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AN EVALUATION OF THE SYSTEMS APPROACH TO BRIDGE DESIGN

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SUMMARY and RECOMMENDATIONS

This study contains the findings from a survey of available integrated computer systems for bridge analysis and design, along with a sample design of a grade separation structure using the two leading design systems, BEST and STRC. It appears that integrated design systems could be applicable to the design of common highway bridges in Virginia, and that such systems might offer savings in engineering design costs and in materials costs. Unfortunately, however, neither BEST, a public system, nor STRC, a commercial system, is readily applicable to the needs of the Virginia Department of Highways & Transportation. A public system that offers greater portability than BEST is needed.

It is recommended that the Department of Highways & Transportation keep abreast of and encourage systems development. The Department should formulate a concept of its specific requirements for a future system. Hopefully, the development of any future system would be done on the widest basis, to meet the needs of a large number of agencies. Virginia's participation in a national or regional development program would seem advisable.

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INTRODUCTION

Considerable effort has been expended in recent years to transfer the mudane and tedious aspects of engineering design to the computer. Highway departments across the nation have recognized the area of bridge design as a fertile one for computer application that could yield both cost and time savings. As a result, all highway departments in the United States employ libraries of computer programs intended to facilitate the several individual steps in the overall design of a bridge. An obvious extension of the use of these individual programs is their combination in a logical sequence to form a system, and a few states have proceeded in this direction. The strength of their commitment, and their interest in the systems approach, can most readily be measured by the time and money invested to produce a computer based bridge design system. The costs range from eight man-years and one-quarter of a million dollars for a modest system to twenty-five man-years and well over a million dollars for a large integrated design system.

An integrated design system is a group of computer programs encompassing the major phases of highway bridge design, as shown in Figure 1, linked together by a data management program. The data management program should allow the execution of the various programs within the system individually, at the discretion of the designer, but its primary role is that of storing data and transferring it as needed between the programs to develop a complete bridge design. In this more powerful mode, the system performs an iterative approach to an optimum design using minimal input data, with potentially great savings in materials. Significant savings in engineering design costs are also possible.

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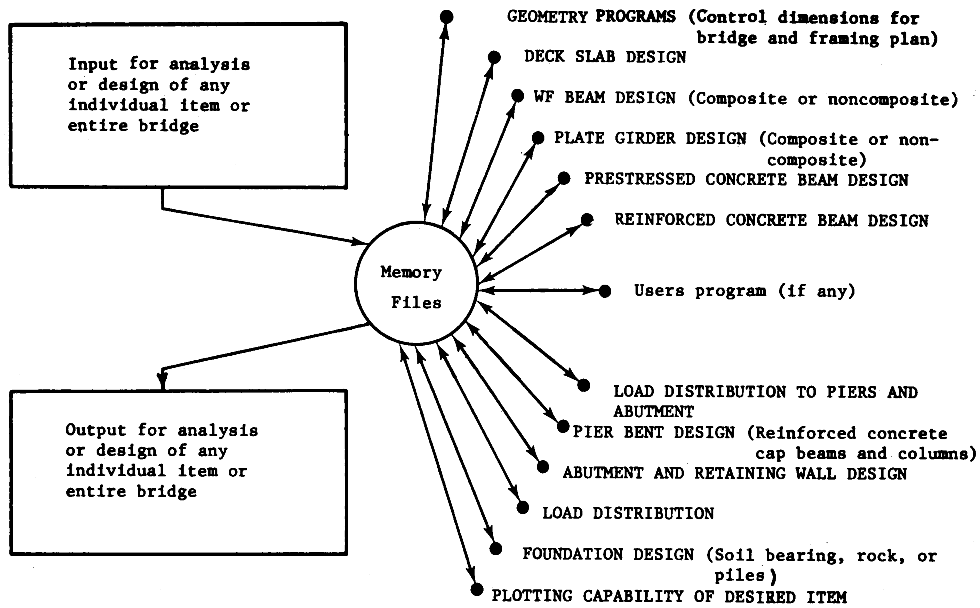

Figure 1. Bridge design subsystems.

Analysis systems, those that compute the stresses in members of known dimensions, are also available. These systems are less complex than integrated design systems since the iterative loops between the programs are not required. Because they are more easily composed and are often more easily adapted to a variety of computer facilities than are design systems, analysis systems have found wider acceptance by highway agencies.

From the literature it would appear that four bridge analysis and design systems have been developed in the United States since the mid-1960's. These are:

1. BEST, the Bridge Engineering Subsystem of TIES, the Total Integrated Engineering System.
2. STRC, a proprietary system available through Omnidata Services, Inc.
3. BRIDGE, the bridge design subsystem of ICES, the Integrated Civil Engineering System.
4. BRASS, the Wyoming Bridge Rating and Analysis Structural System.

Like most highway agencies, the Virginia Department of Highways & Transportation is presently using a variety of computer programs that deal with specific areas of bridge design and analysis. Although these design aids are undoubtedly saving time and money, the integrated system approach, which has not yet been employed in Virginia, could possibly effect much greater savings. However, the tremendous investment in time and effort, involving persons with knowledge of computers and bridge design, required in the development of a design system makes it logical for an agency such as the Virginia Department of Highways & Transportation to adopt the work of others if at all possible.

PURPOSE AND SCOPE

The purpose of this study was to examine existing integrated bridge design systems in an effort to determine if such tools have application for the design of highway bridges in Virginia. An acceptable system must be flexible enough to be adaptable to the design policies of the Virginia Department of Highways & Transportation and yet simple to use so as to prevent the design from being encumbered by complex operating procedures.

All available bridge analysis systems were scrutinized, and the two leading design systems, BEST and STRC, were evaluated through the redesign of an existing bridge first designed for the Department by a consulting engineer. Manpower limitations did not allow a complete check of the two redesigns including all components of the bridge. Instead, the investigation concentrated on evaluating the inherent differences in the approaches of the BEST and STRC systems and those of the Department of Highways. While spot checks were made by researchers, it is acknowledged that a thorough check by design personnel would be required prior to the adoption of any system.

Personal contacts and a questionnaire sent to the various state highway and transportation agencies were also utilized in this study. Information gathered from the latter sources allows a brief description of all of the integrated systems, design and analysis, that were discovered.

PRELIMINARY QUESTIONNAIRE

As an initial step in the review of bridge systems, questionnaires were sent to all of this country's state highway departments asking which, if any, of these systems they used. They were also asked if they had developed or planned to develop their own systems. Responses from 49 departments were received. New York responded that they were using all of the BEST system, while Vermont uses a portion of the system. No states said they used the OMNIDATA programs. California, Hawaii, and West Virginia responded that they are using parts of BRIDGE. Arkansas, Kentucky, North Carolina, North Dakota, West Virginia, and Wyoming stated that they are using or investigating the use of BRASS.

Oklahoma and Michigan indicated in their replies that they were developing their own integrated systems of analysis or design. The Oklahoma system (BRDESIGN) "will allow the engineer to combine geometric and structural programs with connecting and plotting programs, enabling him to produce a set of bridge construction plans from preliminary sketches to final drafting documents—in one continuous process. The first phase of the system covers simple prestressed concrete I-Beam bridges".

Michigan's system, Bridge Design, applies to the superstructure of the bridge. It will design cantilevered simple spans. The sub-programs of this system will perform beam layout, rolled beam or girder design and bearing design, and pier design and determination of all elevations required for deck construction. All of these functions can be executed with a single page of input. An abutment design and plotting routines for superstructure and structural steel details are being added now. In order to minimize input, the Bridge Design program is highly specialized to meet Michigan's standards.

Many states indicated that they use ICES STRUDL for various analysis and design tasks. These were Alabama, Alaska, Arkansas, Oregon, Tennessee, Washington, and West Virginia. STRUDL is basically an analysis program, and it may be applied to a wide range of structural problems, including two-dimensional trusses, frames, plates, and grids, as well as three-dimensional trusses and frames. STRUDL also allows the proportioning and checking of reinforced concrete beams and columns of various shapes and of flat plate floor slabs. The user may control the design of elements by specifying some of the cross section design parameters or by placing upper and lower bounds on these parameters. The proportioning procedure takes into account biaxial bending for columns and flexure, shear, bond, and deflection criteria for beams and slabs and uses the ultimate strength theory. The output consists of cross section dimensions and required reinforcement at the critical design sections. The adequacy of a given member may also be checked against any or all of the criteria.

Georgia, Iowa, Montana, Ohio, Oklahoma, and South Dakota indicated that they use the Control Data Corporation's Bridge Analysis and Rating System (BARS). With this program, bridge ratings are produced at required stress levels for the normal AASHTO lane and truck live loads, state legal loads, and special permit loads. BARS is available to users through Control Data's CYBERNET Services network and on a license basis.

Another available system is the Portland Cement Package Program, PCSPAN. PCSPAN performs the analysis and design of simple span, pre-cast prestressed highway or railway bridges. The designer selects and inputs the main structural parameters, and the computer makes the routine calculations. The program will accommodate the composite and noncomposite sections included in Figure 2, and will compute and print out the following: section properties, dead load and live load reactions, shears and moments, stresses for various loading conditions, ultimate moments required and provided, spacing of shear reinforcement, horizontal shear stress between the composite slab and precast member, midspan elastic deflections for various loading conditions, and the number and center of gravity of prestressing strands required. The program can be operated in any one of the following modes: (1) analysis and design of standard sections with a composite deck slab (sections 1 through 5 inclusive in Figure 2), (2) analysis and design of noncomposite standard sections (sections 6, 7, and 8 in Figure 2) (3) analysis and design of noncomposite single- and double-celled box beams (sections 9 and 10 in Figure 2), and (4) analysis and design of all sections illustrated in Figure 2 when the number and location of prestressing strands is provided as input data.

A byproduct of the questionnaire was information on the computer hardware used by the states for most of their bridge design work. Three states use UNIVAC equipment, three use a Burroughs machine, one uses a CDC computer, and the remainder use IBM equipment, mostly IBM 370 configurations.

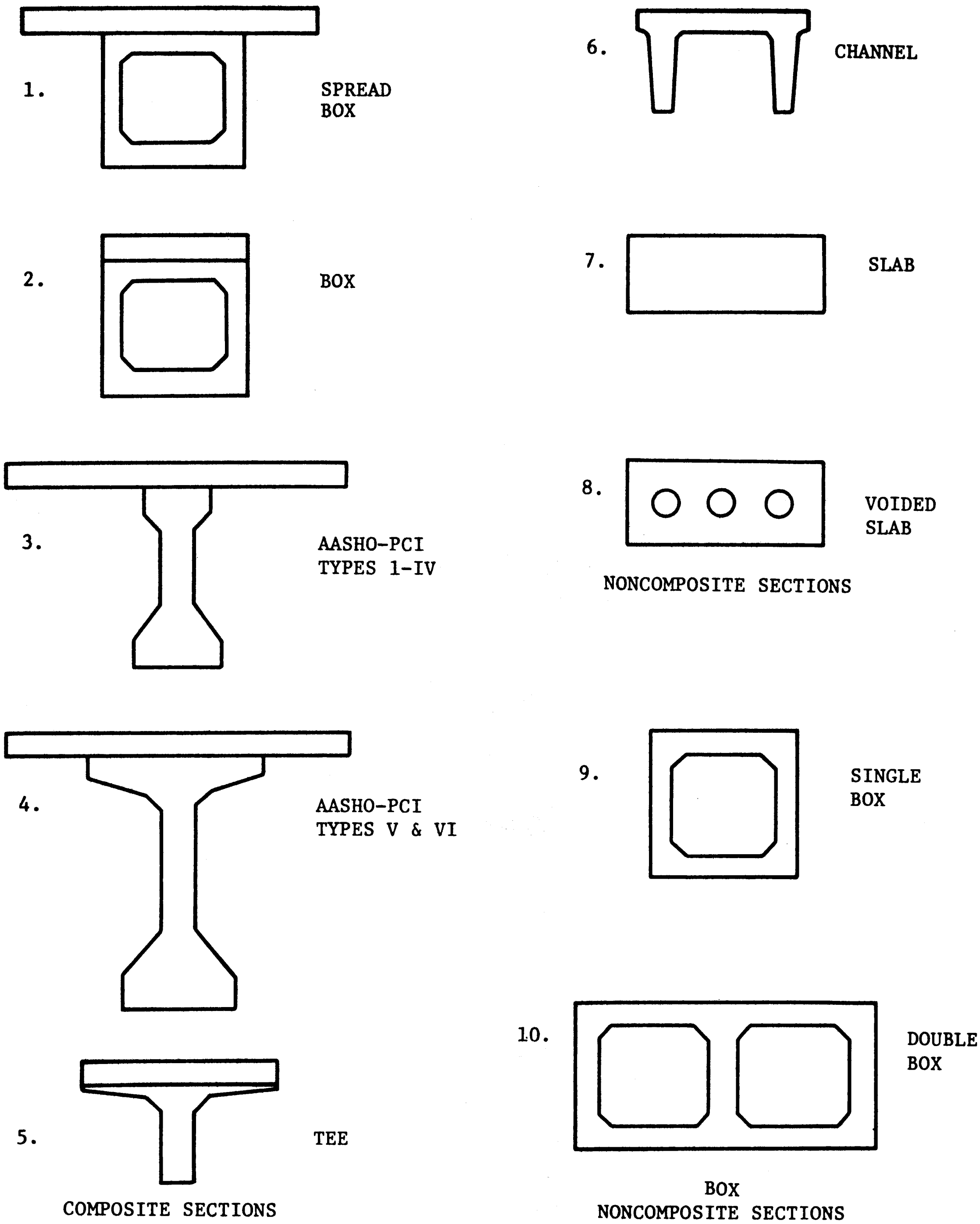

Figure 2. Sections accommodated by PCSPAN, (From—"Analysis & Design of Simple Span Precast Prestressed Highway and Railway Bridges" United Computing Systems, 1969.)

THE MAJOR SYSTEMS

Of the four bridge systems—BEST, STRC, BRIDGE, and BRASS—only the first two approach being truly comprehensive design systems. All four are discussed in this section but only the two design systems will be considered in detail. A comparison of BEST and STRC1 is tabluated in Table 1.

Table 1 Comparison of Capabilities of BEST and STRC1

Subprogram of system	BEST	STRC1
Bridge geometry	X	No
Deck slab design	X	X
WF beam design (composite or noncomposite)	X	X
Plate girder design (composite or noncomposite)	X	X
Prestressed conc. beam design	No	Pre- or posttensioned
Reinforced conc. beam design	X	No
Load distribution to piers and abutments	X	X
Bridge bearing design	X	No
Pier bent design	X	X
Abutment and retaining wall design	X	X
Load distribution to foundations	X	X
Foundation design	X	X
Bridge quanties	X	X
<u>Plotting</u>		
General plan of bridges	X	INGO[1]
Framing plan	X	INGO
Transverse section	X	INGO
Beam and girder schedule	X	INGO
Abutment details	X	INGO
Pier details	X	INGO
Slab bar plan for str. bridges	X	INGO

[1] INGO, Integrated Geometry System, is a separate program for solving problems in geometrics and used for plotting.

The BEST System

BEST is an acronym for Bridge Engineering Subsystem of TIES, and TIES is an acronym for Total Integrated Engineering System. The TIES concept, a complete highway engineering system, was proposed by the Federal Highway Administration as part of its National Program for Research and Development in Highway Transportation. The primary objective of the New York Department of Transportation in developing BEST was to put together an integrated bridge design subsystem that included computer programs to solve computational problems and generate necessary parameters for plotting.(1)

The capabilities of BEST are:

1. The bridge can span up to two roadways.
2. The maximum number of spans is four.
3. The maximum number of beams in a cross section is ten.
4. The bridge must be of constant width with tangent or circular curve alignment.
5. Only simple spans (with composite rolled beams or welded plate girders) can be designed.

Subprograms of BEST

Control Geometry. This subprogram produces control dimensions for a bridge. The program is designed in such a way that an infinite number of layouts are possible. The layout finally selected will be based on the input of control variables such as span-to-depth ratio,, lateral clearances, minimum end span length, and skew to be equalized,which makes it possible to select alternate designs.

Framing Plan. This subprogram seeks the most desirable framing plan for any given conditions, i.e., a plan which results in economy of fabrication by causing as much duplication or similarity of details as possible.

Reinforced Concrete Slab Design. This subprogram designs reinforced concrete bridge slabs with main reinforcement parallel to the supports or normal to the stringers satisfying AASHTO specifications. A designer's option to establish whether the design should have equal tension and compression steel, compression steel equal to half the tension steel, or a balanced design is present.

Beam and Girder Design. This subprogram designs composite and noncomposite beams or girders in a simple span bridge, with or without cover plates, that will satisfy stress and deflection requirements. It processes many designs to select the most economical section within the specified depth range according to AASHTO specifications.

Bridge Bearing Design. This subprogram designs fixed and expansion type bearings for bridge stringers based on the stringer's length and reaction at the bearing according to AASHTO specifications. The program also acts as a collector and provides the necessary input information for the substructure design programs.

Abutment and Retaining Wall Design. This subprogram analyzes and designs stub or pedestal type abutments, solid or high type of abutments, or retaining walls on spread footings or on piles in accordance with AASHTO specifications. It processes a series of designs to select the most economical section based on concrete volume and number of piles, if applicable.

Pier Design. This subprogram analyzes and designs each pier component, including rectangular and circular concrete columns; combined footings on soil, rock, or piles; individual footings on soil, rock, or piles; and the pier cap beam reinforcing steel in accordance with AASHTO specifications. Subprograms detail the reinforcing steel in the beams, columns, and footings.

Bridge Quantities. This accumulates and combines quantities determined in all other design and plot programs.

Another feature of BEST are the subprograms for plotting as shown in Table 1.

In addition to the various design and plot programs described, BEST also will allow the execution of the various programs within the system in a preestablished order. Information can be passed from a given subprogram to any other in the system. By cycling from subprogram to subprogram, BEST attempts to find the minimum cost design.

BEST was introduced by the New York State Department of Transportation in the late 1960's. Yet, at this time the entire system is being used only by New York. The cause of this, and the greatest weakness in BEST, is its being written in ALGOL, for a Burroughs computer. Portions of the system are available in FORTRAN, a more widely used language than ALGOL, but the occasional use of assembly language routines, the common data area feature, and the program linkage mechanisms make the systems highly machine dependent. Some of the program modules are being used as stand-alone programs by other agencies on other than Burroughs computers, but no one has converted the entire BEST system.

BEST is used for the design of approximately 20 percent of the bridges being built in New York State. The New York Department of Transportation intends to supplement the present BEST system to a point where it will be applicable to about 80 percent of the bridges being designed.

The STRC System

Omnidata Services, Inc., offers the STRC1 and STRC2 systems for the design of simple span and continuous span bridges, respectively.

STRC1 is an integrated program consisting of many subprograms which can be used in succession to analyze and design any deck type simple span bridges for the superstructures and the substructures. The superstructures may consist of reinforced concrete slabs with steel beams of rolled wide flange or built-up sections or prestressed reinforced concrete beams. The beams may have composite or noncomposite action.

The substructures may include reinforced concrete piers and abutments on spread footings or piles.

STRC1 observes provisions in AASHTO specifications in loading and stress computations as well as in pertinent design details. The subprograms may be used together to design a complete simple span bridge or individually to design parts of a bridge. When used to design a complete bridge, intermediate answers and solutions relevant to each phase of design are stored in data files and carried automatically from one subprogram to another. However, during the design process automatic cycling from subprogram to subprogram is not done.

Subprograms of STRC1.

BSLAB Designs reinforced concrete bridge slabs with main reinforcement perpendicular to traffic within the span limits given by the AASHTO specifications.

WBEAM Designs composite or noncomposite WF beam stringers in a simple span bridge by choosing automatically the minimum steel weight of a WF beam according to AASHTO specifications.

SGIRD Designs composite and noncomposite steel girder stringers in a simple span bridge by automatically choosing the minimum steel weight of the steel girder according to AASHTO specifications.

PBDES Analyzes and designs prestressed concrete beams, both pretensioned and posttensioned, in a single span bridge according to AASHTO specifications.

DKLDS Solves all bridge deck loads from the superstructure to the substructure of pier bents or abutments according to the requirements imposed by the input data as well as the AASHTO specifications.

REWAD Analyzes and designs bridge abutments and retaining walls resting on soil or rock according to AASHTO specifications.

COLMN Designs reinforced concrete columns of rectangular or circular sections, subjected to combined axial load and two-directional bending moments, according to the AASHTO specifications.

PRFDN Analyzes and designs pier footings resting on soil or rock. The footings may be the individual type carrying a single column or the continuous type carrying multiple columns (maximum of six) from the pier bent.

PBENT Analyzes and designs cap steel for a pier bent for all combinations of loads according to AASHTO specifications.

The system STRC 2 designs deck type continuous span bridges of up to ten spans with any random distribution of moment of inertia along the length of the spans. The end spans may be cantilever spans; the bridge may be symmetrical or unsymmetrical in arrangement; and the deck section construction may be of any of the following types: 1) noncomposite, 2) prestress-composite, 3) steel-composite. STRC2 does not consider curved girders.

The BRIDGE System

The BRIDGE system is part of the ICES system developed at MIT. Because of the publicity given to the ICES system, the impression is frequently given that BRIDGE is a complete, versatile, and available system. This is not the case.

Presently BRIDGE is limited to:

1. A preliminary bridge planning phase called the Geometry Program Block for determining the intersection and the possible alternative configurations of spans, piers, and abutments of a non-superelevated, nonhorizontally curved bridge crossing over a highway, with span arrangements conforming to the standards of the Massachusetts Department of Public Works.
2. The design, or analysis, of a noncomposite concrete bridge deck based on design standards as per AASHTO or the Massachusetts DPW specifications called the Concrete Deck Supported by Steel Stringers Program Block.
3. The preliminary Girder Design Program Block, which will determine maximum moments, shears, reaction design values, and required section moduli for prismatic and nonprismatic simple or continuous girders. An iterative process, based on relative section moduli, is also available.

The present BRIDGE subprogram does not select girder dimensions (design) or analyze a given girder (analysis of a girder), in the composite, noncomposite, or intermediate composite state. At the moment, BRIDGE has limited application since it is primarily an analysis system with few design capabilities.

The BRASS System

The Wyoming system has just been completed. It is referred to as Bridge Rating and Analysis Structural System (BRASS). It has been developed so that a user may analyze, review, or load rate structures, but it cannot be used for the complete design of a bridge. As do BEST and STRC1, BRASS possess a common data base for the subprograms. That is, data from one subprogram can be passed automatically to another.

The system will handle steel girders, concrete girders, concrete slabs, timber beams, and composite concrete-steel girders. When one of these components, e.g., a wide flange girder or built-up steel girder, is to be designed, the designer must first enter dimensions of the flange, the web and the fillets. Thus, the "design" program will analyze a prescribed configuration. It will not automatically choose the minimum steel weight of a wide flange beam or plate girder. The user must first make preliminary layouts of the structural elements to be designed. For the complete design of a bridge from deck to footings, BRASS is quite inferior when compared to BEST and STRC1. As its name implies, BRASS is basically a bridge rating and analysis system.

The components of the system listed by the developers are bridge design, structural inventory, deck design and review, structural analysis, structural loading, and girder section design and review. The system, which consists of a set of 45 computer programs, is used by state highway departments mainly to determine the safe load carrying capacity for a highway bridge and the structural rating for the bridge.

BRIDGE DESIGN EXAMPLES

The structure redesigned in this study was a fairly typical highway bridge carrying an access ramp over a street in the city of Richmond, Virginia. Plans for the bridge were completed in August 1965, and it was subsequently constructed. As shown in Figure 3, the structure was a heavily skewed, three-span bridge, lying on a tangent and a vertical curve. The span lengths are nominally 60, 105, and 82 feet, (18.3, 32.0 and 25.0 m), and the supporting members are composite steel beams, including a 51-inch welded plate girder for the longest span and 36-inch (0.91m) rolled beams with cover plates for the shorter spans. The superstructure is supported on four-column piers and abutments on piles. Further details are provided in Figures4 through 6, which show the framing plan and the transverse section of the bridge and the beam and girder details. The structural details will be discussed more fully when they are contrasted with those developed by the design systems.

It can be assumed that the original structure was designed by conventional methods, perhaps with the use of individual computer programs. The redesigns of the Richmond bridge in this study were performed through the courtesy of the New York Department of Transportation and the Omnidata Corporation. A review of the system design and a contrast with the original design should serve to indicate the capabilities of BEST and STRC1 and the degree of flexibility built into the respective systems.

Design By The BEST System

The BEST system requires minimal input data, essentially road profile and curvature data, and design ground rules, such as the vertical clearance and type of steel to be used. Specifically, the input information consisted of those items shown in Table 2 and Figure 7.

The first program to operate with the input data is the Bridge Control Geometry program, which establishes the basic layout including the stations of the various substructure elements, the point of minimum vertical clearance, and the depth available for the steel stringers, given the minimum vertical clearance. The locations of the abutments are established from the vertical clearance and profile information, and the piers are sited on the basis of the horizontal clearance and maximum span length.

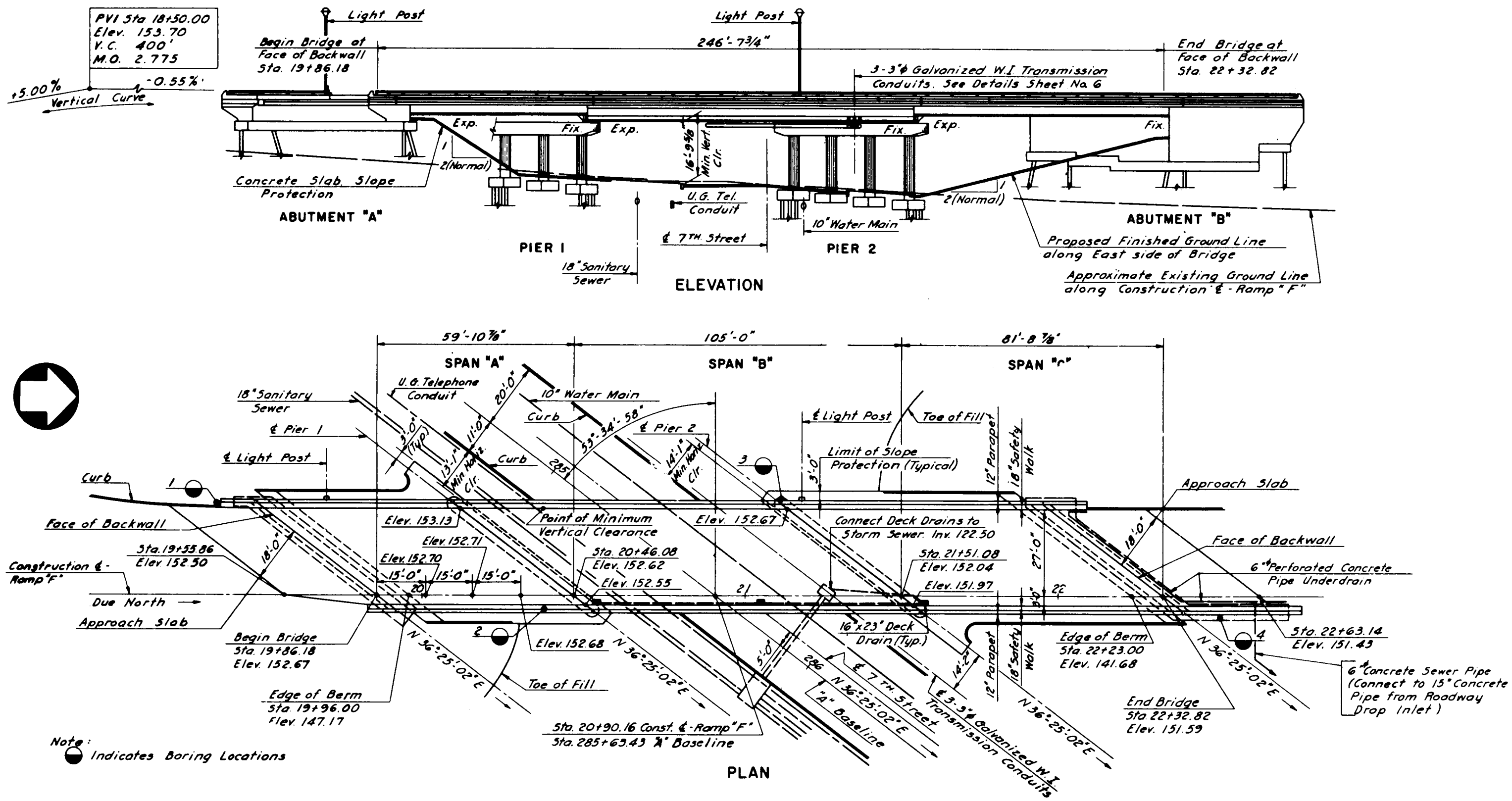

Figure 3. Plan view of Richmond bridge.

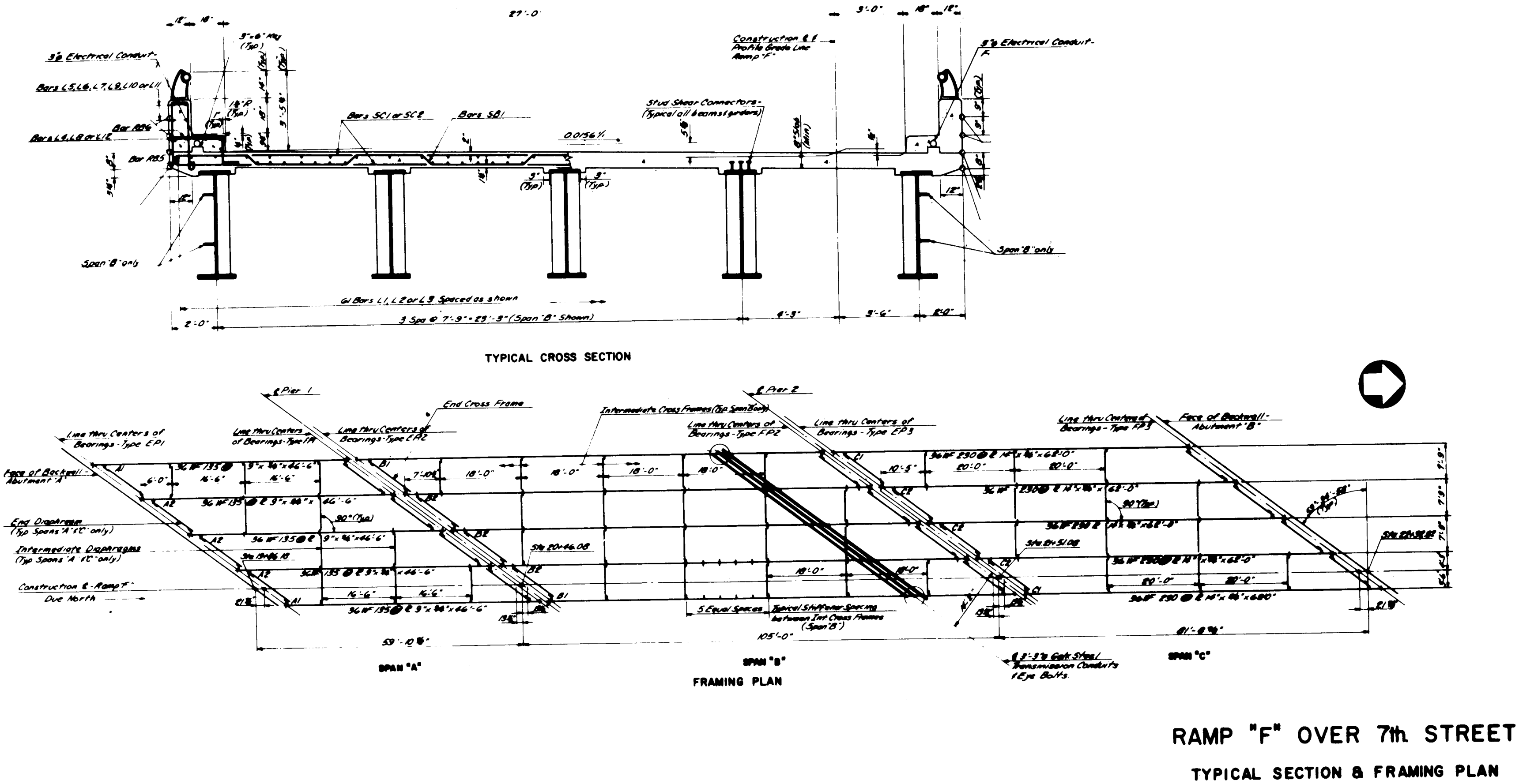

Figure 4. Framing plan and transverse section of Richmond bridge.

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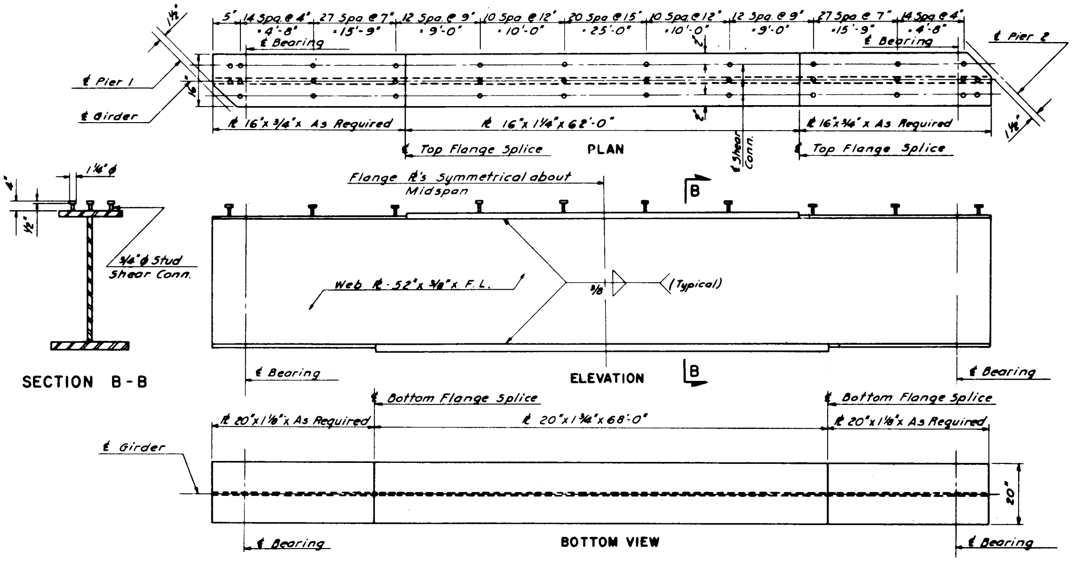
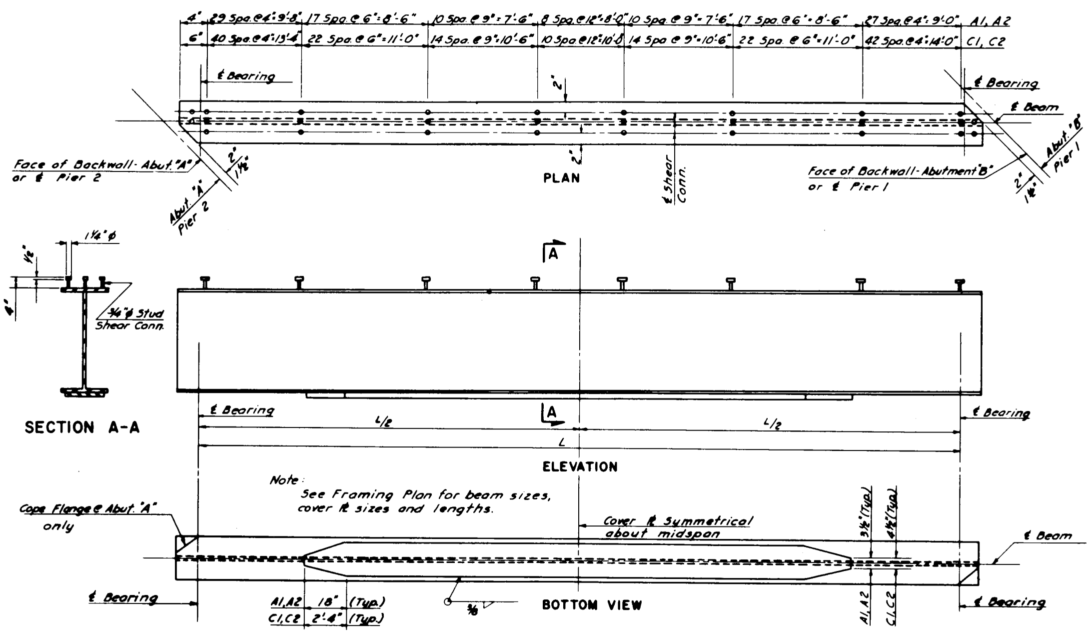


GIRDER DETAILS (B1, B2)



BEAM DETAILS (A1, A2, C1, C2)

Figure 5. Beam and girder details of Richmond bridge.

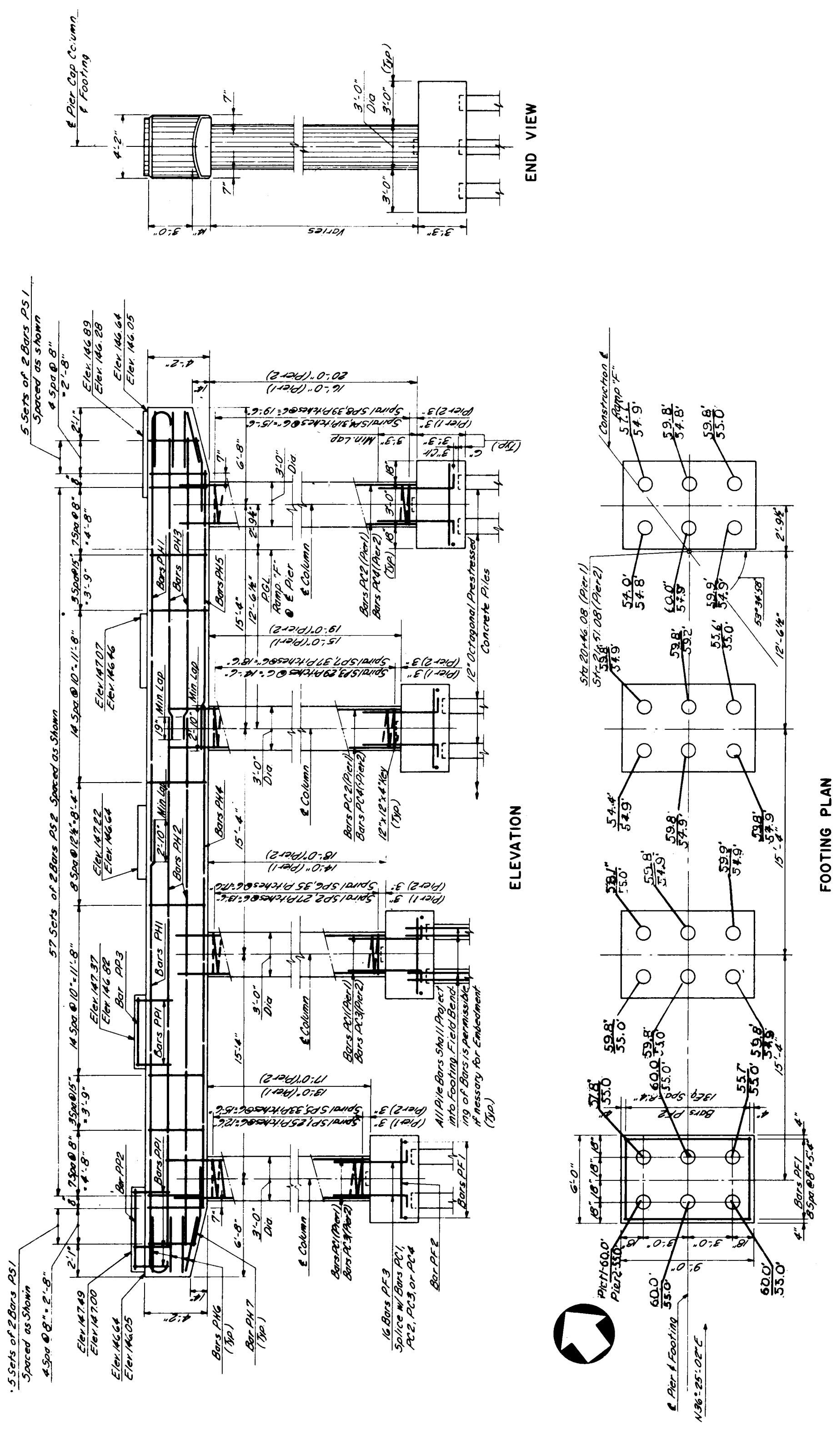


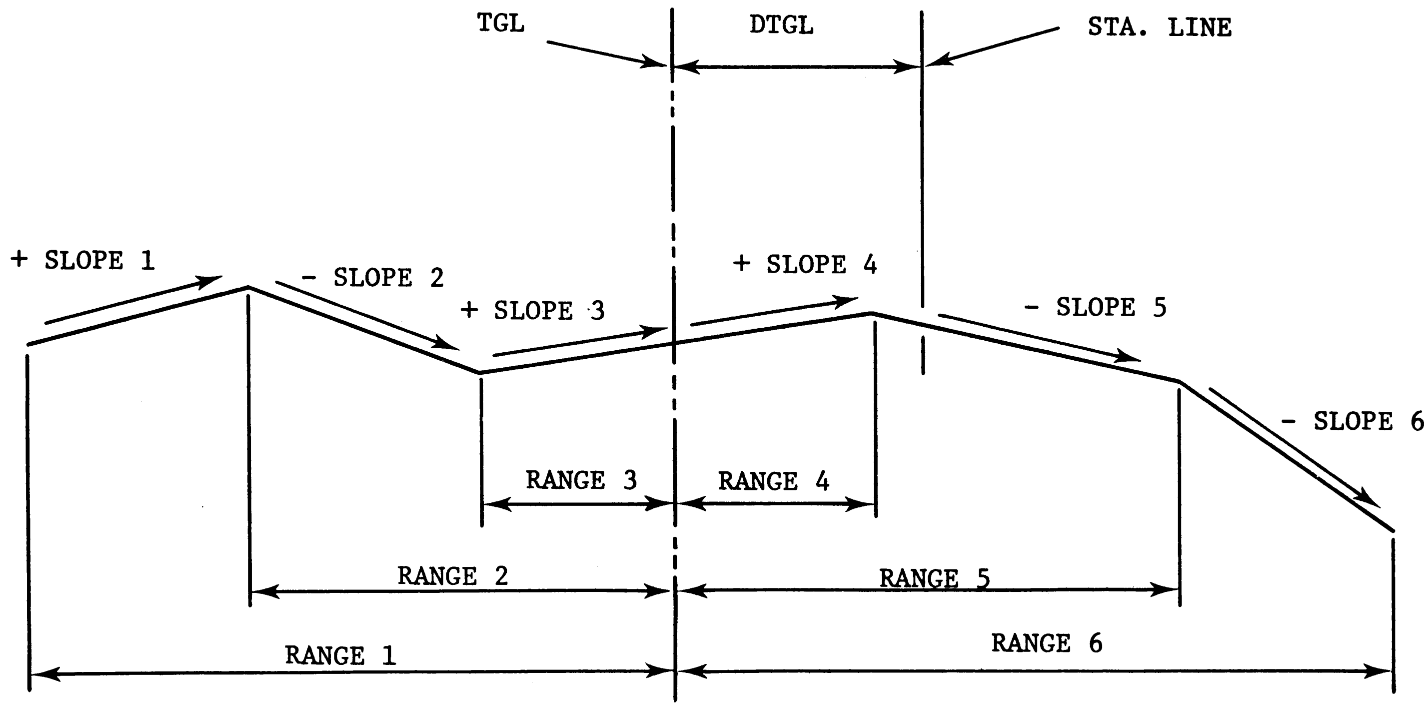
Figure 6. Pier details of Richmond bridge.

Table 2. BEST System, Input Data for the Ramp F Bridge over Seventh Street, City of Richmond.

	Data	Description
Upper roadway data		
	00	Radius of upper roadway
	2099.16	Intersection station with lower roadway
	0°	Azimuth at intersection station
	1850.0	Station P.V.I.
	153.7	Elevation at P.V.I.
	400.0	Length of vertical curve
	5.0	Grade #1 Dfn (lower station values)
	-.55	Grade #2 Dfn (higher station values)
	-29.5	Horizontal offset from construction center-line to left fascia
	5.5	Horizontal offset from construction center-line to right fascia
	-30.67	Horizontal offset from construction center-line to left wall
	6.67	Horizontal offset from construction center-line to right wall
	-27.5	Range #3 - See Fig. 7
	-1.56	Slope #3 - See Fig. 7
	3.5	Range #4 - See Fig. 7
	-1.56	Slope #4 - See Fig. 7
Lower roadway data		
	00	Radius of lower roadway
	28563.43	Intersection station with upper roadway
	36°25'2"	Azimuth at intersection station
	28590.	Station P.V.I.
	124.42	Elevation at P.V.I.
	0.0	Length of vertical curve
	-6.57	Grade #1 (approaching)
	-6.35	Grade #2 (leaving)
Lower road offsets		
	-20.	Left pavement edge - Horizontal
	-.25	Left pavement edge - Vertical
	11.	Right pavement edge - Horizontal
	-.25	Right pavement edge - Vertical
	-4.5	Left shoulder - Horizontal
	0.	Left shoulder - Vertical
	11.	Right shoulder - Horizontal
	-.25	Right shoulder - Vertical
	-38.5	Left ditch - Horizontal
	.75	Left ditch - Vertical
	28.25	Right ditch - Horizontal
	.75	Right ditch - Vertical
Bridge geometry and design input data		
	1.083	Distance from center line bearings to bridge end
	2.5	Sidewalk width (ft.) both left and right
	-.016	Left shoulder slope in ft/ft
	-.014	Right shoulder slope in ft/ft
	2.0	Overhand min. and max. in feet
	.25	Parapet load in (K/ft) left and right
	2.0	Number of lanes on bridge
	16.5	Minimum vertical clearance in feet
	0.0	Distance from tangent grade line to station line
	1.0	Amount slab cut in feet
	0.0	Maximum skew for normalizing ends of slab
	14.0t	Minimum lateral clearance (left) lower road
	13.08	Minimum lateral clearance (right) lower road
	20.0	Skew to be equalized
	25.0	Ratio of span to steel depth
		Maximum Allowable Bottom of Footing Elevation
	143.17	Beginning abutment
	123.22	Pier 1
	118.63	Pier 2
	137.12	Ending abutment
	A36	Steel type
	9.0	Height of curb in inches (left and right)
	4.17	Cap beam width in feet
	72.0	Foundation loads allowed in K/ft^2 for both abutments and piers

Note: Concrete footing support to be used throughout

1.0	Distance from fascia to face of railing in feet (left and right)
127.	Elevation at top of ground - pier 1
123.	Elevation at top of ground - pier 2
45	Design speed of traffic in miles per hour
1.	Fraction of full wind



NOTE: RANGES 1, 2, AND 3 WILL ALWAYS BE NEGATIVE.
IF THE TGL IS TO THE RIGHT OF THE G.L. BRIDGE THE DTGL is (-).

Figure 7. Cross section geometry input required by BEST. (From reference 1.)

Figure 8 shows the basic layout of the bridge developed by the BEST system. A comparison with Figure 3 shows the system designed bridge to have relatively small differences (5 feet (1.5m) maximum) in the stations at its ends and practically no difference in the pier locations. Little significant difference is apparent between the two designs. The depth available for the steel beams was computed to be 5.83 feet (1.777m). This figure is of importance, because the New York design policy is to maximize the spacing between beams, using the maximum available depth, to require the least number of lines of beams.

The framing plan, Figure 9, developed by BEST uses only four lines of stringers, as opposed to the five lines used on the original design (Figure 4). As shown by a comparison of the two transverse sections, Figures 4 and 10, the beam spacing has been increased from 7' (2.36m) to 10' (3.15m). The framing plan program, like others in the system, allows the engineer to override any chosen variables to obtain a desired design.

Increased beam spacing requires deeper members, normally thought to result in a longer bridge, but the integrated system, which considers all variables together instead of one set at a time, can apparently optimize the layout. Thus, although the system designed girders are 69-1/8" (1.753 m) in maximum depth as opposed to 55" (1.397m) in the original design (Figures 5 and 11), the overall bridge length is about 3 feet (0.914m) less for the system design.

The beneficial effect of the use of a larger beam spacing, fewer lines of deeper beams, is most important. Steel quantities, based on the weight of the beams only, neglecting the cross bracing, show the total weight of the system designed girders to be approximately 175 kips (78750 kg.), while the original girders, without cross bracing, weigh nearly 270 kips (121500 kg). This difference would probably offset the greater amount of fabrication required by the BEST design, which uses plate girders throughout all of the spans.

The use of welded plate girders, even on the short approach span, results from the New York design policy, which requires that the fascia beams in all spans have a common depth. It follows that the use of a very deep fascia girder on a short span requires a fairly deep interior member for compatability of deflections. The interior members in the short spans of the BEST designed bridge thus had to be deeper than the 36 inches (0.914 m) available in rolled sections. Conversely, it is Virginia's practice to use rolled sections on step haunches if the span length permits. The approach spans on the original bridge are supported on heavy wide-flange rolled sections with cover plates. This practice could be incorporated into BEST, if desired. However, the original beams are heavier, in total weight, than the more widely spaced girders in the redesigned bridge.

Some slight disadvantages were noted in the BEST system. First, in the original output data the bottom center plate in the lower flange of beams 101 and 104 extended for a length of only 2 feet. (0.6 m). This did not seem to reflect good design practice. However, the BEST designers agreed that tests for these marginal conditions should be incorporated in the programs, and the condition was subsequently remedied. Also, the original plot of the girder details showed a disparity between the overall length of the beam and the sum of the lengths of the plates; the sum of the plate lengths being 6 inches (0.15m) short of the overall length in each case. The overall length shown on the plot was also in error in the case of the end spans. It is apparent that the program for the plot of

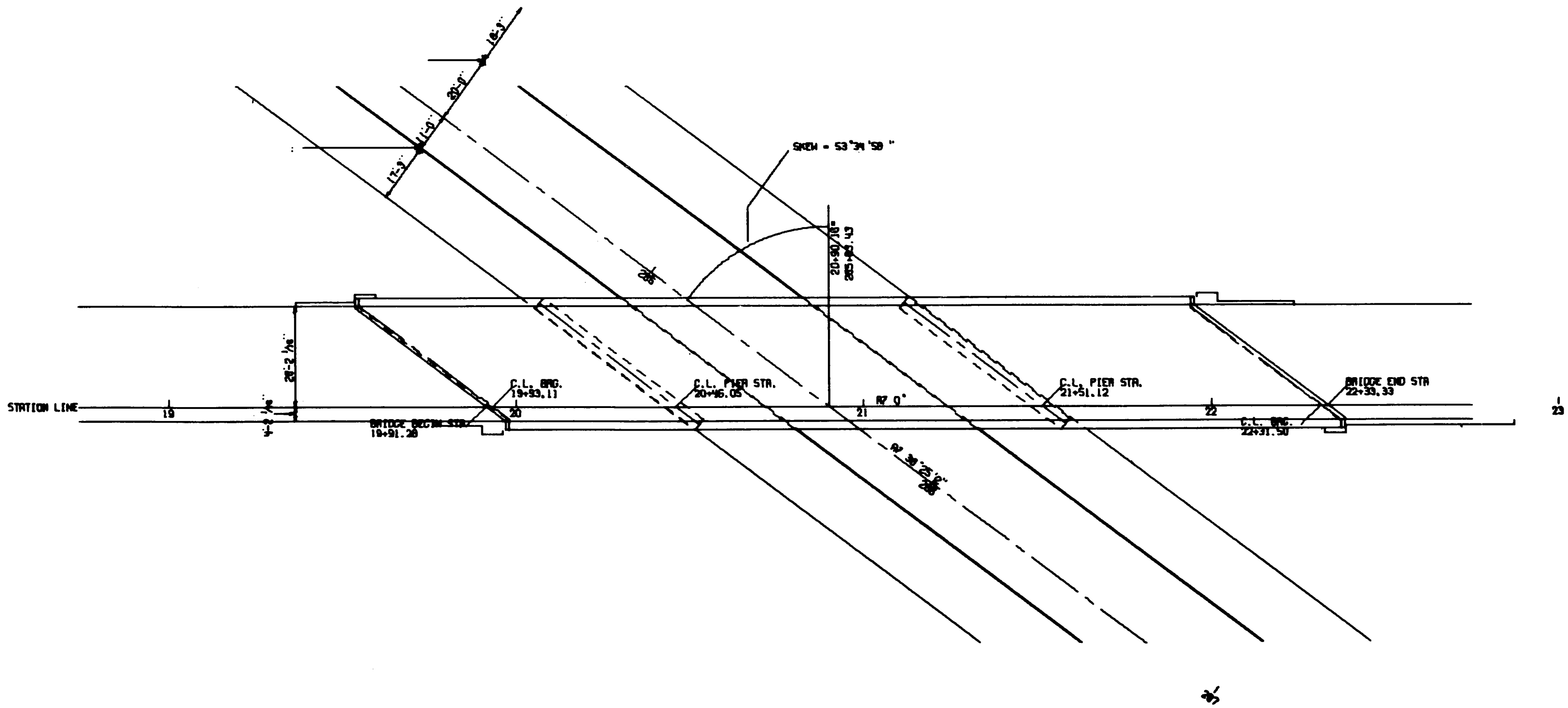


Figure 8. Plan view of bridge plotted by BEST system.

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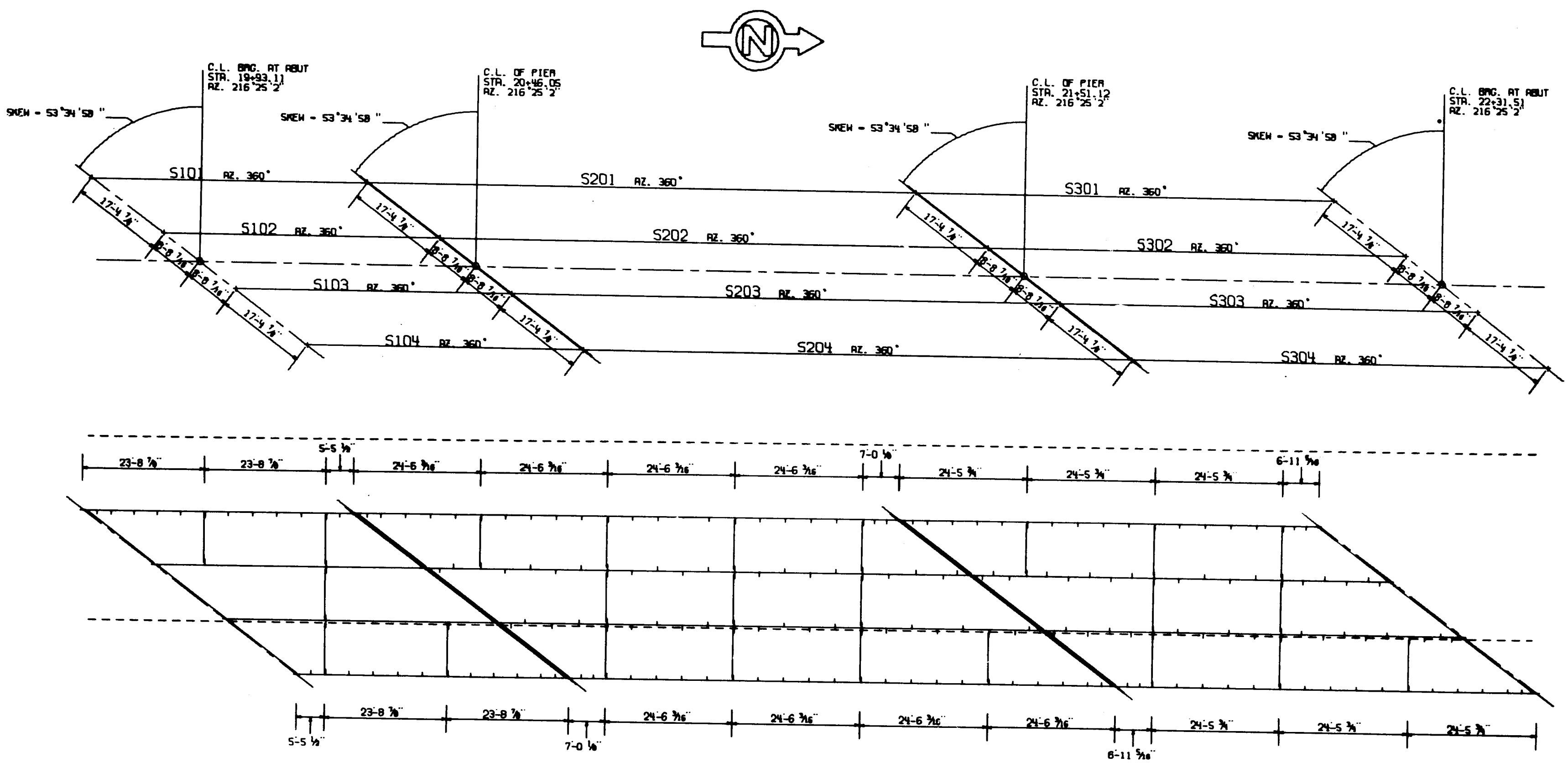


Figure 9. Framing plan designed and plotted by BEST system.

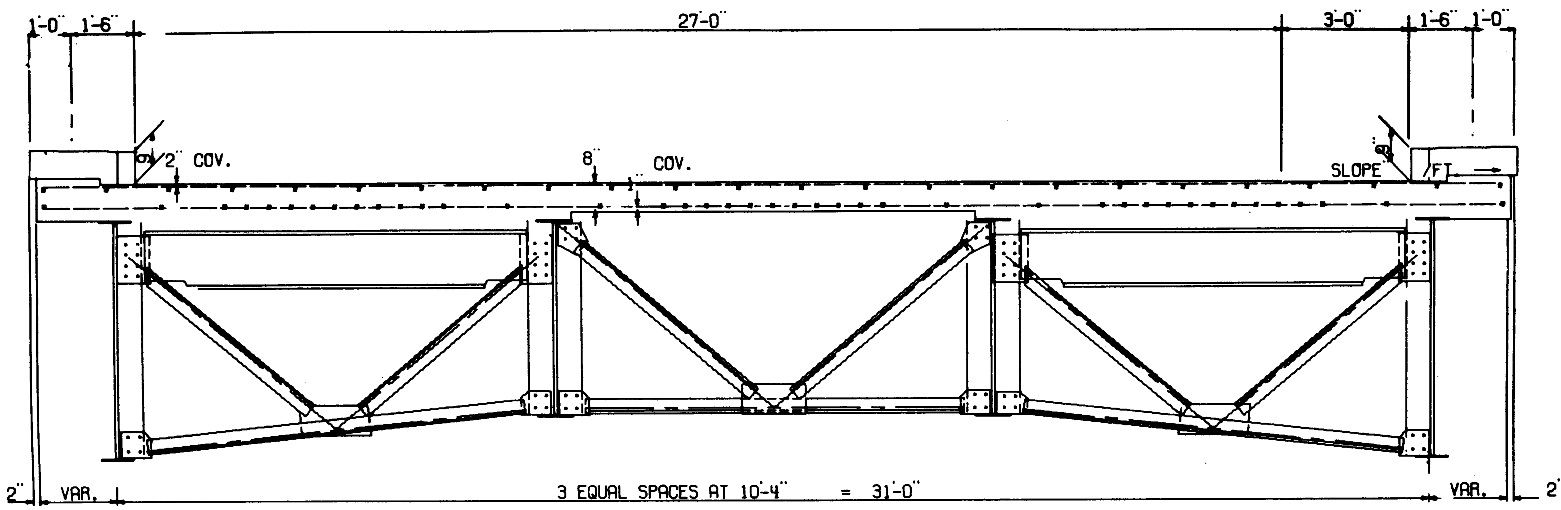
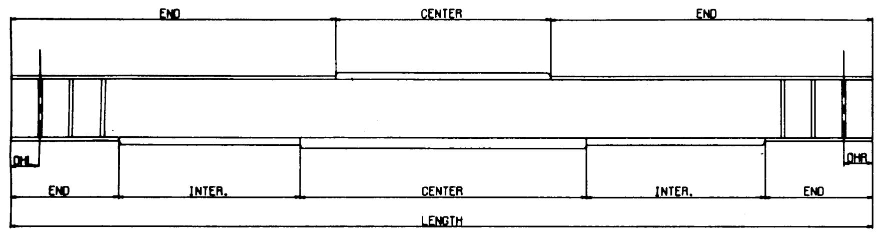


Figure 10. Transverse section designed and plotted by BEST system.

871



TYPICAL STRINGER ELEVATION

NO SCALE

STRINGER	WEB SIZE	TOP END PLATE	WELD	TOP CENTER PLATE	WELD	BOTTOM END PLATE	WELD	BOTTOM INTER.PLATE	WELD	BOTTOM CENTER PLATE	WELD	BEARING STIFF.	INTER.STIFF.	SHEAR CONN.	OHL	OHR	LENGTH
101	66X 7/16			9X 1/ 2X 51- 5- 3	5/16					9X 1/ 2X 51- 5- 3	5/16	2-PL 7X 5/ 8	5X 3/ 8	10	8	8	51-11 3/16
102-3	54X 1/ 2			9X 1/ 2X 51- 5- 3	5/16	9X 1/ 2X 14- 8- 9/16	5/16			9X 13/16X 22- 0	5/16	2-PL 7X 5/ 8		9	8	8	51-11 3/16
104	66X 7/16			9X 1/ 2X 51- 5- 3	5/16					9X 1/ 2X 51- 5- 3	5/16	2-PL 7X 5/ 8	5X 3/ 8	10	8	8	51-11 3/16
201	66X 7/16	15X 5/ 8X 26- 2- 7/16	5/16	15X1- 1/ 8X 52- 0	5/16	17X 3/ 4X 14- 8- 7/16	5/16	17X1- 1/ 2X 14- 0	5/16	17X2 X 47- 0	3/ 8	2-PL 7X 5/ 8	5X 3/ 8	12	8	8	104-10 7/ 8
202-3	66X 7/16	15X 5/ 8X 26- 2- 7/16	5/16	15X1- 1/ 8X 52- 0	5/16	17X 3/ 4X 14- 8- 7/16	5/16	17X1- 1/ 2X 14- 0	5/16	17X2 X 47- 0	3/ 8	2-PL 7X 5/ 8	5X 3/ 8	12	8	8	104-10 7/ 8
204	66X 7/16	15X 5/ 8X 26- 2- 7/16	5/16	15X1- 1/ 8X 52- 0	5/16	17X 3/ 4X 14- 8- 7/16	5/16	17X1- 1/ 2X 14- 0	5/16	17X2 X 47- 0	3/ 8	2-PL 7X 5/ 8	5X 3/ 8	12	8	8	104-10 7/ 8
301	66X 7/16			11X 1/ 2X 78-10- 9	5/16	11X 1/ 2X 11-11- 1/ 4	5/16	11X1 X 7- 0	5/16	11X1- 5/ 8X 41- 0	3/ 8	2-PL 7X 5/ 8	5X 3/ 8	10	8	8	79- 4 9/16
302-3	60X 3/ 8	10X 1/ 2X 25-11- 1/ 4	5/16	10X 3/ 4X 27- 0	5/16	17X 3/ 4X 17- 5- 1/ 4	5/16			17X1- 1/ 4X 44- 0	5/16	2-PL 7X 5/ 8	4X 3/ 8	10	8	8	79- 4 9/16
304	66X 7/16			11X 1/ 2X 78-10- 9	5/16	11X 1/ 2X 11-11- 1/ 4	5/16	11X1 X 7- 0	5/16	11X1- 5/ 8X 41- 0	3/ 8	2-PL 7X 5/ 8	5X 3/ 8	10	8	8	79- 4 9/16

Figure 11. Beam and girder details designed and plotted by BEST system.

girder details is not performing properly, and difficulty was also encountered in running the abutment plot program; however, the difficulties were apparent only in some of the plots, which were later corrected, not in the printed data. Unfortunately, the user's faith in the computer system is often shaken by minor errors such as these.

The BEST system also computes shear connector spacing. Both 4-inch (0.10m) and 6-inch (0.15m) studs were called for on different beams in the redesign, and in contrast to Virginia's practice, a uniform spacing was employed over the length of a beam. Stiffener plates were sized and located, and cross bracing was located along the beam. The cross bracing itself is a standard configuration sized by 1/r ratio for the given beam spacing; it is not designed by the integrated system.

A deck thickness of 8 inches (0.20m) was called for in both designs. Transverse reinforcement, number 5 bars in both designs, is spaced at 6-inch (0.15m) centers on the BEST redesign. The depths of cover, top, and bottom are shown in Figures 4 and 10. It is likely that the BEST system slab, which spans a greater distance between beams, may be less conservative than the practice of the Virginia Department of Highways. The increased quantity of deck reinforcement required in the BEST design to span the larger beam spacing would slightly diminish the material savings realized in the girder design.

The final superstructure program is the bearing design segment, which designs the required fixed and expansion bearings and sets the bridge seat elevations at the piers and abutments. The program can design either low, sliding bearings or high, rocker-type bearings. The latter are generally provided for plate girders, as they were for the BEST redesign of the Ramp F bridge. Thus the bearings used in the redesign are larger, heavier, and more difficult to fabricate than those originally used. Both designs vary the bearing dimensions from span to span. The bearing design subprogram, because it accumulates from the preceding programs the information pertinent to the substructure design, is an important part of the BEST system. It is possible that the module could be replaced by another bearing design program of the user's choice, but apparently few such programs exist. Thus, a user might be forced to accept, at least initially, the New York bearings.

Significant differences were also found in the sizes of the pier elements compared in Figures 6 and 12-14. It can be seen that the BEST redesign had a smaller beam (3'-6" (1.07m) wide by 3'-9" (1.14m) deep versus 4'-2" (1.27m) by 4'-2" (1.27m) for the original bridge), larger columns (3'-6" (1.07m) by 3'-0" (0.91 m) rectangular columns versus 3'-0" (0.91 m) diameter round columns), and significantly larger footings with 19 more piles required. The BEST designed footings, all 3'-6" (1.07m) in depth, were 9'-0" (2.74 m) by 15'-0" (4.57 m) under each of the three columns of Pier 1 and 9'-0" (2.74 m) by 12'-0" (3.66m) under the columns of Pier 2, while the footings under each of the four columns of the original piers were 9'-0" (2.74m) by 6'-0" (1.83m) by 3'3" (0.99 m). The actual analysis procedure was not completely shown in the printed data, and it is difficult to say why the larger footings occurred at the juncture of the relatively short Span A and Span B rather than between Spans B and C. It was apparent, however, that different philosophies were used in the original pier design and the BEST system design. Under BEST, the pier was regarded as a rigid frame, and the thrusts and moments of the frame were carried to the footings. Note that the long dimension of the BEST footings is transverse to the direction of traffic flow, while the long dimension of the original footings lies in the direction of traffic flow. Certainly, use of the BEST pier design subprogram resulted in a more expensive pier.

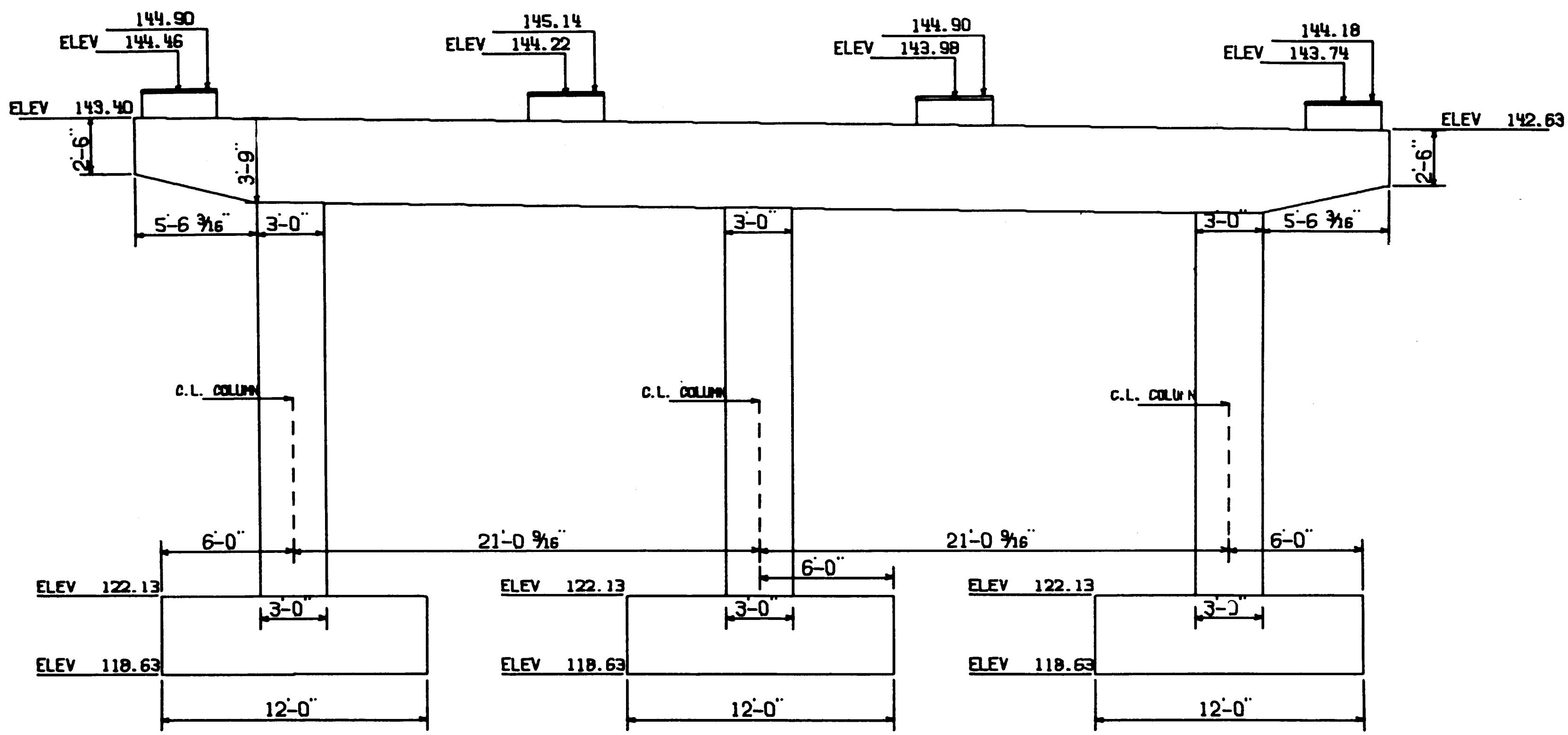


Figure 12. Pier details designed and plotted by BEST system.

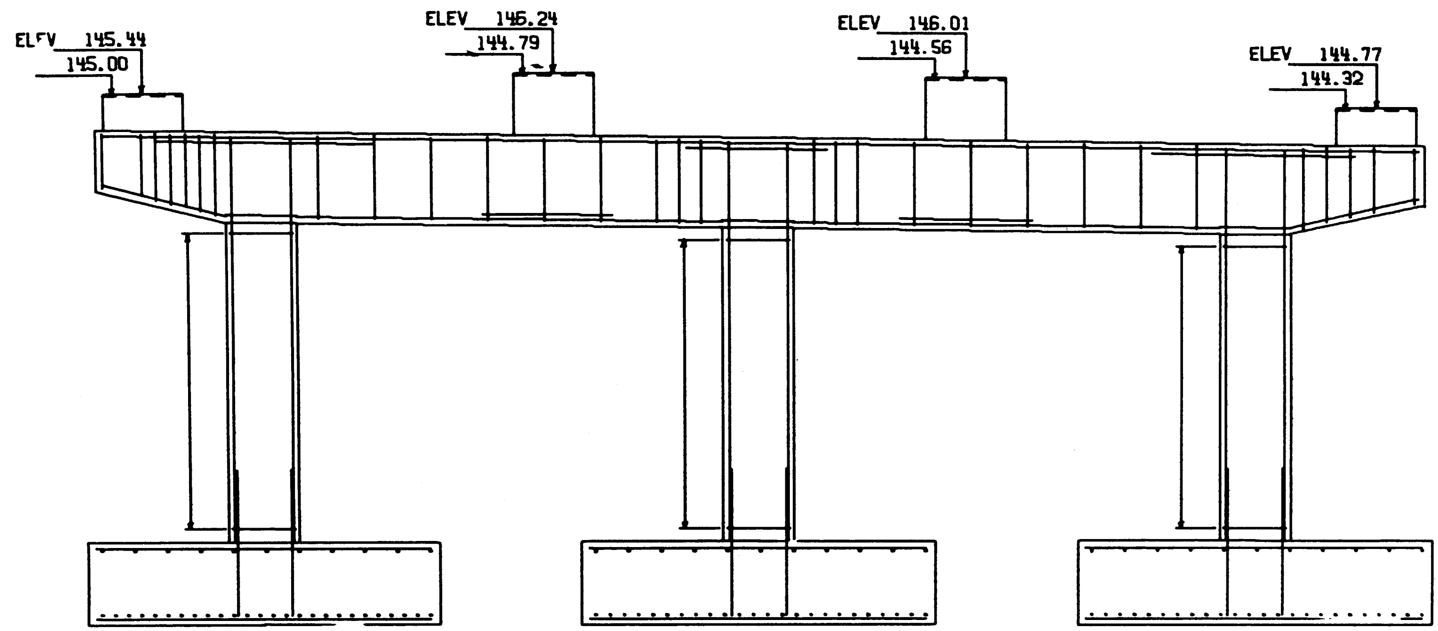


Figure 13. Pier reinforcing details designed and plotted by BEST system.

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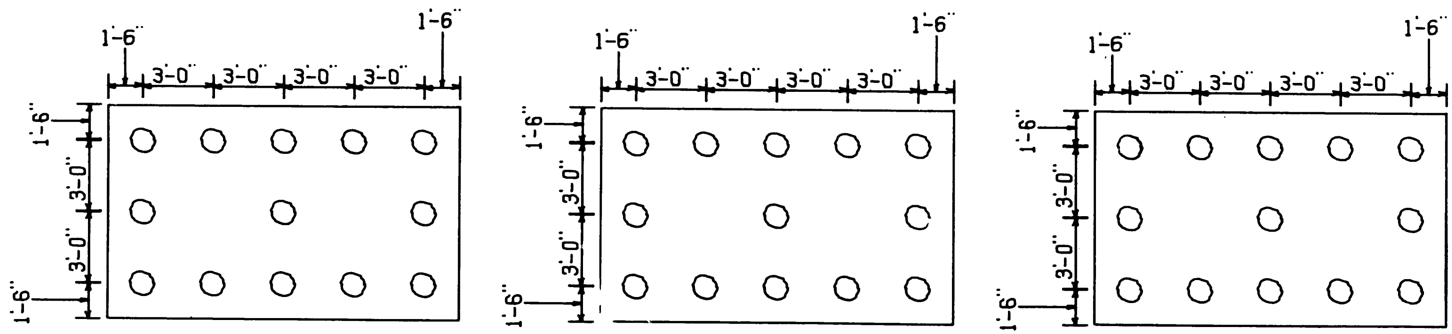

Figure 14. Footings and pile details designed and plotted by BEST system for one of the piers.

This somewhat disconcerting pier design was discussed with the developers of BEST. They stated that, under some conditions, the pier design program produced an overly conservative structure, and they have discontinued its use in their office. They are nearly finished developing new pier programs, which they feel give more consistent and reasonable results. These new programs have not yet been integrated into the BEST system, but they will be in the near future. The footing for one of the piers was redesigned using the new programs. The resulting design was a continuous footing 56'-10" (17.32m) by 8'-0" (2.44m) by 3'-0" (0.91 m) on 16 piles (8 piles/pier less than original). However, both the new pier and the first BEST design contained significantly more material than were required in the original pier of the STRC1 design.

Unfortunately, plots of the system designed abutments are not available. Both designs called for stub or shelf abutments on piles. A detailed comparison was not performed, but great differences are not apparent between the original abutments and those redesigned by the BEST system.

Design By the STRC1 System

More extensive input data were required for STRC1 than for BEST, since STRC1 does not contain a geometry program. Therefore, the input information provided Omnidata consisted of those items shown in Table 2, plus the geometric data and framing plan.

The designer enters the STRC1 system with a firm idea of the bridge layout and geometry, including the beam spacing and lengths. The system will then carry the design through to the foundations. Beam lengths of 58'-11" (17.96 m), 103'-0" (31.39m), and 80'-9" (24.61m) were input, as was the original beam spacing of 7'9" (2.36m), which resulted in five lines of stringers.

The system designed girders are 57 inches (1.45m) in maximum depth as opposed to 55 inches (1.40m) in the original design. The flange plates are 14 inches (0.36m) and 16 inches (0.41m) as opposed to the original 16 inches (0.41m) and 20 inches (0.51m).

The STRC1 system optimizes the weight of the members using either welded girders or rolled sections, as specified by the designer; welded plate girders were used on the Ramp F bridge, even on the short approach spans. For the 58'-11" (17.96m) span the system designed a 32-3/8inch (0.82m) maximum depth welded plate girder as opposed to a 36 inch (0.91 m) rolled beam with cover plates. Also, for the 80'-9" (24.61m) span the system designed a 44-4/5 inch (1.14m) maximum depth welded plate girder as opposed to the 36 inch (0.91 m) rolled beam with cover plates. Steel quantities, based on the weight of the beams only and neglecting the cross bracing, show the total weight of the system's girders to be approximately 190 kips (85500 kg), as compared to 175 kips (78750 kg) for BEST and 270 kips (121500 kg) as built. As with the BEST design, the plate girders selected by STRC1 would involve more fabrication cost than if all rolled beams were chosen.

Significant differences are not found in the sizes of the pier elements. This is due mainly to the fact that data were input into the pier program to design the pier using 4 columns 3'-0" (0.91m) in diameter. Also, the pier cap beam was input to be 4'-2" by 3'-0" (1.27 x 0.91 m) This is similar to the original design as shown in Figure 6. However, significant differences did occur in the footings. The STRC1 designed footings are all 3'-0" (0.91m) in depth, and all vary in plan dimensions. The four footings of Pier 1 are 11'-6" by 11'-6" (3.50 x 3.50 m), 7'-3" by 7'3" (2.21 x 2.21m), 7'-0" by 7'-0" (2.13 x 2.13m) and 10'-6" by 10'-6" (3.20 x 3.20m), while the original four footings are all 9'-0" by 6'-0" by 3'-3" (2.74 x 1.83 x 0.99 m).

Unfortunately, plots of the system designed components were not produced for this example problem. The total fee for this design, three superstructure spans and one pier, would be $310 using STRC1.

SUMMARY OF THE BEST AND STRC1 SYSTEMS

A major difference between BEST and STRC1 is the geometry block that is included in BEST and not in STRC1. This subprogram makes it possible to select optimal control dimensions for a bridge from among an infinite number of layouts. The layout finally selected will satisfy constraints as established by the input of such variables as span to depth ratio, lateral clearances, and minimum end span length.

Both systems select girders or rolled beams by automatically choosing the minimum steel weight. BEST selects a rolled beam design if the span is less than 80 feet (24.4m) or available depth is less than 42 inches (1.06 m). If the span is over 80 feet (24.4 m) or if the depth available is over 42 inches (1.06m), a girder design is automatically selected. For the STRC1 system, the designer must make an initial choice as to whether a rolled beam or plate girder is to be used in the design. The advantage of this difference between BEST and STRC1 is demonstrated in the design example that was performed using the two systems. The total weight of the girders in each design were: BEST - 175 kips (78750kg); STRC1 - 190 kips (85,500kg); as built - 270 kips (121,500kg). The BEST design resulted in a savings of 15 kips (6,750kg) of structural steel over the STRC1 system and 95 kips (42,750kg) over the as built design. This savings was probably due to the iterative design capability of the BEST system, which attempts to find the minimum cost design by cycling from subprogram to subprogram as opposed to STRC1, which optimizes only within a subprogram. While the superiority of the BEST superstructure subsystem in optimizing the girder design was evident, it must be emphasized that certain other subsystems, e.g. the pier design, did not provide even a near optimal design.

THE ACCEPTANCE OF INTEGRATED DESIGN SYSTEMS

This study has proven the ability of an integrated system to design a typical highway bridge. Despite its limitation to simple span structures, BEST was found to be a most impressive system, probably the most comprehensive and sophisticated now available. Yet, although considerable interest in design systems is apparent, the complete BEST system is presently used only by the New York State Department of Transportation, its developer. It appears that several factors contribute to the lack of acceptance of BEST by other agencies.

The most obvious drawback to BEST lies in the computer dependency of the complex system. Computer programs grow in size and complexity proportionate with the degree of the design function assigned to them. Individual analysis programs, which examine only one facet of the bridge design at a time , require only a small or medium size computer for execution. Design programs contain not only a complete analysis program but a creative portion as well. The creativity of a program or system of programs can be measured, to some extent, as an inverse function of the quantity of input data. Therefore, a design system such as STRC, which requires several hundred input items, can design a bridge on a relatively small computer (i.e., an IBM 1130 with three disk drives). The BEST system, by comparison, requires less than a hundred input items for a complete design, but the system was written to perform on a large virtual memory* computer, the Burroughs 5500.

One might wonder if a system of programs such as the one that constitutes BEST can be executed on a conventional medium or even large-scale computer. The answer is a qualified "yes". There are techniques that can be programmer employed (i.e., chaining, overlays, etc.) that allow a program to be executed which normally requires more memory than physically available. It should be noted that these techniques, even when part of the original plan, consume considerable programmer time and, thus, when applying them to existing programs, great difficulties can ensue. Converting BEST to a conventional computer using ANSI compatible FORTRAN would appear to be a large undertaking, perhaps requiring one man-year or more.

It may be that all integrated design systems are too comprehensive for rapid acceptance. For example, no interplay between the designer and the BEST system is required from the time that the minimal input data are entered until the completed print-out is obtained. Although BEST is extensively documented, as are STRC and other systems, an engineer is reluctant to place his faith in a design with which he has little personal association and that is performed by a system developed by another agency. This problem does not seem to be acute in the case of analysis systems which are utilized in the rating of conventionally designed structures. Hopefully, the basic distrust of a design system

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*Virtual memory is a machine architectural feature that allows programs which require memory space greater than the actual memory available to be executed without special preparation by the programmer. It should be noted that, although on the increase, virtual memory computers presently are not in widespread use.

could be lessened by the verification of the resulting design by an experienced bridge engineer.

One must also consider the possibility that any system of eight to ten programs may be of uneven quality, that is, some of the modules are better or more appealing to a given design agency than are others.

This situation is complicated by the differences in design policy between the various agencies. The only real solution would be the development of a system in which programs could be easily substituted. Today's user would have to accept most of the system's design approach, knowing that the procedure is in accordance with the AASHTO specifications.

Thus, the use of any system represents a trade-off. The engineer sacrifices a desired close surveillance of the design in return for the advantages offered by the systems approach, including increased designer productivity and savings in engineering and, possibly, materials costs. An effective evaluation of the systems approach is not possible today, because BEST, the major public system, has not been converted to run on computers other than the Burroughs 5500. A widely usable system is required. As greater experience with integrated design systems is gained, many of the engineer's natural reservations should be overcome, and the great potential of the systems approach in the design of common highway structures may be realized.

CONCLUSIONS

Several conclusions appear warranted on the basis of the bridge design example performed as part of this study.

1. Two integrated bridge design systems, BEST and STRC, are available in operational form at this writing.

2. BEST, a public system, is the most advanced available today. It has the capability of developing a complete bridge design using minimal input data. The programs that compose the system can also be used individually on a stand-alone basis.

3. The use of computer systems offers potential savings in engineering costs, with increased productivity. Savings in materials are also possible because of the optimization inherent in the systems approach. If the design example performed in this report is representative, the savings could be great.

4. BEST does not conform to all of the design policies of the Bridge Division of the Virginia Department of Highways. Options built into the present system could handle some of the variances, such as the New York requirement that all fascia beams be of equal depth. However, more serious differences may exist, as in the case of the slab design, requiring modification of BEST or the substitution of programs within the system for complete conformity.

5. The impressive, albeit spotty performance of BEST in this study indicates that additional nationwide experience with an integrated design system is desirable. Unfortunately, the difficulty of the conversion of BEST from its present Burroughs 5500 status to other machines, such as an IBM 370, remains an open question. Some of the program modules have been converted, but the data management program appears to be highly machine dependent.

Additional conclusions can be made on the basis of the questionnaires sent to highway agencies.

6. There remains considerable interest in design systems; indeed, two states reported efforts in systems development. The economic attractiveness of a system was evidenced by Omnidata Corporation's development of STRC using private capital.

7. The preponderance (85 percent) of computer equipment utilized by highway agencies in this country is of IBM manufacture, and other models include Burroughs, Univac and CDC models. Future systems should allow more portability than was provided during the development of BEST.

ACKNOWLEDGMENTS

The authors deeply appreciate the interest and cooperation of Thomas J. Ogburn III of the Virginia Department of Highways, J.R. Ruby of the New York State Department of Transportation, and Eugene Sheninger of Omnidata Services, Inc. Without the extraordinary cooperation of the New York State Department of Transportation and Omnidata Services, Inc. in redesigning a typical highway bridge, this study would not have been possible. Others who rendered vital service in the course of the project included Don Vannoy, graduate student at the University of Virginia, and the representatives of the many highway agencies and other design offices who responded to the questionnaire and advised the authors on occasions.

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