program and working with them on their various projects. Also about this time I was reading about the work Ivan Sutherland had done with his Sketchpad III system at M.I.T. Using a Cathode Ray Tube (C.R.T.) and a light pen, Dr. Sutherland simply drew the outline of a truss on the screen and applied a load at some point on the truss. The computer

would then compute the forces in each member of the truss and display the results on the truss outline. I had thought about doing the same thing with the plotter but somehow it didn't seem to be the answer to graphicall displaying computed results. One day while I was working with the SYMAP program the thought suddenly occurred to me of trying to use SYMAP to visually represent calculations from structural analysis programs. In a sense I wanted to do the same thing Dr. Sutherland was doing only instead of showing numbers I wanted to use shades of gray or color to represent the stress that was taking place in a truss or any type of structure. From this idea I began to investigate the potential of using both the printer and plotter to display calculated results in such a manner that stresses can be visualized within the structure.

Now that this thesis is over it becomes difficult trying to decide who deserves the most thanks. This research would not have been possible without a very unique combination of people and circumstances. The major portion of the final work was done at the University of Florida, but this would never have been possible without the cooperation of many people at Oklahoma State University. In particular I would like to thank Dr. Thomas S. Dean for having the patience in letting me seek my own way.

The work accomplished at the University of Florida would not have happened without tremendous support from Mr. Bill Wagner, Director of the Bureau of Research in the College of Architecture and Fine Arts. Mr. Wagner has been a long time advocate of pure as well as practical research in architecture and this in itself encouraged me when I began to doubt the validity of my work.

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CHAPTER I

INTRODUCTION

Analysis in Structural Design

> You must learn to think
> as the structure thinks.[1]
> Hardy Cross
>
> The analyst must be able
> to "see" the force mech-
> anisms at work in the
> structure.[2]
> James Ambrose

It is generally conceded by architectural educators involved with

the teaching of structural design that students are not developing a

strong, intuitive feeling for basic structural behavior. With this as a

paramount concern, much effort has recently been expended in hopes of

developing better teaching methods and devices to fill this need.

There are presently available an array of books concerned with the

explanation of structural behavior without reliance upon complicated

mathematics. In fact, most of these books tend to evade using any math-

ematics in their explanation of structural concepts. They all seem to

look at mathematics and numerical values simply as convenient tools in

determining the final physical details of the structure. It is not the

de-emphasis of rigorous mathematics in the formal and final analysis of

a structure which is sought, but rather that there be more emphasis

placed on the study of basic structural behavior. One needs only to

read the introductions of these books to realize that this feeling colors

the whole of their approach. In fact, it is worthy to note that sequen-

tially with the years of publication the plea for a more basic under-

standing of the nature of structures becomes more and more pervasive and

emphatic. The following quotations will seem even more interesting when

viewed in this light:

> We must disregard extraneous details - and especially eliminate
> mathematical procedures and numerical values - to concentrate
> on the problems rather from a more general and qualitative
> point of view. It is absurd to enter into quantitative con-
> cretion without the assurance that there will be a definite
> connection with ideas already being established.[3]
>
> Eduardo Torroja   1958
> Philosophy of Structures

> In other words, theory must find in intuition a force capable
> of making formulas alive, more human and understanding, and of
> lessening their impersonal technical brittleness.[4]
>
> Pier Luigi Nervi   1963
> Structure in Architecture

> But unless he understands the behavior of his structure, the
> architect cannot collaborate intelligently.[5]
>
> H. Seymore Howard, Jr.   1966
> Structure - An Architects Approach

> Emphasis has been placed not on the development of engineering
> design skills, but on the understanding of fundamental con-
> cepts and the visualization of the nature and function of
> structures.[6]
>
> James E. Ambrose   1967
> Building Structures Primer

Not only does one find in these books a unity in spirit, but also a

oneness in thought as to how this goal might best be achieved. Invari-

ably each author stresses or relies on the visualization of both inter-

nal and external forces to explain structural behavior. In the book,

Structure and Architectural Designs, Philip Corkill, Homer Puderbaugh

and Keith Sawyers express their belief in visualization very strongly

when they state:

> This book is a visually oriented structural and design analy-
> sis which resulted from the belief that a student can begin to
> establish a foundation for architectural design through a vis-
> ual investigation of the basic principles of structures.[7]

<div align="right">1965</div>

This belief is certainly reflected throughout the whole of the 317

page book. Every other page contains only visual interpretation and

representations of structural behavior. The other pages contain verbal

descriptions of what is being displayed, but at no time does it exceed

or overwhelm the visual display. It is also interesting to note that

all the visual displays occur on the page that corresponds to the view-

ers right hand side. This may be only coincidental on the part of the

authors, but it does seem to strengthen the total visual effect of the

book. This same technique also occurs in Salvadori and Heller's book,

Structure in Architecture.

James Ambrose is even more emphatic about visualization of structur-

al behavior in his book, Building Structures Primer. Mr. Ambrose claims:

> The importance of visualization can hardly be overemphasized,
> and it places a high priority on those learning techniques
> which stress graphic representation and actual observation or
> reacting structures.[8]

<div align="right">1969</div>

His book, although not as profusely illustrated as the Corkill book, does

contain quite a number of visual aids in trying to explain structural

behavior.

The visual aids that these authors tend to employ vary from simple

diagrams showing the direction in which forces are moving,[9] to more com-

plex diagrams illustrating stress distribution in the structure.[10] An ex-

ample of each type can be seen in figure 1. Figure 2 illustrates how a

few of the authors go even a step further by drawing the force distri-

bution of the structure in perspective.[11]

Direction of Forces   Stress Distribution
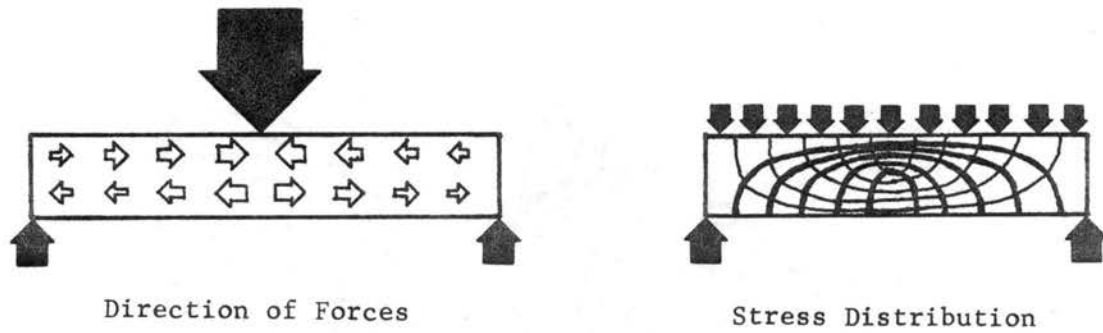
Figure 1.   Typical Visual Aids To Explain Structural Behavior.
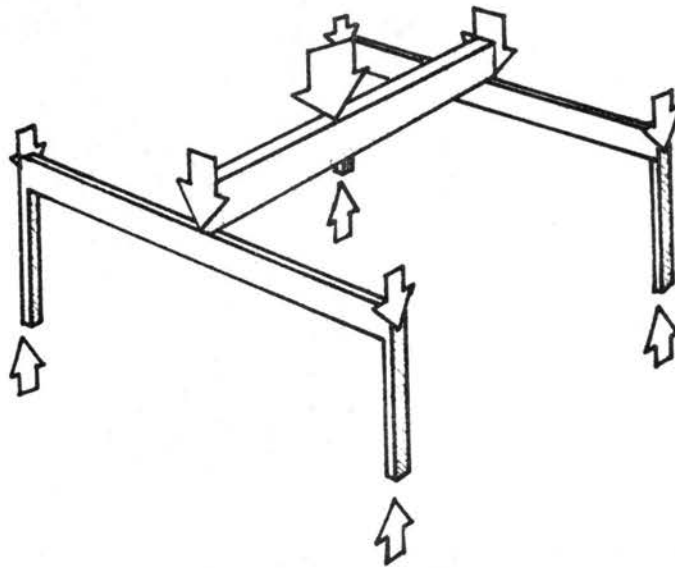
Figure 2.   Force Distribution on Structure

Of course, using visual diagrams to represent force distribution is not new.   Even the earlier books which used the more traditional approaches to structural design relied on the classical types of force diagrams such as those in figure 3.
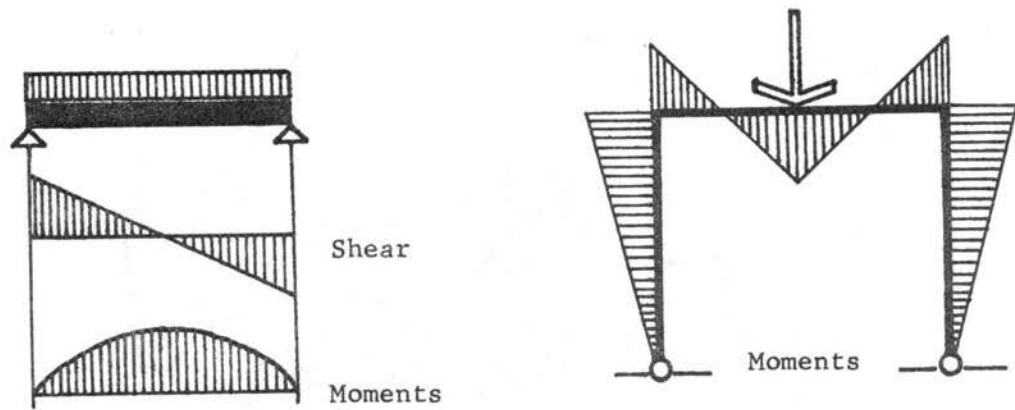
Figure 3. Classical Types of Force Diagrams

In addition to graphic aids, other visual techniques such as scale models and photo-elasticity are being emphasized for demonstrating structural principles. Previously, these techniques were used in deducing accurate stress conditions for unique structures, but they are gradually finding broader use as tools in demonstrating structural concepts such as torsion, slenderness ratios and deflections. However, models and optical devices that are used in identifying the qualitative or natural phenomena of structures are somewhat limited when quantitative or numeric information is desired. The Technology Workshop in Harvard's Graduate School of Design has found that very few models used for demonstrating purposes could be used for actual computations. Finding deflections in a framed structure by varying the stiffness in its members was one of the few examples where a model used primarily as a qualitative teaching aid became useful when quantitative answers were desired.[12]

Unfortunately, the failure of models to bridge the gap between qualitative visualization and accurate quantitative values is also true

of the graphic aids previously mentioned. To date, neither technique has been able to provide a smooth transition between the qualitative understanding of structural behavior and the quantification of that behavior.

As astounding as it may seem this important gap between these two entities has still not been successfully bridged. Pier Luigi Nervi states, "No one doubts that the bridging of this gap is possible and that, if achieved, it would be extremely useful."[13]

Mario Salvadori has probably made one of the most successful attempts thus far by producing one book which deals only with structural concepts, Structure in Architecture, and another which stresses simplified methods of analysis, Structural Design in Architecture. This in itself would not be sufficient except for the fact that Dr. Salvadori has cross referenced the analytical book with the conceptual book. But even this attempt still leaves a lot to be desired in trying to provide an aid which would make learning structures a very exciting experience and also give the designer a feeling of intuitive understanding about structural behavior.

With the rapid advance of digital and analog computers it seemed possible that the quantitative aspects of model analysis could be replaced by numerical methods or even tied back to models in observing the results simultaneously with the preformance.

A system such as this was developed in the Structural Models Laboratory in the Department of Civil Engineering at MIT. The system was called DATALINK and was first used by students during the fall of 1964 in a course dealing with structural models. The whole purpose of the system was to achieve fast accurate data and also allow the experimenter to observe the actual behavior of the structure.[14]

This is the type of cross-linkage between numbers and visualization that has the potential of becoming a dynamic teaching and research aid. The DATALINK system could have this effect for a designer already well versed in structural analysis, but it is not flexible enough for a designer who is just beginning to experiment with structures. This particular system placed too much emphasis on the numerical accuracy of the quantitative data that was obtained from the model. Each model had to be accurately scaled in size and material and then wired with strain gages which in turn were connected to an analog computer. In addition, the visual observation of the model when loads were applied was very minimal because of the brittle materials which had to be used in obtaining accurate results. A model made from balsa wood, plastic or any flexible material produces much more dynamic visual effects when loads are applied than would a similar model constructed from steel, concrete or aluminum. One other major disadvantage was that internal stresses in the individual members of the structure could not be visually observed.

Another system at MIT which had just been completed about the time DATALINK was conceived could be the one which may eventually have the most profound effect on structural analysis and in fact bridge the qualitative to quantitative gap for a designer. This work was being conducted at MIT in the Lincoln Laboratories as a thesis project by Ivan E. Sutherland. He called this now classic project, "Sketchpad: A Man-Machine Graphical Communication System."[15]

In this thesis Dr. Sutherland briefly discussed the possibilities of using computer graphics as an aid in structural analysis. Dr. Sutherland's one page discussion suggested having computer results pictorially displayed on the outline of the structure instead of the usual printout in tabular form. His work in this area was limited to only a

couple of experiments involving trusses. With the outline of the truss
drawn on the screen of the CRT, a load could be applied at any point on
the structure. The computer would then calculate the forces in each
member of the truss and display the numeric results next to each respec-
tive member. In this manner a designer could easily obtain a quick
representation of stress distribution for various loading conditions and
supports.

This was an important step in the man-machine communication gap, but
it did seem to lack an important element. Mainly, that even though the
results were pictorially represented they were not graphically displayed.
A graphic display would indicate some type of visual representation of
numerical data. Line graphics, bar charts, circle graphs, etc. are all
examples of numerical data graphically displayed. However, new develop-
ments in computer graphics now make it possible to obtain a graphic dis-
play of numeric data. Many of these display techniques are quite diff-
erent from the ordinary line graph, bar chart, etc. and therefore could
have a number of exciting applications in structural design.

Proposed Method of Study

This paper will have a two-fold purpose. The first and primary
purpose will be to investigate a form of computer graphics and its poten-
tial as a tool in understanding structural behavior. A secondary
purpose will be to condense, organize and translate a great deal of the
technical information about computer graphics into a form which will
hopefully be more comprehensible to the non-technical person. This
person may then more readily grasp the potentials that exist in the
area of computer graphics.

This two-fold purpose should bring to light the possibilities inher-
ent in the coupling of existing computer graphic techniques with

previously computerized methods of structural analysis. This combination could well bridge the gap between the qualitative understanding of structural behavior and the quantification of that behavior.

The first chapter has introduced the past and present views of various architectural educators who are involved with the teaching of structural design, and who believe that students of architecture are not grasping the fundamentals of structural behavior. Their ideas and proposed solutions to this problem are covered, along with a brief history of the various teaching methods used in the past and those currently being tried. The basic strengths and weaknesses of those methods are discussed and utilized in support of the proposed combined application of computer analysis and computer graphics.

In Chapter II all the condensed technical information about computer graphics as it relates to the material in this paper will be presented. The majority of this information covers only the mechanics of operation of the various pieces of computer graphics machinery or hardware. The programs or software which direct the operation of this hardware will be briefly mentioned.

Chapter III will cover the particular computer graphics program to be used in this study. The program, which is called SYMAP, will be discussed in terms of its general characteristics and uses. A brief outline as to how the program analyzes and displays data will be discussed and shown in an example problem.

A lineprinter, which is one type of computer graphics hardware, and the SYMAP program will be investigated in Chapter IV to determine their usefulness as tools in the analysis of structural behavior. To determine this, an attempt will be made to duplicate the various internal forces that occur in a simply supported beam when it is subjected to a concen-

trated load at midspan. If the lineprinter and SYMAP program prove to be useful in a simple beam analysis, they may also be useful in the analysis of more complex structures since many of these structures are composed of numerous simple beams.

FOOTNOTES

[1]Henry J. Cowan, An Historical Outline of Architectural Science (New York, 1966), p. 48.

[2]James E. Ambrose, Building Structures Primer (New York, 1967), p. 5.

[3]Eduardo Tonoja, Philosophy of Structures, tr. J.J. Polivka and M. Polivka (Berkley, 1958), p. 2.

[4]Mario Salvadori and Robert Heller, Structure in Architecture (New York, 1962), foreword.

[5]H. Seymour Howard, Jr., Structure - An Architect's Approach (New York, 1966), p. VI.

[6]Ambrose, p. V.

[7]Philip A. Corkill, Homer L. Puderbaugh, H. Keith Sawyers, Structure and Architectural Design (Sernoll, 1965), preface.

[8]Ambrose, p. 5.

[9]Corkill, Puderbaugh and Sawyers, p. 21.

[10]Torroja, p. 20.

[11]Corkill, Puderbaugh and Sawyers, p. 21.

[12]Peter M. Green, "An Old School Tries a New Technique", Progressive Architecture, February, 1967, p. 136.

[13]Salvadori and Heller, foreword.

[14]William A. Little and Kenneth F. Reinschmidt, "Engineer's Notebook", Civil Engineering - ASCE, August, 1965, p. 71.

[15]Ivan E. Sutherland, "Sketchpad: A Man-Machine Graphical Communication System", Massachusetts Institute of Technology, Lincoln Laboratory, Technical Report No. 296 (Lexington, 1963), p. 65.

CHAPTER II

TERMINOLOGY OF COMPUTER GRAPHICS

In the early spring of 1961, I. E. Sutherland began investigation of his now classic Sketchpad: A Man-Machine Graphical Communication System. By eliminating typed statements in favor of line drawings, the sketchpad system opened up a new area of man-machine communication. While Sutherland, Steven Coons, and Timothy Johnson were working on the TX-2, in M.I.T.'s Lincoln Laboratory, another team composed of Don Hart and Ed Jack was developing the DAC-1 system at General Motors.

The growth of computer graphics since these pioneering efforts ten years ago is staggering both in terms of hardware and software. An unbelievable number of manufacturers are producing computer graphic hardware. Such devices as plotters, cathode ray tubes, light pens, electronic tablets, joy sticks, and even a device called a "mouse" are becoming common place pieces of peripheral equipment. Software developments have progressed from the simple description of objects as transparent wire frames to their description in surfaces of opaque halftone colors that have textures and shadows. Work is now going on with the use of radar controlled headsets that allow a designer to rotate a computer generated picture on a CRT screen by simply moving his head.[1]

A complete discussion of computer graphics in relation to digital computers would include such areas as data structure, data retrieval systems, pattern recognition systems, optical scanners, and a wealth of information about computer generated pictures using the cathode ray tube.

For these reasons the following material contains only that information which for the most part is relevant to the ideas discussed in Chapters III, IV, and V.

Unfortunately, when one is trying to explore the field of computers and computer graphics he finds it somewhat bewildering and frustrating. Articles about computer graphics appear in a vast diversity of obscure journals and individual papers which are totally unrelated, difficult to obtain and highly technical. In addition, the terminology used in most of these articles is a language of abbreviations, symbols and many other unfamiliar terms. Fortunately, to have a basic understanding of computer graphics hardware, related peripheral equipment, and software techniques it is not necessary to learn a great deal of new terminology.

The present chapter is an attempt to present a brief description of computer graphic terminology which has been condensed, translated and organized from many different sources.

The three most common means of producing a graphical representation of data from a computer are through a lineprinter, a plotter or a cathode ray tube (CRT). In most instances the plotter and CRT are used to compliment the printer. This pattern is quickly changing as the cost, efficiency and versatility of plotters and CRT's continue to become more competitive with the lineprinter.[2]

The Lineprinter

The lineprinter was one of the first means by which alphanumeric information could be extracted from a digital computer. As the name implies a lineprinter prints one complete line of alphanumeric character at a time.[3] A typewriter can achieve the same effect but it can only print one character at a time.

Most lineprinters will print 132 alphanumeric characters per line

on paper which is 13 inches wide. Each line is printed as a continuous ream of paper advances line by line in one direction past either type bars or type cylinders. Type bars and cylinders are constructed and operate in a rather unique matter. A type cylinder has 132 bands of characters along its 13 inch length. Each band contains an identical set of characters. A standard band contains 51 characters which are arranged in a checkerboard pattern so that they are separated from characters on adjacent bands by approximately 1/8 inch. This space reduces the possibility of smudges which are caused by characters on bands adjacent to the one being printed. A character on each band is selected by electronic signals from the central processor unit of the computer. When a character has been selected for every band, the line is printed. This entire process requires only .3 of a second on the newer printers which operate at 1400 lines per minute.[4] Generally, a lineprinter will only be equiped with upper case letters, the digits 0 to 9 and a number of punctuation characters and symbols which are common to all typewriters.

Lineprinters can operate either on-line or off-line with the computer, but they are completely non-interactive. In other words, when a lineprinter or any type of extra equipment is electrically connected into a complete computer system it is referred to as being "on-line" with the computer. If it is not connected directly into the system it is referred to as being "off-line". An interactive piece of equipment is one which is capable of both supplying information to a computer and retrieving information from a computer. In addition, this exchange should take place fast enough to give the user the feeling that he is conversing with the computer system.

Aside from simple graphics produced with the various symbols such as asterisks and periods, printers were seldom used to produce any

graphic displays. Finally someone noticed that by overlaying characters, different tones or shades of grays could be achieved. In the fall of 1963, Howard T. Fisher, working at Northwestern Technological Institute, developed such a program under the name Synagraphic Mapping System, or SYMAP.

SYMAP is a computer program which graphically depicts any quantitative or qualitative information.[5] It is generally used to produce maps, but is suited to a broad range of applications. Numerous options make the program flexible enough to meet widely varying requirements. For example, one particular option will produce a map with 10 different shades of gray. The lighter areas are produced by the printing of some punctuation character, such as the period. The darker areas are the result of overprinting more than one character.

The Laboratory for Computer Graphics and Spatial Analysis at Harvard has been the prime developer of SYMAP. This organization was established in 1965 and based the majority of its early works on SYMAP. A very good description of their efforts is available in their book entitled Laboratory for Computer Graphics and Spatial Analysis - Selected Projects, by William Warntz.

One of the most interesting uses of SYMAP was conducted by Robert Stevens at Harvard. His paper entitled, "Four Dimensional Mapping: One Variable Represented in Three-Dimensional Space," demonstrates SYMAP being used to represent data three-dimensionally. A cubic assembly of small wooden blocks were stacked together to form the study area. Every surface of each block had some SYMAP output mounted on it. Data fluctuations are not only visible on the surface, but can be seen internally by the removal of one or more of the cubes.[6]

Allen Bernholtz's program RUMOR uses SYMAP in yet another application.

By setting up a desired inter-relationship between different areas and feeding them into a computer a number of floor plans will be randomly generated. Mr. Bernholtz then uses SYMAP to display these randomly generated physical arrangements.[7]

Thus far, SYMAP has been the greatest single factor in the success of the printer as a means of graphical output.

<div align="center">The Plotter</div>

The digital plotter, like the lineprinter, is a non-interactive piece of computer graphics hardware. It also can be operated on-line or off-line with the main computer unit. Due to its ability to "draw , it has become of great interest to architects and engineers as a slave machine to replace the draftsman.

Plotters take two distinct physical forms which are referred to as the "drum" type and the "flat-bed" type.[8] As the name indicates, a drum type plotter consists of about a 6" drum on which paper is mounted and able to rotate forward and backwards. A pen is mounted directly above the drum and moves sideways across the length of the drum. With the combination of the drum moving formard and backwards plus the pen moving the length of the drum, a line of any shape can be produced. Drum plotters range in size from 11-25.55 inches in width and are able to handle a 120 foot roll of paper.

Flat-bed plotters operate in a little different manner. The paper is taped to the bed of the plotter and remains stationary. Some flat-bed plotters use a vacuum system on the bed of the plotter to hold the paper in place. The pen is mounted on a parallel bar that spans the width of the plotter and can move along the parallel bar. With this combination of a moving parallel bar and a moving pen, it is also possible

to produce lines of any shape. The most common flat-bed plotters have workable surface areas which range from 35" X 30" to 72" X 54".

Both of these machines are very entertaining to watch and can perform virtually the same tasks. Flat-bed plotters are a little more versatile in that they are able to use any type of paper to draw on, while a drum plotter requires paper which has a continuous series of holes on both sides. These holes keep the paper stationary on the drum. Another slight advantage of the flat-bed plotter is being able to view the whole drawing surface at all times. For most people, however, these advantages do not offset the increased cost and floor area which are required for the flat-bed plotter.

Ball-point pens, felt-tip pens and rapidograph ink pens can all be used by either plotter. There is generally only one pen per plotter, but some of the new plotters use a series of four pens mounted side by side. Pen movement is controlled by various instructions from the main computer system. These instructions simply identify where the pen should move to and whether this movement should take place with the pen against the paper or slightly away from the paper. On the plotters with multiple pens, each pen is operated independently from the others in the same manner.

The movement of the pen takes place in sequence of incremental, zig-zag steps. On the earlier plotters a curved line would always appear as a series of zig-zag lines. This zig-zag effect was a result of the plotter's movements being a series of incremental steps in a limited number of directions. An incremental step is the shortest line a plotter can draw and is determined by the gear ratio in the plotter. In the earlier plotters the smallest increment was 0.01 of an inch in an 8-vector format. The newer plotters have reduced this to 0.005 and even

0.001 of an inch, and they have also increased to a 24-vector format.
In addition to these improvements, plotting speeds have increased over 8
times. The first digital plotters had a maximum operating speed of 200-
300 increments per second. Cal Comp's new 700 series Zip-Mode plotters
can plot at speeds up to 1687 increments per second. In terms of inches-
per-second for increments of 0.005 this would break down to 6.5 inches-
per-second along the horizontal-vertical axis and 9.1 inches-per-
second along the diagonal axis.

Since digital plotters cannot possibly keep up with the speed of
the main computer, on-line plotting is very costly. Off-line plotting
is far less expensive in terms of computer time and it enables repeated
plotting of the same information without additional computer time. In
the past most plotting was done on-line with a small computer to drive
the plotters. Today many systems have a combination magnetic tape unit
and plotter. With these units the data to be plotted is recorded on
magnetic tape by the main computer and played back on the tape unit
which is connected to the plotter.

Cal Comp (California Computer Products, Inc.) was one of the first
producers of plotting equipment. Today they are probably the largest
corporation dealing in computer graphics. Their hardware line includes:
drum plotters, flat-bed plotters, disc drive units, tape units, visual
monitors and microfilm units. In addition, they offer 3000 basic plot-
ting software packages in their library. These packages contain such
things as: circles, spirals, dashed lines, ellipses, polygons, dimension
lines (with arrow heads, centerlines, bar graphs, shading between lines,
smooth curves through a set of data points, perspective views of func-
tions, and even stereo drawing that have to be viewed through red and
blue stereo glasses.

One other very unique type of digital plotter which will only be mentioned is a laser beam plotter. A laser-graphics plotter operates by exposing a photographic film to a small beam of laser light. This small beam of light, either 0.005 or 0.01 inches in diameter, is swept across a piece of film 42 inches wide. The sweep is a linear sweep with 8000 individual dot locations for the 0.005 inch diameter spot. This size sweep will produce a resolution of 200 lines per inch. After each sweep the film is advanced 0.005 inches and the process is repeated. Since each dot may have as many as 16 intensities from white to black, the resulting picture is capable of a tonal range of 16 intensity levels. A black and white TV only has about 10 intensity levels. The plotters speed is equally as amazing. Moving in only 0.005 inch increments, it can completely expose 100 feet of film 42" wide in 35 minutes.

If it were not for the high costs involved in buying and operating these plotters, they could become a fantastic tool in graphical communications.

<center>The Cathode Ray Tube</center>

The last and perhaps the most significant piece of computer graphics hardware to be discussed is the Cathode Ray Tube (CRT). When someone refers to a "dynamic display" he is probably referring to some type of CRT display unit. It is the only piece of computer graphics equipment which is interactive and capable of creating a dynamic exchange of information with the user. The CRT is to date the most direct and effective means of man-machine interface.

Even though a complete understanding of how a CRT works is not important, a little knowledge is helpful and as the saying goes - dangerous. The CRT is composed of three main parts. These are a controllable

source of electrons (cathode rays), an electronic optical section and a screen or target. See figure 4.
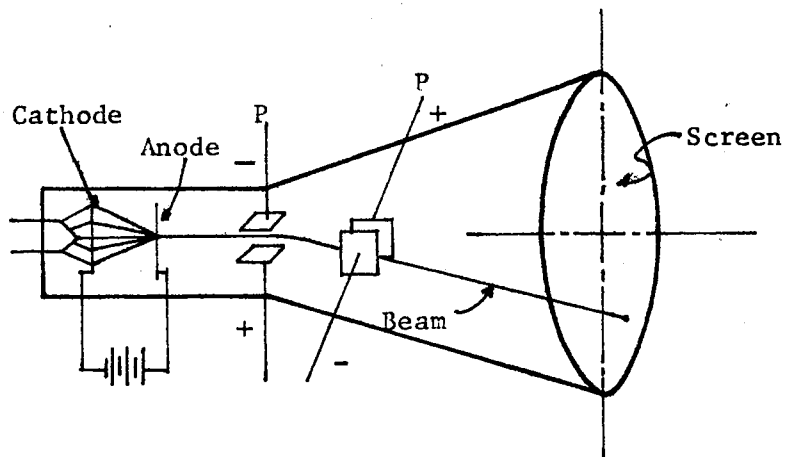
Figure 4. Cathode Ray Tube

The electrons emitted by the cathode are formed into a beam, focused, and directed to a screen by a combination of electronic and magnetic fields as it passes between plates P1 and P2. The screen is coated with a calhodoluminescent phosphor and will glow for about one twentieth of a second when struck by a cathode ray. Because of this fast decay rate the screen must be scanned 20-40 times per second to maintain a flicker free picture.[9]

The way in which the cathode ray scans the screen and ultimately forms a picture indicates the type of CRT being used. If the beams scan the screen from left to right and top to bottom, the CRT is called a raster display. Standard television sets use this method of display. The other type of display is referred to as a calligraphic display and forms the desired picture by moving from place to place in a pattern which traces out the individual lines and characters of the picture. In

other words, a raster display works in a set sequence and a calligraphic display works in a random pattern. Since a raster display is much less costly it is the more commonly used.[10]

A basic change occurs in a raster display unit when it is connected to a digital computer. The normal continuous beam scan is replaced by a matrix dot structure. The light on the screen still appears to be the same but if the screen were magnified it would be easy to see that each line is a series of tiny dots instead of a usual unbroken line of light. This structure, which is approximately a 1000 X 1000 matrix of 0.002 diameter dots at a minimum, is used to form any images whether they are letters, numbers, lines or curves.[11]

In the past the big disadvantage in using a CRT with a digital computer was the constant regeneration of the image on the screen. This constant regeneration tied up a large segment of the computer memory unit. Fortunately, some of the new CRT units have screens that are capable of storing a picture for hours at a time. This is accomplished by coating the screen with a special phospher which has a very slow decay rate. Since the image on the screen does not need to be constantly regenerated, the computers memory is free to perform other operations. Other new CRT units are equipped with a small memory which does nothing but constantly regenerate the image being displayed on the screen.[12]

Both of these new systems have a few disadvantages, but they are completely overshadowed by two things. One is the distance these units can be located from the central computer system and the other is cost. Early model CRT's had to be located no further than 2500 feet from a main computer. Since either of these new CRT units can be operated over telephone lines, they can be located thousands of miles from the computer.

The new CRT units cost from $10,000-$13,000 depending on the amount of peripheral equipment attached to them. This is quite a decrease when compared to the old CRT units such as IBM's 2250 which cost about $50,000. An even bigger savings is in the amount of computer time use. The new CRT units need only a few minutes of computer time for every hour of display time. On the old CRT units an hour of display time meant an hour of computer time. At $500-$600 per hour this can mean a fantastic savings.

All of the above simply explains how a CRT works, but it does not explain how it works the computer. A CRT is only a device for communication between the computer and the user. It cannot solve any problems. A computer must do all the problem solving and send the answers through the CRT. If it were not for the peripheral equipment which permits the interaction with CRT units, they would lose much of their usefulness as a dynamic tool in the man-machine interface.

The peripheral equipment which are normally used with a CRT include the light pen, the Stanford Mouse, the Rand tablet, the Sylvania tablet, the Grafcon tablet, the M.I.T.-3D Ball, the Lincoln Wand, a joystick, function switches and a normal keyboard. These are all "input" devices to the main computer and the CRT becomes the "output" device. A simple version of this combination is shown in figure 5. Even though it would probably be possible to have all these devices coordinated to work with one CRT, it is highly unlikely the combination would ever exist. The main reason being that some of the devices duplicate each other. For instance, the "mouse" and the joystick tend to perform the same function. The light pen, function switches and keyboard are most commonly used with a CRT unit.
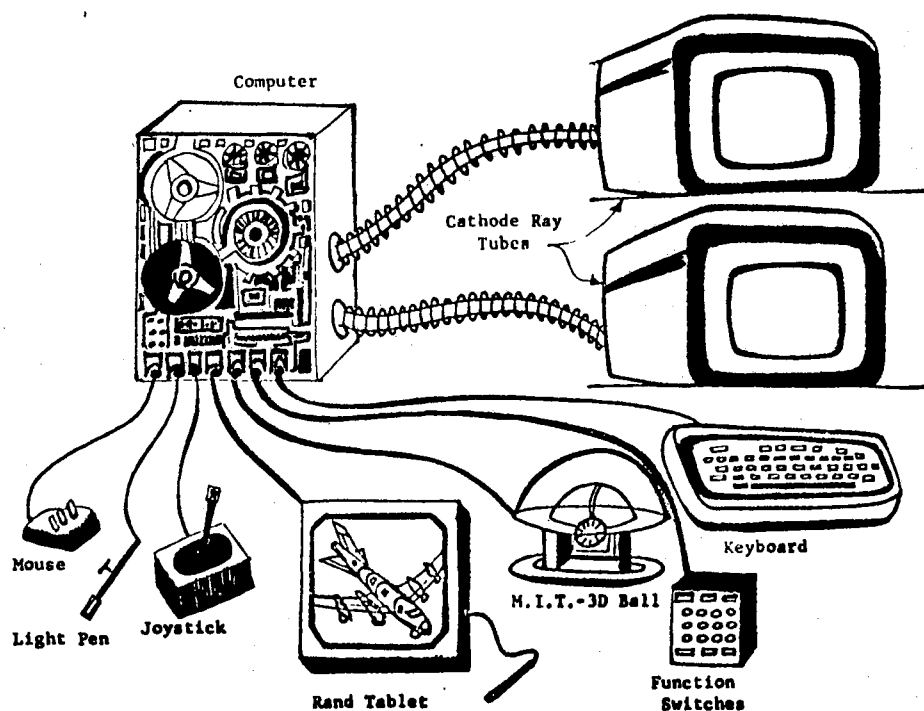
Figure 5. Computer, Peripheral Equipment and CRT Units

The light pen has proven to be the most important and useful of the peripheral input devices. The pen is a hard-held photocell which will report to the computer whenever an electronic beam on the display screen falls within its field of view. The photocell is about the size of a fountain pen and looks very much like a pen, hence the name. Figure 6 shows a diagram of the light pen used by Ivan Sutherland while he was working on his Sketchpad system.[13] This particular pen does not have to be held directly against the surface of the screen as do some types of light pens. The pen was designed so its amplifier would only be sensitive to the brigh blue flash of the first intensification of a spot of the screen and not to the dim yellow afterglow.

CATHODE RAY TUBE SCREEN

DISPLAYED POINT (BRIGHT DOT)

SHUTTER

SHUTTER BUTTON

POWER DC COUPLED / SIGNAL AC COUPLED } SAME WIRE

CONNECTOR

COAXIAL CABLE

LENS

FIELD-OF-VIEW

PHOTO DIODE

FOR SMALLER FIELD-OF-VIEW, ROTATE BARREL TO MOVE DIODE BACK FROM LENS

SPLIT SHELL FOR REMOVAL OF PEN CAP FROM CABLE

TRANSISTOR PREAMPLIFIER
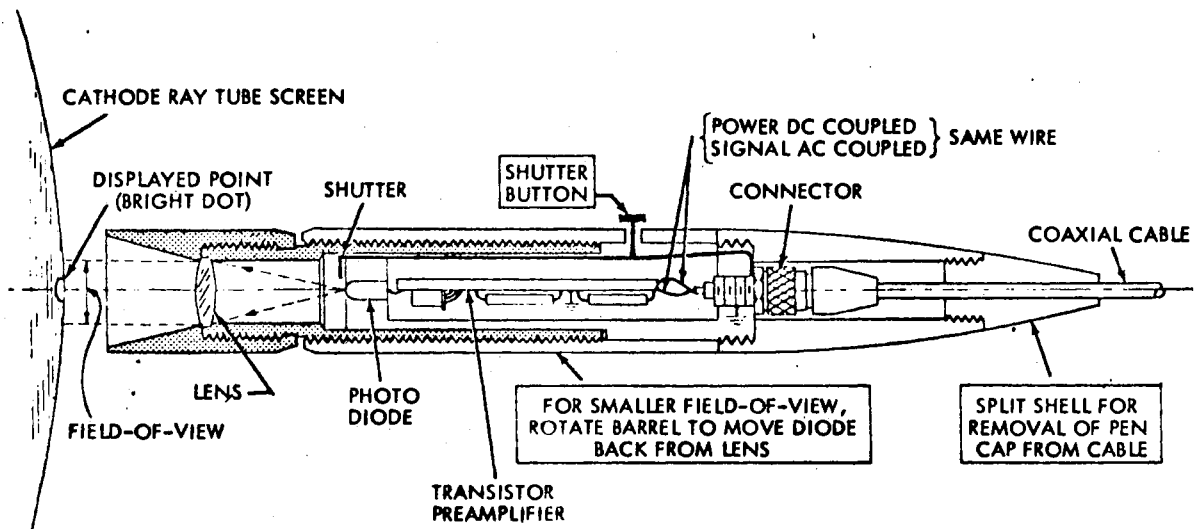
Figure 6. Cross Section of Light Pen

When watching the operation of the light pen it appears to be "drawing" on the CRT screen. This gives the impression that the light pen is feeding electronic impulses into the computer when actually the pen is picking up one light dot from the screen and letting the computer determine the X-Y coordinates of that dot. The information that a person wishes to relay or retrieve from this position is then assigned to this dot position.

The information that is assigned to a dot is normally transferred to the computer by either function switches or keyboard. Function switches generally occur in some combination with a CRT in circuits of about 30 switches. In addition to performing operational functions, they can be used to get the computer ready for some particular action. An example of their use occurs when the user would like the computer to store all the information which is on the screen of the CRT. The user would simply press the function key marked "store" and the information which was needed to generate the picture would be stored in the computers data

bank.

A keyboard operates in much the same fashion as do function switches, but they have greater versatility. Instead of being able to handle only a limited number of operations they can be used to type any information the computer has been programmed to accept. As mentioned in the previous example, if some information on the screen of the CRT needed to be stored, one function switch marked "store" could relay the command to the computer. When a keyboard is being used instead of function switches, the word "store" would have to be typed out. In this case using function switches would be more convenient, but if the information needs to be stored and used in another program the keyboard could easily type this more detailed information to the computer.

The remainder of the peripheral equipment to be discussed has only recently become available on the open market. For the most part, they are rather unique devices that have been used only in research.

The Sylvania Tablet, Rand Pad and Grafcon Tablet are all trade names to describe a flat tablet with an electronic stylus.[14] As the stylus is moved across the tablet, its path is recorded as a series of points and each point is assigned an X-Y coordinate. Because the stylus does not have to touch the surface of the table or tablet, a drawing can be placed on its surface and traced with the stylus. In this manner each line of a drawing can be assigned an X-Y coordinate and its location can be sent to the computers memory unit.

The tablets are fast, accurate and can easily be connected to a computer. Their primary limitation is the high cost and small size of the tablet - about 12 X 12 inches.

Another similar device is an optical scanner. Optical scanners are electronic reading devices which can recognize alphanumeric or

drawn information on paper and translate that information into electri-

cal impulses that are then transmitted to the computer. When this equip-

ment is perfected to its ultimate, it will be able to transfer an indiv-

idual's handwriting or sketches directly from paper to the computer.

This could eventually eliminate the need for punched cards.

Other closely related pieces of peripheral equipment are the

Stanford Mouse, the M.I.T.-3D Ball, and the joystick.[15] Using similar

methods of operation they all function as steering devices for someone

to maneuver an object on the screen of a CRT.

The Stanford Mouse was developed at the Stanford Research Institute

by Doublas C. Englebart, and it has the physical appearance of being a

small mechanical mouse with two wheels at right angles to each other

mounted in the bottom. If it is placed on a flat surface and pushed

forward, backwards or sideways, the wheels will turn one at a time. When

it is moved at some **angle**, both wheels will turn. If the mouse is used

in conjunction with a CRT, the position of a point of light along the

X-Y coordinates of the screen can be controlled. This controlled point

of light can thus be used in the same manner as a light pen.

The M.I.T.-3D Ball is a mounted sphere about 6 inches in diameter

which can be rotated in any direction. The rotation of the sphere will

rotate an object on the screen of a CRT. Where the Stanford Mouse only

provides movements in the X-Y plane, the M.I.T.-3D Ball will accomplish

rotation above the X,Y and Z plane.

The joystick is a small lever device which is about the size of the

Stanford Mouse. The similarity of a joystick to air and space craft

controls make it particularly useful in simulated aerospace vehicle

maneuvering display units. Positioning accuracy of the joystick is gen-

erally superior to that of a light pen, but it is not particularly useful

in sketching applications.

Future Developments

This chapter has contained only a brief discussion of the three most widely used pieces of computer graphics hardware and some of the peripheral equipment and software which must be part of a total computer graphics system. The lineprinter was the first efficient means of communicating with the computer, but it is somewhat limited as a tool in the graphics area. The main improvements on newer models seem to be increased speed with no greater variety on types of characters.

The plotter was the most used piece of computer graphic equipment for a number of years. The plotter is still relatively slow, but it is capable of drawing a variety of forms. If equipment and operating cost can be reduced on the laser beam plotter, it could have a profound influence on plotting systems. The great speed of the laser beam plotter makes it an ideal partner for a CRT unit.

The CRT is by far the most dynamic piece of computer graphics equipment. It is the only interactive graphics hardware and can give the user a feeling of actually working directly with the computer. Growth in this area has been fantastic during the last five years and should continue for some time. The possibilities and potentials that exist with its use in structural design are quite exciting and will be further discussed in Chapter V.

To date the most astounding application the author has personally witnessed is a film called "City-Scape". The film was produced at the Visual Simulation Laboratory of General Electric by Peter Kamnitzer and Rod Rougelot. The impression is the same as if a TV camera is moving about in a very modern city. Everything is in color and three-dimensional Even when one knows that things like this are possible, it is a little

startling to view a city which exists only as electrical impulses in the computer.

FOOTNOTES

[1]Nicholas Negroponte, The Architecture Machine (Cambridge, 1970),
p. 37.

[2]Frank Skinner, "History of Computer Graphics", Computer Graphics
in Architecture and Design, ed. Murry Milne (New Haven, 1969), p. 8.

[3]Ibid., p. 2.

[4]Charles J. Sippl, Computer Dictionary and Handbook (Indianapolis,
1966), p. 337.

[5]Reference Manual For Synagraphic Computer Mapping (Version V,
Cambridge), p. 5.

[6]William Warntz, Laboratory for Computer Graphics and Spatial
Analysis - Selected Projects (Cambridge, 1969), p.III.67.

[7]Ibid., p. IV.2.

[8]David Campion, Computers in Architectural Design (London, 1968),
p. 71.

[9]Herman W. Pollack, Applied Physics (Englewood Cliffs, 1964), p. 566

[10]Ivan E. Sutherland, "Computer Displays", Scientific America, June,
1970, p. 57.

[11]Ibid., p. 59.

[12]"Visual Information Display Systems - A Survey", National Aeronau-
tics and Space Administration, NASA SP-5049 (Philadelphia, 1968), p. 11.

[13]Sutherland, p. 26.

[14]Skinner, p. 3.

[15]Ibid.

CHAPTER III

CHARACTERISTICS OF SYMAP

As mentioned in Chapter II, the program called SYMAP, synagraphic

mapping system, has been the greatest single factor in the success of

the printer as a producer of computer maps. This program has recently

been modified so the same data displayed by the printer can now be

displayed as a three dimensional line-drawing by a plotter. An example

of each of these techniques for data display can be seen in figures

7 and 8.
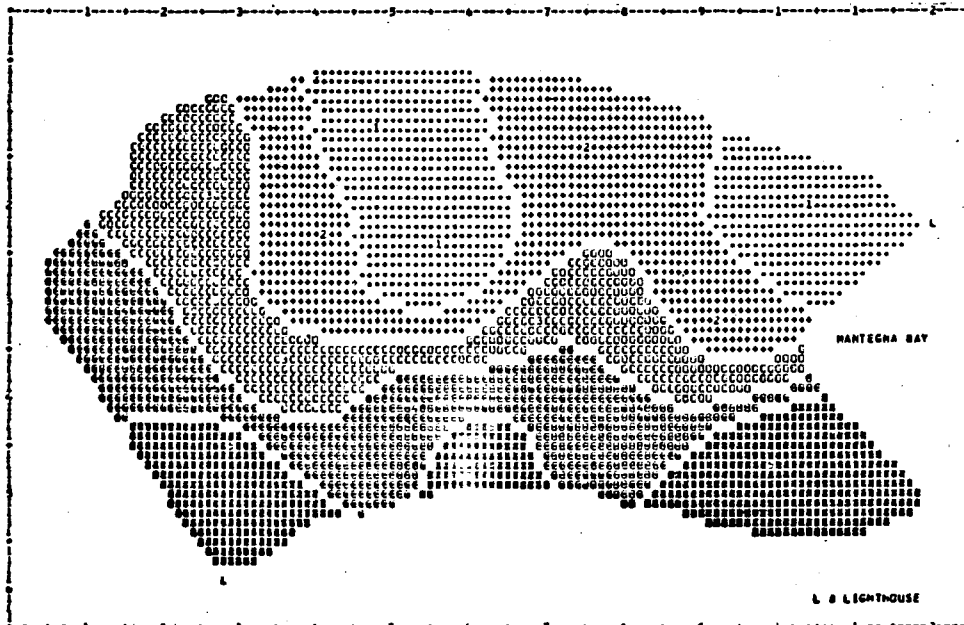
Figure 7.   SYMAP Output Using Printer
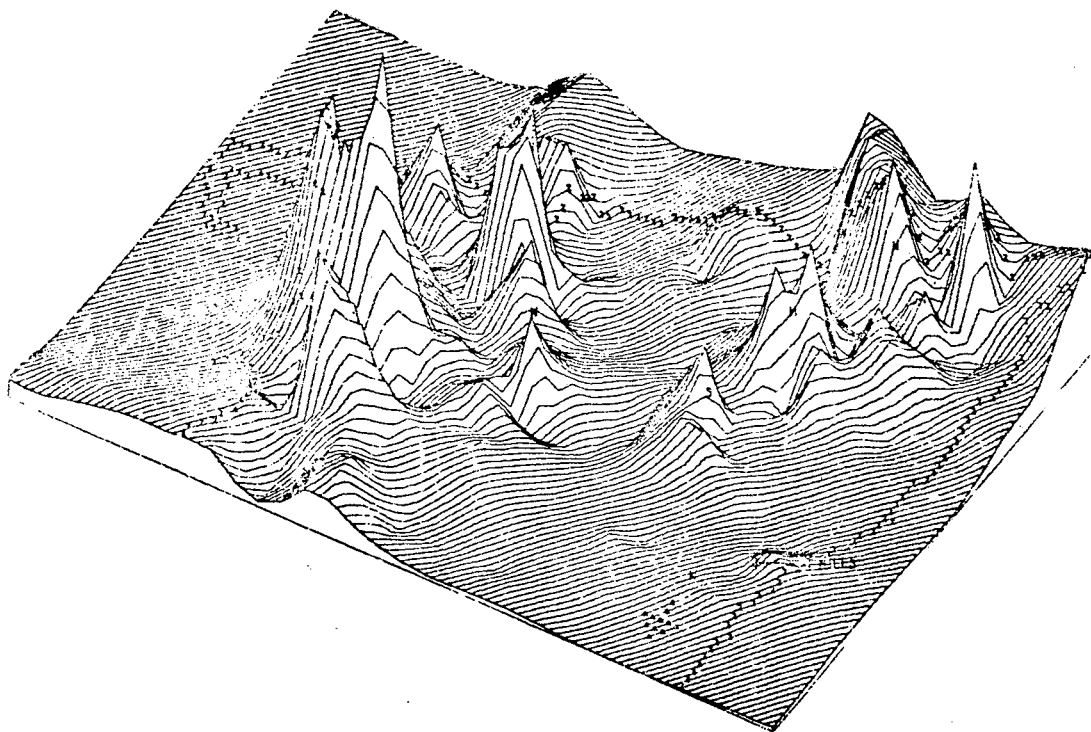
Figure 8.   SYMAP Output Using Plotter

The reference manual for SYMAP describes the program as "... a

computer program for producing maps which graphically depict spatially

disposed quantitative and qualitative information."[1] The manual goes on

to say that due to the many options in the program it is suited to a

broad range of applications of widely varying requirements. However,

the most intensive use of SYMAP has been in the area of city planning.

One of the first maps that Mr. Fisher produced with his program in 1964

showed 352 people living in a block containing only 8 houses. Mr. Fisher

was using data from the Census Bureau and later verified that this was a

mistake in the census of 1960. Since that time countless maps have been

produced showing distribution of population, pollution, segregation,

traffic, crime and many other quantities of data that need to be mapped in the study of cities.

The success of SYMAP in this capacity has been due to the speed, low cost, and efficiency of computer mapping. The cartographer's efforts in transforming complex statistical information to visually usable maps has been reduced from a three day or three month endeavor to an unbelievable map a minute or second. With maps easier to make, more data is being collected and analyzed which should lead to better solutions of complex problems.

<p align="center">Program Capabilities</p>

The SYMAP program is over five thousand cards in length and written in a computer language called Fortran IV. It is able to take data of any kind and produce three basic types of maps. These maps are referred to as a contour map, a conformant map and a proximal map. A SYMAP contour map looks very much like a normal contour map except, instead of only lines to indicate all points of the same numeric value, shades of gray are used to express the contour. Figure 7 is an example of a SYMAP contour map. The SYMAP manual suggests that since a continuous variation between two contour lines is assumed, the contour map should be used only to represent continuous information, such as topography, rainfall and population density.

Conformant maps are based on a different principle than are the contour maps, and take on a different appearance. By confining itself to the boundaries of data zones or areas, it is well suited for qualitative or quantitative data whose areal limits are important and the representation as a continuous surface is inappropriate. By making each data zone a predefined spatial unit, the whole unit can be given the same value, and the appropriate symbolism is assigned the same value

according to the numeric class the unit is in. Variation of the data from one edge to another will not be apparent, but on the average, they will be correct. To a large extent this depends on the number of data points being used.

The last type of map which can be produced is the proximal map. It looks very similar to a conformant map, but is based on point information and the nearest neighbor concept. The value of each printed character on the finished map is determined by the data point nearest that character. Boundaries are formed where the values change and thus a map which looks like a conformant map is produced.

To what extent each type of map might be effective and useful in structural design or the teaching of structural behavior will be investigated in Chapter IV.

Data Requirements

Even though the SYMAP program is based on the fundamental properties of maps, the program will accept and manipulate data related to points, lines or areas, and does not demand that the user organize his data according to any rigid set of arbitrary or prescribed practice. A standard data format is normally used, but if data of another format needs to be used the program can easily be modified to accept it.

Location of where data originates must be specified in terms of some coordinate system. It is standard to use an X-Y coordinate system but again the user can specify any type of coordinate system and use any type of measuring unit to express or define the relationship between data points. For normal map making, measuring units such as miles, feet, inches, meters, longitude and latitude are used.

The flexibility of SYMAP is provided by the use of over twenty-five options by which a user can utilize data to produce maps unique to his

specific purposes. These options have been chosen on their applicability to most mapping situations and will provide variation in map scale, size, type of symbols, number of data levels, percentage of data to different levels and a number of other items. Only a limited number of the options are necessary to produce a map and the need to use every option for a single map would probably never occur.

In addition to the flexibility provided by these options, the SYMAP program also includes a special subroutine called FLEXIN. By using this subroutine various mathematical methods can be employed to change existing data. Using various mathematical methods such as addition, subtraction, multiplication and division, data can be combined to form new information about an area. This new information can then be mapped in the same fashion as the original data.

With the combinations of these separate features in the program - three types of maps, 25 options for each map and the subroutine FLEXIN - it would be possible to produce hundreds of different maps from the same data. Once the outline of an area has been coded from a coordinate system and stored in the computer's memory along with data about the area, a whole series of maps can be quickly produced. In this manner many different studies of the same area are inexpensively produced. The economic advantage is usually lost, however, if the data or map is made only once.

Once all the decisions as to the type of map, size, scale, etc. are made, the data is transfered to computer cards and organized into different groups called "packages". The data in each package covers a specific type of information about the future map or maps. The titles of these packages and the sequence in which they must be used are as follows:
A-OUTLINE, A-CONFORMOLINES, B-DATA POINTS, C-OTOLEGENDS, D-BARRIERS,

E-VALUES, El-VALUES, and F-MAP. A more detailed explanation of each

package can be found in Appendix A.

Of these eight packages it is not mandatory that they all be used

at one time. For a normal contour map it is only necessary to include

the A-OUTLINE, B-DATA, E-VALUES and the F-MAP packages. If special

legends or symbols are required the C-OTOLEGENDS package would be

included. Since the F-MAP package controls all the options available

in the program, it is required for each map desired.

Map Scale

Studies using SYMAP have included a small living cell, land parcels,

blocks and tracts of land, towns, states and continents. The factor

common to all of these studies was the spatial distribution of variables

and a need to display the patterns these variables caused. Supposedly

applications of SYMAP are independent of the scale at which one wishes

to display data. In a sense this is true but only if the physical size

of the finished map is also taken into account.

The importance of this scale-to-size relationship can probably be

better understood by looking at the space occupied by each character on

a lineprinter. Refer to figure 9. A standard printer set to print 6

rows per inch will produce characters located in rows one-sixth inch in

height and columns one-tenth in width. This fixed cell size of one-

sixth by one-tenth inch is the same for all characters. Thus each map

is a composite grid of character cells. It is therefore important to

remember that an area can be made only so small before the character

sizes begin to effect the validity of the displayed data.
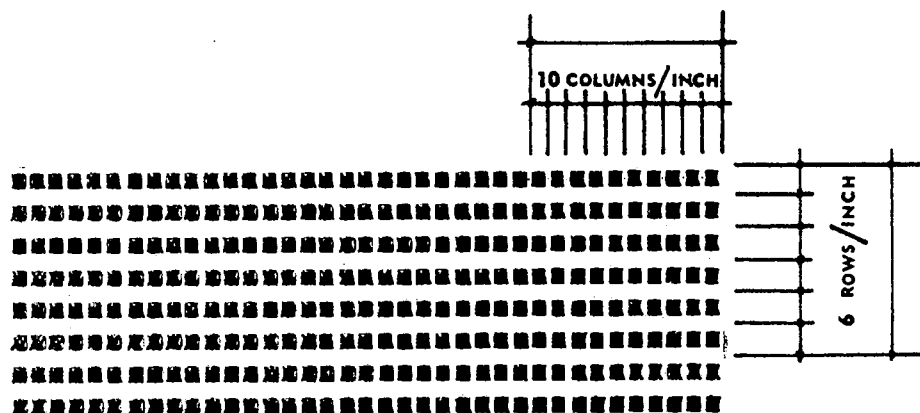
Figure 9. Character Size

This character size limitation does not mean that a small area cannot be studied, however. The area simply has to be scaled to a size large enough to compensate for any discrepancies due to character size. Maps which have been coded at a certain scale can be rescaled by using one of the options in the program.

Even though a printer is only 13 inches wide, maps of any length or width can theoretically be produced. This is accomplished by taping sections of the printer paper together to increase the width. If no specific size of map is called for, the program will make maps up to six feet wide or long. This dimension can be increased by using one of the twenty-five previously mentioned options.

Data Points

Data points are the points on the study area for which data is available and used. The location of data points is left arbitrarily up to the user. In most cases data points are located in the centers of areas or they are distributed evenly over a large area. However, since this is not a mandatory requirement, it is always important to know the exact location of all data points before drawing any conclusions from a

map produced by SYMAP.

The number of data points used in a study area can become as important as their location. If too few points are used the distributed data will cover too large an area and cause inaccurate visual data patterns to be printed. Increasing the density of the data points will eventually have no effect on the final maps, but will increase the computer time necessary to produce them.

The distribution of data in the SYMAP program is carried out by a searching and selecting procedure in determining which data points are to be used and interpolated between. In the initial or primary search the computer will select five to eleven points based on the density and spread of the points. Using one point as a focus it selects a scanning radius which will on the average include seven points. Working from the focus point it then takes the difference in values between two points along with the distance between these two points and runs a standard interpolation to determine the location at which a balance occurs between the two points. This procedure is then repeated with the remaining six points. When all seven points have been analyzed, a new focus point is selected and the process is repeated. This continues until all the data points have been used as focus points.

The three options by which a user can control the initial search radius, the maximum search radius and the number of data points used for interpolation are perhaps the most important options a user can employ. With these three options the greatest degree of sensitivity can be gained from data to finished map.

The density and location of data points as well as an effective search radius which give meaningful interpretation of data for studying structural behavior will be investigated for the various types of maps

in Chapter IV.

Output

Typical Maps

The following example will be used to introduce the reader to the contour, the conformant, and the proximal maps and briefly explain some of the output information which is produced with each map.

The example area to be studied is shown in figure 10, and only the shape inside the rectangle will be considered. The outline of this shape could be that of a city, a building or a room. If only the contour and proximal maps were being investigated, the outline of the shape would be used and the interior divisions would not be used. However, since a conformant map will only work with more than one area at a time the divisions were necessary. The example area is deliberately being kept small so the output can be shown at full scale instead of a reduced scale.

EXAMPLE AREA
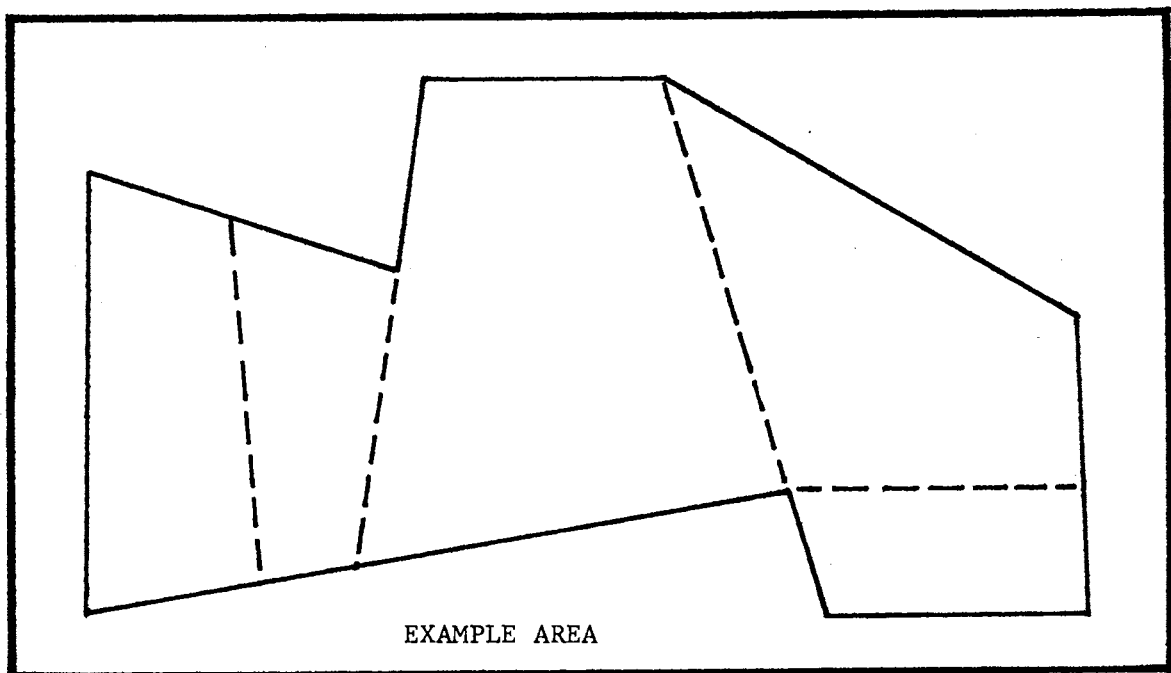
Figure 10. SYMAP Study Area

In figure 11 all the vertices, data points and legends have been referenced in an X-Y coordinate system. The particular scale for this map is the standard SYMAP scale of 8 rows per inch vertically and 10 columns per inch horizontally. Since the printer used in this study prints at 6 rows per inch instead of 8 rows per inch, the output will appear at 6 rows per inch. One of the options will be used to compensate for this difference.
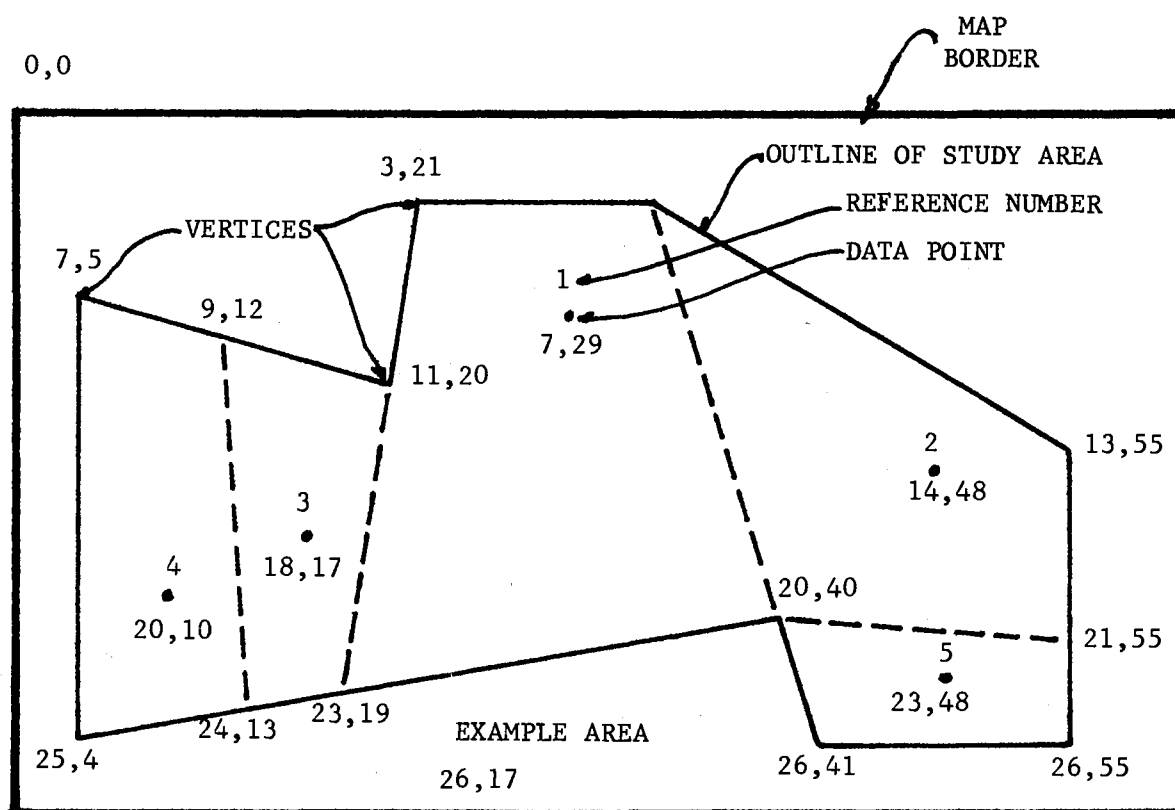
Figure 11.   X-Y Coordinates of Study Area

The information from Figure 11 is next organized and punched on computer cards and placed into the proper packages which will be needed to produce the maps. Table I shows the data and its arrangement in the various packages. The data was fed into the computer in the order it appears in Table I.

The A-OUTLINE package shows the coordinate location of the vertices on the study area. For the contour and proximal maps only the outside boundaries of the study area need to be defined. The inside areas were defined use in the A-CONFORMOLINES package. In either of these packages the first point must be described twice for the computer to identify the correct shape. The "9999" card which appears at the end of the A-OUTLINE package as well as the others is a code that signals the end of a package.

The B-DATA POINT package shows the locations of where the data goes and the E-VALUES package gives the value of that data. The first location in the B-DATA POINT array, the second value to the second location, etc.

The first line of the C-OTOLEGENDS package tells the computer to reserve 12 spaces for a legend which starts at location 26.,17. The second line contains the legend which will appear at that location. The legends are only those which will appear inside the map border. An elective in the F-MAP package controls legends outside the map border.

The F-MAP package gives the computer specific information about the maps to be produced. Such things as map size, scale, intensity levels and margins can be controlled using this package. An unlimited number of maps can be run using the data in the other packages, but one F-MAP package is required for each map produced.

TABLE I

SYMAP DATA

A-OUTLINE

3.	21.
3.	34.
15.	55.
26.	55.
26.	41.
20.	40.
25.	4.
7.	5.
11.	20.
3.	21.

99999
B -DATA POINTS

7.	29.
14.	48.
18.	17.
20.	10.
23.	48.

99999
C -OTOLEGENDS

12	P	26.	17.

EXAMPLE AREA
99999
E-VALUES

0.
93.
22.
43.
71.

99999
F-MAP
C EXAMPLE MAPS FOR THESIS
C APRIL 19, 1971
C TONY R. WHITE

1	3.5	6.		
2	0.	0.	3.5	6.
8				
13	1.			
14	0.	0.	0.	0.
15	6.	10.		
26				
27				

99999
F-MAP
C EXAMPLE MAPS FOR THESIS
C APRIL 19, 1971
C TONY R. WHITE

1	3.5	6.		
2	0.	0.	3.5	6.

TABLE I (CONTINUED)

```
    8
   13            1.
   14            0.           0.           0.           0.
   15            6.          10.
   26
   31
   36
   37
99999
A-CONFORMOLINES
    1     A      3.          21.
                 3.          34.
                20.          40.
                23.          19.
                 3.          21.
    2     A      3.          34.
                13.          55.
                21.          55.
                20.          40.
                 3.          34.
    3     A      9.          12.
                11.          20.
                23.          19.
                24.          13.
                 9.          12.
    4     A      7.           5.
                 9.          12.
                24.          13.
                25.           4.
                 7.           5.
    5     A     20.          40.
                21.          55.
                26.          55.
                26.          41.
                20.          40.
99999
F-MAP
C EXAMPLE MAPS FOR THESIS
C APRIL 19, 1971
C TONY R. WHITE
    8
   13            1.
   15            6.          10.
   26
99999
999999
```

Figure 12. Contour Map

Figure 13. Proximal Map

```
*-----+-----1-----+----2----+----3----+----4----+----5----+----*
I                                                              I
I                        ................                      I
I                        ................▓▓▓                   I
I                        .................▓▓▓▓▓                 I
+      ౧                 ..........1......▓▓▓▓▓▓▓               +
I    υυυυ౦౧౫             ...............▓▓▓▓▓▓▓▓▓               I
I    ౧౦౦౦౦౫౫౫+++         ...............▓▓▓▓▓▓▓▓▓▓▓             I
I    ౧౦౦౦౦౫౫౫++++++      ................▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓       I
I    ౧౦౦౦౦౫౫౫++++++      .................▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓      I
1    ౧౦౦౦౦౫౫౫+++++++.......................▓▓▓▓▓▓▓▓5▓▓▓▓▓▓      1
I    ౧౦౦౦౦౫౫౫+++++++......................▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓      I
I    ౧౦౦౦౦౫౫౫+++++++.....................▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓      I
I    ౧౦౦౦౦౫౫౫+++2++.....................▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓       I
I    ౧౦౦౦౦౫౫౫++++++++...................▓▓▓▓▓▓▓▓▓▓▓▓▓▓▓        I
+    ౧౦౦౦౦౦౫౫౫+++++++.................     ⊖⊖⊖⊖⊖⊖⊖⊖⊖▓▓▓▓▓▓      +
I    ౧౦౦౦౦౫౫౫+++++++.........             ⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖      I
I    ౧౦౦౦౦౫౫+++++                         ⊖⊖⊖⊖⊖⊖⊖4⊖⊖⊖⊖⊖⊖      I
1    ౧౦౦                                 ⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖      I
I              EXAMPLE AREA               ⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖⊖౧౦     I
2                                                              2
*-----+-----1-----+----2----+----3----+----4----+----5----+----*
```
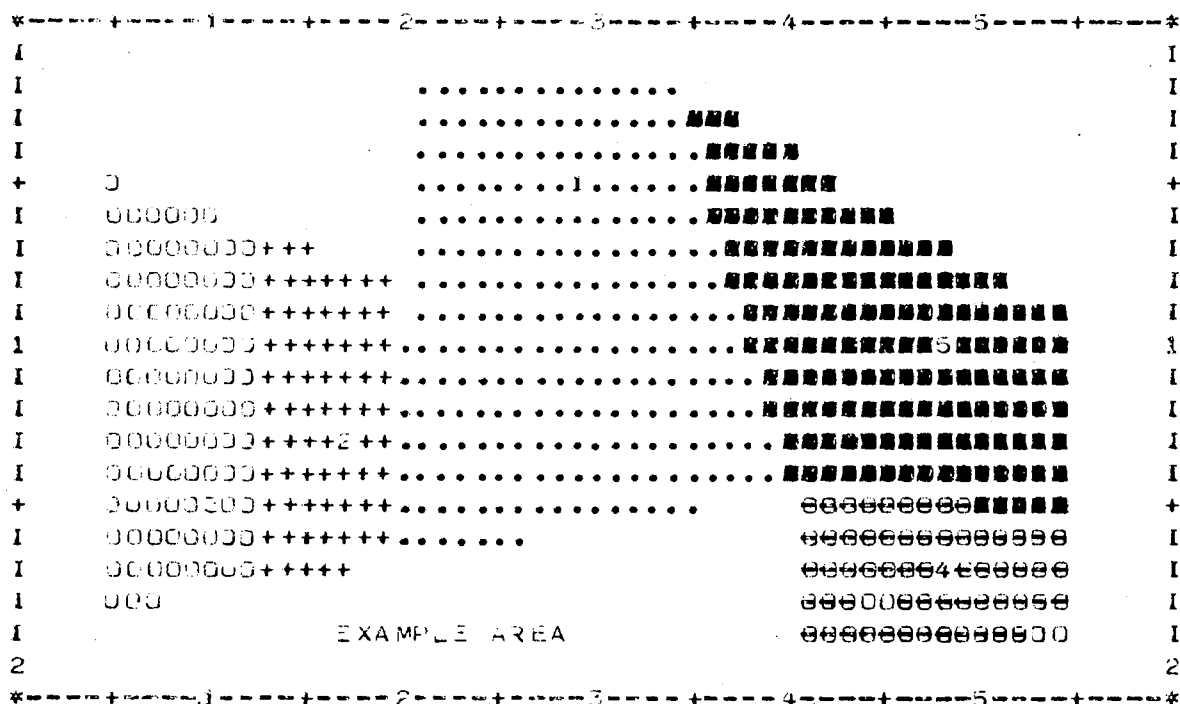
Figure 14. Conformant Map

The finished maps as they appear in figures 12, 13 and 14 were pro-
duced on an IBM 360/65 computer. The total time for all three maps was
0.13 of a minute and cost $2.61.

In addition to the finished maps, the SYMAP program produces a
small amount of statistical information so the user will have a better
understanding of how the program has interpreted the data. The three
"C's" appearing directly below the map are simply three comment cards
by which the user is able to make special notes about the map. If, for
instance, the user needs to keep a record of what day different maps are
produced, he would change the card that contained that information in
the F-MAP package. These special titles should not be confused with the
titles, legends and notes that appear on the actual map. That informa-
tion is controlled by the C-OTOLEGEND package. See Table IA.

TABLE IA

SYMAP STATISTICAL INFORMATION

C EXAMPLE MAPS FOR THESIS

C APRIL 19,1971

C TONY R. WHITE

DATA VALUE EXTREMES ARE   0.0   93.00

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
        ('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	18.60	37.20	55.80	74.40
MAXIMUM	18.60	37.20	55.80	74.40	93.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

          20.00   20.00   20.00   20.00   20.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5
	===========	===========	===========	===========	===========
	....	++++++++++	0000000000	8888888888	##########
	....	++++++++++	0000000000	8888888888	##########
SYMBOLS	....1.....	+++2+++++	0000300000	8888488888	###5#####
	....	++++++++++	0000000000	8888888888	##########
	....	++++++++++	0000000000	8888888888	##########
	===========	===========	===========	===========	===========
FREQ.	1	1	1	1	1
	1 I..1..I	I++2++I	I003001	I884881	I##5##I

From the DATA VALUE EXTREMES the minimum and maximum data values which were used in the map can be determined. In this case the values could have just as easily been found by looking at the data as it appears in the E-VALUES package. As more and more data is used, however, it becomes a tedious task to locate the minimum and maximum values from the E-VALUES package.

The next four lines of printing relate to the range of the actual values provided, and show how that range has been distributed into various levels. In these examples the value range from 0. to 93. has been distributed into five levels. The lowest level extends from 0.0 to 18.60 but does not include 18.60. The highest level extends from 14.40 to 93.00 and includes 93.00. The maximum for each level is included only in the highest level. For the other levels, the maximum falls just short of the highest value given. It is standard to have all the data values considered and used in the maps, but the user can specify any minimum or maximum values.

The next two lines of printing provide related information in terms of percentages of the total value range. Each level contains 20% because it is standard to evenly distribute the value range. If only four levels had been needed they would have each contained 25% of the total value range. Again it is possible for the user to control the percent distribution into each level.

The frequency distribution chart is the next bit of information. The identifying number of each level is shown along with the symbolism used for that level. It is standard to use five levels, but it is possible to use from one to ten levels. The last line shows the frequency a data point occurred at that level. In this example there were

only five data points and one occurred at each level. If more than
five data points are used, the frequency distribution will appear as a
bar chart or "histogram" with the bars projecting down from the symbols.
When the maximum number of data points has been used (1000) the value of
the bar chart becomes much easier to understand.

A small amount of other information also appears with each output,
but in general it does not help the user interpret the map. In most
cases it is only useful in determining if the data input was correct or
not. This type of information is very minimal however, and of little
value when trying to figure out why the program didn't work as specified
in the manual. The program does not give any error messages when data
is incorrectly used and only responds by not producing a map. Without
this self-diagnostic feature a great amount of time can be spent in
looking for a very simple error.

FOOTNOTES

[1]_Reference Manual For Synagraphic Computer Mapping_ (Version V, Cambridge), introduction.

CHAPTER IV

COMPUTER GRAPHICS AND STRUCTURES

The investigation of computer graphics and its usefulness in the study of structural behavior requires an indepth study of the computer hardware and software combinations which could eventually become the tools for either practical structural analysis or educational purposes.

The total number of variables which could possibly play a part in this study can be broken into four major categories. These four categories would be: (1) the type of structure being studied; (2) the type of load being applied to that structure; (3) the particular force phenomena the user is interested in studying; and (4) the computer equipment to be used in the study. Under each of these major categories an unbelievable number of sub-categories would begin to form producing almost unlimited combinations which could be tested in trying to find workable solutions. For this reason the following method of study will be used.

Procedure

The procedure to be followed in this study will be one which is very similar to those used in simulation studies, or other situations where known results are tested against models which represent the real situation. In this case the SYMAP program and lineprinter will be studied to determine whether they can accurately represent known

internal forces in a structural member under load.

As in any simulation study, certain variables must be held constant or fixed while others are allowed to change. In this case the three categories of variables to remain fixed will be: (1) type of structure; (2) type of load; and (3) the force phenomena. In the fourth category, which represents the type of computer hardware and software utilized in the investigation, the computer hardware will remain constant. This hardware consists of an IBM 360/65 computer and an IBM 1403 lineprinter. The main concern here is the lineprinter. It is presently only capable of producing one size of either alpha or numeric characters, and thus automatically becomes a constant. If various character sizes were available it would then become necessary to determine what character size would be the most desirable to work with. The SYMAP program, therefore, becomes the only variable to be considered in this study.

Since the SYMAP program has a standard operating procedure which it follows unless otherwise directed, it may be possible to obtain the desired results without changing any of these procedures. With this in mind the initial run of each new combination of structure, load and desired force diagram will be handled according to standard SYMAP procedures. If the desired results are not obtained in all three types of maps, the various options in the program will then be manipulated in an effort to obtain those results.

<div align="center">Simple Beams</div>

A great number of complicated structures are composed of many smaller members which are simple beams acting in either tension or compression or both simultaneously. Investigating how to graphically

display the various forces in these smaller members using the SYMAP

program then makes it possible to study a variety of complicated

structures. Using this as a basic premise, the first combination of

structure, load and internal force to be graphically displayed will

be the bending moments that occur in a simply supported beam when

a load is applied at midspan. The resulting graphical display of the

bending moments produced by the computer should bear a close resemblance

to the hand drawn ones in Figure 15.

The beam and the location of the data points for the initial

contour and proximal maps can be seen in Figure 16. The three data

points are located at the points where the maximum and minimum moments

occur in the beam. Figure 17 shows how the beam has been divided

into three sections for the conformant map. This is necessary

because the conformant map does not work unless the area to be studied

is divided into more than one part.

The maximum moment in a simply supported beam can be determined by

the formula:

$$\frac{PL}{4} \qquad\qquad (4.1)$$

Assuming a span of 16 feet and a load of 20 kips, the maximum moments

is thus (20K) (16 ft.)/4 = 80 ft.-k. Since no moments occur at the

free end of a beam, the values at these points will be zero.

Table II shows all the data used in an attempt to produce a contour

map, a proximal map and a conformant map for this particular beam. The

data was read into the computer in the order it appears in the table.

20 k

TYPE OF STRUCTURE

TYPE OF LOAD

FORCES BEING DISPLAYED

TYPE OF MAP

|1-FT.|

SCALE IN FEET
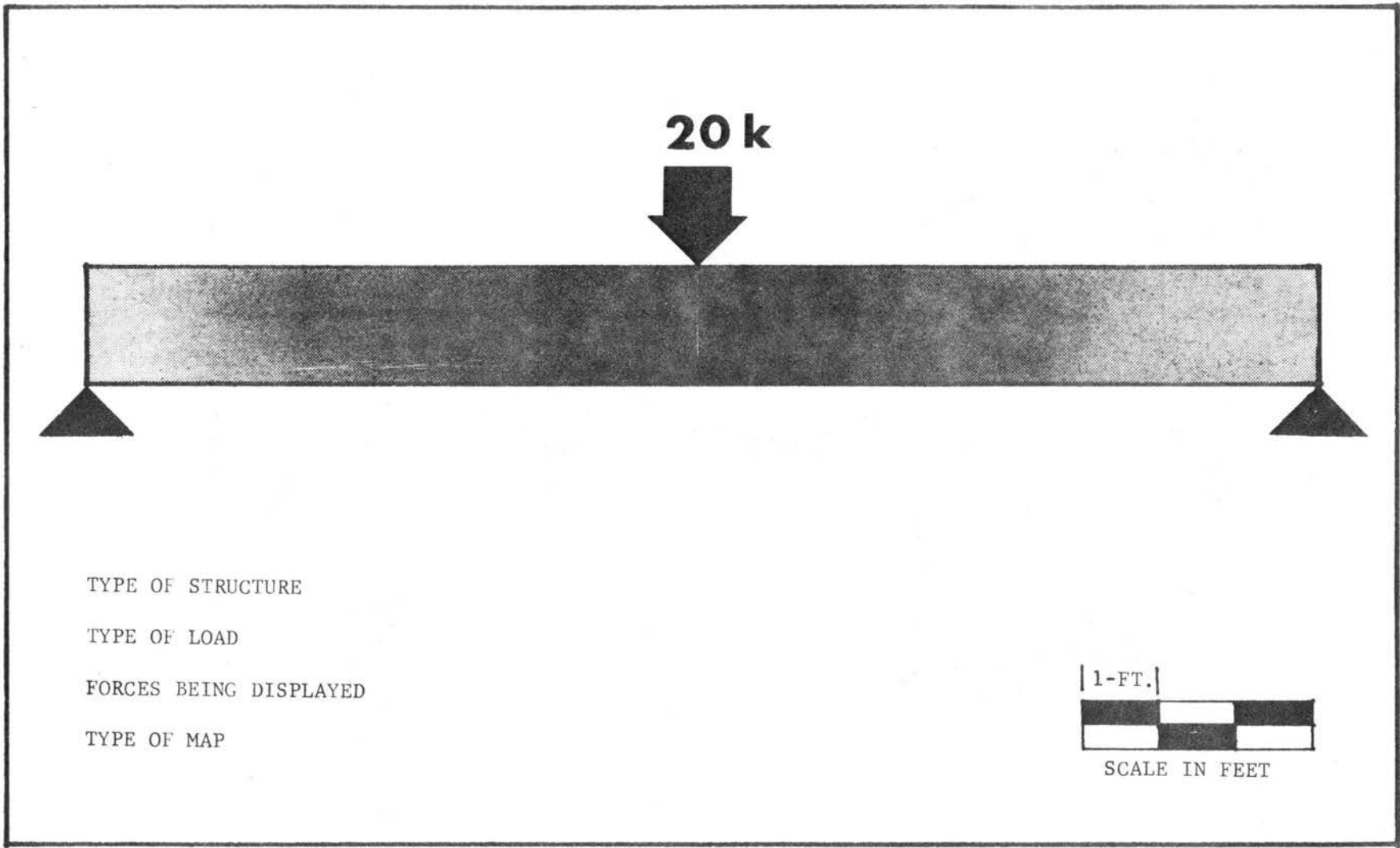
Figure 15. Normal Bending Momemts in Beam

20 k

TYPE OF STRUCTURE

TYPE OF LOAD

FORCES BEING DISPLAYED

TYPE OF MAP

|1-FT.|

SCALE IN FEET
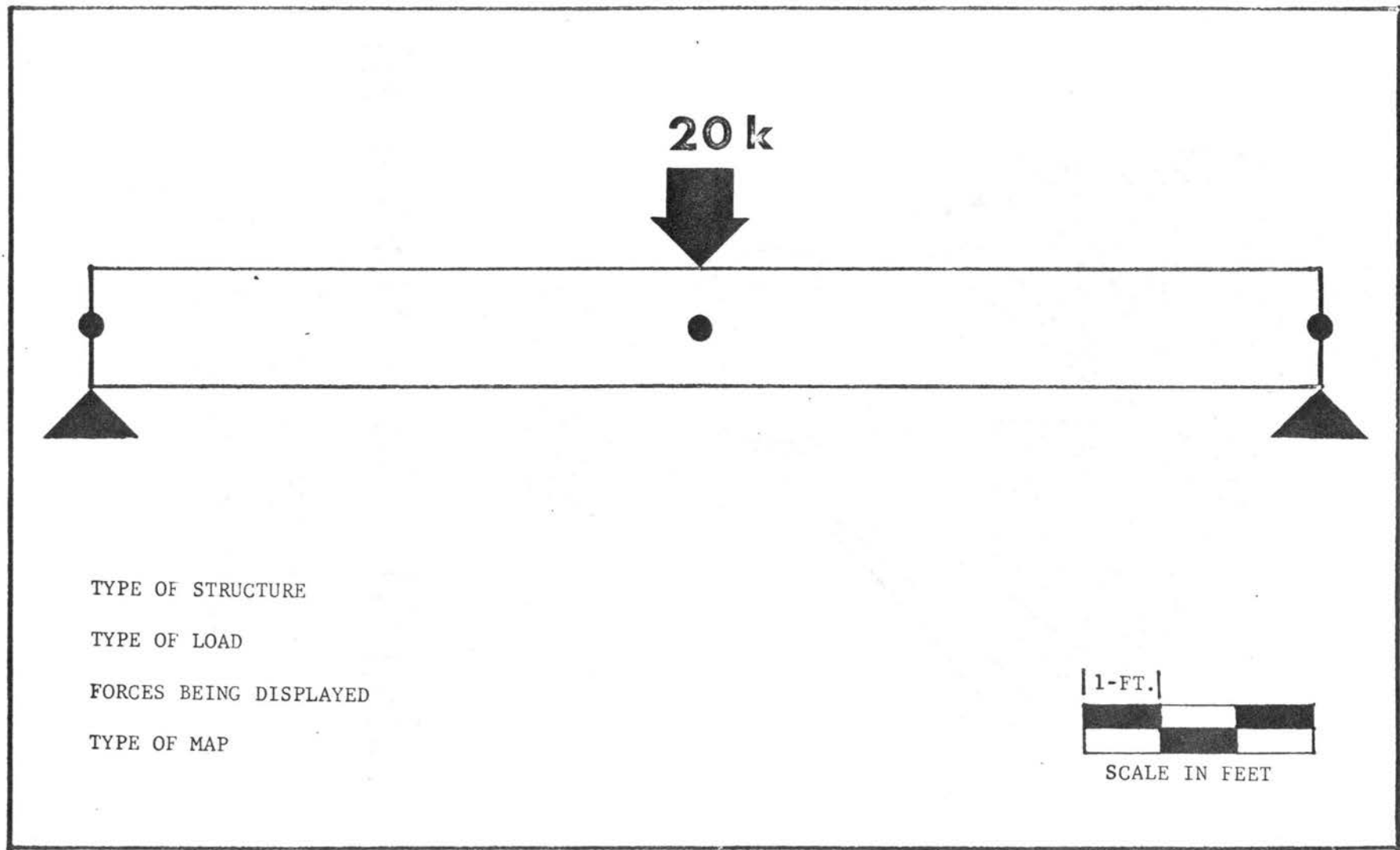
Figure 16.   Data Point Location for Contour and Proximal Maps

20 k

TYPE OF STRUCTURE

TYPE OF LOAD

FORCES BEING DISPLAYED

TYPE OF MAP

|1-FT.|

SCALE IN FEET
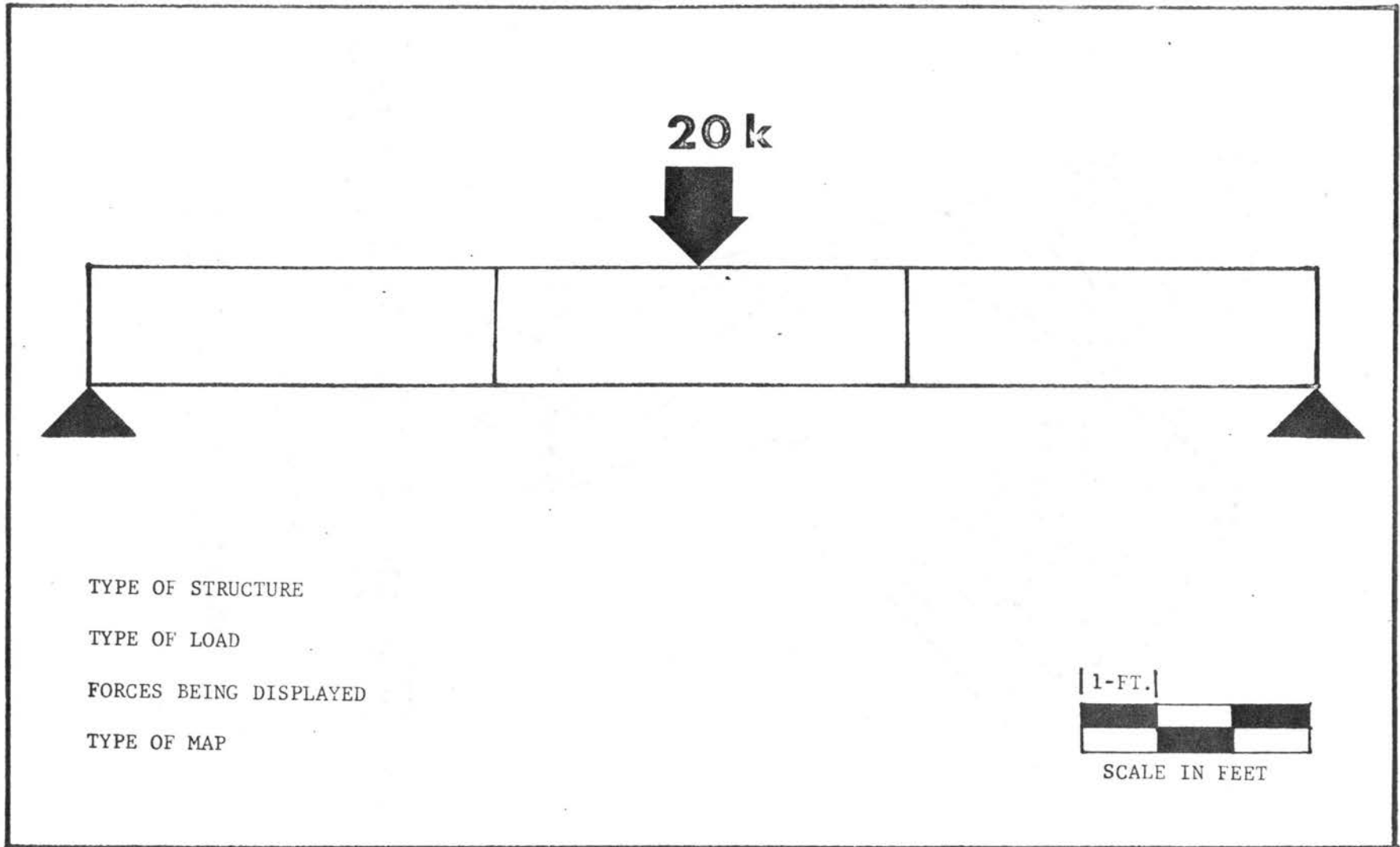
Figure 17.   Zones on Conformant Map

TABLE II

SYMAP DATA FOR BEAM I

A-OUTLINE

		14.	5.
		14.	85.
		20.	85.
		20.	5.
		14.	5.

99999
B-DATA POINTS

		17.	5.
		17.	45.
		17.	85.

99999
C-OTOLEGENDS

| 18 | P | 30. | 5. |

TYPE OF STRUCTURE:

| 11 | P | 32. | 7. |

SIMPLE BEAM

| 13 | P | 33. | 5. |

TYPE OF LOAD:

| 23 | P | 34. | 7. |

CONCENTRATED AT MIDSPAN

| 23 | P | 36. | 5. |

FORCES BEING DISPLACED:

| 7 | P | 37. | 7. |

MOMENTS

| 12 | P | 39. | 5. |

TYPE OF MAP:

| 7 | P | 40. | 7. |

CONTOUR

| 6 | P | 37. | 69. |

******

| 6 | P | 37. | 79. |

******

| 6 | P | 38. | 74. |

******

| 4 | P | 37. | 75. |

2222

| 5 | P | 38. | 69. |

11111

| 5 | P | 38. | 80. |

33333

| 6 | P | 35. | 69. |

- 1 FT. -

| 13 | P | 39. | 72. |

SCALE IN FEET
99999
E-VALUES

		0.
		80.
		0.

TABLE II (CONTINUED)

```
99999
F-MAP
C LOAD = 20 KIPS
C 3 DATA POINTS
C JUNE 1, 1971
      1               5.5          12.5
      2               0.            0.           5.5          12.5
     13               1.
     15               6.           10.
     26
99999
F-MAP
C LOAD = 20 KIPS
C 3 DATA POINTS
C JUNE 1, 1971
      1               5.5          12.5
      2               0.            0.           5.5          12.5
     13               1.
     15               6.           10.
     26
     31
     36
     37
99999
A-CONFORMOLINES
      1      A        14.           5.
                      14.          32.
                      20.          32.
                      20.           5.
                      14.           5.
      2      A        14.          32.
                      14.          59.
                      20.          59.
                      20.          32.
                      14.          32.
      3      A        14.          59.
                      14.          85.
                      20.          85.
                      20.          59.
                      14.          59.
99999
F-MAP
C LOAD = 20 KIPS
C 3 DATA POINTS
C JUNE 1, 1971
      1               5.5          12.5
      2               0.            0.
     13               1.
     15               6.           10.
     26
99999
```

Unfortunately no maps resulted from this data. The data was then broken down into three separate packages and submitted as three different jobs. From these runs the conformant package was the only one which produced a map and as can be seen in Figure 18 it was not complete.

This was a rather perplexing problem and over a month was spent in trying to first determine why the contour and proximal packages would not produce any maps and second why the conformant map was incomplete.

As mentioned in Chapter III, the SYMAP program does not give error messages to help the user locate mistakes in his data. If the data is not correct the program simply does not run. This is a very serious fault with the program. A great deal of time and money could have been saved if a small amount of diagnostics were in the program. The only clue to the problem was found in statistical portion of the output. The program always prints out what standard search radius was used to analyze the data. The standard search radius is determined by the density and location of the data points and for this data it should have been about 4.5 inches. It was instead 0.0 inches. In addition the program printed out a new note which stated that the initial scanning radium was 0.0 and also had the word "error" printed beside it.

Using this small clue as a guide, electives numbers 34, 35 and 36, which are all options in the F-Map package, were used in trying to correct the error. Elective 34 controls initial search radius and is usually used to preserve the initial search radius from a previous map after altering the number of data points or the location of edge data points. Elective 35 controls the maximum search radius the computer will look for data points and elective 36 controls the minimum and

```
*----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8----+----*
I                                                                                          I
I                                                                                          I
I                                                                                          I
I                                                                                          I
+                                                                                          +
I                                    ***                                                   I
I                                    ***                                                   I
I                                 ******                                                   I
I                                 *****                                                    I
I                                   *                                                      I
I                      ████████████████████████████ ...........................           I
I                      ████████████████████████████ ...........................           I
I      1               ████████5███████████████████ ...........................1          I
I                      ████████████████████████████ ...........................           I
+                      ████████████████████████████ ...........................           +
I      *                                                                          *        I
I    ***                                                                        ***        I
I  *****                                                                      *****         I
I                                                                                          I
2                                                                                          2
I                                                                                          I
I                                                                                          I
I      TYPE OF STRUCTURE:                                                                   I
I        SIMPLE BEAM                                                                        I
+      TYPE OF LOAD:                                                                        +
I        CONCENTRATED AT MIDSPAN                                                            I
I      FORCES BEING DISPLAYED:                              -1FT.-                          I
I        MOMENTS                                            ******2222******                I
I      TYPE OF MAP:                                         11111******33333                I
3        CONFORMANT                          1             SCALE IN FEET                    3
I                                                                                          I
I                                                                                          I
*----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8----+----*
```

Figure 18.   Incomplete Conformant Map

maximum number of data points on which interpolation is based. None of these electives, however, had any positive effect on any of the maps. The problem was finally resolved by calling the Laboratory for Computer Graphics and Spacial Analysis at Harvard University and talking with one of the programmers who works with the SYMAP program. In this telephone conversation he stated that no one he knew of had ever tried to use the program in this particular manner and he had never known anyone to have this particular problem.[1] His only idea as to what might be causing the problem was that the three data points being in a straight horizontal line would imply using some type of linear analysis. Since the SYMAP program is based on spacial analysis it would not work for data points in this arrangement. He suggested trying a dummy data point outside the study area or staggering the data points on the study area. In regards to the conformant map he felt as if something was probably wrong with the portion of the program which produces the conformant map and suggested that the entire program be returned to Harvard so it could be checked for programming errors. This brought an end to further studies using the conformant package.

A dummy data point was first included with the three previous data points and given a value of 0.0. This data point as can be seen in Figure 19 was located at a position of 40.0, 45.0.

The first results using the dummy data point can be seen in Figures 20 and 21. The spaces or white lines which occur between the different levels are called contour lines. On a large contour map they are quite useful in helping to locate where the levels change, but in this instance they are quite distracting. They also occur on the proximal in two locations and are not quite as distracting but still

20 k

TYPE OF STRUCTURE

TYPE OF LOAD

FORCES BEING DISPLAYED

TYPE OF MAP

|1-FT.|

SCALE IN FEET

Figure 19.   Location of Dummy Data Point

```
*----+----1----+----2----+---3----+----4----+---5----+----6----+----7----+----8----+----*
I                                                                                        I
I                                                                                        I
I                                                                                        I
I                                                                                        I
+                                                                                        +
I                                        ***                                             I
I                                        ***                                             I
I                                     ******                                             I
I                                      *****                                             I
I                                        *                                               I
I      .............. ++++++  OOOOO  eeee  ████████████████████  eeee  OOOOO  ++++++ ............. I
I      ............... +++++  OOOOOO eeee  ████████████████████  eeee  OOOOO  +++++++ ............. I
I    1............... +++++++ OOOOO  eee  ████████5██████████  eee  OOOO  +++++++ ...............1 I
I      ............... +++++++ OOO  eeeee  ███████████████████  eeeee OOOO  ++++++ .............. I
+      ............... ++++++  OOOO  eeeee  ███████████████  eeeee  OOOOO  ++++++ ............... +
I      *                                                                              *  I
I     ***                                                                            *** I
I   *****                                                                          ***** I
I                                                                                        I
2                                                                                        2
I                                                                                        I
I                                                                                        I
I     TYPE OF STRUCTURE:                                                                  I
I        SIMPLE BEAM                                                                      I
+     TYPE OF LOAD:                                                                       +
I        CONCENTRATED AT MIDSPAN                                                          I
I     FORCES BEING DISPLAYED:                                    -1FT.-                    I
I        MOMENTS                                                ******2222******           I
I     TYPE OF MAP:                                              11111******33333           I
3        CONTOUR                               1                   SCALE IN FEET          3
I                                                                                        I
I                                                                                        I
*----+----1----+----2----+---3----+----4----+---5----+----6----+----7----+----8----+----*
```

Figure 20. Contour Map Using Dummy Data Point

TYPE OF STRUCTURE:
  SIMPLE BEAM
TYPE OF LOAD:
  CONCENTRATED AT MIDSPAN
FORCES BEING DISPLAYED:
  MOMENTS
TYPE OF MAP:
  PROXIMAL

-1FT.-
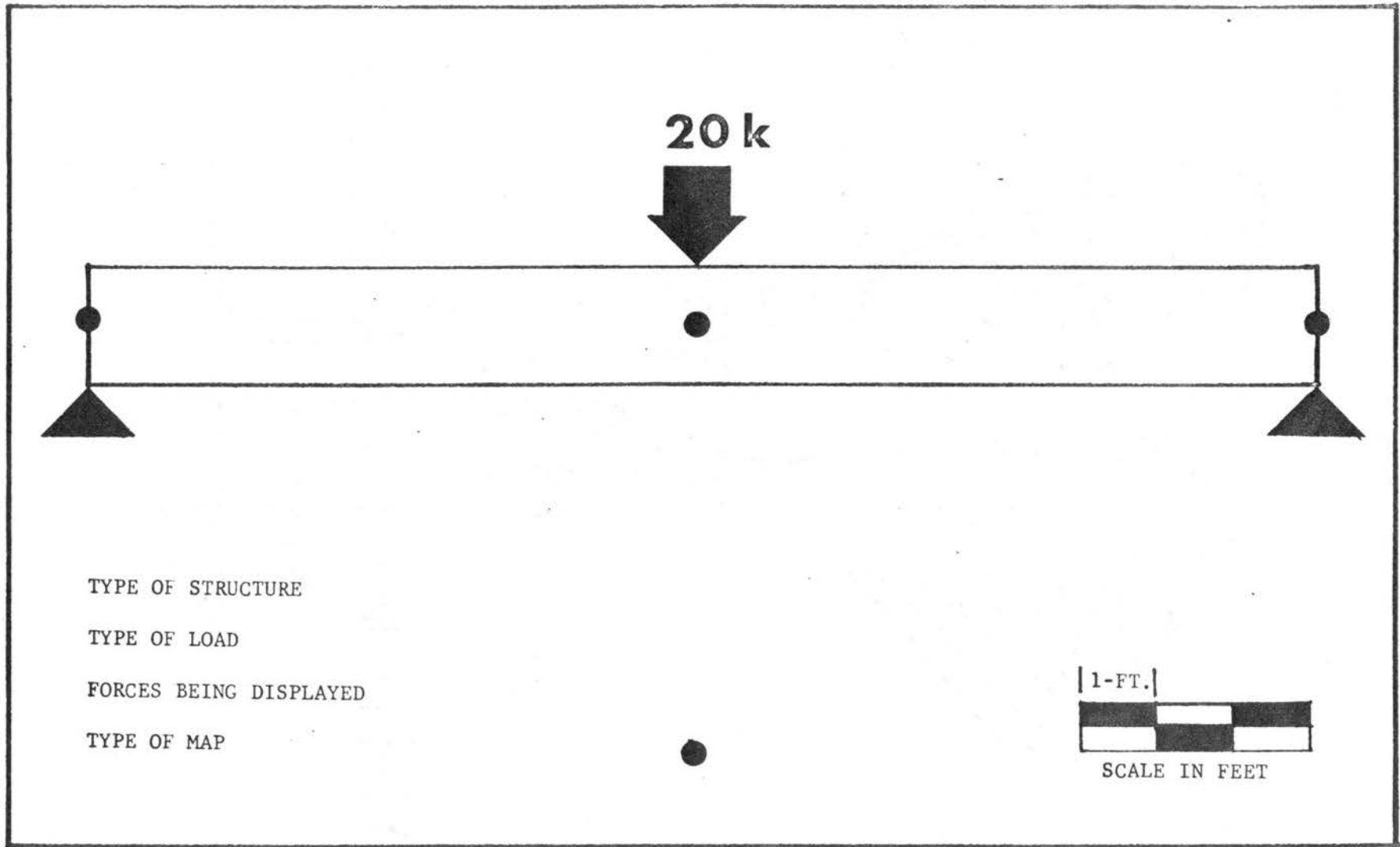*****2222******
11111******33333
SCALE IN FEET

Figure 21. Proximal Map Using Dummy Data Point

of no use for this particular case. By adding elective number 8 to the F-Map package the lines or voids were eliminated. The contour map without the lines can be seen in Figure 22.

The only other noticeable errors on the maps in Figures 20 and 21 are the data points on the right and left hand side of the beam. They should be located one unit towards the beam so they would appear to be on the study area instead of just off the beam.

The most plausible explanation for this slight shift is that when the number of lines are changed from eight per inch to six per inch vertically a small change also occurs in the horizontal dimension. The original beam was coded to be 80 units long and 6 units deep. The output at a scale of 1:1 is only 79 units long and 5 units deep. The condition can be partially corrected by using elective 13 in the F-Map package to double the scale of the output. The output then becomes 160 units long but only 9 units deep. In this case the depth has little importance in trying to show how the moments vary across the beam. If the length and depth are both critical it would probably be better not to control the scale of the map and simply allow the computer to properly proportion the length to the depth.

Data Points

The emphasis at this point in the study is simply to find the most effective use of data points in regard to location and density.

The feasibility of using a dummy data point was first studied. How much effect did the dummy data point location have on visual representation of the beam? The location which was used to produce Figure 19 gave the beam a very even distribution of the forces. Would this always be true?

Figure 22. Contour Map Without Contour Lines

Table III shows the various dummy data point locations which were tried. The first three dummy data point locations produced quite similar results when produced with the contour map package at a 1 to 1 scale. These small differences became much more apparent when the scale was doubled. The remaining two beams and dummy data points produced contour maps which were very distorted and thus gave a strong indication that the use of the dummy data point must be carefully regulated for each structured shape for which it is used. The proximal maps produced from these data points also indicated the need to carefully control the location of the dummy data point.

Since the location of a data point off the structure is very arbitrary, it seems best to investigate various arrangements of data points which were located directly on the structure.

Table IV shows four arbitrarily selected arrangements of data points which were tested using 3 data points and 10 intensity levels to determine what type of force patterns they would produce. After a preliminary run of each beam, the first, third and fourth beams, plus one with a dummy data point were chosen for further investigation. All the beams and data point locations which were tested can be seen in Table V. Table VI shows the various electives which were used with the beams for both the contour and proximal maps. A complete explanation of the electives used in Table VI can be found in Appendix B.
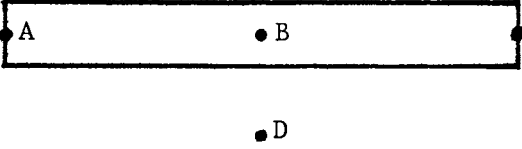
TABLE III

DUMMY DATA POINT LOCATIONS
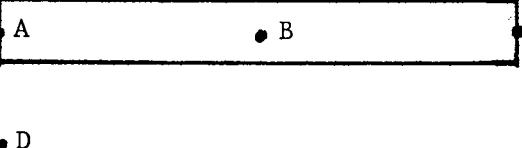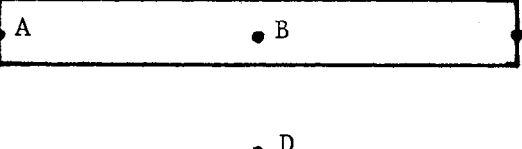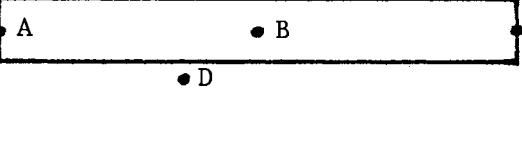
NO.	BEAM AND DATA POINTS	DATA POINTS			
		PT.	DOWN	ACROSS	VALUE
1		A	17.0	5.0	0.0
		B	17.0	45.0	80.0
		C	17.0	85.0	0.0
		D	40.0	45.0	0.0
2.		A	17.0	5.0	0.0
		B	17.0	45.0	80.0
		C	17.0	85.0	0.0
		D	40.0	5.0	0.0
3.		A	17.0	5.0	0.0
		B	17.0	45.0	80.0
		C	17.0	85.0	0.0
		D	80.0	75.0	0.0
4.		A	17.0	5.0	0.0
		B	17.0	45.0	80.0
		C	17.0	85.0	0.0
		D	22.0	30.0	0.0
5.		A	1.0	5.0	0.0
		B	17.0	5.0	0.0
		C	17.0	45.0	80.0
		D	.0	85.0	0.0

TABLE IV

DATA POINTS ON STRUCTURE
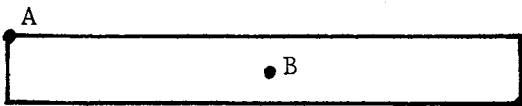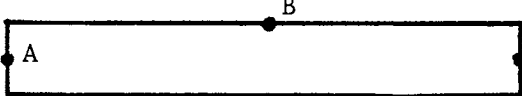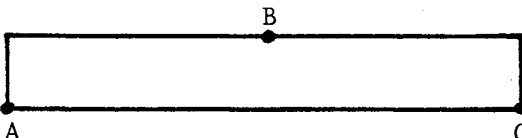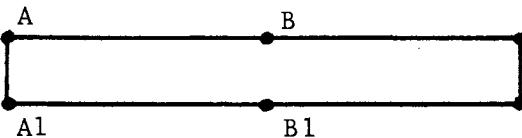
NO.	BEAM AND DATA POINTS	DATA POINTS			
		PT.	DOWN	ACROSS	VALUE
1.		A	14.0	5.0	0.0
		B	17.0	45.0	80.0
		C	20.0	85.0	0.0
2.		A	17.0	5.0	0.0
		B	14.0	45.0	80.0
		C	17.0	85.0	0.0
3.		A	20.0	5.0	0.0
		B	14.0	45.0	80.0
		C	20.0	85.0	0.0
4.		A	14.0	5.0	0.0
		B	14.0	45.0	80.0
		C	14.0	85.0	0.0
		A1	20.0	5.0	0.0
		B1	20.0	45.0	80.0
		C1	20.0	85.0	0.0

TABLE V

BEAMS AND DATA POINTS

NO.	BEAMS IN DATA POINT SERIES	DATA POINT LOCATIONS AND VALUES											
		PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE
1.		A	20.0	5.0	0.0								
		B	14.0	45.0	80.0								
		C	20.0	85.0	0.0								
2.		A	20.0	5.0	0.0								
		B	14.0	25.0	40.0								
		C	20.0	45.0	80.0								
		D	14.0	65.0	40.0								
		E	20.0	85.0	0.0								
3.		A	20.0	5.0	0.0	G	20.0	65.0	40.0				
		B	14.0	15.0	20.0	H	14.0	75.0	20.0				
		C	20.0	25.0	40.0	I	20.0	85.0	0.0				
		D	14.0	35.0	60.0								
		E	20.0	45.0	80.0								
		F	14.0	55.0	60.0								
4.		A	20.0	5.0	0.0	G	20.0	35.0	60.0	M	20.0	65.0	40.0
		B	14.0	10.0	10.0	H	14.0	40.0	70.0	N	14.0	70.0	30.0
		C	20.0	15.0	20.0	I	20.0	45.0	80.0	O	20.0	75.0	20.0
		D	14.0	20.0	30.0	J	14.0	50.0	70.0	P	14.0	80.0	10.0
		E	20.0	25.0	40.0	K	20.0	55.0	60.0	Q	20.0	85.0	0.0
		F	14.0	30.0	50.0	L	14.0	60.0	50.0				

TABLE V (Continued)

NO.	BEAMS IN DATA POINT SERIES	PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE
5.		A	14.0	5.0	0.0								
		B	17.0	45.0	80.0								
		C	20.0	85.0	0.0								
6.		A	14.0	5.0	0.0								
		B	15.0	25.0	40.0								
		C	17.0	45.0	80.0								
		D	19.0	65.0	40.0								
		E	20.0	85.0	0.0								
7.		A	14.0	5.0	0.0	G	19.0	65.0	40.0				
		B	14.0	15.0	20.0	H	20.0	75.0	20.0				
		C	15.0	25.0	40.0	I	20.0	85.0	0.0				
		D	17.0	35.0	60.0								
		E	18.0	45.0	80.0								
		F	19.0	55.0	60.0								
8.		A	14.0	5.0	0.0	G	16.0	35.0	60.0	M	19.0	65.0	0.0
		B	14.0	10.0	10.0	H	17.0	40.0	70.0	N	19.0	70.0	0.0
		C	14.0	15.0	20.0	I	17.0	45.0	80.0	O	20.0	75.0	0.0
		D	15.0	20.0	30.0	J	17.0	50.0	70.0	P	20.0	80.0	10.0
		E	15.0	25.0	40.0	K	18.0	55.0	60.0	Q	20.0	85.0	0.0
		F	16.0	30.0	50.0	L	18.0	60.0	50.0				

TABLE V (Continued)

NO.	BEAMS IN DATA POINT SERIES	PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE
						DATA POINT LOCATIONS AND VALUES							
9.	A B C / A₁ B₁ C₁	A	14.0	5.0	0.0								
		B	14.0	45.0	80.0								
		C	14.0	85.0	0.0								
10.	A B C D E / A₁ B₁ C₁ D₁ E₁	A	14.0	5.0	0.0								
		B	14.0	25.0	40.0								
		C	14.0	45.0	80.0								
		D	4.0	65.0	40.0								
		E	14.0	85.0	0.0								
11.	A B C D E F G H I / A₁ B₁ C₁ D₁ E₁ F₁ G₁ H₁ I₁	A	14.0	5.0	0.0								
		B	14.0	15.0	20.0	H	14.0	65.0	40.0				
		C	14.0	25.0	40.0	I	14.0	85.0	0.0				
		D	14.0	35.0	60.0								
		E	14.0	45.0	80.0								
		F	14.0	55.0	60.0								
12.	A B C D E F G H I J K L M N O P Q / A₁ B₁ C₁ D₁ E₁ F₁ G₁ H₁ I₁ J₁ K₁ L₁ M₁ N₁ O₁ P₁ Q₁	A	14.0	5.0	0.0	G	14.0	35.0	60.0	M	14.0	65.0	40.0
		B	14.0	10.0	10.0	H	14.0	40.0	70.0	N	14.0	70.0	30.0
		C	14.0	15.0	20.0	I	14.0	45.0	80.0	O	14.0	75.0	20.0
		D	14.0	20.0	30.0	J	14.0	50.0	70.0	P	14.0	80.0	10.0
		E	14.0	25.0	40.0	K	14.0	55.0	60.0	Q	14.0	85.0	0.0
		F	14.0	30.0	50.0	L	14.0	60.0	50.0				

NOTE: AN A1, B1, C1, ETC. POINT IS IN A VERTICAL LINE WITH AN A, B, C, ETC. POINT AT 20.0 UNITS DOWN. THE VALUE FOR ONE OF THESE POINTS IS THE SAME AS THE POINT ABOVE IT.

TABLE V (Continued)

NO.	BEAMS IN DATA POINT SERIES	PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE	PT.	DOWN	ACROSS	VALUE
13.	A◇ •B ◇C / •D	A	17.0	5.0	0.0								
		B	17.0	45.0	80.0								
		C	17.0	85.0	0.0								
		D	40.0	45.0	0.0								
14.	A◇ •B •C •D •E / •F	A	17.0	5.0	0.0								
		B	17.0	25.0	40.0								
		C	17.0	45.0	80.0								
		D	17.0	65.0	40.0								
		E	17.0	85.0	0.0								
		F	40.0	45.0	0.0								
15.	A◇ •B •C •D •E •F •G •H •I / •J	A	17.0	5.0	0.0	G	17.0	65.0	40.0				
		B	17.0	15.0	20.0	H	17.0	75.0	20.0				
		C	17.0	25.0	40.0	I	17.0	85.0	0.0				
		D	17.0	35.0	60.0	J	40.0	45.0	0.0				
		E	17.0	45.0	80.0								
		F	17.0	55.0	60.0								
16.	A◇ B C D E F G H I J K L M N O P Q / •R	A	17.0	5.0	0.0	G	17.0	35.0	60.0	M	17.0	65.0	40.0
		B	17.0	10.0	10.0	H	17.0	40.0	70.0	N	17.0	70.0	30.0
		C	17.0	15.0	20.0	I	17.0	45.0	80.0	O	17.0	75.0	20.0
		D	17.0	20.0	30.0	J	17.0	50.0	70.0	P	17.0	80.0	10.0
		E	17.0	25.0	40.0	K	17.0	55.0	60.0	Q	17.0	85.0	0.0
		F	17.0	30.0	50.0	L	17.0	60.0	50.0	R	40.0	45.0	0.0

TABLE VI

ELECTIVES USED WITH MAPS

BEAM NO.	CONTOUR MAPS												PROXIMAL MAPS														
	3						8	13		14	15	26	3						8	13		14	15	26	31	36	37
	5	6	7	8	9	10		1	2				5	6	7	8	9	10		1	2						
1.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
2.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
3.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
4.	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•
5.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
6.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
7.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
8.	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•
9.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
10.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
11.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
12.	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•
13.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
14.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
15.	•	•	•	•	•	•	•	•	•	•	•	•	•						•	•	•	•	•	•	•	•	•
16.	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•

The idea behind increasing the number of data points was to determine what combination of data point density, number of intensity levels and scale produced the best representation of the forces in the beam. For instance it might be possible that three data points with an intensity level of 10 and a scale of 1 would produce the same patterns as 17 data points at 10 levels and a scale of 2. If this were true then once the maximum and minimum forces in a structure were described to the computer it could graphically depict the distribution of these forces from maximum to minimum throughout the entire structure. This would eliminate the need for many data points being used and save a great deal of coding time on a large structure.

Analysis of Results

In determining which combination of data point density, number of intensity levels and scale produce the best graphical representation of the beam, it became necessary to study the character density per intensity level and the physical shape of each intensity level.

The density of characters in each intensity level was important in determining how evenly the characters were distributed among the various levels. For a map to resemble Figure 15 an even distribution of characters would be needed. Closely tied to character density was the actual physical shape the intensity levels had as they appeared on the maps. A square, rectangular shape was considered a desirable representation for the bending moments in this case.

An initial survey of the final maps revealed that all the beams in groups 1-4 and 5-6 were unacceptable. The off-set or zig-zag data point arrangement used in beams 1-4 had a tendency to cause wedge-shape patterns to develop for each different intensity level. This

was even true when 17 data points, which is one per foot, were used.

Figure 23 shows an example of these wedge-shaped patterns.

Beams in the 5-8 series also had a similar distortion except instead
of being wedge-shaped the intensity levels were slanted. This slanting
effect was not particularly noticeable in the maps for beams 5 and 6,
but became more distinct in the maps for beams 7 and 8. Doubling the
scale for any of the maps caused this slanting to become even more
predominant. An example of this slanting effect can be seen in
Figure 24.

The remaining two series of beams produced four maps that appeared
to be almost identical to Figure 15. These maps, one proximal and one
contour from each series, occurred in beams 12 and 16 when 9 intensity
levels were called for at a scale of 2. These contour maps are
shown in Figures 25 and 26. The proximal map in Figure 27 represents
both series of beams since their output was identical.

Essentially the only difference in these beams was the number
of data points used for each series. Beam 16 used 17 data points on the
actual study area plus one dummy data point off the study area.
Beam 12 used 34 data points all of which were located directly on the
study area. The seemingly strange implication that 17 data points
would produce the same results as 34 points can easily be resolved by
comparing the number of different numeric values used with the total
number of data points and their relative locations on each beam.

In both cases only 9 different numeric values represented the bending
moments at one foot intervals along the beams. Beam 12 used two data
points per foot while beam 16 used only one point per foot, but
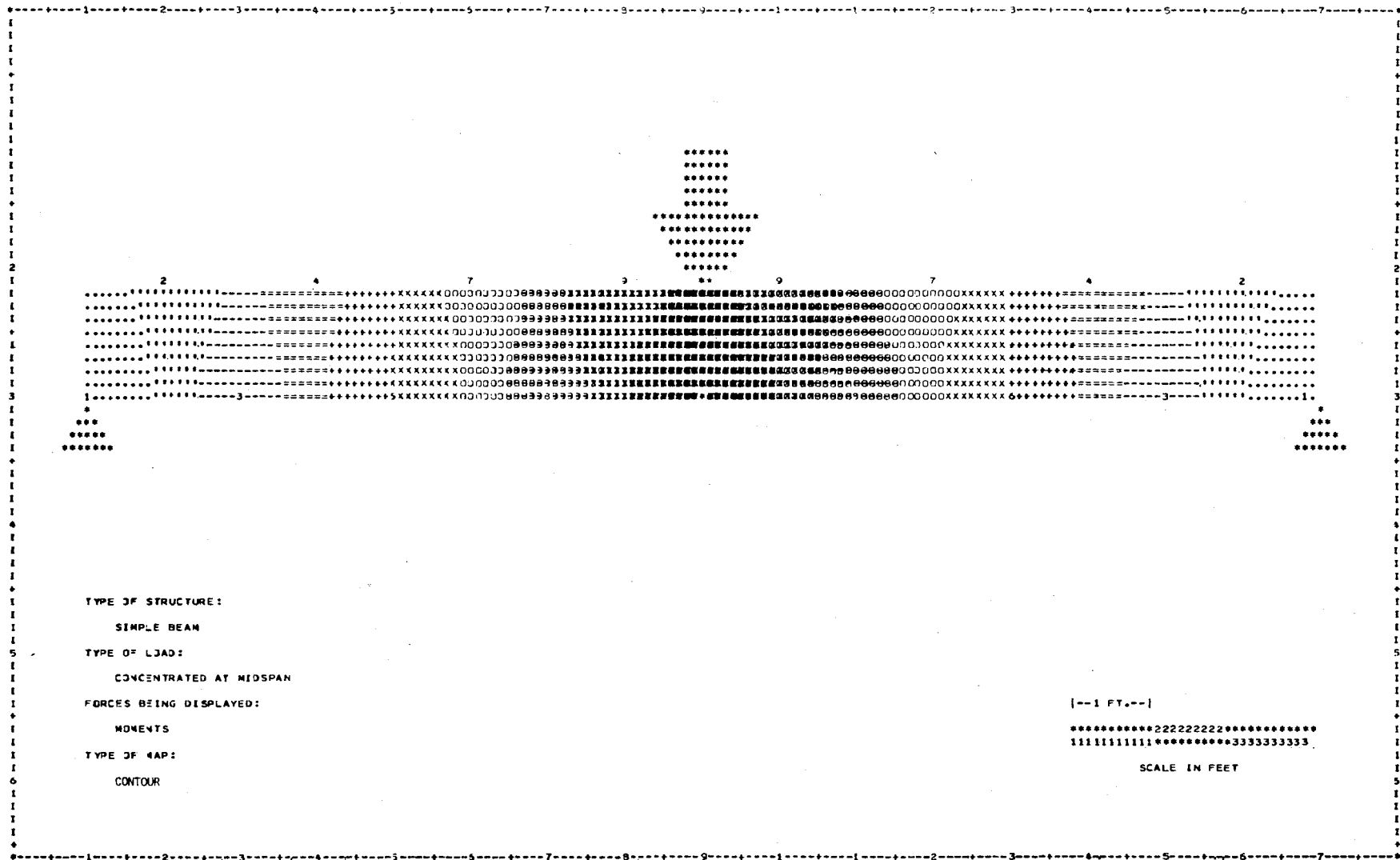regardless of the vertical location of these points the moment for a

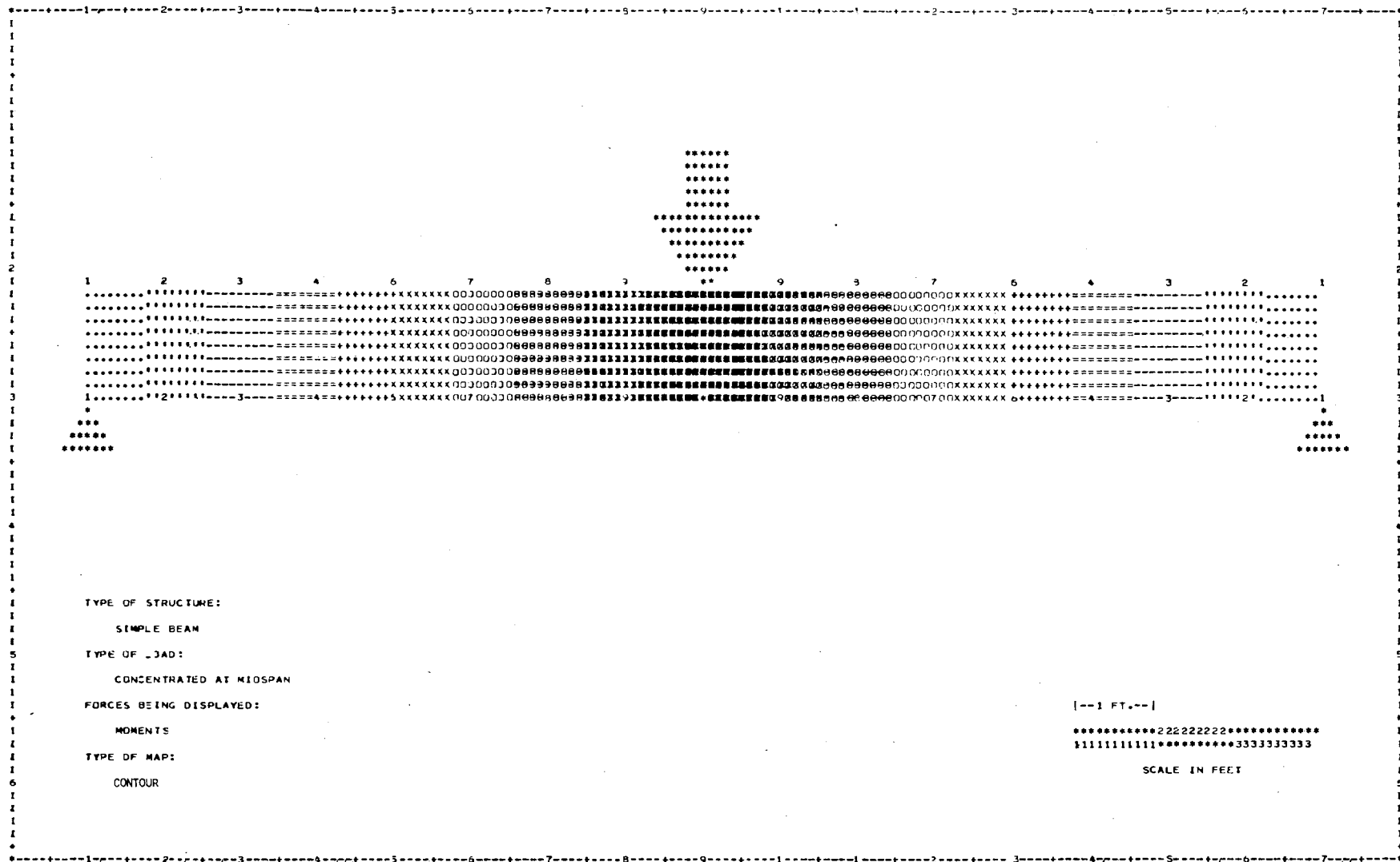Figure 23.   Wedge Shape Pattern Using 17 Data Points

Figure 24. Slanting Effect Caused by Data Point Arrangement

Figure 25. Map of Bending Moments Using 34 Data Points

TYPE OF STRUCTURE:

    SIMPLE BEAM

TYPE OF LOAD:

    CONCENTRATED AT MIDSPAN

FORCES BEING DISPLAYED:
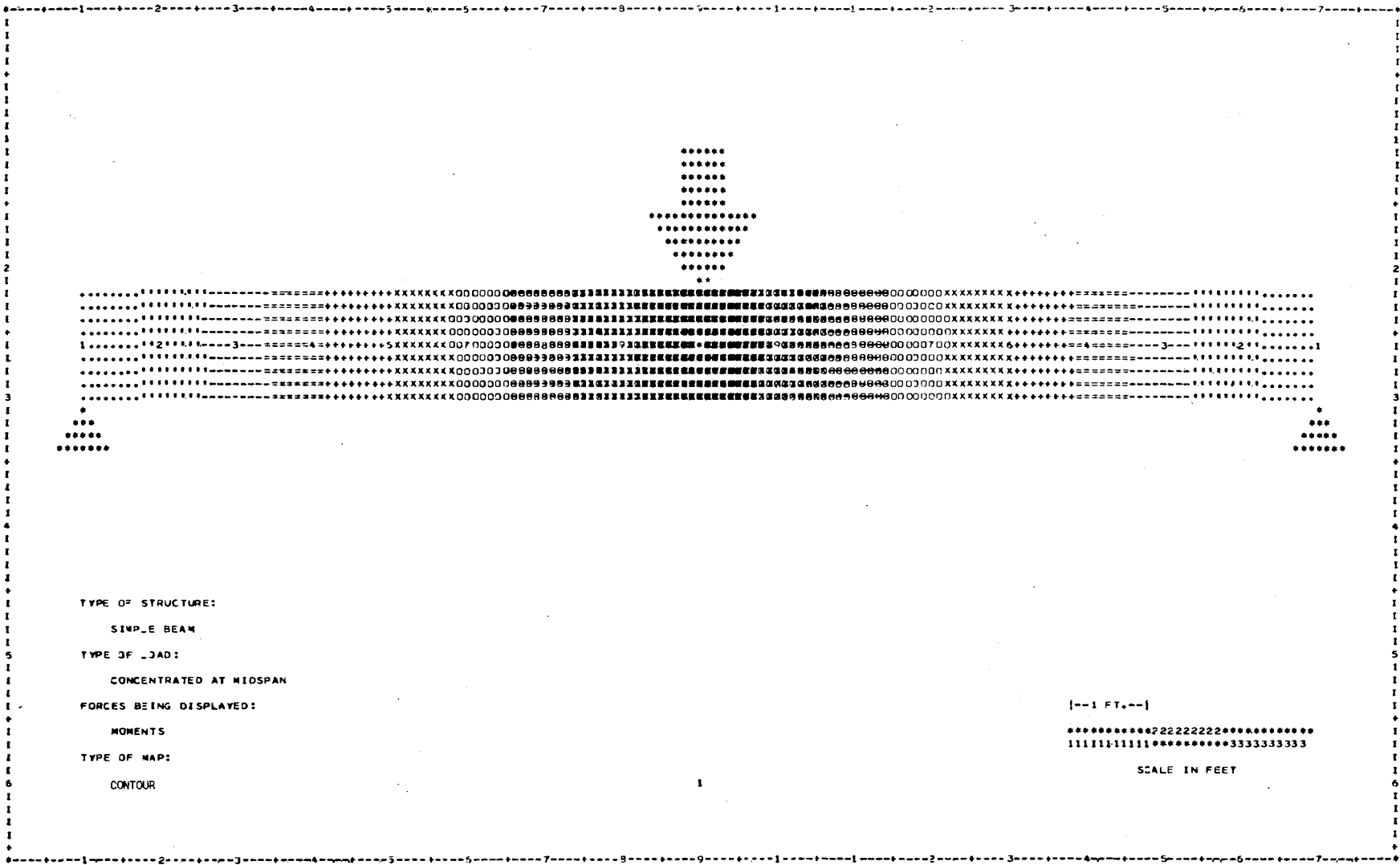
    MOMENTS

TYPE OF MAP:

    CONTOUR

|--1 FT.--|

SCALE IN FEET

Figure 26. Map of Bending Moments Using Dummy Data Point
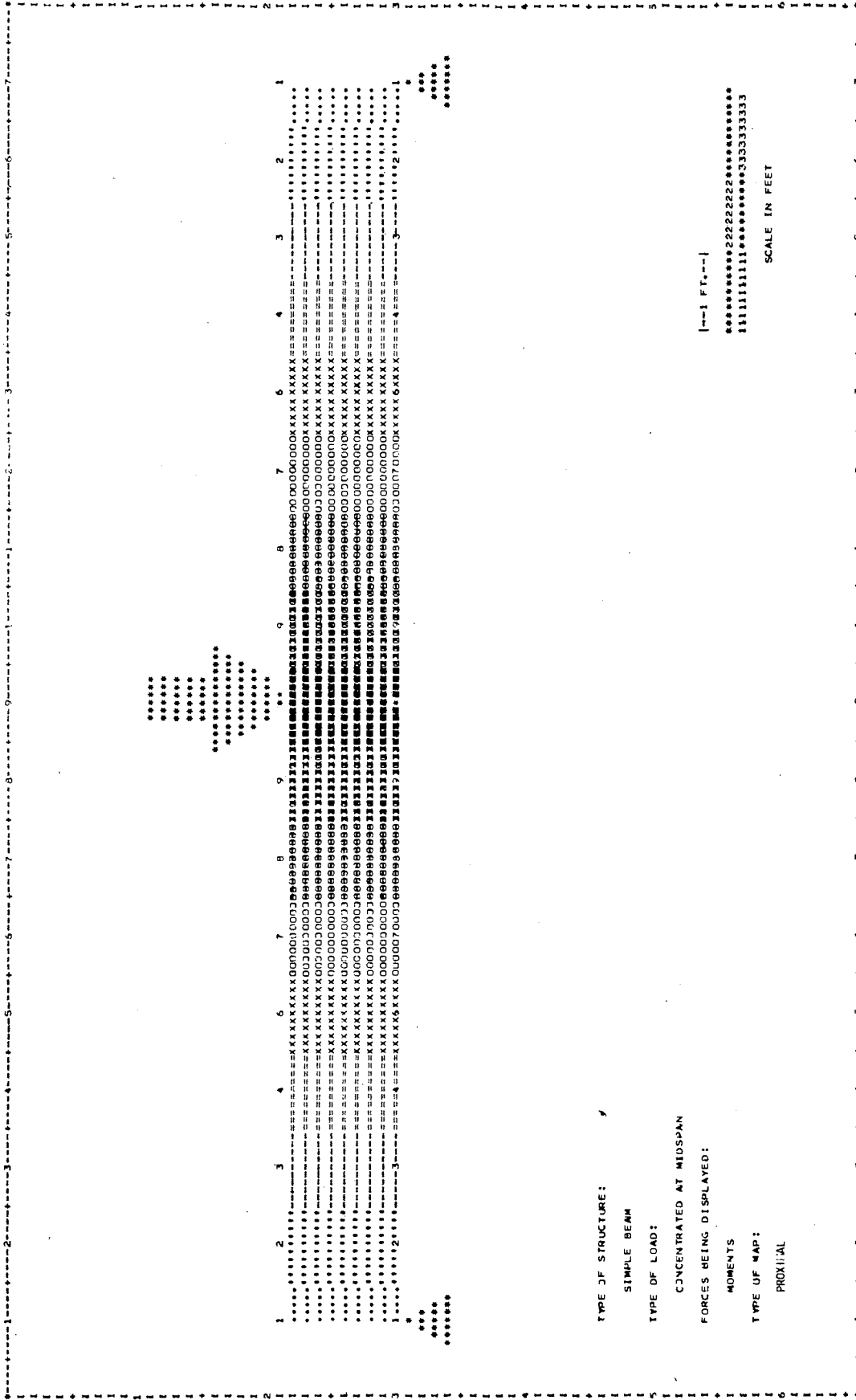
Figure 27. Proximal Map of Bending Moments Using 3/4 Data Points

particular section would remain constant. Since these sections covered

a small amount of area, it was only the relative location of the

point which was important. If the scale would have been increased four

or five times, the two contour maps for the beams would not have so

closely resembled each other. The proximal maps, however, would have

appeared the same at any scale because each character location on a

proximal map is assigned the value of the data point nearest to it.

Only increasing the number of values would cause these maps to vary.

The rest of the contour maps in these two series of beams revealed a

number of other maps which were also quite similar to Figure 15. These

similarities all occurred in beams 12, 15 and 16 at both scales 1 and

2, but in general the maps at a scale of 2 appeared more uniform in

character density than those at a scale of 1. The proximal maps,

according to how many different numeric values were used with a

beam, appeared the same for each series of beams.

A general conclusion about all these maps would have to be that

the data point arrangement in beams 13-16 produced the most consistent

maps based on character density per intensity level and shape of

intensity level. There would probably be less chance for errors,

however, in using the data point arrangements in beams 9-12 since the

dummy data point still poses a problem of location with each new

structure.

Whether a contour or proximal map should be called for would

depend on the number of data points and different numeric values being

used. In most cases data points located at one foot intervals will

give the most satisfactory results. Until the number of different numeric

values equals nine or ten, contour maps will produce more consistent

character densities than will proximal maps. The scale for either
type of maps should be as large as possible.

Comments

The SYMAP program and lineprinter have, to a limited extent,
proven capable of producing a simulated visual representation of
known internal moments in a simple beam load at midspan. Whether or
not this particular computer graphics software and hardware combination
could be used with other structures and force phenomena can only
be theorized. Each new structure to be investigated will undoubtedly
present new problems of data point location and number. Complicated
structural arrangements should increase this problem a great deal, but
many of the SYMAP program capabilities have not been investigated
in this study and will probably prove to be quite useful if not a
necessity for an accurate visual representation of the forces in these
structures.

FOOTNOTES

[1]Telephone interview with programmer at Laboratory for Computer Graphics and Spacial Analysis, Harvard Graduate School of Design, by the author, on April 25, 1971.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this study has been to investigate computer graphics
and its potential as a tool in the study of structural behavior. A
brief history of past and present teaching methods used in trying to
bridge the gap between the visual, qualitative understanding of struc-
tural behavior and the numeric quantification of that behavior showed
that no single technique has successfully accomplished this task. New
developments in computerized structural analysis and computer graphics
were shown to possibly provide a unique combination which would satisfy
both the qualitative and quantitative criteria for studying structural
behavior.

Assuming that most readers would be unfamiliar with computer graphic
terminology, a brief survey and discussion of the three most commonly
used pieces of computer graphic hardware was presented. This survey
introduced the lineprinter, the plotter and the cathode ray tube as the
three most widely used pieces of computer graphics hardware. A more
indepth discussion of one computer graphics software package called SYMAP
sought to explain how such programs worked in conjunction with computer
graphics hardware.

An investigation using the SYMAP program and lineprinter as a com-
bined tool was initiated to determine whether this combination could
accurately represent known internal forces in a structural member under

load. The bending moments in a simple beam with a concentrated load at midspan were chosen as a test case. Using variations in data point locations and SYMAP options, over 200 visual representations of the bending moments were produced. Four of these visual representations were shown to accurately depict the known bending moments in the beam.

Future Investigation

In this study the lineprinter was the only form of computer graphic hardware to receive any consideration. As was mentioned in Chapter II, it is the least visual, interactive or dynamic piece of graphic equipment.

If this technique is to become a useful communication device in the study of structural behavior, future studies should concentrate on working with computer graphic systems which are more interactive and dynamic for the user. Currently the only system to provide both these features is the cathode ray tube. Using the CRT with any of the new software developments which produce colored, opaque pictures could open exciting and unlimited areas of study for the use of computer graphics in structural analysis.

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APPENDIX A

TYPE OF PACKAGES

A-Outline

This package describes the outline of the study area if non-rectangu-
lar, by specifying the coordinate locations of the outline vertices.
It is used for contour and proximal maps only.

A-Conformolines

This package is used to give the positions of zones to which data
is to be related, by specifying the coordinate locations of vertices
on the zonal outlines. This package is required only for conformant maps.

B-Data Points

This package is used to specify the coordinate locations of data
points to which data is to be assigned. Data points may be either the
points for which data is available, or the centers of areas, called data
zones, for which data is available. This package is required for contour
and proximal maps.

C-Otolegends

This package is used to specify the relative position of legends whic
are adjusted automatically if the size and/or scale of the map are altered

D-Barriers

This package is used to give the coordinate location and strength of
impediments to interpolation at specified vertices.

E-Values

This package is used to assign numerical data to the data points and/or data zones, by specifying the "values" involved. While normally required, this package may be omitted if you wish to procure a preliminary "base map" for checking locations before applying values.

El-Values Index

This package is used to adjust the reference order of data values in the E-Values package.

F-Map

This package is used to specify below the map an appropriate title for the identification of each separate map you may wish to run. In addition, it instructs the computer to make each specific map pursuant to certain "electives." These electives provide a variety of options for obtaining maps suited to the users particular needs. An F-Map package is required for each map desired.

APPENDIX B

ELECTIVES USED IN TABLE IV

Elective Number 3

Used to specify the number of intensity levels which the total data value range is to be divided into and displayed. Two to ten intensity levels are possible with the standard being five.

Elective Number 8

Will suppress the white contour or similar lines between adjacent levels of symbols.

Elective Number 13

Controls the scale of the output map. If the scale of the map is specified as "1.0", each inch on the output map will represent one source-map measurement unit. If the source-map measurement unit is in inches, these two maps will be at the same scale. To increase the scale of the output map, increase the specified number; to decrease the scale of the output map, decrease the specified number.

If not specified, the scale will be calculated from the size of map and from extreme points.

Elective Number 14

This elective is used to obtain a margin between extreme points of the study area and the corresponding output map borders. It may also be used to narrow the content of the output map.

<u>Elective Number 15</u>

Used to specify the number of characters per inch vertically and horizontally at which the maps will be printed. This elective is primaril for persons who may need to use a printer other than one printing at 8.0 lines per inch.

<u>Elective Number 26</u>

With certain computers, the overprint of characters will appear one line above the original print line. This elective will correct that error

VITA

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