Semi-Integral Bridges: Movements and Forces

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For six decades the state of Ohio has been building continuous concrete slab bridges with flexible integral abutments. For three decades it has been building continuous steel beam and girder bridges with flexible integral abutments. Although this type of construction is now routine in Ohio for most bridges, there were a number of exceptions for such applications. For example, bridges skewed greater than 30 degrees, continuous bridges longer than 300 ft (91.4 m), and bridges with abutments on rigid foundations were routinely provided with movable deck joints at abutments. More recently, however, Ohio has conceived and is developing a semi-integral abutment concept that has enabled it to extend the application range of bridges with jointless decks to most bridges—even to those applications with exceptional characteristics. This semi-integral abutment concept is also now being used to retrofit existing end-jointed continuous bridges. Ohio's concept for semi-integral bridges is described, and a number of the peculiarities that should be recognized and provided for are discussed. Properly designed and constructed, this semi-integral bridge concept should extend the application range of bridges with jointless decks to most applications—even to those not normally associated with integral types of construction.

A semi-integral abutment concept has been developed and adopted by Ohio for the design of some new highway bridges and the retrofitting of single-span and multiple-span continuous bridges. However, to understand and appreciate why this type of design has been adopted by Ohio, while the design details and construction procedures are still evolving, will require a brief acquaintance with Ohio's experience with the development and adoption of both end-jointed continuous bridges and continuous integral bridges.

Beginning in the early 1930s Ohio adopted, for most applications, embankments, stub-type abutments, and continuous construction for single- and multiple-span stream crossings and grade separation structures. This was true for bridges of concrete and steel. For the shortest multiple-span bridges and those with span lengths of less than about 50 ft (15 m), continuous concrete slabs were used. Of particular interest is that these original concrete slab designs and most subsequent similar designs used integral abutments, with each abutment supported by a single row of vertical piles. Consequently, with respect to continuous concrete bridges, Ohio has been building fully continuous integral bridges for over 60 years.

For steel bridges, fully continuous members were first achieved in the early 1930s by the use of riveted splices at piers. At the same time, the use of field welding was being perfected and some of the shortest beam bridges were made continuous by the use of field-welded splices at piers. These initial splices consisted of partial butt-welded beams supplemented by fillet-welded cover plates. By the mid-1940s, all field splices of rolled beam bridges with span lengths of up to 84 ft (25.6 m) were field butt welded at piers to achieve continuity.

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Until 1955, steel girder bridges were of riveted construction. In 1955, the first fully welded girder bridges were constructed. Thereafter, all rolled beam and girder bridges were of fully welded continuous construction. In 1963, high-strength bolts were adopted in place of welding for field splices.

In the early 1960s, the first integral details were developed and adopted for steel structures. Since that time, Ohio has been building continuous integral bridges with main members of steel or reinforced concrete.

In summary, Ohio has been building continuous integral concrete slab bridges for over 60 years and continuous integral steel bridges for over 30 years. These bridges were not exceptions. This type of construction was adopted as standard, and most bridges were constructed this way. The primary goal of Ohio designers was the elimination of bridge deck joints whenever practicable.

However, with respect to the application of end-jointed continuous bridges and integral continuous bridges, there were a number of notable exceptions. Bridge decks longer than 600 ft (183 m) were provided with end joints and an intermediate joint. Bridges skewed greater than 30 degrees, those longer than 300 ft (91.4 m), curved bridges, and those bridges with wall-type abutments or stub-type abutments on rigid foundations were still provided with deck joints at abutments. With these few exceptions, almost all of Ohio's other bridges were constructed as fully continuous integral bridges. The others that did not lend themselves to integral types of construction were provided with movable joints at abutments and, except for the bridges with extreme skews, elastomeric joint seals.

If the bridge deck joint sealing systems available to transportation departments had been of a higher functional quality and durability, further interest in expanding the application range of integral types of design probably would have waned. However, the poor quality of these systems and the constant maintenance that they required compelled bridge designers to seek ways to adapt the attributes of integral construction to those bridges still being provided with movable joints at abutments. Figure 1 shows the basic design configuration that has evolved from that search.

The basic features of the semi-integral abutment concept of Figure 1 include the absence of a bridge deck joint; a superstructure that moves longitudinally on elastomeric bearings almost independent of rigid abutment foundations; abutment members, including piling, that can be designed to operate well within the usual allowable stress limits; superstructure end areas that are reduced, resulting in less passive pressure and pressures that are less eccentric with respect to the neutral axis of the superstructure (i.e., lower axial loads and bending moments because of passive pressure); and abutment and end diaphragm configurations that are simple to design, simple to reinforce, and relatively simple to construct.

Note, however, that this design does not eliminate the need for movable joints. In fact, it doubles their number because, in addition

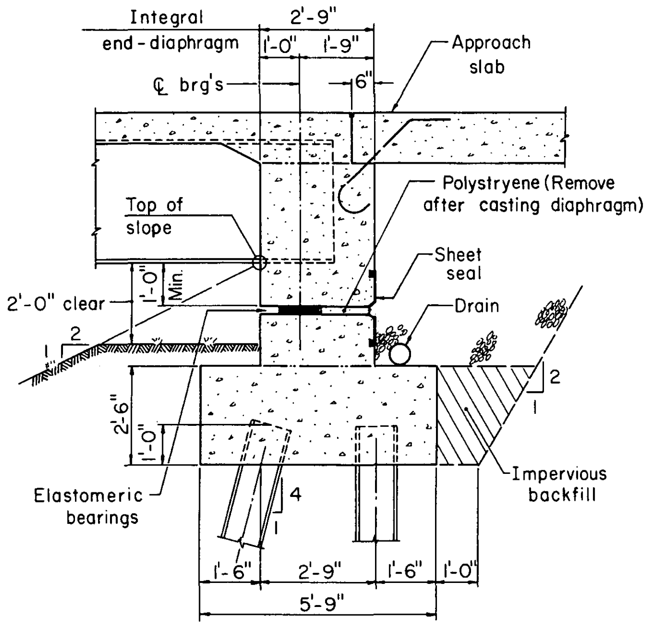

FIGURE 1 Semi-integral abutment concept similar to that of Ohio for single- and multiple-span continuous bridges on rigid supports (spread footings on bedrock, two or more rows of piles, pedestals to bedrock, etc.). This design concept is not recommended for footings on soil or flexible foundations (single row of piles, etc.).

to a movable joint at the level of the bridge seat, another movable joint is needed between the approach slab and approach pavement. However, although it has doubled their number, this design concept has reduced a bridge's vulnerability to substantial maintenance. If these joints fail to function as desired, their failure will not have the damaging consequences that have come to be associated with malfunctioning deck joints and joint sealing systems.

However, a few words of caution. Although it has expanded the application range for bridges without deck joints, the semi-integral design concept described in this paper possesses a number of unusual characteristics that must be recognized and provided for. Otherwise, application of this type of design may result in bridges that do not satisfy all of their functional requirements. A discussion of these characteristics is the primary focus of this paper.

SUPERSTRUCTURE RESTRAINT

Of all the characteristics of the semi-integral bridge concept described in this paper, the longitudinal, lateral, and vertical restraints of the superstructure are the most important. This type of structure should not be considered for design unless its designer is familiar with these characteristics and makes appropriate design provisions to account for them.

Longitudinal Restraint

The details in Figure 1 show that the superstructure that is supported on movable elastomeric bearings moves almost independently of the abutments. That is why this design concept is adaptable to bridges with various types of rigid abutments. For bridges without fixed piers, it receives its longitudinal restraint almost exclusively from sources not normally used in bridge design for this purpose. Longitudinal restraint comes from approach slab-subbase friction, shearing resistance of elastomeric bearings, and the compressive resistance of structure backfill. However, during cold weather, after the superstructure contracts away from the abutments (and away from the backfill), only the shearing resistance of half of the bearings and the frictional resistance of the approach slabs moving relative to the subbase will be immediately available to restrain the superstructure against externally applied longitudinal forces. For this reason, it would be desirable if the granular backfill at abutments could be placed and consolidated during cold weather or at night during hot weather so that the backfill could initially contribute more restraint to supplement that of the approach slabs and bearings for resisting longitudinal forces.

Providing turn-back wingwalls cantilevered from the superstructure in place of straight wingwalls would provide additional longitudinal restraint by mobilizing the resistance of backfill-wingwall friction, or for wingwalls with irregular surfaces, the shearing resistance of the backfill. For longer multiple-span structures, attaching the superstructure to a free-standing pier would be another way of providing additional resistance to longitudinal forces.

Generally, longitudinal resistance provided by approach slabs and bearings should be sufficient to satisfy specification requirements respecting the resistance to longitudinal forces. For moderate earthquake forces, the resistance provided by the consolidated backfill should provide the additional longitudinal restraint needed for moderate-length bridges, even during cold weather. For longer bridges, anchorage to piers can provide the extra longitudinal restraint needed, even for large longitudinal forces.

Lateral Restraint

Figure 2 shows an elevation view of a typical semi-integral abutment. In this view, the superstructure is separated from the abutment by an essentially horizontal movable joint at the bridge seat and vertical movable joints between the superstructure and transverse wingwalls. The horizontal bridge seat joint is shown in Figure 1. The vertical wingwall joints are similar except that only fillers and sealers are provided for unskewed bridges. Consequently, the abutments of this semi-integral bridge concept function essentially as longitudinal guides for the superstructure.

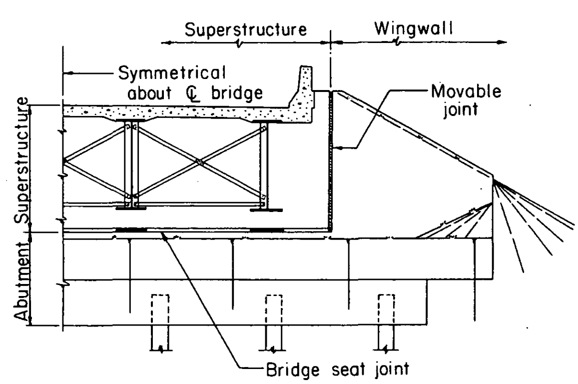

FIGURE 2 Semi-integral abutment with transverse wingwalls.

Vertically, the superstructure is supported by elastomeric bearings in the bridge seat joint. Laterally, the superstructure is supported by the interaction of the superstructure, approach slab, and backfill; to some extent by the compressive resistance of the filler in the lateral joints; and to some extent by the shearing resistance of the elastomeric bearings in the bridge seat joint. For applications in which substantial lateral resistance is necessary [such as skewed structures (described later) or structures exposed to stream flow pressure or earthquake forces], guide bearings are necessary and their use in the wingwall joints or elsewhere between beams is recommended.

For superelevated bridges where bridge seat joints (Figure 2) are sloped parallel to the deck surface and where elastomeric bearings are also sloped, lateral guide bearings are needed to resist the lateral component of the superstructure reaction. Otherwise, support bearings should be set on level bridge seat surfaces. When considering most of the application situations that have to be contended with in the design of semi-integral bridges with characteristics similar to the concept described in this paper, the routine use of guide bearings should be considered as standard for most, if not all, such applications.

Rotational Restraint

On the basis of the analysis given below, superstructures of some skewed semi-integral bridges will, unless restrained by guide bearings, tend to rotate in a horizontal plane. This tendency will be greater for bridges with greater skews. Horizontal rotation will initiate sooner for longer bridges. The characteristics of this behavior are described as follows.

As superstructures of semi-integral bridges expand in response to rising ambient temperatures, superstructure elongation (ΔL) will be resisted by backfill being compressed at abutments (Figure 3). Force is required to compress backfill, and this same force will restrain superstructure elongation by inducing compressive stresses in the superstructure. When considering the relative compressibility of backfill and a reinforced concrete superstructure—even thoroughly consolidated granular backfill—it should be clear that almost all of the expected superstructure elongation will occur as compression of backfill. Only a slight amount of compression will occur in the superstructure, as evidenced by a slight reduction in the amount of superstructure elongation that would have been evident if the elongation had been unresisted. These compressive stresses are shown summarized in Figure 4 as the resultant longitudinal superstructure compressive force $P_p \sec \theta$. The centralized location of this resultant force is based on the assumption that structure backfill is homogeneous and that it would be uniformly compressed throughout the width of the superstructure. The components of this resultant force against the backfill are the normal force as a result of passive pressure P_p and the lateral force $P_p \sec \theta \sin \theta$, or in simpler terms, $P_p \tan \theta$. If lateral guide bearings for the superstructure are not provided and the force $P_p \tan \theta$ is not adequately resisted at the structural backfill interface [by friction of backfill on superstructure end-diaphragms ($P_p \tan \delta$) or by the shearing resistance of backfill ($P_p \tan \phi$)], differential movement at the structural backfill interface will commence. When considering the shearing resistance of backfill ($P_p \tan \phi$) or the frictional resistance of backfill on smooth concrete surfaces ($P_p \tan \delta$), usually the latter force will be found to be the smaller of the two, and it will govern behavior at the structural backfill interface.

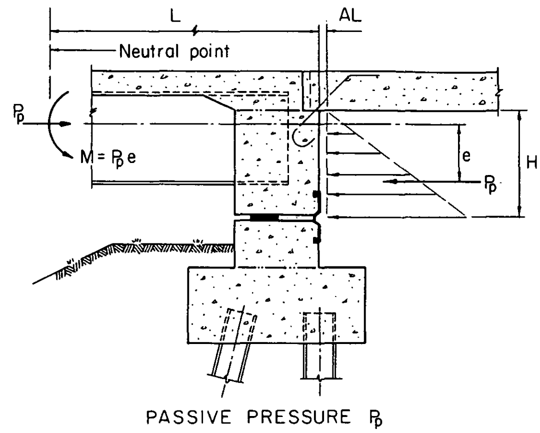

FIGURE 3 Passive pressure development for semi-integral bridges.

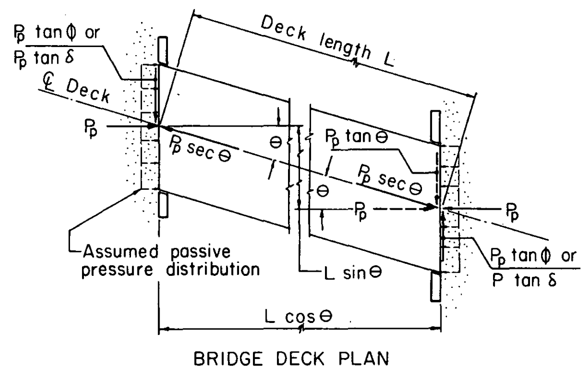

FIGURE 4 Elongation and rotation of semi-integral bridge superstructures before rotation.

Because the external forces act on both ends of the superstructure of a semi-integral bridge (Figure 4), the eccentric longitudinal force component P_p will tend to rotate the superstructure toward the acute corners of the structure or, for the skew shown in Figure 4, in a clockwise direction. The lateral force components on the other hand ($P_p \tan \phi$ or $P_p \tan \delta$) will tend to resist this rotation.

Using the shearing resistance of an idealized granular backfill and the frictional resistance of backfill on the backfill-structure interface surfaces, it can be shown that superstructures of semi-integral bridges skewed greater than about 15 degrees will be unstable unless they are provided with guide bearings at both abutments.

With respect to Figure 4, and the symbols tabulated below, that statement can be justified by a short series of computations as follows:

L = bridge deck length,

θ = bridge skew angle,

P_p = total passive pressure,

FS = factor of safety,

ϕ = angle of internal friction of backfill, and

δ = angle of structural backfill interface friction.

For the superstructure of a skewed bridge to be stable, the force couple tending to resist rotation ($P_p \tan \delta L \cos \theta$) must be equal to or greater than the force couple tending to cause rotation ($P_p L \sin \theta$) or

$$P_p L \sin \theta \leq P_p \tan \delta L \cos \theta \quad (1)$$

Providing a factor of safety against rotation

$$P_p L \sin \theta \leq P_p \tan \delta L \cos \theta / FS \quad (2)$$

Because the weight of attached approach slabs and slab-subbase friction will tend to resist movement, a safety factor of 1.5 seems sufficient for this situation. Inserting this factor in Equation 2 and simplifying yields the following:

$$\sin \theta \leq \tan \delta \cos \theta / 1.5$$
$$\tan \theta \leq \tan \delta / 1.5$$
$$\theta \leq \arctan (\tan \delta / 1.5) \quad (3)$$

Assuming that the angle of friction at the structural backfill interface (δ) is 22 degrees, as discussed in a previous work (*1*, p. 7.2–63) about granular backfill on a smooth concrete surface, Equation 3 suggests that the bridge skew angle θ must be equal to or less than 15 degrees to be stable. For greater skews, it is likely that rotation will be initiated unless guide bearings are provided at both abutments to resist the forces inducing such movement.

Other observations can be made with respect to Equations 1 and 3. Although Equation 1 indicates that some level of passive pressure must be generated to cause rotation, Equation 3 indicates that the skew angle at which rotation will be initiated is independent of both passive pressure and bridge length and directly related to structural backfill interface friction.

What would be the result of the restrained elongation of the superstructure and differential movement at the structural backfill interface? Figure 5 and the speculative analysis described below are offered as an answer for this question.

As before, it is assumed that sliding friction ($P_p \tan \delta$) will govern the behavior at the structural backfill interface. Because the force caused by sliding friction would not be sufficient to resist the lateral force component $P_p \tan \theta$ for bridges with large skews, sliding (rotation) of the superstructure toward the acute corners of the structure will be induced.

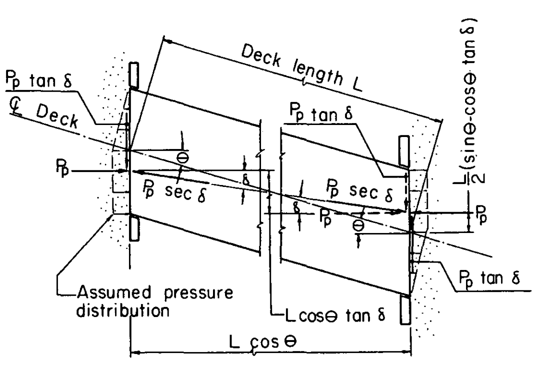

FIGURE 5 Elongation and rotation of semi-integral bridge superstructures after rotation.

Rotation of the flat-ended superstructure will alter the earth pressure distribution within the backfill. As rotation commences, the obtuse corners of the superstructure will move into and compress the backfill while the acute corners will move away from and allow the backfill to expand. The amount of movement into and away from the backfill may appear insignificant when compared with the original movement into the backfill (ΔL) caused by thermal elongation of the superstructure. However, slight movements of soil-retaining structures can have significant effects on soil pressures. Earth pressure research documented previously (*1*, p. 7.2–60; *2*) indicates that a fair amount of structural movement into the backfill (about 5 percent of its height) is needed to achieve full or ultimate passive pressure. On the other hand, only a very small amount of movement away from the backfill (about 0.1 percent of its height) will result in active pressures. On the basis of these relationships of movements to pressure, it is assumed that backfill compression caused by the rotational movement of the obtuse corners into the backfill would only slightly increase passive pressure because this movement is so small relative to the initial superstructure elongation, ΔL. However, at the acute corners, the slight rotational movement of the superstructure away from the backfill probably will result in a drop of soil pressure from the initial passive pressure caused by ΔL to active pressure.

The slight rise in soil pressure at the obtuse corners and the significant drop in pressure at the acute corners of the structure will alter the pressure distributions within the backfill throughout the width of the structure. This change in pressure distribution will be accompanied by a lateral shift of the pressure resultant, identified as P_p in Figure 5 (the designation P_p is actually a misnomer because this pressure resultant is now intended to represent a summation of a whole spectrum of pressures from active pressure near the acute corners through various levels of passive pressure to a maximum passive pressure at the obtuse corners). This shift of the pressure resultant will decrease the lateral distance between the resultants and consequently the moment couple-inducing rotation will diminish.

Figure 4*b* illustrates the condition in which the force components tending to induce sliding ($P_p \tan \theta$) have diminished until they equal the forces caused by frictional resistance ($P_p \tan \delta$). Similarly, the moment couple tending to induce movement ($P_p L \sin \theta$) has diminished to $(P_p)(L \cos \theta \tan \delta)$ and is in equilibrium with the force couple resisting rotation $(P_p \tan \delta)(L \cos \theta)$.

It is presumed that the movements described were the result of a single increase in the ambient temperature. Subsequently, a temperature drop would be accompanied by a shortening of the superstructure or a movement of the end of the structure away from the backfill. In response to this movement, the backfill would expand and soil pressure would drop to active pressure or less, depending on the composition and state of consolidation of the backfill.

Depending on the amount of backfill reconsolidation that would occur while the superstructure was withdrawn, it is presumed that a similar but more modest superstructure rotation would accompany each cycle of superstructure elongation. Over time, the significant number of thermal cycles that would take place suggests that the superstructures of semi-integral bridges should continue to experience incremental and accumulative rotation until or unless such rotation is terminated by the restraint provided by some other stable part of the structure.

The motions described will be prevented or moderated as a result of approach slab-subbase friction and the shearing resistance of elastomeric support bearings and by the compressive resistance of fillers used in the movable joints between the superstructure and wingwalls. Depending on the characteristics of the bridge seat joint seal, even this device may offer some resistance to horizontal rotation of the superstructure. When considering these supplemental resistance elements, it seems apparent that for some structures the most susceptible period for rotational movement would occur during construction when the superstructure would be exposed to "at-rest" placement pressures before approach slabs have been placed.

In an Ohio project planned for early construction, there is one site where twin semi-integral bridges with skews of 45 degrees are to be constructed. They are to be provided with removable guide bearings so that after their completion the guide bearings could be removed from one of the bridges. This would provide the opportunity to observe the behavior of essentially similar bridges exposed to the same environmental effects with one bridge with guide bearings and the other bridge without. The construction of these bridges and their early performance under service conditions should provide some of the experience needed to determine with greater certainty the effects of skew on the movement of semi-integral bridge superstructures.

In addition, more formal semi-integral bridge research is being planned by the Ohio Department of Transportation—research that is intended to provide some of the factual background on which the design and construction of future semi-integral bridges can be based.

Earth pressure measurements at the Forks Bridge of Forks, Maine, appear to provide some support for the analysis described. The Forks Bridge is a skewed long span steel rigid frame structure. According to the report (*3*, p. 2)

> Earth pressures were measured at 8 pressure cells on each abutment with measurements on both sides of the abutment centerline and at different elevations. . . . The effect of skew was noticeable during the summer, although the average increase for all cells at El. 583 was 1,200 psf, the increase at the obtuse sides was 1,800 psf, while the increase at the acute sides was 620 psf. . . .

Since pressure measurements at this structure are to continue, the final report for this project should provide valuable background for subsequent pressure research on semi-integral bridges.

The magnitude of guide-bearing reactions is another indication of the potential for superstructure rotation. Because most of the thermal movement of a superstructure will be parallel to the longitudinal axis of a bridge, guide bearings should be placed parallel to this axis. Then on the basis of the lateral force components shown in Figure 4, the guide-bearing reaction, which would be normal to this axis, is given by $P_p \tan \theta \cos \theta$, or in a simpler form, $P_p \sin \theta$. On the basis of this relationship, the required capacity of guide bearings for a structure skewed 30 degrees is equal to $0.5P_p$, or one-half of the total passive pressure. For a 45-degree skew, the required capacity equals more than 70 percent of the total passive pressure. Consequently it is clearly evident that neither the frictional resistance ($P_p \tan \delta$) nor the shearing resistance ($P_p \tan \phi$) of the backfill can resist forces of this magnitude. Consequently, guide bearings should be provided for structures with large skews if a stable superstructure and a fully functional bridge are to be provided.

Vertical Restraint

Because of their jointless construction, many types of integral bridges are buoyant when they become submerged. This is true for many I-beam bridges and some spread-box beam bridges.

The weight of diaphragms and abutments provides some resistance to uplift. But generally, some positive design provisions must be made to ensure that integral bridges have a reasonable factor of safety against flotation. I-beam webs can be pierced near top flanges by holes 3 in. (76 mm) in diameter spaced uniformly throughout the beam length; the space between spread boxes can also be vented by placing horizontal vent ducts 3 in. (76 mm) minimum diameter near the top flange of all beams. These ducts should pass completely through the beams from one web to the other, and they should be placed in concrete diaphragms or be completely encased in concrete to prevent floodwaters from entering beam voids; counterweights could be used but their weight must be taken into account during beam design. Uplift restraints could be provided at pier bearings, or some piers can be integrally constructed with the superstructure to add sufficient uplift restraint to counteract buoyancy.

In place of vent holes, added weight, uplift restraints, or integral pier construction, the use of the most buoyant structures should be restricted to those bridge sites where the highest floodwater levels are well below the superstructure.

DESIGN ASPECTS

Movable Joints

As mentioned earlier, the semi-integral bridge with its attached approach slabs has eliminated bridge deck end joints. In their place, it has incorporated two other joint types: a movable joint at the level of the bridge bearings and one at the pavement end of the approach slab. Although it doubles their number, the design has minimized their significance. Less-than-desirable performance for either of these joints will not have the significantly adverse consequences that have come to be expected with the failure of bridge deck joints. The bridge seat joint and cycle control joint are the two joints that have been provided to accommodate the movement of semi-integral bridges. In addition, one must mention that rigid approach pavements also must be provided with effective pressure relief joints to guard semi-integral bridges from uncontrollable approach pavement growth.

Bridge Seat Joints

In the design shown in Figure 1, the troublesome bridge deck joint has been eliminated. However, in its place, a movable joint has been introduced at the level of the bridge seat. Corrosion-resistant elastomeric bearings are provided so that the superstructure can move longitudinally almost independent of rigid abutments.

The movable bridge seat joint must be provided with a durable elastomeric seal because it is buried in the backfill and consequently is not accessible for repair or replacement. Otherwise its most important characteristic is its ability to prevent backfill from being forced into the joint by compressed backfill. It would be desirable but not absolutely necessary for the seal to be watertight. It must also permit unrestrained differential movement between the abutment and superstructure, even for bridges with large skews, and it must retain these characteristics for many years without the need for repair or replacement.

Although the bridge seat joint seal is an important aspect of the semi-integral bridge design, Ohio has yet to adopt a design that appears to fulfill all necessary functional and durability characteristics. A number of trial designs have been developed and used. Initially, standard compression seals were used. Then it became apparent that a reinforced elastomeric sheet-type seal was more functionally suitable for square and skewed applications. The sheet seal now being used is nylon reinforced neoprene $^3/_{32}$ in. (2.4 mm) thick. It is attached to the bridge by various means, including elastomeric anchor rods in formed recesses, steel clamp bars with expansion anchors, washers and masonry nails, or bonding adhesives. It remains to be seen which one or more of these attachment methods will be adopted and perfected by Ohio for this critical joint.

Cycle Control Joints

Semi-integral bridges with attached approach slabs lengthen and shorten in response to temperature and moisture changes. Consequently, for such structures, the boundary between approach slabs and approach pavement should be provided with a cycle control joint to facilitate such movement. Otherwise, longitudinal cycling of both structure and approach slabs can damage both flexible and rigid approach pavements.

At present, standard pavement expansion joints with compressive fillers are being provided for shorter semi-integral bridges. Longer bridges are being provided with pavement pressure relief joints (wide joints filled with asphalt concrete).

Because of the restrained growth of approach pavement it is imperative that semi-integral bridges built adjacent to rigid pavement also be protected from pressures. Effective pressure relief joints should be provided for all semi-integral bridges—even the shortest bridges. Consequently, for bridges adjacent to rigid approach pavement, two types of pavement joints are required: one to facilitate the cyclic movement of the bridge and the other to protect the structure and cycle control joints from the effects of pavement growth. Designs by four transportation departments were illustrated elsewhere (*4*); as noted, all designs in use have their limitations.

For longer integral bridges, Ohio is using wide pressure relief joints to serve both purposes. Because integral bridges and semi-integral bridges are such new conceptions, much additional development is needed if the approach pavement joints adjacent to such structures are to provide all of the necessary attributes that these joints must have to satisfy structural requirements without continuous maintenance.

Backfill

Backfill for semi-integral bridges should not be considered a nuisance that has to be contended with, as is the case with the fully integral bridge on flexible abutments. Instead, backfill should be recognized as an integral and important part of the semi-integral bridge concept. As in the case of a retaining wall supported by spread footings on subsoil, when properly designed the wall will interact compositely with the subsoil and be adequately supported by the soil vertically and laterally. Similarly, the superstructure and backfill of semi-integral bridges form a partially composite interactive structure. In this context, the backfill performs multiple functions. Although rigid abutments provide vertical and lateral support for the superstructure, the backfill supplements this support by providing vertical support for approach slabs and both longitudinal and lateral support for the superstructure. The ultimate success or failure of the semi-integral bridge concept will depend to a great extent on methods and procedures that are developed by the bridge engineering profession to enhance the interaction between the superstructure and backfill. Because backfill is such an integral part of a semi-integral bridge concept, every effort should be made to ensure that it is properly selected, constructed, and maintained.

Backfill should be selected and designed to have characteristics suitable for superstructure-backfill interaction: it should be of a composition that protects it from erosion and it should be protected from above by full-roadway width approach slabs. For bridges with confined drainage (raised curbs, barriers, parapets, etc.) approach slabs must be provided with curbs with a height of at least 6 in. or more to confine roadway drainage and conduct it along bridge approaches and away from the backfill. Approach roadway curb inlets should be considered and provided if necessary to ensure effective drainage control. An effective subdrainage system should also be provided in the backfill above impervious embankments to ensure that the retention of subsurface water is minimized.

Provisions also should be made to intercept subsurface approach roadway drainage and discharge it away from the abutment backfill. Granular subbases should be provided with efficient lateral drains to discharge subbase drainage laterally to embankment side slopes. Roadway underdrains must be terminated beyond the bridge approach slabs and provided with lateral drains to embankment side slopes. Otherwise, underdrain accumulations should be conducted in closed conduits longitudinally through the backfill and abutments.

Finally, bridge maintenance engineers should become familiar with semi-integral bridge characteristics so that they can properly appreciate the importance of backfill superstructure interaction and provide the corrective maintenance that such a structure must have if they are to provide the service life that their design anticipated.

CONSTRUCTION ASPECTS

Unlike their jointed bridge counterparts, the design peculiarities of the semi-integral bridge concept have created concrete placement and curing problems that are unique to this type of design. These problems have to do with the forming for and the placement and curing of second- or subsequent-stage concrete elements of the bridge while attempting to bond them to the first-stage elements that will be moving in response to ambient temperature changes.

End Diaphragms

The integral end diaphragm indicated in Figure 1 is part of the superstructure of semi-integral bridges; consequently it will move both longitudinally and rotationally with the superstructure. However it is cast in forms that are usually fastened to and supported by rigid abutments. In fact, the abutment bridge seat covered by fillers and elastomeric bearings usually serves as a rigid bottom form for the end diaphragm. So while ambient temperature changes during and shortly after end-diaphragm concrete placement, superstructure stringers either will be elongating or shortening in response to those changes, resulting in differential movement between stringers and the rigidly supported end-diaphragm forms. If these movements are appreciable, and occasionally they can be, they can damage freshly placed end-diaphragm concrete. This problem is more acute for the more thermally responsive steel stringers. It is magnified in longer bridges, and it can be compounded in geographical locations where rapid and significant ambient temperature changes can occur during end-diaphragm concrete placement and setting.

Generally, it is not practicable to restrict concrete placement to those days of the year with the smallest temperature range and consequently to those periods with the smallest potential for large superstructure movements. But for the shorter, more usual moderate-length semi-integral bridges, it is practicable to limit concrete placement to days when large and rapid temperature changes are not expected and to periods during the day when superstructure movement is smallest, generally shortly after the ambient temperature approaches, reaches, and departs from the day's peak temperature. A plan note to provide such control and protection for freshly placed end-diaphragm concrete can be phrased somewhat as follows:

> Concrete for end diaphragms shall be placed during days when sudden temperature changes are unlikely and be completed at least 4 hr before the concrete placement day's peak ambient temperature.

For longer structures where such placement controls may not be sufficient to protect fresh concrete, end diaphragms can be placed in two separate placements. The first placement, up to but slightly below the superstructure stringers, can be placed without concern for superstructure movement. Then, after an appropriate cure time, the stringers and end-diaphragm forms can be attached to and supported by this first placement. Subsequently, this first placement, the end-diaphragm forms, and stringers will move in unison so that the remainder of the end-diaphragm concrete can be placed at any convenient time without regard for ambient temperature changes.

Approach Slabs

Construction of approach slabs is similar to that of the end diaphragms in that slab concrete must be placed on a rigid bottom form (the subbase) while the leading edge of the slab is connected to a moving superstructure. Consequently, similar placement controls can be used for placement of approach slab concrete for the moderate-length semi-integral bridges. A plan note similar to the following can be used:

> Approach slab concrete shall be placed toward the superstructure during days when sudden temperature changes are unlikely and be completed at least 4 hr before the concrete placement day's peak ambient temperature.

To protect approach slab-superstructure connections, an attempt should be made to reduce the force necessary to move the slabs. This can be accomplished by requiring a smooth subbase surface to serve as a bottom form for the approach slab.

For longer semi-integral bridges, it may be necessary to place approach slabs in two placements. The first placement can extend from the far end of the slab to a construction joint located within 3 ft (0.9 m) of the superstructure. Then after this first segment has been placed and cured, it can be connected to the superstructure with several longitudinal tie bars with mechanical connectors, and the remaining portion of the slab can then be placed using a note similar to the one mentioned earlier to protect the freshly placed concrete. If there is superstructure movement, the mechanically connected tie bars should be sufficient to pull the approach slab without stressing the fresh concrete. This will relieve the second-stage concrete placement and connection reinforcement from movement-induced stresses.

Backfill

Because superstructures of semi-integral bridges are restrained in place longitudinally by backfill at abutments and to some extent by the shearing resistance of elastomeric bearings, placement of this backfill needs to be controlled to avoid unbalancing backfill pressures and shifting the superstructure. Therefore, a backfill procedure is necessary to ensure that backfill is placed simultaneously at both abutments.

As mentioned earlier, it would be advantageous to place and consolidate backfill during low-temperature periods to improve confinement of the superstructure. During hot weather, placing backfill at night should be considered.

SUMMARY

The first bridge with semi-integral characteristics similar to those that have been described in this paper was constructed in 1978. This bridge services Ohio's Route 555 and spans the Muskingum River at Zanesville, Ohio. It is an unskewed three-span girder structure 540-ft (164.6-m) long. It uses approach slabs and turn-back wingwalls to engage or embrace the backfill. Since then a number of similar shorter structures have been constructed. The concept has been used most often to retrofit existing end-jointed bridges. A number of other semi-integral bridges are being planned for both new and retrofit applications, some with significant skews. As of this writing, skewed semi-integral bridges with guide bearings have not yet been constructed. The response of local maintenance engineers to these bridges has been good. It is primarily through their continual urging that many of these bridges were built.

For new structures, the main emphasis of the Ohio Department of Transportation is on the construction of fully integral bridges with flexible abutments. However, for those applications where rigid abutments are necessary, the semi-integral bridge concept is now being adapted and used with increasing regularity. The actual performance of these bridges throughout the next several years will influence its further development and ultimately its suitability for further applications.

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