

BEBO Concrete Arch Structural System

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In December 1969, U.S. Patent 3,482,406 was issued to cover a new concept of using precast concrete. Normally considered a rigid material, the precast concrete is placed in a state of "flexible stability" to attain a safe and efficacious earth-covered structure for spanning up to about 60 ft under fills of from less than 2 ft to more than 40 ft and service loads in excess of 300 tons. The key to the in-service success of the Beton Bogen (BEBO) concrete arch, which was originally tested in 1966, is the balancing of arch deformations against the counterdeformation action of passive earth pressures generated by the deformation of the uniform arch ring itself. The engineering problem was to design a standardized system that attained this balanced result over a range of practical spans. Further, the system had to be easily fabricated, transported, and placed; able to sustain lateral forces generated by asymmetrical backfilling and compaction operations; and, once in service, be virtually maintenance free. To date, 76 bridges have been built by using the BEBO system in Europe and the Near East under a wide variety of foundation conditions. Some of these projects included multispan designs, but only a very few required wingwalls. The system has been successfully adapted for nine underground garages by using reinforced concrete ties. The usual span for these structures is 60 ft, and they have overhead clearances of 10 ft. Since its original 1966 prototype structure, the BEBO system has been modified and improved, but its basic successful concept has been retained. Postconstruction performance has substantiated original expectations, and competitive bidding has demonstrated its economy of construction.

Of the 566 000 bridges in the inventory of the Federal Highway Administration (FHWA), more than 212 000 have been designated as deficient either structurally or functionally. Many of these have spans less than 55 ft. With this fact in mind, it was decided that it would be worthwhile to study the Americanization of a Swiss bridge system called the Beton Bogen (BEBO) concrete arch. The BEBO concept was developed by a Swiss civil engineer, Werner Heierli, who was familiar with the phenomenon of soil-structure interaction through his studies at the Massachusetts Institute of Technology in 1961 and 1962. In 1966, a full-scale test structure was erected and tested near his home city of Zurich (Figure 1). (In this figure, an asymmetrical load of 340 tons is shown on the 49-ft 2.5-in clear span. The arch ring is slightly less than 6.5 in thick and the span/rise ratio is 3.4:1.) The experiment was so successful that the Swiss federal government decided to apply it to a site on Federal Highway Number 1. Built in 1967, this bridge still serves with a maintenance-free record. Since that time, 80 other structures have been built by using the BEBO concept. They include bridges on a variety of sites, cut-and-cover tunnels, and underground parking garages. In addition, the West German government required a second test structure and a university-based research program to ascertain that all structural details were safe and durable. In August 1981, the first bridge outside of Europe and the Middle East was built in Edina, Minnesota.

HISTORICAL BACKGROUND

It was the Roman engineer that made the arch the standard structure for highway bridges and aqueduct stream crossings. The Roman arch was invariably a semicircle with massive piers (or abutments) and deep arch stones.

The two hazardous times in the life of a Roman arch were the dropping of the wood centering during construction and an extraordinary flood. During the Dark Ages, Roman arches became convenient local quarries for precast stone, and akin to this hazard was military destruction. Service load failures were virtually unknown.

It was Perronet (1708-1792) who perfected the circular arch segment as a means for substantially increasing bridge spans without a concomitant increase in rise. Other forms of the arch appeared in the 18th century even for shorter spans, and the ellipse became particularly popular. As the craft of architecture began to merge with mathematics and mechanics into the art of engineering, so the use of mathematical forms such as the parabola was introduced into bridge practice for both timber and stone.

Throughout the 19th century, most practical engineers used empirical rules developed from the geometry of successful bridges, although elastic analysis is found in American texts at the turn of the 20th century. When concrete was introduced as a structural material for arch bridges, the fixed-end assumption persisted for some time, even though the two-hinge theory was well developed. After World War I, reinforced concrete structures became increasingly popular and elaborate hinge configurations were designed for reinforced concrete arch-rib bridges for spans more than 55 ft. For shorter spans, the old masonry rules remained as common practice.

Before closing this historical survey, it is interesting to note Brunel's Maidenhead Bridge of 1837. This railroad bridge's three arches each spanned 128 ft but had a rise of only 24 ft. Such a daring flat design provoked much controversy and speculation that it was doomed to collapse. After its first century of service without the slightest problem, no one doubts its safety; but this same question arose during the Edina BEBO project.

AMERICANIZATION OF THE SWISS CONCEPT

Despite the obvious success of the BEBO arch system in Europe, there was some doubt as to whether it was a competitive form for the United States. Although the mathematical basis for structural analysis of the BEBO design was widely accepted in American universities, it was American practitioners who had to decide on the structural merits of the system.

Figure 1. Original BEBO test structure in Zurich, Switzerland (1966).



Many of these engineers were not familiar with the mathematical intricacies of finite-element analysis, and even those that were looked at a mass of computer printouts with less than enthusiasm. Therefore, one step in the Americanization process was to develop a simplified analytical technique by which local, county, state, and federal engineers along with consultants could review BEBO plans with a minimum of time and effort. Other programs that were developed included hydraulic analysis for stream crossings and foundation design.

The structural analysis program is calibrated to the more refined finite-element method (FEM). It is basically concerned with service loads and variations in overfill depths, whereas FEM not only considers these cases, but it also determines stresses in the precast elements generated during handling, transporting, erecting, and backfilling. As it turns out, the most critical stresses in the elements may not occur during service but rather during their preservice life. Thus, the steel in an arch element is the same whether the overfill is the minimum of about 1 ft or as much as 6 ft or more.

The original BEBO structures were built of precast reinforced concrete plates about 6 ft by 20 ft by 8 in. The units were set on a special steel erection frame and then doweled and grouted together at the joints. Each day after one set of plates was in place, the frame was jacked into position for the next set of plates. In general, spandrel walls were not used; instead, the fill was sloped down over a special set of end plates.

Talks with American engineers, precasters, and contractors quickly revealed that the plate system would have limited success in the United States. It was decided to concentrate on a single-leaf or twin-leaf modification, the latter having had some application in Europe for smaller spans. Further, because of the nature of the American precast market, it appeared advisable to consider precasting the spandrel walls, the wingwalls, and the arch base.

The final geometry of the American version of BEBO was based on structural considerations (pre-service and service), hydraulic characteristics, and regulations that govern the transportation of heavy loads in each of the 50 states.

The project sequence for the Americanized system is as follows:

1. A catalog model is selected based on site geometry, hydraulic requirements, and clearances.
2. The foundation slab size is determined by local site conditions.
3. The site is excavated to foundation grade and the foundation slab is cast in place.
4. The erection of the precast elements begins with the precast arch bases and ends with the wingwalls.
5. Backfilling is accomplished in prescribed lifts. Grossly unsymmetrical fills are not permitted.
6. Paving, landscaping, riprapping, guardrails, and other nonstructural items are completed and the bridge put in service. Elapsed time is about two to six weeks, depending on the overall size of the project, seasonal factors, etc.

EDINA EXPERIENCE

The American engineer responsible for Americanizing BEBO was fortunate to have an experienced precaster who had a penchant for innovation on his first project of this type to be built in the United States. Through a cooperative effort with the Swiss firm, all the details of producing a bridge meeting all American Association of State Highway and Transpor-

Figure 2. First BEBO arch built in the United States in Edina.



tation Officials (AASHTO) standards as well as local standards and requirements were completed in a matter of months. The City of Edina followed standard competitive procedures, and the final low bid for using the BEBO structure was approximately the same as the estimate, the lowest being \$113 000. An alternate system was offered at \$22 500 more than this low bid. Figure 2 shows the completed bridge. It has a span of 40 ft 4 in and a rise of 9 ft 8 in. The total width is 74 ft and there is 2 ft of fill over the crown. The service load is HS-20. There are 12 arch elements, each 48 ft 5 in long, 6 ft wide, 10 in thick, and weighing 18 tons. There are two spandrel elements, each 44.5 ft long, 12 ft high, 12 in thick, and weighing 18 tons. There are eight wingwall elements, four high units (sloping from 13 down to 9 ft), and four low units (sloping from 9 to 5 ft). The high units weigh 9.5 tons and the low units 7 tons. All wingwall units have a stem thickness of 10 in.

The cast-in-place foundation required about a week, but the erection of the precast elements was accomplished in less than two days. With more experience, it is believed that only one day would be enough. Because there are no special hinges between the arch elements and the foundation, about 2 h for grouting was all that was needed. Backfilling took another day or so. Because of the newness of the system, the Edina engineering department made a series of on-site measurements.

SUMMARY

From experience gained since studies of applying the Swiss short-span arch-bridge system to the United States began in 1979, it appears that it has certain advantages within the span range of from about 15 to 55 ft and within span:rise ratios of about 4:1 to 2:1.

From an engineering standpoint, the system has the following characteristics:

1. Low installation cost;
2. Low maintenance cost (virtually none);
3. Short construction time;
4. Meets AASHTO design standards for Interstate use;
5. Live load impact effects muffled;
6. Live load stress reversals;
7. Temperature stress reversals minimal, thus increasing durability;
8. Structurally durable and reliable;
9. Useful hydraulic properties;
10. Readily site adaptable;
11. Desirable conservation characteristics (natural stream bed);
12. Aesthetically pleasing;

13. Resistant to extreme flooding;
14. Maximum use of local materials;
15. No bridge deck to deteriorate and no joints in road;
16. Low hazard from ice glazing;
17. Minimal inspection required by owner; and
18. Not sensitive to unequal settlement.

From the precasters and contractors viewpoints, the system has the following characteristics:

1. Meets load limitation and clearance standards for transporting in all states;
2. Requires no special processes (prestressing, steam curing, etc.);
3. Requires no special materials;
4. No special erection equipment needed;

5. Low initial capital investment;
6. Requires no new skills, but present skills must be augmented;
7. Precise pricing possible once operation established;
8. Increases construction season;
9. Not sensitive to backfilling when prescribed backfilling operations are used; and
10. Small on-site work force.

For the above reasons, it is believed that the Americanized version of the Swiss BEBO system will find many applications in the United States.

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Bridge Structure Construction System That Uses Treated Lumber

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For generations, timber has been considered an economical material for bridge construction. Although for years railroads made good use of treated timber in their bridges, little thought was given to design or permanence of timber for highway bridges, which resulted in timber being viewed as a second-class material. Even though preservative-treated wood was eventually used, it is only in recent years that serious consideration has been given to the design of treated timber for use in short-span highway bridges. Treated timber offers economical advantages, but it provides other advantages as well. Treated-timber material will not crack, crumble, or rot. It cannot be damaged by continuous freezing and thawing, and it is not affected by temperature, alkali soil, or acids. When properly designed, a timber bridge provides flexibility and lower costs in design, simplicity in construction, short construction duration, little or no maintenance, minimal weather considerations during construction, and compatibility with the surrounding environment. One type of economical timber bridge is the longitudinal laminated-floor design, which is especially easy to construct. To form the superstructure, 3- or 4-in planks are set on edge in the direction of the span; they are offered in spans up to 38 ft in length. Deck planks are laminated together into panels approximately 6 ft wide by using ring shank dowels. Panels are attached to each other at the site by using dome head drive spikes through a shiplap joint. The structure, which is usually completed in a few days, minimizes cost and inconvenience to the taxpayer.

If the term "wood bridge" is mentioned, most of us immediately picture an old-fashioned covered bridge (Figure 1) or perhaps an old, broken down, poorly constructed wood crossing (Figure 2). Actually, the first wood bridge probably was a log laid across a chasm. For years thereafter wood was an important material used in the construction of bridges.

Railroads and their company engineers long ago recognized the value of wood as a basic bridge material. Wood was readily available. It was durable; easy to use; easily maintained, repaired, or modified; and the use of wood preservatives made it permanent. By applying engineering practices, treated wood became a predominate material. Virtually thousands of timber railroad bridges were built, and many still provide excellent service.

Wood bridges for roads or highways, however, were often built with little thought given to design or concern for permanence. Wood was usually a material

put together quickly and cheaply to meet society's basic need of getting from one stream bank to another. Thus, for highway bridges, wood evolved as a second-class material. Gradually, data on timber construction offered by most engineering schools decreased. Many practicing engineers have had almost no background in timber construction. It is ironic that wood as a construction material has been around almost as long as man and yet is probably the least understood common building material. Wood is a highly desirable raw material because it is a renewable resource that is provided by significant amounts of forests in the United States. It is a long way from that small stream crossing for the horse and buggy compared with the demands that present-day traffic puts on major highway bridges. (You might say it is like comparing a Model T with a Cadillac. In between there are a lot of bridge needs, and a good many of them are on rural and township roads. The Model T is inadequate, but the Cadillac is more than is needed. The key is to match the solution to the need; i.e., adequate design, permanence and integrity, and economical cost. That is where treated timber can help.)

There is nothing second-class about timber bridges (Figure 3). Treated timber offers economical advantages over other materials. It will not crack, crumble, or rot. It cannot be damaged by continuous freezing and thawing. Salt will not pit it, water will not rust it, and it is not affected by temperature, alkalai soil, or acids. As a matter of fact, chemical companies such as DuPont have been using preservative-treated wood box culverts in effluent discharge systems for years. They found treated wood to be the best material available to withstand the chemical action of toxic wastes.

When properly designed, treated timber provides flexibility; it can be easily modified, expanded, dismantled, or moved from one location to another should needs change. Treated timber provides econ-