Table 1. Cost analysis.

<table>
<thead>
<tr>
<th>Construction Type</th>
<th>Example</th>
<th>Span (m)</th>
<th>Curb-to-Curb Width (m)</th>
<th>Framing System</th>
<th>Cast-in-Place</th>
<th>Precast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Thickness (mm)</td>
<td>Field Erection Time (days)</td>
</tr>
<tr>
<td>Deck replacement</td>
<td>1</td>
<td>23.8</td>
<td>16.0</td>
<td>Multiple steel I-beams</td>
<td>203</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>29.1</td>
<td>7.3</td>
<td>Steel-truss with floor beams</td>
<td>330</td>
<td>25</td>
</tr>
<tr>
<td>New bridge</td>
<td>3</td>
<td>19.8</td>
<td>10.4</td>
<td>Multiple prestressed concrete I-beam</td>
<td>241</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>34.2</td>
<td>20.7</td>
<td>Multiple steel I-beams</td>
<td>317</td>
<td>26</td>
</tr>
</tbody>
</table>

1. New bridge construction—(a) Improved structural efficiency, (b) fewer support elements, (c) decreased manpower requirements, and (d) less construction time;
2. Replacement deck construction—(a) Decreased on-site construction time and manpower requirements, (b) less time required for traffic control, (c) less inconvenience to the traveling public, and (d) decreased dead-load weight and potential for increase in live-load capacity.

In addition, precast concrete elements fabricated in a controlled environment under "factory" conditions provide for improved quality control, which can ultimately result in improved durability of the completed deck.

REFERENCES


Abnormal Rotations of Skewed and Curved Bridges

MARTIN P. BURKE, JR.

The abnormal rotation of skewed and curved bridge superstructures is described and illustrated. Various types of compound bearings that accommodate this type of rotation are described. Specific examples of structure distress due to abnormal rotation and inappropriate bearing selection are given. Although present design specifications are mute concerning this phenomenon and research that is specifically focused on it is scarce, it is suggested that the designers of severely skewed or curved bridges should consider the consequences of abnormal rotation and furnish an appropriate bearing design for such structures.

The present American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges (1) recognize the need for other than flat bearing surfaces for bearings of bridge spans of 50 ft or more. Section 1.7.32 of the specifications states that "spans of 50 feet or greater shall be provided with a type of bearing employing a hinge, curved bearing parts, elastomeric pads, or pin arrangement for deflection purposes." However, nothing is stated about the need to make similar provisions for bridges with severe skews or curves, yet the need of accommodating the actual rotations of skewed or curved bridge superstructures, laterally as well as longitudinally, is in some cases equally important (2).

This paper attempts to highlight this subject of combined lateral and longitudinal superstructure rotations (abnormal rotations). Some of the major bearing types that have been developed during the past two decades to accommodate these rotations are described as well as the bearings that some Ohio bridge engineers have chosen for their bridges.

For example, consider bridge CUY-480-1572 de-
signed by Murray of Alden E. Stilson and Associates. It is a bridge with a two-span, continuous through-girder superstructure designed to carry the two tracks of the Penn Central Railroad over I-480 in Cleveland, Ohio. It has spans of 159 and 190 ft and a skew of about 67°. Part of the framing plan of this structure is shown in Figure 1. In this framing plan, notice that point A of the north girder is located more than 90 ft from its girder bearing but only 37 ft from the bearing of the adjacent south girder. A schematic cross section of the superstructure at point A is shown in Figure 2. The dashed lines represent the girders and transverse floor beams in an unloaded position and the solid lines the members deflected due to live load. In this exaggerated sketch showing girder deflection in a vertical plane, the type of deflection usually assumed in bridge design, it should be obvious that the reverse bending of the floor beams should be accompanied by lateral bending and/or rotation of the girders.

A more realistic assumption of structure deformation is shown in Figure 3, where the deflection of the girder at point A is associated with bending of the floor beams and rotation of the girders. Because the rotation of the left girder is occurring at a bearing, the type of bearing used at this location must be able to accommodate not only longitudinal rotation but lateral rotation as well; otherwise, bearing edge loading will occur and be followed by girder, bearing, and bridge seat distress.

During the past two decades, several types of bridge bearings have been developed for applications in which abnormal rotations must be accommodated. These various bearing types have come to be known as pot, spherical, elastomeric, and disk (3).

For his Penn Central Railroad structure, Murray selected and designed pot bearings to accommodate the skew-related abnormal rotation of the structure. The bearings he designed will accommodate all abnormal rotations and longitudinal translation and will support reactions of up to 4000 kips. They will be the largest bearings of their kind in Ohio.

Typical pot bearing details are shown in Figure 4. These bearings are circular in plan and rather flat in outline. The bottom cylindrical section, or pot, which contains an elastomer of either natural rubber or neoprene, is covered by an upper cylindrical section, or piston. The elastomer confined within the pot is subjected to a vertical pressure of about 3500 psi, which causes the elastomer to behave much like an incompressible fluid. Rotation of a bridge superstructure causes a redistribution of the elastomer within the pot, thereby minimizing the eccentricity of the vertical reaction. To aid in the redistribution of the elastomer within the pot, some manufacturers use a lubricant on the elastomer; others sandwich the elastomer between two thin disks of Teflon. To prevent the elastomer from being extruded from the pot by the pressure of the loosely fitted piston, manufacturers have developed a number of different types of sealing rings.

Because of the fit of the piston within the pot, differential horizontal translation between the superstructure and the bridge seat is prevented by the pot design shown in Figure 4. To provide for horizontal translation, this basic design is modified by the addition of an abutting pair of sliding surfaces, one faced with stainless steel and the other with Teflon. This type of pot bearing design is shown in Figure 5. The pair of guide bars shown in this figure is intended to restrict the lateral translation of the superstructure. Without guide bars, the bearing would be capable of accommodating both lateral and longitudinal translation.

Figure 6 shows a pot bearing that was designed by Kopetz of Howard Needles Tammen and Bergendoff for
Elastomeric bearings are unique in that, for short metallized surface is then machined and polished to types of compound bearings. Bearing is also supplemented with sliding surfaces similar to those that are incorporated in the other and horizontal translation without any moving and it appears that they will survive the structure. Shortly after this first installation, Erickson of Ericksson Engineering provided elastomeric bearings for a bridge BB1-7-2789 (see Figure 8). This structure consists of continuous steel beams supported on integrally framed transverse girders, which in turn are supported on widely spaced pier columns. Because of the deflection and rotation of the transverse girders and the simultaneous deflection and rotation of the longitudinal beams, it was obviously necessary to provide for the combined rotational effects (abnormal rotation) with compound elastomeric bearings. All of the intermediate pier bearings of this structure are elastomeric. The largest of those bearings are 3 ft in diameter and 7.5 in thick. They were installed in 1966.

Designs for elastomeric bearings have become quite large. Some bearings with 3-ft, 10-in diameters were manufactured by the Merriman Company. In this particular design, lateral translation of the superstructure is allowed by the metallizing process. This is one of the more efficient and an economical alternative for the more expensive pot, spherical, and disk bearings. Part allow for the abnormal rotations of the curved superstructure of bridge COL-30-3661, Hendricks of Glaus, Pyle and Dehaven chose a spherical bearing design that has details similar to those illustrated in Figure 7. Note that this type of bearing has two sliding surfaces: a curved or spherical lower surface to provide for the combined rotational rotations of the superstructure and an upper flat surface to provide for horizontal translation. In this particular design, lateral translation of the superstructure is prevented by the use of twin guide bars.

With respect to the sliding surfaces, these bearings were designed with two different types of sliding surfaces. The spherical surfaces were lubricated bronze, and the upper flat surfaces were faced with stainless steel and Teflon. A lubricated bronze surface is a bronze surface that has trepanned concentric recesses that are filled with a compressed lubricant. The recommended design coefficient of friction for such a surface is 10 percent. The upper sliding surfaces were faced with stainless steel and Teflon fabric, the first time that Teflon fabric was used in a compound bearing for an Ohio structure. This is one of the more efficient and a durable forms of Teflon available to the bearing designer. The coefficient of friction for such a surface is well below 5 percent.

Recent improvements have been made in the spherical bearing designs by the Merriman Company. Instead of using lubricated bronze for the spherical sliding surfaces, manufacturers are now able to furnish a spherical convex surface faced with stainless steel (by welding with stainless electrodes) and a spherical concave surface faced with Teflon fabric.

Based on recent conversations with an official of a metallizing company, it now appears practicable to apply a stainless surface on regular structural steel--AS88, for example--by the metallizing process. In metallizing, a spray of heated particles of the desired facing metal is applied to a structural substrate. After the particles have fused with the substrate to an appropriate thickness, the metallized surface is then machined and polished to the desired finish.

A third type of bearing is the elastomeric. Elastomeric bearings are unique in that, for short structures, they provide for both abnormal rotation and horizontal translation without any moving parts. An anticipated movement is accommodated by deformation of the elastomer within the bearings. For long structures, the basic elastomeric bearing is also supplemented with sliding surfaces similar to those that are incorporated in the other types of compound bearings.
elastomeric bearing, which uses an unconfined but restrained elastomer under moderate pressure, the disk bearing is based on the use of a specially compounded unconfined elastomer under high pressure (up to 3800 psi). Apparently, the characteristics of the Adiprene disk, identified in Figure 9 as the Bonafy Structural Element, are such that it can withstand these high pressures and imposed rotations of more than 2° without apparent distress. We are familiar with Adiprene and its impressive properties, but we have no experience with this material in such a demanding application. However, Grant of Arvid Grant and Associates chose these bearings for his Pasko-Kennewick cable-stayed structure that was recently completed in Washington State. They have also been chosen for many other major structures throughout the world.

As Figure 9 shows, lateral and longitudinal translation is provided for by sliding surfaces similar to those of the other three types of compound bearings.

In view of the availability of these four basic types of compound bearings, we have wondered why so many bridge engineers fail to consider their use when they are choosing bearings for skewed or curved bridges. Probably the traditional use of rockers, rollers, pinned bolster, and other similar structural bearings has conditioned many engineers to their use. The existence of Federal Highway Administration (FHWA) and state standard bearing design drawings that are designed for normal rotations but contain no limitations in this respect has probably supported such conditioning. The simplified design procedure that must be used in the design of multibeam or girder-deck-type structures has probably also contributed to such conditioning. We conceptually isolate a primary member and consider it acting alone, supporting a specific portion of the dead load and the superimposed live load. We size the member, calculate its required camber, verify the live load deflection, calculate the bearing reaction, and, in some instances, compute the amount of member rotation at the bearings. And in all of those calculations, we visualize the behavior of a single member deforming in a vertical plane, not a portion of a well-integrated structural system responding to randomly located vehicular live loads. Finally, the conditioning process appears to be supported by the actual performance of standard single-axis structural bearings. Bearing performance is...
generally considered very good. If a structure is experiencing some distress, seldom is it recognized that the distress may be associated with, or indeed may even be caused by, a type of bearing that is not accommodating the actual superstructure rotations. The standard specifications contain no clue to this potential problem. Article 1.7.32 of the AASHTO specifications (1) requires rotational provisions in bearings of spans "50 feet or greater... for deflection purposes." Since deflections are generally visualized as occurring in a vertical plane, this terminology tends to guide the design engineer to the choice of a bearing with a rotational axis that can be placed normal to the vertical plane.

Article 15.6.1.1 of the Ontario Highway Bridge Design Code (2) is somewhat better. It states, "bearings...shall accommodate the required translation and/or rotation of the structure." At least in this code, the engineer is directed to consider the rotation of other than a "member" when choosing a bearing type and bearing components.

Finally, Article 1.7 of the AASHTO Guide Specifications for Horizontally Curved Highway Bridges (3) is more specific. However, its very specificity only compounds the problem of bearing selection and bearing orientation. Consider a portion of the second paragraph of this article: "Thus, regardless of the direction of displacement allowed at a support, if rotation is permitted about only one axis, that axis should be perpendicular to the centerline of the web at the bearing." This text is probably appropriate for a slightly curved structure with radially placed substructures. It obviously is not intended for sharply curved structures on parallel substructures or for superstructures with severely skewed substructures. The text of this article is unfortunately worded in several respects. First, the choice of bearing or its orientation will not enable the engineer to "permit" the rotation of a bridge about only one axis; second, the use of a bearing with only one axis of rotation will generally be inappropriate; and, finally, if the one axis is placed normal to the web of the member, it will probably not coincide with the axis of rotation of the structure.

As pointed out in the introductory section of this paper, the AASHTO design specification requires special bearing designs to facilitate the deflection of bridge spans of 50 ft or more. But, since the average bridge engineer appears to have been conditioned to contemplate vertical deflections and normal rotations with respect to span length, the effects of skew and curvature on the deflection and rotation of the structures under consideration are generally ignored. This oversight has little consequence for shallow skews and moderate curves, for superstructures with unstaftiffed rolled beam flanges, or for superstructures that have been provided with compound bearings. However, for large skews and sharp curvatures, especially for longer spans, this omission of specification recognition is in large measure responsible for the fact that many bridge design engineers fail to consider the effects of these geometrics on the function, integrity, and durability of their bearing and bridge designs.

Consider the bearings that were used on the curved approaches to the Poplar Street bridge in St. Louis, Illinois. They were standard cast steel pinned rockers and bolster. They failed to function appropriately and had to be replaced with elastomeric bearings after substantial girder distress was discovered (4). In Ohio, the pinned rocker bearings of the 154-ft single-span deck girder bridge carrying I-768 over East Market Street in Akron, Ohio, have failed to function as designed (2). The bridge is skewed 67°, and the abnormal rotation of the superstructure at the bearings has caused the extrusion of the lead bearing pads from beneath the bearings. The pinned portions of the bearings are inoperative since the rotation of the superstructure at the bearings is about an axis that parallels the abutment rather than the rotational axis of the individual bearings.

One of the few reported examples of structure distress related to abnormal rotations is contained in a paper by Karol (5), who writes, "The performance of roller, rocker, or cylinder bearings can only be satisfactory if the 'door hinge' analogy is followed, that is, if all the hinges are in line." With respect to the condition of the bearings shown in Figure 10, he writes, "Although several causes of the described failure were considered (too low strength of mortar pads, incorrect setting of bearings, blocked expansion joints) the type of failure points to the main cause being associated with the geometry of the bridge and bearings and their inability to rotate laterally."

To help focus attention on this subject, Bishara of Ohio State University is currently engaged in a research project funded by the State of Ohio and FHWA to study the abnormal rotations of skewed superstructures. It is hoped that the results of this research will result in an AASHTO specification that requires the recognition of actual superstructure rotations in the choice and design of superstructure bearings. In the interim, the bridge engineer given the responsibility of designing heavily skewed and/or sharply curved structures, especially long-span structures, should choose a bearing design that will facilitate the abnormal rotations of the actual bridge superstructure and function well within reasonable stress limits.

REFERENCES
Skewed Bridges with Integral Abutments

L.F. GREIMANN, A.M. WOLDE-TINSAE, AND P.S. YANG

As background to a theoretical investigation to establish tentative recommendations on maximum safe lengths and skew angles for concrete and steel skewed bridges with integral abutments, a survey of the highway departments of all 50 states was made to obtain information on the design and performance of skewed bridges with integral abutments. The findings of the survey are summarized, including various design criteria and limitations being used; typical pile orientations being used in bridge design by the different states and types of analysis used for thermal expansion and contraction; assumptions being made regarding selected design parameters; specific construction details being used, such as approach slab, backfill, and pile cap; long-term performance of skewed bridges with integral abutments; and previous research on skewed bridges with integral abutments. The variation in design assumptions and length limitations among the various states in their approaches to the use of integral abutments is discussed. The problems associated with thermal-induced abutment movement and the solutions developed by the different states for most of the ill effects of abutment movement are summarized. In view of the lack of theoretical and experimental research in this area, it is hoped that the survey will provide some useful empirical experience and information on the design of skewed bridges with integral abutments.

The routine use of integral abutments to tie bridge superstructures to foundation piling began in the United States about 30 years ago (1-4). Kansas, Missouri, Ohio, and Tennessee were some of the early users. This method of construction has steadily grown more popular. Today, more than half of the state highway agencies have developed design criteria for bridges without expansion joint devices. Most of the states that use integral abutments began by building them on bridges less than 100 ft long. Allowable lengths have been increased based on good performance of successful connection details. Full-scale field testing and sophisticated rational design methods were not commonly used as a basis for increasing allowable lengths. This led to wide variations in criteria for the use of integral abutments from state to state. In 1974, the variation in the criteria between Kansas and Missouri was 200 ft (1). A survey conducted by the University of Missouri in 1972 (5) indicated that allowable lengths for concrete bridges with integral abutments were 500 ft in some states and only 100 ft in others. Continuous steel bridges with integral abutments in the 300–ft range have performed successfully for years in such states as North Dakota, South Dakota, and Tennessee. Continuous structures 500–600 ft long with integral abutments have been constructed in Kansas, California, Colorado, and Tennessee (6). In Iowa, the maximum bridge length for which integral-abutment construction is allowed has been limited to 265 ft (7). The Federal Highway Administration (FHWA) recommends integral abutments for steel bridges less than 600 ft long and for unrestrained bridges, those in which the abutment is free to rotate as with a stub abutment on one row of piles or an abutment hinged at the footing (8).

The primary purpose for building integral abutments is to eliminate bridge deck expansion joints and thus reduce construction and maintenance costs. A sketch of a bridge with integral abutments is shown in Figure 1. Conventional bridge bearing devices often become ineffective and are susceptible to deterioration from roadway runoff through open or leaking deck joints. A cross section of a bridge with stub abutments and deck joints is shown in Figure 2.

In an integral-abutment bridge with flexible piling, the thermal stresses are transferred to the substructure by way of a rigid connection. Various construction details have been developed to accomplish the transfer; one such detail from the state of Iowa is shown in Figure 3. The abutments contain sufficient bulk to be considered a rigid mass. A positive connection to the girder ends is generally provided by vertical and transverse reinforcing steel. This provides for full transfer of temperature variation and live load rotational displacements to the abutment piling.

PREVIOUS RESEARCH

Several of the states that use integral abutments have performed research to develop guidelines for the use of integral abutments. A summary of these research efforts follows.

California

California (7) began informal studies of some of its long structures without expansion joints about 15 years ago. Efforts consisted of identifying appropriate structures and conducting periodic inspections to monitor performance. A total of 27 bridges, varying in length from 269 to 566 ft, were studied; 18 of the bridges had integral abutments, and the others had semi-integral abutments. Although a final report on this study is not yet available, the Office of Structures Design, California Department of Transportation (Caltrans), in