ELECTRONIC COMPUTATION IN BRIDGE DESIGN

L. R. SCHUREMAN
Chief, Electronics Branch
Division of Development, Office of Operations
Bureau of Public Roads, U.S. Department of Commerce
Washington, D. C.

My discussion will deal primarily with applications of electronic computation in everyday bridge design problems, both those which are now in use and those which can and should be developed. First, however, I should like to spend a few minutes on the computer itself to avoid possible misunderstanding about what kind of machine is involved.

As most of you know, there are two general categories of electronic computers—digital and analogue. In the analogue computer, quantities or physical conditions such as pressure, temperature or flow are represented by analogous electrical quantities. This type of computer is used extensively in industrial processes but it is not, in general, well suited for highway or bridge engineering problems. The digital computer, as its name implies, works with digits or numbers and can solve, with practically any degree of precision desired, any problem which can be expressed in mathematical terms. Either type of computer may be designed for a special purpose or for general usage. It is the *general purpose electronic digital computer* which is proving to be such a valuable tool in highway and bridge engineering computations and my discussion will be limited to this type of machine.

General purpose electronic digital computers are made by a number of companies and vary widely in cost and in sizes and capacity. All of them, however, regardless of cost, can do essentially the same things although the more expensive machines will do them at a higher rate of speed. They can add, subtract, multiply and divide. In addition, they can perform a long series of computations without human intervention and, during the course of the computation, they can compare two numbers and follow one course of action or another depending upon which number is the larger.

These characteristics, combined with the fantastic speed with which they can perform arithmetic operations, make electronic computers extremely valuable devices for bridge design computations. By relieving the designer of routine, time-consuming computation, they make it possible for him to devote a much greater part of his time to creative work. Also, because a number of alternate arrangements can be analyzed on the computer in less time than it would take to make one analysis by the usual methods, the designer has greater latitude in conducting design studies. In addition, because of the speed with which computations can be made, substantial reductions in the time required to advance projects to the contract stage are possible.

Let us consider, as an example, the design of a continuous steel beam bridge.

First of all, the designer needs influence lines. Instead of computing influence line ordinates on a desk calculator, he can furnish the electronic computer the span lengths and obtain the values of all the ordinates for the complete set of influence lines in about five minutes. In some types of computers, these values will be automatically typed in tabular form as they are computed. In other types of computers, the results of the computation will be punched on cards or paper tape from which tabulation can be produced automatically on a tape-actuated typewriter or a line printer. There are also available electronic plotters which will accept the punched cards or tape as input data and produce the plotted influence lines thus eliminating manual plotting.

There are two types of electronic plotters, the point plotter which simply plots the points on the curve, and the line plotter which plots the points and in addition, connects successive points with straight lines. In the latter case, the result is a series of connected straight lines rather than a smooth curve. The approximation to a smooth curve can of course, be improved by computing influence line ordinates at the twentieth points or the fortieth points rather than the tenth points. The mechanical plotting of a complete set of influence lines on either of these plotters would take perhaps ten or fifteen minutes.

Using the influence lines, the designer can then determine the placement of live loads for maximum moments and shears. With this information as input, the electric computer can produce the values of the ordinates for maximum moment and shear diagrams. This may take four or five minutes. Again the electronic plotter can be used so that both tabulations and moment and shear diagrams can be produced mechanically.

Assuming that rolled beams are being used, the designer can determine from the maximum moment diagram the sizes of beams and cover plates needed and then return to the electronic computer to obtain the stiffness factors, carry over factors and fixed-end moments corresponding to the actual pattern of variation in moment of inertia. This information, recorded by the computer on punched cards or tape, can then be fed back into the computer to obtain new influence line ordinates. The maximum moment and shear computation can then be repeated, new diagrams produced, and a redetermination made of the beam and flange plate sizes required. Still another cycle can be completed if necessary.

This is one example of the way in which the electronic computer can be used in bridge design. The designer makes all design decisions, the computer simply does the arithmetic. The complete solution extending through the final determination of beam and flange plate sizes requires only a very small fraction of the time which would be required using a desk calculator.

Computer programs have been completed for computing influence line ordinates for continuous beams and for computing design constants for continuous beams of variable moment of inertia, that is, stiffness and carry over factors and fixed-end moments. A complete program for computing the values of maximum moment and shear diagram ordinates has not yet been developed and this is the missing link in the procedure used in the example. If any of you would care to develop such a program, I can assure you that lt will be gratefully received. It is, of course, complicated by the necessity for including both the H and HS systems of loading each with both truck loads and equivalent lane loads.

The same general procedure described in the example can, of course, be adapted to reinforced concrete construction and to continuous plate girder spans. In these cases also, there is need for computer program development.

Except for some pioneer work in the American Bridge division of the U.S. Steel Corporation begun early in 1955, all of the applications of electronic computers to bridge design computations have been developed in the last year and a half. In this period, excellent progress has been made and computer programs covering a broad range of problems have been developed. At the present time, the following problems are being handled on electronic computers in one or more State highway departments, consulting firms or other organizations:

1. Bridge bearing elevations
2. Geometry of skewed bridges on straight alignment
3. Geometry of skewed bridges on curved alignment
4. Bridge deflections
5. Influence lines for continuous beams
6. Design constants for continuous beams
7. Composite beam design
8. Prestressed beam design
9. Analysis of columns subjected to direct stress and bending
10. Rigid frame pier design
11. Single span box culvert design
12. Backwater computation

As you can see, the coverage in the area of bridge geometrics is quite good. In the area of structural design, additional problems are in process of being programmed for solution on the electronic computer including continuous truss analysis, fixed arch analysis, abutment design and multispan box culvert design. These programs, together with those previously mentioned as already in use, give fairly good coverage in this area. In the area of hydraulic design for bridges and culverts, very little has been done to date.

There is a considerable range in complexity among the computer programs which have been completed. In some cases they are quite simple. For example, the program for the analysis of columns subjected to direct stress and bending consists basically of the solution of the formulas given in the American Association of State Highway Officials "Standard Specifications for Highway Bridges."

In contrast to this case, the composite beam design program involves a series of mathematical solutions and covers the complete design of a composite beam. Using this program, the electronic computer will calculate all composite properties for the initial section, develop the necessary maximum live and dead load moments, and find the stresses due to these maximum moments. If the bottom flange proves to be overstressed, it will increment the bottom cover plate thickness, then recompute properties, moments and stresses. This procedure is repeated until a satisfactory stress is obtained. If the top flange is overstressed, the computer will type out the maximum moments and stresses and stop so that the designer may increase either the basic section or the top cover plate thickness before the machine continues. When the flange stresses are satisfactory, the computer proceeds to determine cover plate cut-off points. Shears are then computed at the reaction, the one-tenth point, the three-tenths point and mid-span if there are no cut-off points. Where there are cut-off points, shear values are obtained for those points instead of the one-tenth or three-tenths points. Theoretical shear connector spacing and horizontal shear stress in the flange are computed for each of these points. The computer then proceeds to compute the reactions, the dead load deflection, and the live load deflection ratio. Finally the quantities of concrete and steel are computed. This program contains about 1500 computer instructions and the computing time for the complete solution ranges from 10 to 20 minutes.

Another program, developed in the Division of Development of the Bureau of Public Roads, goes still further in demonstrating the extent to which the computer can be used in solving design problems. This is a program for the design of continuous steel beam bridges of 3, 4 or 5 equal or unequal spans. The computer is given the number of spans, the span lengths and the loading and produces the sizes of the interior and exterior beams required and the numbers, sizes and lengths of cover plates needed at intermediate supports. For a 3-span bridge, the entire computation requires about 10 minutes. The approach is different from that used in the example described previously in that influence lines are not used. Live loads are placed for maximum positive and negative moments, an initial determination of beam size and cover plate requirements is made, design constants corresponding to the variable moment of inertia are computed, maximum moments are recomputed and finally a redetermination of beam and cover plate sizes is made. If necessary, an additional cycle can be completed. The entire computation is done in a continuous computer operation.

The bridge geometry problems are essentially exercises in applied trigonometry. Nevertheless, they can be quite complex and may involve a large amount of computation, particularly in the case of multispan skewed bridge on curved alignment. For both straight alignment and curved alignment, the computer programs are designed to find, first of all, the intersections of a series of reference lines with a series of working lines. The reference lines represent the bridge deck center line or base line, the fascia lines, curb lines, profile grade line, etc. On curved alignment, the reference lines are concentric circles. The working lines represent the inside faces of abutment backwalls and the center lines of piers, bents or bearings.

In cases where the alignment is straight, the computer then develops the following information:

1. The station of each point of intersection measured along the center line or reference base line whichever is used for stationing.

2. The distance from each point of intersection to the stationing line measured along the working line.

3. The distances between points of intersection on one working line to corresponding points on adjacent working lines.

4. The roadway surface elevation at each point of intersection.

5. The slopes of the beams.

6. The lengths of the beams.

7. Bearing seat elevations for each beam at the center line of bearing.

Where the alignment is curved, the following information is computed:

1. The station of each point of intersection measured along the center line or reference base circle whichever is used for stationing.

2. The radial offset from the stationing circle to each intersection point.

3. The angle between a radial reference line through the P. C. and a radial line through each intersection point.

4. The distances along each working line from the stationing circle to all points of intersection of other circles with that working line.

5. The chord distances between points of intersection on one working line to corresponding points on adjacent working lines.

6. The angles which these chords make with working lines for exterior beam chords and reference base circle chords.

7. The roadway surface elevations at all intersection points.

8. The stations and finished grade elevations at the beginning and end of the bridge.

9. The spacing of all beams both normal to interior beams and along working lines.

10. The slopes of all beams.

11. The lengths of all beams.

12. For each beam, the distance measured along the beam from center lines of bearing to working lines.

13. Bearing seat elevations for all beams.

The program is designed to "lay-in" interior beams parallel to each other and approximately evenly spaced between the outside beams which are placed on chords of concentric circles.

In order to avoid misunderstanding, the designer provides the basic data needed on a standard form. Upon completion of the computation, he receives a complete tabulation of the results. For an average problem of this kind, the computation takes not more than 20 minutes which is a very small fraction of the time required to do the job with a desk calculator. Skewed bridges on curved alignment are becoming more and more common in our highway work and the electronic computer provides a means of saving very large amounts of design time in working out their geometrics. In a test run made recently in one of the State highway departments, 11 minutes were required for the electronic computer method whereas the manual method, using a desk calculator, required 22 man-days.

About 30 State highway departments and an equal number of highway consulting engineering firms are now using electronic computers for highway or bridge work or for both. Seven different makes or models of computers are used. Since each type of computer uses a different machine language or coding system, the programs developed by the highway departments and consultants are not completely interchangeable. To overcome this difficulty, as well as to provide a central point for the receipt and distribution of electronic computer programs, a computer program library has been established in the Bureau of Public Roads. Each program received for the library is adjusted to remove terminology peculiar to the computer for which it was developed and to assure completeness and clarity. The final library version of the program expressed solely in English and mathematical terms, can then be coded for use with any digital computer. In this way, the

Bureau of Public Roads program library supplements the work being done in the several computer user groups and makes possible complete program interchange regardless of the types of computers used. Memoranda are issued periodically to the highway departments and others advising them of the programs received and those converted to library form. To date, we have received about 60 programs for the library and others are being received each week. The rate of conversion to library form is being accelerated and in a relatively short time, there should be available a substantial array of programs covering a wide range of highway and bridge problems.

The mystery with which electronic computers were surrounded in the beginning is steadily being dispelled although there is still a paucity of literature written in a form understandable to civil engineers. We have learned how the computer works, what it will do, and how to use it. We have also learned that it is not an "electronic brain" but only a calculating machine. It will do only what it is told to do and no more, and furthermore it has to be told what to do in minute, specific detail and in a language it can understand.

In order to use an electronic computer to solve a particular problem of any kind, we have first to analyze the problem—what results are desired and what data must be furnished to obtain those results; what computations have to be made and in what sequence; what special cases have to be considered? We then either write in word form the specific detailed steps which must be taken from beginning to end to solve the problem, or we develop a flow chart or block diagram which does essentially the same thing. All of this can be done without reference to the type of computer which is to be used—it is simply a step-by-step procedure for solving the problem and could be used with a desk calculator as well as with an electronic computer. This then is the computer program. When it is completed and tested against longhand solutions, it is translated into the coding system used in the particular computer which is to be used to solve the problem. This coding operation can be done by a specialist in coding and need not be done by the engineer. The result is called the coded program. This is punched into cards or tape for feeding into the computer.

Any highway or bridge engineer with a general knowledge of computer capabilities can develop a computer program up to the coding stage. Some of you who have not done it may wish to try. Electronic computer methods are rapidly becoming firmly established in highway and bridge engineering and inevitably will become the conventional methods of the future. All of us should learn as much as we can about electronic computers and how to use them. The best way to learn is by doing.

The general tendency in developing computer programs for bridge work has been to follow exactly the procedure used in solving the problem using pencil and paper or a desk calculator. This is one reason such rapid progress has been made in program development. However, because the computer performs mathematical operations so rapidly, we have greater latitude in the selection of methods. Assumptions and approximate design procedures now used to avoid lengthy or complex mathematics can be discarded in favor of methods which take into account the actual deformations and deflections of the structure in computing stresses. For example, in the design of a bridge deck composed of a slab supported by longitudinal members which are inter-connected with transverse diaphragms, we should take into account the behavior of the deck acting as a grid and compute the load distribution and the resulting stresses accordingly. While the complexity of this method of solution may discourage its consideration when the computations must be done on a desk calculator, this should not be a major difficulty in solving the problem on an electronic computer.

As we reach a condition in which we have complete or nearly complete program coverage of our common bridge problems so that production is not impeded, we can then take the time to explore possibilities of developing more refined design methods thus realizing in still greater measure the advantages inherent in electronic computation.

DENSE GRADED AGGREGATE BASE CONSTRUCTION

A. L. Howell
Supervisory Construction Engineer
Kentucky Department of Highways

The project on which application of dense graded aggregate base is to be discussed is a section of US 31-E in Larue County known as F 10 (3) Hodgenville-Magnolia Road and is 5.857 miles in length. Nally & Gibson of Springfield, Kentucky, and Geohegan & Mathis of Bardstown, Kentucky, were joint contractors and Mr. Earl Calhoun was Resident Engineer on this work. This road was designed and constructed to 44-56 section with a 24-foot surface, with dense graded aggregate base of 14 inches compacted depth, with the top 2 inches to contain 1.0 lb. per sq. yd. of calcium chloride, with 2 inches of bituminous concrete binder and 1½ inches of bituminous concrete surface.

The preparation of the subgrade was done in compliance with Article 2.8.0. of the 1945 Standard Specifications under which the project was constructed. In rough grading, the grade was left sufficiently high that enough shoulder material could be secured by cutting down to subgrade elevation.

The layout of the blue top and tack line was performed in the same manner as in waterbound base construction.

The required gradation of the dense graded aggregate material was as given below:

SPECIAL SPECIFICATION NO. 58-R2

Passing 1" Screen	100%
Passing ¾" Screen	75-100%
Passing ⅜" Screen	50-80%
Passing No. 4 Sieve	35-65%
Passing No. 10 Sieve	25-50%
Passing No. 40 Sieve	15-30%
Passing No. 200 Sieve	5-15%

The average gradation of the material—as taken from samples at the crushing plant and from check samples taken during construction—was as follows:

Passing 1" Screen	100%
Passing ¾" Screen	99.3%
Passing ⅜" Screen	75.5%
Passing No. 4 Sieve	54.2%
Passing No. 10 Sieve	35.8%
Passing No. 40 Sieve	17.1%
Passing No. 200 Sieve	7.2%

The water was added to the dense graded aggregate in a central mixing plant located at the Kentucky Stone Company Quarry at Upton, Kentucky, approximately 10 miles from the south end of the project. A Barber Greene, Model 828 stabilization mixing unit of 300 to 500 tons per hour capacity was used in the operation. The material was loaded from the stockpile with two 2¼ yd. Michigan loaders into a 15-ton hopper with a syntron vibratory feeder. This discharged the material onto a 30-inch conveyor belt which fed directly into the pugmill. The mill was similar to that on a Barber Greene Bituminous Mixing Plant, except that it was equipped with a series of perforated spray bars, each with a cut-off valve, through which water was applied. There was a meter on the main water line which registered the gallons of water being used, making it possible to determine fairly accurately the amount being added per ton of stone; however, attention was given at all times to the amount of free moisture in the material as it came from the stockpile, and adjustments had to be made in the amount of water added in the mixer as the stockpile material varied in moisture content. From 7 to 8 percent total moisture was necessary to secure the required density, and this provided a desirable and workable mix. An inspector was at the plant at all times it was in operation.

The material was hauled to the project in dump trucks. From 30 to 50 trucks were used and the maximum day's production was 4193 tons.

A Jersey spreader mounted on a D-7 Caterpillar tractor was used to lay the dense graded material, and sufficient material was spread for one-half width, or 12 feet, and 6 inches in compacted depth. When from 500 to 1000 feet was spread in this manner the spreading machine was brought back and the other half was brought up in a like manner; however, it was found that during hot dry weather it was desirable to take shorter lands to prevent losing moisture from the material spread on the beginning side.

After both sides had been spread with the machine a power patrol grader was used to manipulate and shape the material to a typical section before the rolling and compaction operation began. The spreader was hardly wide enough to make the full 12-foot spread of material on either side and it was necessary to work sufficient material into the center with the patrol grader, which caused a certain amount of segregation. This segregation, however, was not serious enough to cause any appreciable damage to the final results.

After the patrol grader had properly shaped the material, the compaction was started by using a 13-wheel wobble wheel roller followed by a Terrapac vibratory roller, both of which were pulled by rubber tired tractors. This operation was continued until the required density was secured, after which a 10-ton, three-wheel roller was used to iron out any irregularities left on the surface.

The minimum required density was 85 percent of solid volume. The specific gravity of the limestone used was 2.68, which made a minimum requirement of 142.1 lbs. per cu. ft. The average density, as taken over the entire project with a balloon density machine, was 87.1 percent of solid volume or 145.6 lbs per cu. ft.

The quantities set up on the project were based on 115 lb. per in. per sq. yd., or 153.3 lb. per cu. ft. Theoretically the application of 115 lb. per in. per sq. yd. would have made a slightly thicker spread than the designed thickness; however, because of the extra material used on the edges (as will be explained later), the total thickness of all courses was very close to the designed thickness.

It was usually necessary to maintain the surface from two to three days by sprinkling and rerolling to prevent the top from drying too fast before the entire depth had bonded, and if any raveling spots appeared it was necessary to reshape them with the patrol grader before sprinkling and rerolling. Both the vibratory and the three wheel roller were used in this maintenance operation. It required from 9 to 10 inches of loose depth of material to make the desired 6 inches compacted depth.

Considerable difficulty was encountered in attempting to hold the outside edges to a vertical position even with the placing of compacted earth against them. Since the rolling operation started along the edges, the wet, fine graded material would push down and out. It was found that unless extra width was allowed for this sluffage the course was not to the required width, and when the next course was applied to the required width, a part of its edge was lying on the compacted earth shoulder. It is felt that, in future design of this type and depth of base, either extra material should be set up to allow for approximately 1:1 slope on both edges of the base course or forming should be required. The extra charge that the contractors would make for forming, however, would probably be more than the cost of the additional material required for a 1:1 slope on either side.

After the first 6-inch course was placed on approximately one-half of the project, the contractor elected to drop back and start placing the second 6-inch course, which was applied in the same manner as previously described. When the loaded trucks started hauling the material over the first course for the second course, some isolated spots of raveling occurred and it was necessary to reshape, sprinkle and recompact these areas before the second course was placed. These areas did not exceed, however, those which would normally be encounterd under the same conditions on a waterbound job where the second course was being applied—possibly not more than 0.5 percent of the total area.

As previosly stated, the plans specified that 1.0 lb. per sq. yd. of calcium chloride be used in the top 2 inches of the 14-inch dense graded base. The calcium chloride was applied at the mixing plant by the use of a Barber Greene fines feeder, discharging the calcium chloride onto the conveyor belt which fed the aggregate into the pugmill. The feeder was equipped with a control gate set to discharge a given amount at a given time and by determining the rate of flow of the aggregate at the syntron gate it was possible to regulate the application of calcium chloride fairly accurately.

The two-inch course of calcium chloride treated material was placed and compacted in the same manner as the previous courses; however, considerably more maintenance was required for the first three or four days after laying to prevent raveling. This was attributed to the damp cool weather at the time it was being placed, September 1957; but after about four days it bonded tightly and areas on either side where the traffic was most prevalent sealed almost to a glazed surace.

This course was allowed to cure for seven or more days before the RT-2 (prime) was applied. The penetration was very little, particularly in the tracks which were glazed. Approximately 0.2 gal. per sq. yd. was all that could be used, and this was applied in two passes to prevent it from running off, the second application being placed within a few hours after the first. Even after being permitted to cure for several days, however, this would track up on car wheels on the glazed places. It is thought that possibly better results could have been secured if the calcium chloride had been used in the middle course, which was placed during warmer and dryer weather, and more penetration been secured in the top course with the tar without the calcium chloride being used.

The binder and surface were applied in the usual manner for that type of construction.

If I were asked to make a suggestion or criticize the dense graded aggregate which was used on this project, my mean suggestion would be that a larger top size aggregate be used, possibly 2- to 2½-inche material on projects where plant mixing is required. Of course I know it would be harder to produce, but other states, particularly Tennessee, are using a dense graded material with a larger top size and are getting it produced somehow. It may require blending, but I believe that a dense graded material with a larger top size would have much more stability than the gradation that we are now using.

For anyone present who might have similar construction in the near future, there are some conditions that you might be forewarned against; namely, if a vibratory roller is used the vibrator should always be cut off before the roller starts turning around or it will beat the aggregate out of section while turning on a short radius, also the tractors pulling either the vibratory roller or pneumatic roller should have smooth tires, as heavy treads will dig into the base, particularly in turning at the end of a section being compacted.