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COMPUTER GRAPHICS

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The subject of this paper is CONSTRUCTS — computer-generated graphics system, designed for the structural steel fabrication industry. The Constructs System performs both structural design and graphic construction functions. The primary theme of this paper is the graphics phase, i.e. the generation of steel shop drawings by the computer, and computer-related equipment.

CONSTRUCTS is a computer-guided system which synthesizes the complete shop drawing drafting operation, known in the vernacular of the industry as "detailing." It maximizes the use of computer-programmed logic in those detailing operations that can be considered standard. The system is able to develop drawings for all members for which the logic of dimensioning, fitting and drawing has been pre-programmed.

CONSTRUCTS was developed with funds provided by Control Data Corporation to its Meiscon Division. The purpose of the project was to direct applied research to the problem of automated drafting, and to determine the effectiveness of passive display devices in a standardized drafting application. The system was not only to be developed by Meiscon, but was to be used in the performance of actual contract work to assess its value and to determine its strengths and weaknesses.

Control Data organized its Meiscon Division in February 1963, and authorized the Constructs Project in July of that year. Upon completion of an approximate 25 man-year effort spread over two years, the system entered field test status. It developed completed drawings for actual use on a detailing job in May of 1965.

Since CONSTRUCTS does not utilize any of the pioneering forms of hardware, this paper will dwell on the requirements of the application itself, and

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the approaches to make this and other similar automated graphic operations feasible. It is our judgement that not only are hardware and software techniques important in the development of automated or computer aided graphic systems, but that the analysis of the application itself and the methods of coordinating manual and automated operations are critical to the success of the project.

Background

At this point, it seems worthwhile to review the operation of the structural steel fabrication industry, as it has existed for the past four years. It is an industry that is strictly cost and production oriented. Stiff competition exists among a handful of very large companies and a large number of medium to small firms. All but the very largest are independent firms and must purchase their supplies of raw rolled steel from the large mills. In the main, the fabricated pieces are sold to still other companies that construct, or erect, the finished structure.

Fabrication work is obtained through competitive bidding. Due to the cyclical nature of heavy construction, the competition may range anywhere from fierce to slight. Fabrication prices fluctuate drastically and, when pressure exists, the resulting low prices must be compensated for by limiting operating costs.

Orders for raw rolled steel must be carefully worked out so that basic costs may be minimized. The orders must be created swiftly to meet the earliest rolling schedules of the steel mills and to assure delivery in time to avoid fabrication shop delays due to lack of material. Shop drawings must be produced in the shortest possible time. This operation is continually under pressure since the engineering drawings, from which the draftsman receives his information, are generally still being produced after the fabricator begins work, and the shop is continually demanding a supply of drawings to insure that their work will not be delayed.

The fabricator purchases his raw material from a steel mill in the form of lengths of steel in standard rolled shapes and sizes. From this raw rolled steel, the exact lengths are cut to allow the members to fit into place. If need be, the pieces are trimmed so that interferences will not occur. Holes are punched in the members to allow bolts to connect a supporting member to a supported member, or to connect secondary material such as handrails and stairways. The locations of all holes are carefully figured to minimize layout and punching problems in the shop. Pieces are fitted together in the shop so that the field erection job may be as easy as possible. All of this work must be performed with great care since mistakes mean waste of expensive material, or may bring large back-charges against the fabricator for causing erection delays or field repair.

In order to communicate the proper instructions to sub-technical personnel in the shop, the practice has developed of preparing a shop drawing which shows in large pictorial form real-looking views of each member with the positions and dimensions of all holes and attachments. A typical shop drawing is shown in Figure 1. The picture of each member is drawn realistically and clearly so that a minimum of visualization is required of shop personnel. Straight and clear line work and clear characters are important since they affect visualization of the member and interpretation of the measurements.

To prepare these shop drawings, fabricators require a large number of well trained draftsmen, either from their own organization or from independent job shops. These draftsmen have special abilities, training and temperament. They are careful, have good mechanical ability and three dimensional visualization, are able to turn out large volumes of the same type of work day after day without losing interest, and have an understanding of the way in which structural steel should be fabricated and erected.

The draftsman studies the engineer's design drawing, which is a line drawing containing the location and size of all members of the building. In his mind, the draftsman visualizes how the pieces fit together, and arrives at a decision as to how they should be connected. He calculates the proper number of bolts, or amount of weld; designs a connection to fit these needs; determines how to minimize punching by placing bolts from several members through as many common holes as possible; and continually reviews his decisions to be sure that there is adequate clearance for erection and for access of a wrench in order to tighten the bolts. In order to build up a complete picture, the draftsman must relate all connecting members so that bolts on one member have fitting holes accurately placed on attaching members. He then makes an appropriate record on the drawing in a form understandable and suitable to the shop.

The member drawings are placed on sheets in a logical and compact manner. The sheet sizes vary, but generally measure about 24 in. x 36 in. Each contains from four to ten individual pictures. Pictorial realism and clarity are retained although the pictures are generally drawn to scale in only one direction. Vertical scaling is accurate, but the horizontal scale is allowed to vary to compact the individual picture and so conserve sheet space. Each drawing generally represents only one member, and is used just

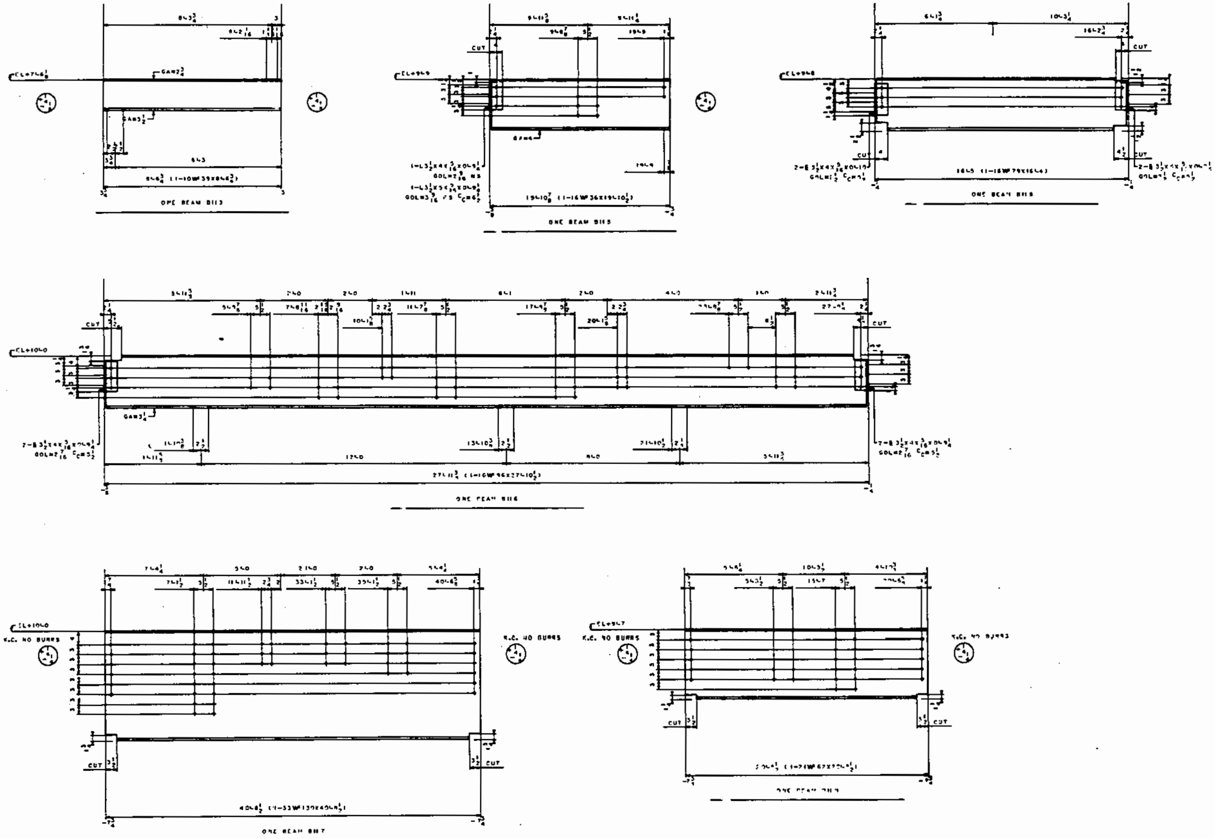


FIG. 1

twice: once in the shop when the member is fabricated, and once in the field when the member is erected. Drawings of this type are essential, but because of the low utilization factor, they are prepared with the least possible cost. They are prepared in high volume with large jobs having as many as 2,000 to 5,000 sheets of up to ten-member drawings.

In summary, the application to which we have applied computers and graphic devices is one which requires that a large number of simple, clear, visually real drawings be produced with very accurate dimensions, at low cost, and in a minimum of time. Although a human draftsman can perform these services, there is need for improvement in efficiency and costs, and a need to supplement the pool of available persons which is being depleted by the attractions of more glamourous occupations.

Research Project

It was decided that there were a significant number of features within this particular application to warrant its selection as the subject of our research project. As our study progressed, it became apparent that the simple development of the picture by the computer would not be the proper way to attack the problem. The cost of the "art work" by manual techniques is low because of the simplicity of line work and the relatively standardized and semi-schematic presentation of the drawing components. This indicated the need for the computer to perform operations other than just graphic output, in order to gain economy. One logical step was to have the system calculate the dimensions that were to appear on the drawing, in addition to producing the drawing itself. Since the shop drawings are made up largely of standardized components selected by rather well-defined logic, the system could perform the selection function also. Having the system perform this standardized selection function was not just desirable for economy, it was essential unless man-machine interaction was on a high level, since the calculation of dimensions and the selection of connection type are mutually dependent.

In 1964, we were faced with an unavailability of hardware and software needed to develop an efficient means of man-machine graphic communication. At that time, Control Data's Burlington Laboratory was just beginning work on the Digigraphic System, utilizing cathode ray tube (CRT) and light pen techniques. Although it was obvious that the lack of an efficient interactive medium would not prohibit development of our system (because the needs were for production of large volumes of standardized drawings resulting from fixed logic), it did inhibit system capability in terms of decision flexibility and ease of development of input data. Our input technique remained the punched card prepared from a dataform. Without ready interaction, it would be impossible , except under a few special conditions, to allow the draftsman to impose his will on the system by reacting to system calculations. Without convenient man-machine communication, we also decided to make the system as independent as possible, thus causing the system to be one of automated drafting rather than of computer-aided drafting. Although this approach was recognized as being expensive, and less flexible, it would, in addition to producing pictures, attack the detailer's greatest problem, namely, that of reducing human errors in data correlation and transfer.

Each member would require many logical decisions and many computations based on logic iteration. Large amounts of data would have to be stored to define the structure, and to define all of the many small details of each member, not only in its real physical state, but also in its graphically represented state. The speed and storage requirements of the computer to be used were significant.

We selected a Control Data 3600, which had just been installed in Control Data's data center in Minneapolis. The configuration has 131,000 words of core storage, each of 48 bits. Cycle and add times were 1.2 and 2 micro-seconds respectively. At the time the design of the Constructs System took place, the computer had 12 tape drives but no random access storage. To provide our office in Chicago with access to the Minneapolis data center, we installed a Control Data 160A computer, with card reader, tape drives and printer, to transmit and receive data by telephone lines. All program development as well as production runs have been performed through this process. Data received in Minneapolis from our office are stored on tape, and then inserted into our batch process.

A graphic device for producing the drawings also had to be selected. Our previous experience had been with a high speed CRT-to-film device. The results, which we obtained from the 1000 x 1000 grid on a four-inch CRT, indicated to us that, when the film was blown-up to the required size of 24 in. x 36 in., the resolution would be unsatisfactory. The through-put rate, however, would be fairly well balanced with that of the computer.

We reached the conclusion that it was more important to produce a drawing of the type and quality needed to allow the shop personnel to perform their work with the least retraining, than to balance the system through-put, since the computers involved would not be dedicated solely to this application.

After considerable study, we selected a 45 in. x 60 in. flat bed, analog, mechanical plotter for our output device. It has a plotting tolerance of ± .015 in., which is approximately that of a draftsman. Line work is created by ink on hard copy from one of three different size reservoir pens mounted in a program-addressable turret. Characters may be printed by a print head mounted on a translating arm along with the pen turret, or they may be drawn by pen. The plotter is off-line and accepts simple line and point commands from magnetic tape. The plotting speed is about 144 in. per second for lines, or about three characters per second by print head.

Detailing System

The CONSTRUCTS detailing system can be thought of as being divided into three basic phases. Each of these phases simulates the thought processes and physical actions of an experienced draftsman.

In the first phase, CONSTRUCTS simulates the draftsman's study of engineering design drawings by reading minimal data from punched cards. Figure 2 is a sample of just such a design drawing, or framing plan, as produced by the design engineer. The framing plan shown depicts a structural floor arrangement, showing the floor beams as straight lines, and the supporting columns as as H or I shaped symbol. In practice, framing plans display structural systems much larger and more complex than this sample. The system input data are the information portrayed on the engineer's design drawings, regarding each member's relative location within the framing plan (i. e. 10 ft. - 0 in. from vertical plane A, 2 ft. - 3 in. from floor plane 1, etc.), as well as declarations of the absolute location of the structure's vertical and floor planes. Since these dimensions are available on the design drawings, the draftsman creating input need only record what he sees displayed on his source document. He need not make tedious and error-prone mental summations to compute coordinates, nor be concerned about connection design or dimensional determination since the system handles these functions. The location of each member, its shape, size and orientation are also input. In addition, a declaration is supplied of the members which *support*, but not those supported by, the piece in question. A small amount of subsidiary information regarding the type of shop and field fastenings is also input. These data are written on well laid-out, but rather typical, preprinted input forms. Figure 3 is one of the three data forms available to record input information to the system. A major part of the dataform is reserved for special overrides to normal conditions, and thus is used only for these special conditions.

It was recognized that by asking the draftsman to transfer data from graphic form to a dataform rather than between graphic forms as he was used to doing, we were increasing the potential for error. To help overcome this, an extensive series of validation tests are applied to the input data by

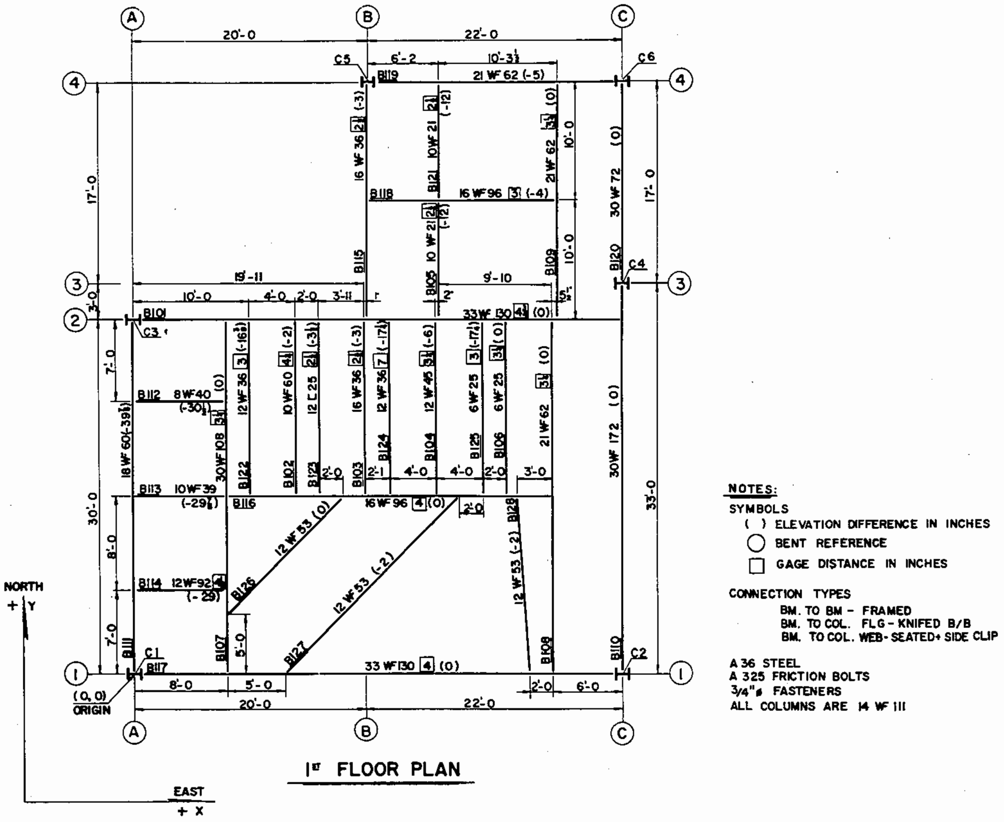
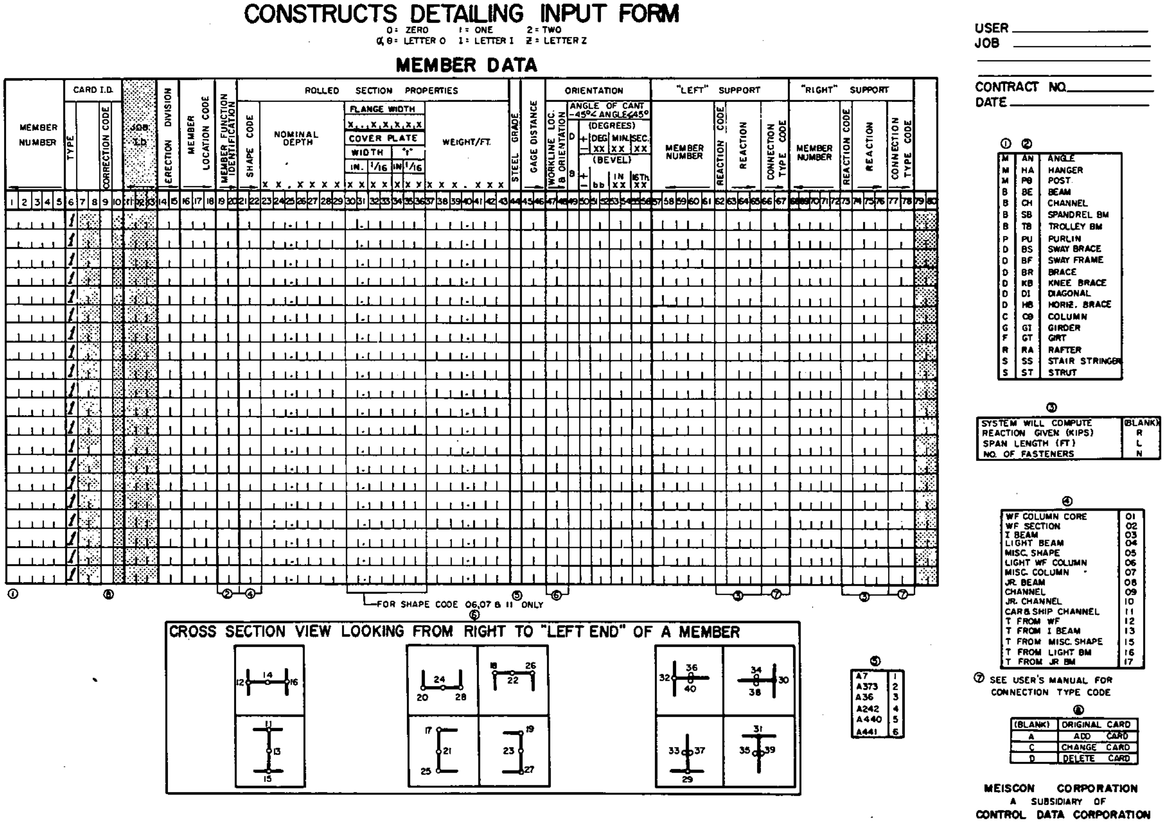

A
B
C
1
2
3
4
20'-0
22'-0
17'-0
33'-0
30'-0
3'-0
C1
C2
C3
C4
C5
C6
B101
B102
B103
B104
B105
B106
B107
B108
B109
B110
B111
B112
B113
B114
B115
B116
B117
B118
B119
B120
B121
B122
B123
B124
B125
B126
B127
B128
21 WF 62 (-5)
16 WF 96 3 (-4)
10 WF 21 2 (-12)
16 WF 36 2 (-3)
30 WF 72 (0)
30 WF 172 (0)
33 WF 130 4 (0)
33 WF 130 4 (0)
16 WF 96 4 (0)
12 WF 53 (0)
12 WF 53 (-2)
12 WF 53 (-2)
8 WF 40 (-30½)
10 WF 39 (-29¾)
12 WF 92 4 (-29)
18 WF 60 (-39⅛)
30 WF 108 3½ (0)
12 WF 36 3 (-16⅞)
10 WF 60 4½ (-2)
12 ⊏ 25 2½ (-3½)
12 WF 36 7 (-17¼)
12 WF 45 5½ (-6)
6 WF 25 3 (-17¼)
6 WF 25 3½ (0)
21 WF 62 3½ (0)
6'-2
10'-3½
10'-0
19'-11
9'-10
4'-0
2'-0
3'-11
2'-1
5'-0
8'-0
7'-0
6'-0
5½"
NORTH
+ Y
EAST
+ X
(0, 0)
ORIGIN
1st FLOOR PLAN
NOTES:
SYMBOLS
( ) ELEVATION DIFFERENCE IN INCHES
○ BENT REFERENCE
□ GAGE DISTANCE IN INCHES
CONNECTION TYPES
BM. TO BM - FRAMED
BM. TO COL. FLG - KNIFED B/B
BM. TO COL. WEB - SEATED+ SIDE CLIP
A 36 STEEL
A 325 FRICTION BOLTS
3/4"ø FASTENERS
ALL COLUMNS ARE 14 WF 111

FIG. 2



CONSTRUCTS DETAILING INPUT FORM

0: ZERO 1: ONE 2: TWO
Ø, θ: LETTER O I: LETTER I Ƶ: LETTER Z

MEMBER DATA

USER ____________
JOB ____________

CONTRACT NO. ____________
DATE ____________

MEMBER NUMBER (1–5) ①
CARD I.D.: TYPE (6) — (7–8) — CORRECTION CODE (9) ⑧ — (10)
JOB I.D. (11–13)
ERECTION DIVISION (14–15)
MEMBER LOCATION CODE (16–18)
MEMBER FUNCTION IDENTIFICATION (19–20) ②
ROLLED SECTION PROPERTIES: SHAPE CODE (21–22) ④ — NOMINAL DEPTH X X . X X X X (23–29) — FLANGE WIDTH X . . X . X . X . X . X / COVER PLATE WIDTH IN. 1/16, "t" IN 1/16 X X X X X X (30–36) — WEIGHT/FT. X X X . X X X (37–43)
└FOR SHAPE CODE 06,07 & 11 ONLY ⑥
STEEL GRADE (44) ⑤
GAGE DISTANCE (45–46)
ORIENTATION: WORKLINE LOC. & ORIENTATION (47) ⑥ — ANGLE OF CANT −45°< ANGLE ≤ 45° (DEGREES) D + − DEG XX MIN XX SEC. XX — (BEVEL) B + − bb IN XX 16Th XX (48–56)
"LEFT" SUPPORT: MEMBER NUMBER (57–61) — REACTION CODE (62) ③ — REACTION (63–65) — CONNECTION TYPE CODE (66–67) ⑦
"RIGHT" SUPPORT: MEMBER NUMBER (68–72) — REACTION CODE (73) ③ — REACTION (74–76) — CONNECTION TYPE CODE (77–78) ⑦
(79–80)

①	②	
M	AN	ANGLE
M	HA	HANGER
M	PO	POST
B	BE	BEAM
B	CH	CHANNEL
B	SB	SPANDREL BM
B	TB	TROLLEY BM
P	PU	PURLIN
D	BS	SWAY BRACE
D	BF	SWAY FRAME
D	BR	BRACE
D	KB	KNEE BRACE
D	DI	DIAGONAL
D	HB	HORIZ. BRACE
C	CO	COLUMN
G	GI	GIRDER
F	GT	GIRT
R	RA	RAFTER
S	SS	STAIR STRINGER
S	ST	STRUT

③

SYSTEM WILL COMPUTE	(BLANK)
REACTION GIVEN (KIPS)	R
SPAN LENGTH (FT)	L
NO. OF FASTENERS	N

④

WF COLUMN CORE	01
WF SECTION	02
I BEAM	03
LIGHT BEAM	04
MISC. SHAPE	05
LIGHT WF COLUMN	06
MISC. COLUMN	07
JR. BEAM	08
CHANNEL	09
JR. CHANNEL	10
CAR & SHIP CHANNEL	11
T FROM WF	12
T FROM I BEAM	13
T FROM MISC. SHAPE	15
T FROM LIGHT BM	16
T FROM JR BM	17

⑤

A7	1
A373	2
A36	3
A242	4
A440	5
A441	6

⑦ SEE USER'S MANUAL FOR CONNECTION TYPE CODE

⑧

(BLANK)	ORIGINAL CARD
A	ADD CARD
C	CHANGE CARD
D	DELETE CARD

CROSS SECTION VIEW LOOKING FROM RIGHT TO "LEFT END" OF A MEMBER

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CONTROL DATA CORPORATION

FIG. 3

the first phase of the system to keep detectable errors from passing through the system. Member sizes are checked for validity against the steel section table. Abnormally long, short or skewed members are brought to the user's attention as possible error conditions. The support declaration made by the user is verified for consistency. From this information a model of the structure is created in memory, through a simple list processing technique, to determine the design sequence of the members. Once the tree-structured model has been produced, a string of pointer indexes is generated for each member, identifying the list address of all connected members. The declaration of shop and field fastening modes for the various classes of members are also cross-validated to avoid inconsistencies in fabrication procedures. If any error conditions are uncovered, printed messages indicating the source and cause of the error are given. Corrections of errors may be made by edit and update programs.

After the input has been approved by the user, it is rearranged by the system into the proper detailing sequence for submission to the connection design phase. The individual connections of two or more members are designed by the detailing procedures recommended by the American Institute of Steel Construction, and by the additional detailing criteria input supplied by the user. All of the basic facts regarding each member, such as deciding on the member's end and interior connections, cuts, copes, fasteners, wrench clearance, etc., are determined by the system through program logic and stored for image generation.

During processing in the connection design phase, a record of 3000 characters minimum is constructed for each member, completely describing all details of the member in final fabricated form. This record is the most compact description of the complete structural piece and its attachments. From this information, the third or graphic phase of the system formulates the plotter output in a three-step process. The first step is problem oriented in that the programs interpret the data from the structural steel member record and builds-up a series of graphic entities into the specific kind of shop drawing for portraying the member.

The second step converts the shop drawing graphic entities into a general graphic representation not at all related to shop drawings. The third step converts this general representation into the specific command structure of the plotter through a post processer type of operation.

The object of step one is to select, for each particular member type, a series of graphic entities, or sub-pictures, that are manipulated and joined together to form an entire picture. Figure 4 shows six graphic entities which

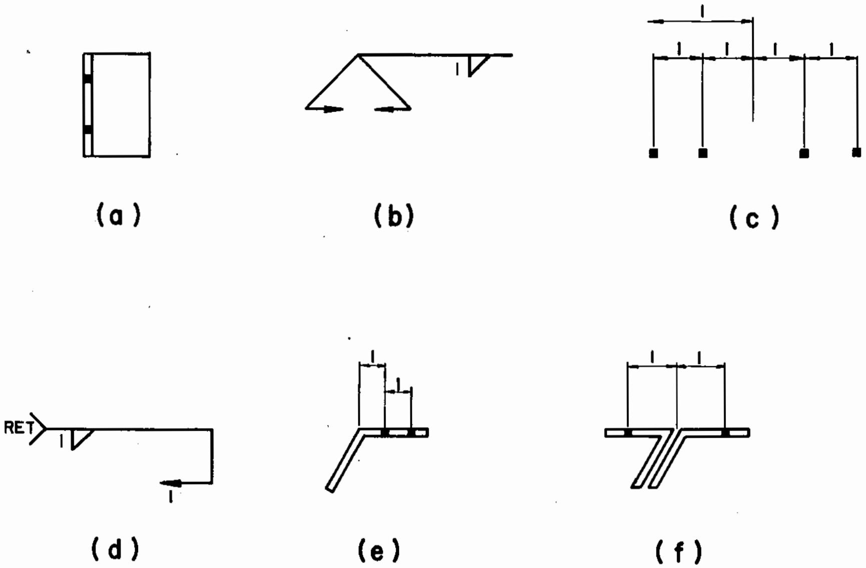

FIG. 4

are contained in a file of master drawings. The graphic entities are preprogrammed from a scaled layout of a "unit picture". Each unit picture is a generalized component of a particular member image, and is stored with all of its dimensions and variable patterns shown as unity. If a series of circles, which represents a hole pattern, is to be drawn as part of the entity, the unit picture is shown with one circle set and a spacing factor. Each of the points of the entity may be identified as being scalable or not. Linkage points with other entities are pre-defined. Lines which are viewed as solid lines in the basic position, and which become hidden when viewed from the other side, are also pre-indicated.

Coding of the basic entity is accomplished by a separate file-builder program which can interpret a small vocabulary of convenient English language code words. The master entity file is prepared in advance of a production run, or may be held constant from a previous run, and is made available to the system during run time.

Each structural member drawing has its own local origin and referred axis. From the particular type of member, the program logic determines the proper graphic entities to be used and their order of build-up. As the system builds each picture, it extracts codes and parameters from the member record to allow the programs to select the names of the proper graphic entities stored in file, and to create the proper factors which will later translate, rotate, stretch, reflect, fill annotation positions, and develop repetitious subportions of this entity.

In Figure 5, two separate graphic entities are displayed in various conditions.

Figure 5.1 is a connection angle shown in:

- a. With minimum bolt holes
- b. With call for four holes
- c. As opposite hand
- d. As rotated
- e. As viewed from the opposite side, with one line and the bolt holes becoming hidden

Figure 5.2 shows a weld symbol:

- a. Normal
- b. Opposite hand
- c. Rotated

Figure 5.3 shows the weld symbol related to the connection angle, by linkage points.

Manipulation of entities is not actually performed at this stage of the system. The entity name and manipulation factors are carried along with the record and are applied to each entity by the general graphic programs in step two. The graphic entity may be rescaled in total or with programmed constraints. Linkage points set in the basic entities cause all related entities lower in the hierarchy to be manipulated relative to the parental entity.

As an example of the steps of picture build-up, a structural beam has its ends formed first with from one to five individual entities. As each intermediate entity is developed by the system, the ends are spread apart sufficiently to assure adequate room so that no overwrite of characters or lines occurs. When the number and type of each series of dimensions is determined, the system develops an adequate number of line levels to hold each series of dimensions, and stretches the lines to connect related entities. The dimension values are extracted from the member record and placed in relation to a preprogrammed annotation point that has been properly translated due to the stretching of the dimension line.

During the build-up of the member picture, a small two-dimensional space availability table is checked off by the program as each unit of space

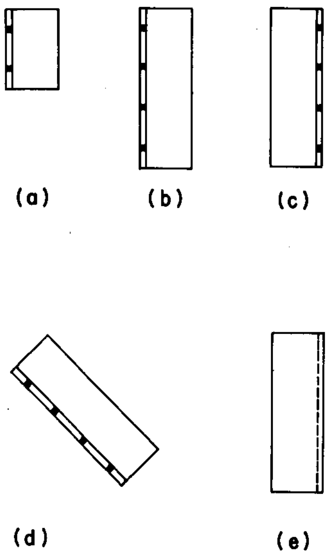

FIG. 5.1

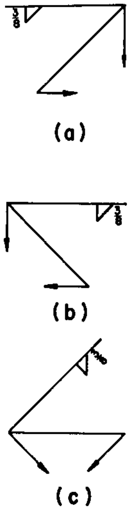

FIG. 5.2

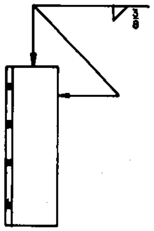

FIG. 5.3

is filled by the expanding member picture. Upon completion of the member picture, the space-availability table is compared against a similar table for the entire drawing sheet being developed. Program logic places the member in the position on the drawing sheet which allows maximum compaction. Translation factors are then applied to the member picture to properly place it in the selected available position. When each sheet is filled, it is numbered. All members on the sheet are then named relative to the sheet number and the drawing is then stored for processing by the general graphic programs.

The second step of the graphic processing extracts the description of the entity named in step one, this being in terms of lines, points and characters, and applies the associated manipulation factors to the series of general line, point and character generation descriptions which make up the entity. The graphic description is based on a general two-dimensional cartesian coordinate system, without regard to the command structure, or special idiosyncrasies of the particular plotter. All entity manipulations, i.e. scaling, rotation, reflection, etc., are performed with the present graphic constraints being observed in this step of the graphic phase.

The third step, or post process stage, formats the plotter commands and performs line interpolation as required by the plotter, selects character or plotting mode, pen, or whatever other facilities are available on the device. A bill of materials is produced in conjunction with the drawings. The information source is the basic member tape produced in phase two.

Project Results

Figure 1 is a view of a completed detail sheet as prepared and arranged by CONSTRUCTS. The five members shown are right angle beams for a building floor system.

Figure 6 shows a close-up of one right angle floor beam with one intermediate connection. An unusual difference of end elevations of this member's supports has caused the unusual dropped connection on the right end.

Programs for the Constructs System are written entirely in Fortran for the Control Data 3600. There are three major phases operating in an overlay mode under the monitor system. The three phases are composed of in excess of 200 sub-programs made up of more than 50,000 source state-

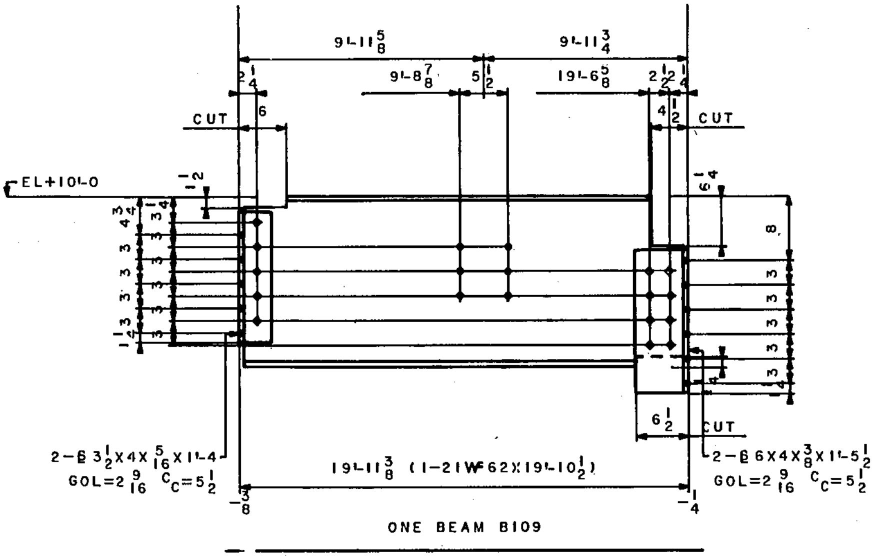

FIG. 6

ments. We currently are converting CONSTRUCTS to a Control Data 3150 for installation in a steel fabrication firm. The 3150 will have a memory of 32k, 24 bit words, and two high-speed disk units.

The CONSTRUCTS steel fabrication detailing system has been in use in our office as a service operation for two and one-half years. A few of our observations on the effectiveness of the system are as follows:

A. Cost
When analyzing the entire cost of shop drawings performed by the system, including manual completion and correction, and calculating computer costs at service bureau costs, we have found cost reductions reaching a maximum of 25 percent.

B. Timeliness
Small jobs have brought little or no time reductions, while jobs with large numbers of members have realized time reductions of 30 percent.

C. Manpower Leverage
Considerably fewer men of lesser experience have been required on jobs having substantial amounts of CONSTRUCTS oriented work.

D. Additional Outputs
The next planned stage of system extension will be the development of production information directly from the member record. This information will include tapes for member punching, templates for plate cutting, as well as expanded data for inventory management. We look forward to the use of an interactive light pen and scope to add increased flexibility. We consider this to be a decision-making tool to achieve a wider range of connection decisions, and to facilitate the development of graphic entities tailored to a particular job. We do not consider using these devices for the basic drafting operation due to the low drawing cost value and high production requirements for this type of drawing.

E. Flexibility
By developing a system which minimizes man-machine communications, flexibility of operation has suffered. Lack of flexibility would have been more noticeable had the effort to program decision logic not been as extensive as it was. We have had little trouble in applying CONSTRUCTS on a job basis; however, on some jobs CONSTRUCTS leaves members incomplete, a condition which we feel can best be satisfied by interactive devices.

In summary, we feel that CONSTRUCTS illustrates the feasibility of producing low-value, high-volume drawings in an economical manner by automated drafting techniques. Although the project has been successful, it should be noted that the effort required to equal the adaptive and highly productive human in a graphic operation is significant, must be well planned to suit the particular application, and should not be treated lightly.