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Full-Depth Modular Precast, Prestressed Bridge Decks

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Precast modular deck construction has been used successfully since 1967. It is still used in a modest but effective fashion, as exemplified by several installations. The details used to connect the panels to the supporting structures, provide composite action, permit vertical adjustment, and develop shear resistance between adjacent panels are critical. A deck protection system to prevent chemical penetration should be incorporated in the design. Construction costs were estimated for four design examples and compared with costs of conventional cast-in-place construction. In each case, the modular system proved to be more economical. Benefits of precast, prestressed decks include greater structural efficiency, reduction in the number of support elements required, less construction time, reduction in interruption to traffic for replacement decks, potential for increasing capacity of existing structures through reduction in dead load, and better quality control.

Current practice in the construction of concrete bridge decks supported by a structural framing system uses cast-in-place reinforced concrete. This is predominantly used for bridge deck replacement and for new bridge construction.

Some of the problems generated by this construction technique have been overcome through the development of new materials and improved procedures, such as concrete overlays, epoxy-coated rebars, and stay-in-place forms. However, others have not. These include the very time-consuming and labor-intensive procedures inherent in the use of cast-in-place concrete and the inefficient use of the materials that occurs when the full advantage of the compressive strength of concrete is not exploited.

One alternative to conventional cast-in-place bridge deck construction that could be more cost efficient is full-depth, precast, prestressed bridge deck panels. This system is equally adaptable to new construction and to deck replacement projects.

STATE OF THE ART

In 1967, Purdue University, in cooperation with the Indiana State Highway Commission, initiated research to establish design criteria for a full-depth, precast, prestressed deck system (1). This study was followed by an implementation phase consisting of the replacement of decks on two structures: IN-37 over Bean Blossom Creek and IN-140 over Big Blue River. This work was completed in 1970 (2). Subsequently, the deck on a third structure in Indiana (Tonkel Road over Cedar Creek) was replaced with precast elements.

Deck panels for these bridges were cast full width in sections approximately 1.2 m (4 ft) wide. The panels were prestressed in the transverse direction of the bridge and were posttensioned in the longitudinal direction after erection. Composite

action between the deck and the supporting members was not developed.

Slabs for the IN-37 bridge were match-cast with a tongue-and-groove joint assembly. Spring clips bolted to concrete inserts were used to anchor the panels to the top flange of the system. Vertical adjustments at the stringer bearing areas were achieved by welding shim plates of variable thickness to the top flange of the structure.

The replacement deck for the IN-140 bridge was constructed in a similar fashion except that the slab had a variable thickness to obtain the desired roadway crown. This was necessary since the steel framing was constructed in a level plane.

The Tonkel Road replacement deck was attached to the beams by using a "Z-clip" in lieu of the spring clip. A fiberglass expansion joint material was placed between the slab and the stringer flange. The adjacent panels were connected to each other on the top surface by a plate welded to inserts cast in the panels. An asphalt wearing surface was placed with variable thickness to provide the required roadway crown.

These structures are performing reasonably well after 12 years of service. Minor problems have developed with concrete spalling at the joints between panels and in connections used to attach the panels to the supporting members.

Since this pioneering effort, a number of agencies have designed replacement decks with precast panels. The New York Thruway has probably constructed more square footage of precast deck than any other agency. These designs did not call for prestressing but rather used mild reinforcing. This was a policy decision based primarily on concern about corrosion of the steel due to the heavy application of salts for snow and ice control.

Precast slabs used by the Thruway Authority were cast with block-outs over the supporting stringers. The slabs were placed on a thick epoxy bed applied to the stringer flange to provide uniform bearing. Studs were welded to the stringer flange through the block-outs, and the void was filled with additional epoxy mortar. This provided a positive connection between the slab and the stringer and also developed some horizontal shear capacity, although the Thruway does not rely on composite action. Keyed transverse joints between adjacent slabs were filled with epoxy. Longitudinal posttensioning was not used. A waterproof membrane and asphalt wearing surface were placed over the completed deck.

In 1979, the Pennsylvania Turnpike Authority replaced the deck on the Clark Summit Bridge near Scranton, Pennsylvania, using precast mild rein-

forced deck panels. Panels were cast with haunches over the girders to allow for variable thickness of cover plates. Neoprene strips were glued to the supporting members as a side form for the placement of epoxy grout between the slabs and the flange. Posttensioning ducts were provided in the longitudinal direction. Threaded rods with sleeve nuts were inserted and used to pull adjacent slabs together snugly. A keyed joint was then filled with a non-shrink grout.

The deck on the High Street Overhead Bridge near Oakland, California, was also replaced by using precast panels. A unique feature of this project was the use of two-headed bolts placed through threaded inserts in the slab and located over the supporting stringers. These bolts were used to adjust the panels to the desired elevation. Wooden side forms were attached to the stringer flange, and a fast-setting concrete mortar was placed between the slab and the stringer.

Railroads have also used precast elements in deck replacement programs. The Atchison, Topeka and Santa Fe Railway Company has developed precast, prestressed deck slab construction standards for use in replacement of timber decks (3). The concept differs from those already discussed in that there are no mechanical attachments between the slabs and the supporting structure. Bolts with spring clips are used at two points on each slab in place while curing of the mortar is completed.

After removal of the timber deck, the girder flanges are sandblasted. Plywood forms are attached to the edges of the flange, and a pourable epoxy bedding material is placed. Slabs are then erected while the mortar is still plastic. The spring clips are used to hold the slab in place while curing of the mortar is completed.

The railroad reports that the epoxy mortar between the slab and the beam develops sufficient shear capacity to ensure composite action between girder and slab (3). This provided sufficient increase in the live-load capacity of the structure to overcome the additional dead load resulting from the concrete deck. In most instances, it also eliminated the need to make structural repairs to the supporting girders to increase capacity.

The primary concern in constructing the replacement deck for each of the examples cited was to minimize the interruption of traffic on the facility. Spin-off benefits included increased capacity, improved quality control in the concrete deck, and economy. Minor problems that developed included details to compensate for the irregular surface of the top girder flange connection of the slab to the girder and joints. Overall, each of these projects was judged to be highly successful by the responsible agency.

DESIGN CONSIDERATIONS

The American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges (4) provide load distribution formulas, procedures for developing maximum design moments, and the magnitude of wheel loads to consider in the design of concrete bridge decks. These are applicable to either cast-in-place concrete decks or precast decks. These specifications permit the use of more sophisticated procedures for the analysis of forces. This should be considered in those instances where very wide spacing of beams is used or where savings could be realized by a more precise analysis.

The current AASHTO specifications permit tension in the concrete under service loads of $6\sqrt{f'_c}$. This is reduced by 50 percent in corrosive environ-

ments. For bridge decks, tension should be allowed only where significant economy can be achieved and with due consideration for the possibility of harmful chemicals penetrating the slab through resulting tension cracks. Whenever tension is permitted, mild reinforcement should be provided.

Composite action between the framing system and the precast deck can be used to provide an efficient design. Careful attention to details is required to provide for the horizontal shear at the interface.

The design of the slab cantilever must include provision for proper development length for moment resistance from the prestress force. Mild reinforcement should be included when the length available for the stress transfer from the prestressing strand is insufficient.

CONSTRUCTION DETAILS

To obtain the maximum utility from the precast concept, it is important to develop details that will provide an efficient procedure for construction, provide the flexibility necessary to accommodate variable geometrics, and permit the structure to operate in accordance with the design assumptions. Critical details include joints, slab-support interface, geometrics, strand and duct placement, and protection for the deck surface.

Joints

Several types of joints have been used between adjacent precast slab elements. These include keyed or tongue-and-groove joints, butt joints, and grouted keyway joints.

The butt joint is simple to cast and erect but has the disadvantage of providing no inherent shear transfer capacity. This can be developed through frictional resistance from longitudinal posttensioning.

The keyed joint required careful fabrication and minimum fabrication tolerance. When match-casting techniques are used, this can provide a superior end product as well as develop adequate shear transfer. Several configurations of this joint are shown in Figure 1.

The grouted joint, shown in Figure 2, has been effectively used by the New York Thruway Authority and the Pennsylvania Turnpike Authority. It permits greater construction tolerance than the other joints and, when properly grouted, provides the desired shear transfer.

Bridge decks for structures that carry more than two traffic lanes will usually require multiple-width slabs. The longitudinal joint between these sections can be placed over a supporting stringer or somewhere between supporting stringers. In the former case, a lapped joint such as that shown in Figure 3 can be provided. This should not be considered to develop continuity over the support. When continuity is required, a cast-in-place concrete section should be used, properly reinforced with mild reinforcing steel. Sufficient reinforcing should extend from the precast units to provide the required development length.

Where the joint falls between supports, an open joint can be provided. If drainage runoff is a potential problem, the joint should be sealed. Details should include edge-reinforcing protection to minimize maintenance.

Framing Connections

Details must be developed to provide a positive attachment between the precast slab elements and the support frame. Where composite action is required,

Figure 1. Keyed joints.

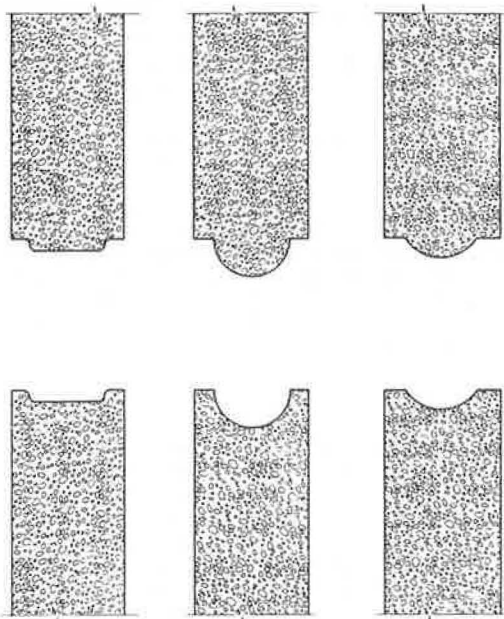
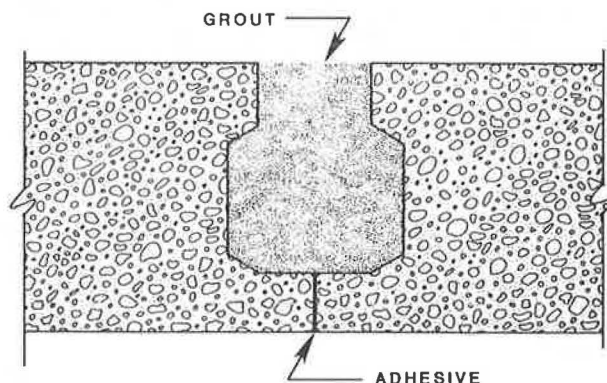


Figure 2. Grouted joint.



the construction must be adequate to transfer horizontal shear and provide lateral stability to the girder flange. Several systems have been developed, including shear studs, bolt clips, and bolts, adaptable to either steel framing or precast concrete framing.

Bolt clips, shown in Figure 4, were used on some of the earlier installations for connecting the slab to steel stringers but have not proved to be satisfactory except for providing a temporary connection during construction. This detail was used on the Tonkel Road Bridge in Indiana.

A more durable detail incorporates high-strength bolts placed in recessed holes in the slab and connected to the top flange of the steel stringer. The bolt head is on the underside of the flange, and the nuts and washer are placed in the recessed hole in the concrete deck. A similar system used by the New York Thruway, which included a cast steel bushing, is shown in Figure 5.

The connection can also be made with shear studs attached to the supporting steel girder through preformed openings in the deck slab. The void is then filled with a nonshrink or epoxy mortar. This detail provides a very simplistic construction procedure and does not call for extremely tight con-

Figure 3. Lap joint over stringer.

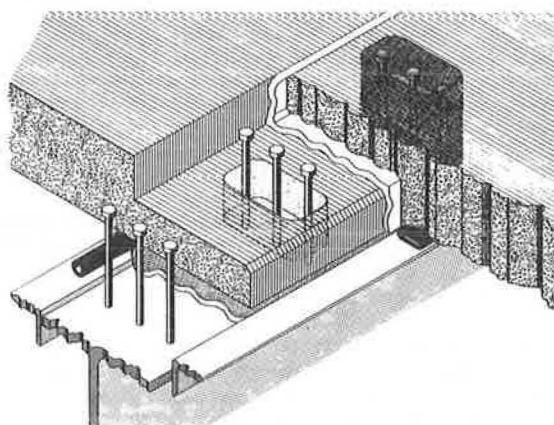
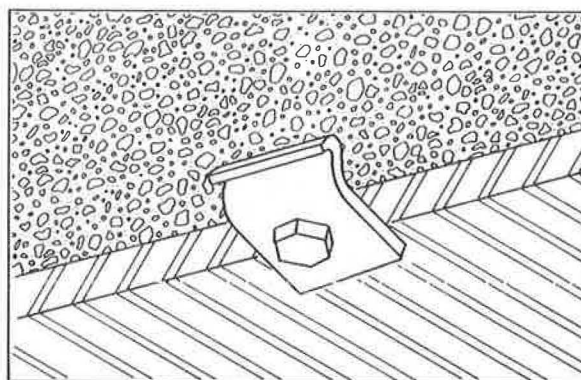


Figure 4. Typical bolt clip.



struction tolerances. This procedure, like the others discussed, is adaptable to either new construction or replacement decks on steel framing.

For precast concrete support framing, different details are required. Figure 6 shows an example of a detail for precast girders. A plate is anchored to the girder during prefabrication and later used to attach shear studs. Slotted holes in the plate provide additional horizontal shear capacity. Studs are attached to the girder through preformed openings in the deck unit. These cavities are later filled with nonshrink grout or a suitable epoxy mortar.

A similar detail can be developed for replacement decks. After removal of the existing slab, stirrup shear connector bars are cut off several inches above the concrete. A slotted plate is placed over these bars. The bars are then bent over and welded to the plate as shown in Figure 7. After placement of the precast unit, shear studs are welded to the plate through preformed holes. Again, cavities are filled with grout.

A high-strength bolt connection similar to that already described for steel beam supports can be used for new construction. The bolts are placed in inserts cast in the concrete beam.

An alternative to this is grouting bolts in preformed holes cast in the concrete beam. The precast deck units are then placed, and the tie downs are completed as shown in Figure 8.

Geometrics

Superelevation, transitions, and vertical and hori-

Figure 5. High-strength bolt connection.

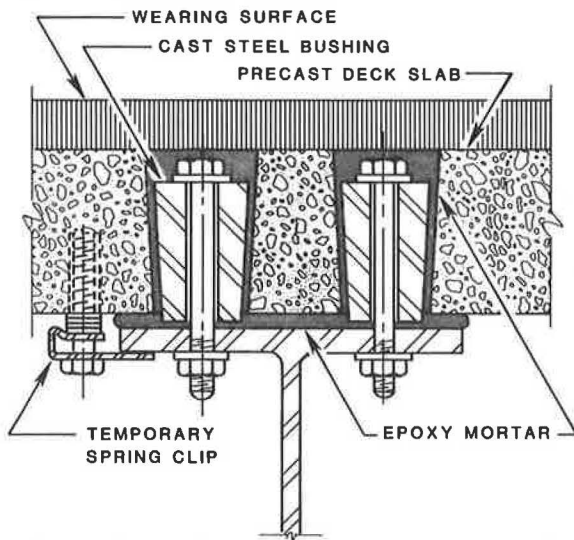
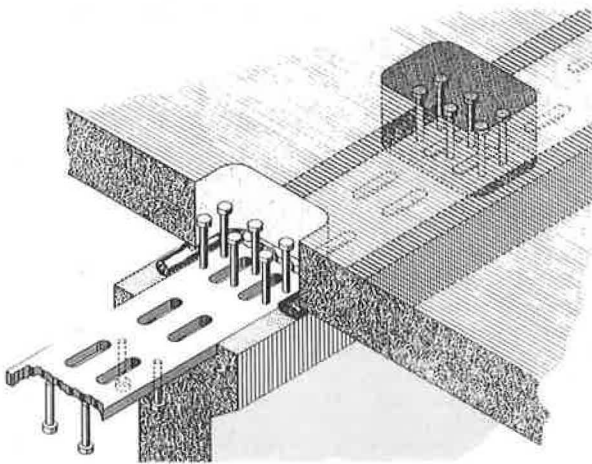


Figure 6. Precast slab connection to precast girder.



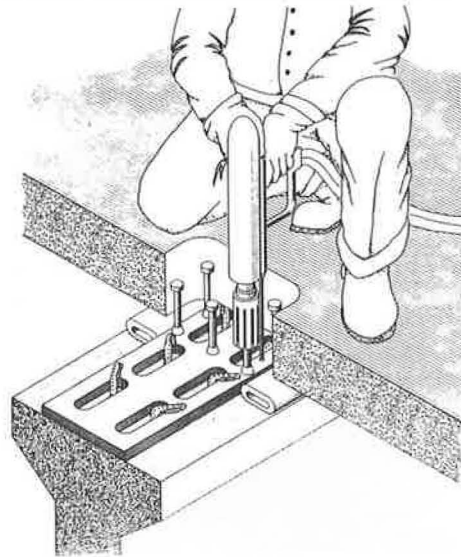
zontal curvature can be handled satisfactorily during the deck unit precasting operation. However, significant field problems are created as a result of irregularities in the supporting elements. Details must be developed that permit vertical adjustment of the individual slab units in the field. These details must also ensure proper temporary support as well as final bearing on the supporting beams.

Several systems have been developed to accomplish these objectives. One system requires the "buttering" of the top flange of the support elements with grout. The slab is placed while the grout remains plastic, and the excess material is squeezed out as the slab reaches the desired position. Hardening of the grout provides the final bearing.

A second method uses shim pads, which are placed under the slab in sufficient thickness to satisfy the required vertical alignment. Epoxy mortar is placed between the deck slab and the beam flange to provide final bearing.

Figure 3 shows a detail that incorporates side angles welded to the top flange of a steel support member. These angles are placed to compensate for variable flange plate thickness. Grout is placed by using the angles and a neoprene sealing tube as a

Figure 7. Precast slab connection to precast girder for replacement decks.



side dam. This detail is equally adaptable to new construction and to replacement decks. Careful attention must be given to welding details to ensure that undesirable fatigue characteristics do not result.

A detail that provides excellent versatility for vertical adjustment and adequate temporary support during construction and meets all requirements for final bearing is shown in Figure 9. It consists of a bolt extending through a threaded insert cast with the deck slab. The slab can be adjusted to the proper elevation by increasing or decreasing the extension of the bolt below the bolt head. The number of bolts provided is dictated by design requirements for dead load and the requirements for adjustment. After the slab has been adjusted to the proper elevation, the void below the slab and beam flange is filled with grout. Collapsible neoprene tubes are used for side dams to contain the grout. After the grout has cured, the leveling bolts are removed and the remaining void is filled with grout.

Deck Protection

Because the same factors that have caused the rapid deterioration of cast-in-place bridge decks are present with precast decks, a protection system should be provided where deicing chemicals are used. In most instances, it is also desirable to place a wearing surface of either concrete or bituminous material over the precast deck. A bituminous overlay provides a mechanism for eliminating irregularities in the roadway surface and, when constructed with a waterproof membrane, provides protection from the intrusion of chloride ions. In lieu of a membrane, the concrete surface could be treated with a penetrating sealer. Dense concrete or latex-modified concrete overlays will also provide an effective protection system. It is highly desirable to specify epoxy coating for all mild reinforcing in close proximity to the deck surface.

COST ANALYSIS

Design Examples

To assess the potential cost benefits of using precast deck panels, four hypothetical examples were developed. Two of the examples involve an existing

Figure 8. Precast slab connection to concrete beam.

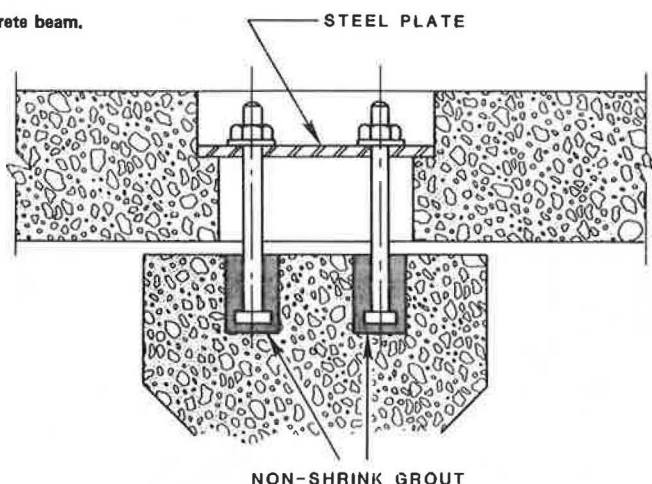
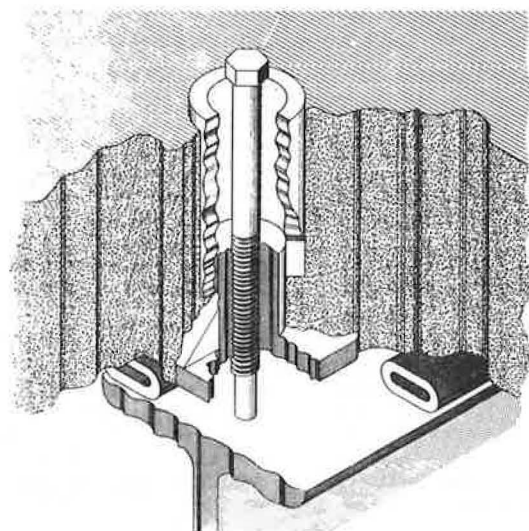


Figure 9. Adjustable support.



deck that requires replacement, and the other two are related to new construction. Each example involves a different support framing system.

The examples and the estimated construction cost include only the deck itself and not other parts of the structure. Changes in dead load and in the cost of the framing system have not been included in the economic analysis.

Each example is developed by using current AASHTO specifications and an HS20 live load.

Example 1

Example 1 involves the replacement of an existing deck on a 24-m (78-ft) simple-span, multiple steel girder bridge. The shoulder width on the deck is increased to provide additional safety, and a minimum of one lane of traffic in each direction is maintained at all times. A typical section of the existing and proposed bridge superstructure, which uses precast slab construction, is shown in Figure 10.

The precast deck is composed of 2.4-m (8-ft) wide modules. Units are cast for each half of the deck with a lap joint over the center stringer. Attachment to the steel stringers is made by welding studs through preformed openings in the precast deck unit,

which are then filled with grout. Bedding and vertical adjustment is obtained as described earlier with the screw-type inset (Figure 9). The bridge is longitudinally posttensioned. The precast deck is 178 mm (7 in) deep and the cast-in-place concrete is 203 mm (8 in) deep to comply with current specifications.

Example 2

In example 2, the deck on an existing 29-m (95.5-ft) span-through truss bridge is replaced with a modular deck slab system that spans between existing floor beams (existing stringers are removed). Figure 11 shows a typical cross section for the existing bridge and for the proposed precast deck replacement.

The precast deck units are 2.1 m (6.9 ft) wide and cover one-half of the bridge length. The slabs are continuous over intermediate floor beams. A lap joint is used between the ends of adjacent panels at the center floor beams, and a grouted keyway is used in the longitudinal direction between adjacent units. Attachment to the floor beams is by shear studs, as in example 1. Vertical adjustment is obtained with screw-type inserts.

The precast slab is 241 mm (9.5 in) deep, and the cast-in-place alternative requires a 330-mm (13-in) deep slab to carry the same live load.

Example 3

Example 3 is a new bridge design. A single-span, 19.8-m (65-ft), prestressed concrete, multiple-I-beam bridge was selected. The bridge was designed for composite action between the deck slab and the I-beam. Roadway width accommodates two lanes of traffic with 1.5-m (5-ft) shoulders. A typical section of the structure is shown in Figure 12.

The precast modular deck units are 1.4 m (8 ft) wide and cover the full cross section of the bridge. Curbs are cast monolithically with the slab. Stringers have been spaced to optimize the efficiency of the precast slab. The required slab thickness is 190 mm (7.5 in) for the prestressed alternative and 241 mm (9.5 in) for the conventional cast-in-place concrete design (with the same stringer spacing).

Joints between adjacent slabs are tongue and groove. The slabs are connected to the support stringers by welding studs to a steel plate embedded in the top flange of the I-beam through preformed holes. These connectors also develop sufficient horizontal shear capacity for composite action.

Figure 10. Typical section: example 1.

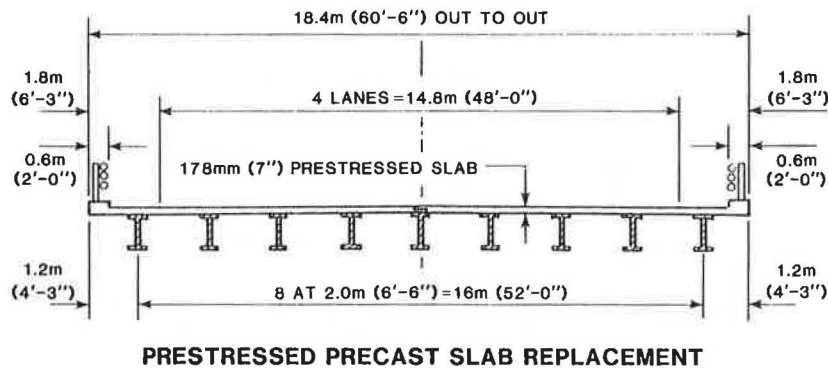
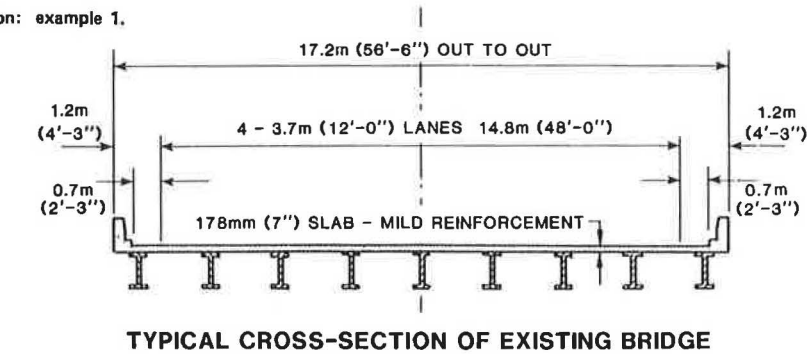


Figure 11. Typical section: example 2.

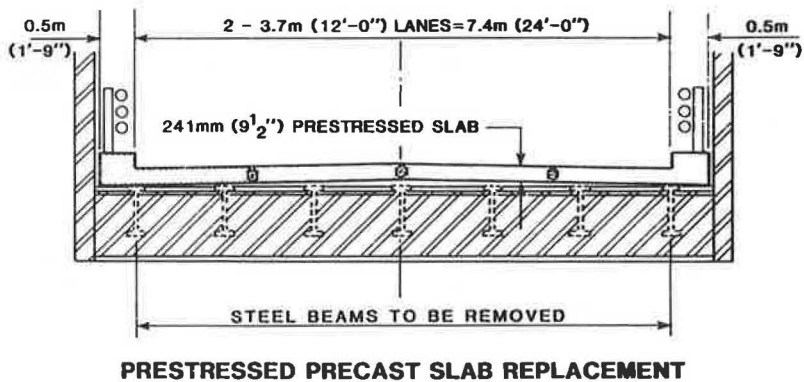
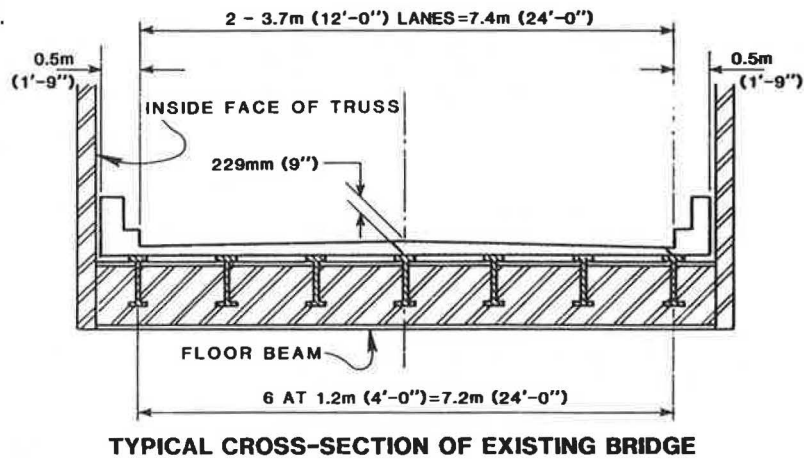


Figure 12. Typical section: example 3.

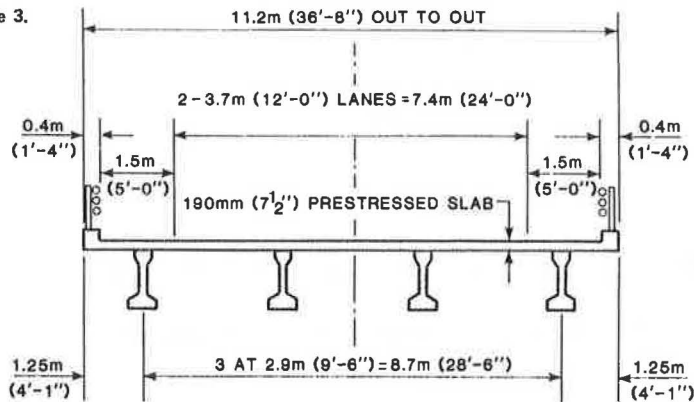
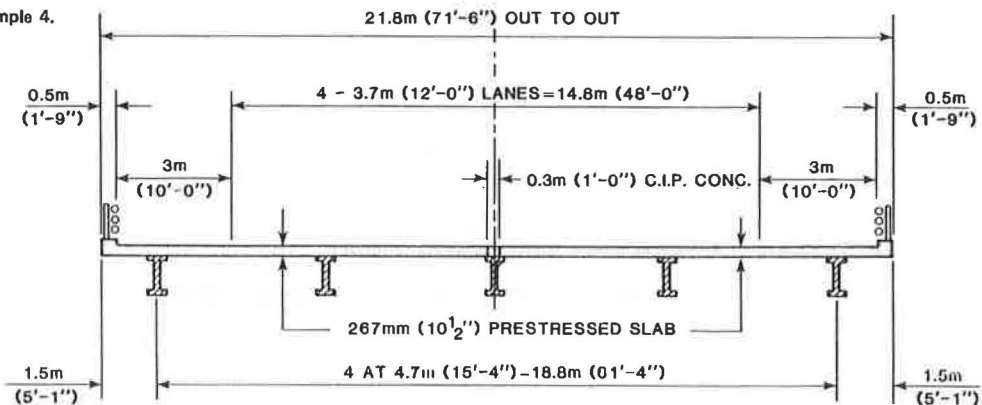


Figure 13. Typical section: example 4.



Leveling bolts, as in the previous examples, are used for vertical adjustment. The void between the top flange and the underside of the deck panel is filled with grout by using O-ring sealers.

Example 4

Example 4 demonstrates the applicability of using a prestressed, precast deck to minimize the number of required stringers and thereby improve overall economy. A multiple-steel-beam, 34.2-m (112-ft), single-span structure was selected. The roadway accommodates four lanes of traffic with full-width shoulders. Composite action is developed between the beams and the deck slab. Continuity of the deck over the center support is achieved by casting in place the section directly over the center stringer. This section is reinforced and made continuous with the adjacent deck panels. A typical section of the structure is shown in Figure 13.

The precast modules are 2.4 m (8 ft) wide and cover one-half of the deck. Longitudinal posttensioning is specified. Joints, leveling procedures, and grouting requirements are similar to those for the other design examples. The precast, prestressed deck requires a thickness of 267 mm (10.5 in) and the cast-in-place, conventionally reinforced deck requires a thickness of 318 mm (12.5 in).

Results

A construction cost estimate has been developed for each of the examples described above for the precast alternative and for the cast-in-place alternative. Estimates are based on complete installation of the deck, including curbs and appurtenances. Costs associated with the supporting framework have not been included. Costs have been included for traffic

control for the two examples that involve deck replacements. No consideration has been given to those costs associated with user delays and the like. Estimates are based on 1980 dollars.

A summary of the results of the analyses is given in Table 1. In each case, the modular system is less costly, although marginally so for example 1. However, the significant saving in field construction time, which translates into additional savings in user cost, has not been considered.

CONCLUSIONS

The concept of transverse prestressed, precast modular bridge deck construction has definite advantages when compared with conventional cast-in-place deck construction using mild reinforcement. A review of bridges with precast decks that have been in service for a number of years indicates that they have performed favorably compared with cast-in-place construction.

The concept is applicable to both new bridge construction and replacement deck construction. In each of the design examples investigated, a cost estimate was made, and in each instance the precast alternative proved to be more economical. In addition, the time for field construction was significantly reduced.

Improved economy is primarily the result of a decrease in the amount of materials required due to the increased structural efficiency of the prestressed deck. Where time is a factor that has quantifiable costs, this further enhances the economic viability of the concept of precast, prestressed construction.

Other benefits of modular construction for new bridge construction and for deck replacement have been identified:

Table 1. Cost analysis.

Construction Type	Example	Span (m)	Curb-to-Curb Width (m)	Framing System	Cast-in-Place			Precast			Cost Savings (%)	Potential Savings over Conventional Construction
					Thickness (mm)	Field Erection Time (days)	Deck Construction Cost (\$)	Thickness (mm)	Field Erection Time (days)	Deck Construction Cost (\$)		
Deck replacement	1	23.8	16.0	Multiple steel I-beams	203	41	64,900	178	7	63,700	7	—
	2	29.1	7.3	Steel-thru truss with floor beams	330	25	37,200	241	5	33,200	5	Member strengthening not required
New bridge	3	19.8	10.4	Multiple prestressed concrete I-beam	241	20	35,200	190	4	27,400	4	Fewer supporting members required
	4	34.2	20.7	Multiple steel I-beams	317	26	119,000	267	13	102,600	13	Fewer supporting members required

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.

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Abnormal Rotations of Skewed and Curved Bridges

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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-