Recommended Practice for Segmental Construction in Prestressed Concrete

Reported by

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This PCI committee report presents recommendations for the design and construction of precast prestressed concrete structures which are composed of individual segments that are tied together using post-tensioning. Primary emphasis is placed on bridge construction.

The recommendations cover the fabrication, transportation, and erection of the precast component segments, the construction of joints, details of tendons and anchors, and design considerations applicable to segmental construction.

It should be emphasized that this report is published as a guide on segmental construction and should not be considered a specification.

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CHAPTER 1—INTRODUCTION

1.1—General

Segmental construction is defined as a method of construction for bridges, buildings, tanks, tunnels, and other structures in which primary load carrying members are composed of individual segments post-tensioned together.

This report is a recommended practice on segmental construction, not a building code or specification.

It is presented as a guide to the design and construction of structures using segmental elements to insure safety and serviceability. Professional engineers must add engineering judgment to applications of the recommendations.

Throughout the report, major emphasis is on bridge construction. Very recent developments applying segmental construction to other structures such as stadiums and cooling towers are not considered. The committee intends to revise and update the report, to more fully consider future developments in segmental construction of buildings as well as bridges.

1.2—Scope

These recommendations are intended to cover those conditions which affect segmentally constructed members differently from non-segmentally constructed members. They consider the fabrication, transportation, and erection of the *precast* component segments, the construction of joints, details of tendons and anchors, and design considerations applicable to segmental construction.

1.3—Definitions

Adhesive—A bonding material used in joints.

Anchorage—The means by which the prestressing force is transmitted from the prestressing steel to the concrete.

Coating—Material used to protect against corrosion and/or lubricate the prestressing steel.

Couplers—Hardware to transmit the prestressing force from one partial-length prestressing tendon to another.

Grout—A mixture of cement, sand, and water with or without admixtures.

Joint—The region of the structure between interfaces of precast segments, with or without adhesive or grouting materials and with or without reinforcement.

Prestressing steel—The part of a post-tensioning tendon which is elongated and anchored to provide the necessary permanent prestressing force.

Segment—A precast element made out of concrete, with or without reinforcement, prestressed or nonprestressed.

Sheathing—Enclosure around the prestressing steel.

Tendon—The complete assembly for post-tensioning, consisting of anchorages, couplers, and prestressing steel with sheathing.

CHAPTER 2—FABRICATION OF PRECAST SEGMENTS

2.1—General Considerations

During design of a segmental structure, consideration should be given to the formwork necessary to achieve economy and to obtain efficiency in production. It is generally preferable to use as few units as possible, consistent with economic shipping and erection.

In the case of girder segments, economy and speed of production may be increased by:

(a) Keeping the length of the segments equal and keeping them straight, even for curved structures.

(b) Proportioning the segments or parts of them, such as keys, in such a way that easy stripping of the forms is possible.

(c) Maintaining a constant web thickness in the longitudinal direction.

(d) Maintaining a constant thickness of the top flange in the longitudinal direction.

(e) Keeping the dimensions of the connection between webs and the top flange constant.

(f) Beveling corners to facilitate casting.

(g) Avoiding interruptions of the surfaces of webs and flanges caused by protruding parts for anchorages, inserts, etc.

(h) Using a repetitive pattern, if practical, for tendon and anchorage locations.

(i) Minimizing the number of diaphragms and stiffeners.

(j) Avoiding dowels which have to pass through the forms.

Variation of the cross section of girder segments is generally limited to changing the depth and width of the webs and the thickness of the bottom flange. Curves in the vertical and horizontal direction and twisting of the structure are easily accommodated if longitudinal features of the segment remain at the same horizontal distance from the centerline.

Segmental construction is distinguished by the type of joint between elements. The following types have been used:

(a) Wide (broad) joints.

(b) Match-cast joints.

(c) Wide joints made to match in a later state.

The sharpness of line of segments assembled with wide joints depends mainly on the accuracy of the manufacturing of the joints during erection and less on the accuracy of the segments. Curvature and twisting of the structure may be obtained within the joint.

The principle of the match-cast joint is that the connecting surfaces fit to each other very accurately, so that only a thin layer of filling material is needed in the joint. Each segment is cast against its neighbor. Use of a bond breaking agent allows the segments to be taken apart. The sharpness of line of the assembled construction depends mainly on the accuracy of the manufacture of the segments.

2.2—Methods of Casting

Segments to be erected with wide joints may be cast separately. Match-cast joint members are cast by the "long-line" or "short-line" method.

2.2.1—The long-line method

Principle—All of the segments are cast, in correct relative position, on a long line. One or more formwork units move along this line. The formwork units are guided by a preadjusted soffit. An example of this method is shown in Figs. 1a through 1c.

Advantages—A long line is easy to set up and to maintain control over the production of the segments. After stripping the forms it is not necessary to take away the segments immediately.

Disadvantages—Substantial space may be required for the long line. The minimum length is normally slightly more than half the length of the longest span of the structure. It must be constructed on a firm foundation which will not settle or deflect under the weight of the segments. In case the structure is curved, the long line must be designed to accommodate the curvature. Because the forms are mobile, equipment for casting, curing, etc., has to move from place to place.

2.2.2—The short-line method

Principle—The segments are cast at the same place in stationary forms and against a neighboring element. After casting, the neighboring element is taken away and the last element is shifted to the place of the neighboring element, clearing the space to cast the next element. A horizontal casting operation is illustrated in Figs. 2a through 2c. Segments intended to be used horizontally may also be cast vertically.

Advantage—The space needed for the short-line method is small in comparison to the long-line method, approximately three times the length of a segment. The entire process is centralized. Horizontal and vertical curves and twisting of the structure is obtained by adjusting the position of the neighboring segment.

Disadvantage—To obtain the desired structural configuration, the neighboring segments must be accurately positioned. Concrete at the top of segments, which are intended for horizontal use, but which are cast vertically, may be of lower quality and has to be finished properly.

2.3—Formwork

2.3.1—General

Formwork must be designed to safely support all loads that might be applied without undesired deformations or settlements. Soil stabilization of the foundation may be required, or the formwork may be designed so that adjustments can be made to compensate for settlement.

Since production of segments is based on reusing the forms as much as possible, the formwork must be sturdy and special attention must be given to construction details. Forms must also be easy to handle. An example of a form used to construct I-shaped girder segments is shown in Fig. 3.

Paste leakage through formwork joints must be prevented. This can normally be achieved by using a flexible sealing material. Special attention must be given to the junction of tendon sheathing with the forms.

The forms may need to be flexible in order to accommodate slight differences of dimensions with the previously cast segment. They must be designed in such a way that the necessary adjustments for the desired camber, curvature and twisting can be achieved accurately and easily.

Special consideration must be given to those parts of the forms that have to change in dimensions. To facilitate alignment or adjustment, special equipment such as wedges, screws or hydraulic jacks should be provided.

Anchorages of the tendons and inserts must be designed in such a way that their position is rigid during casting.

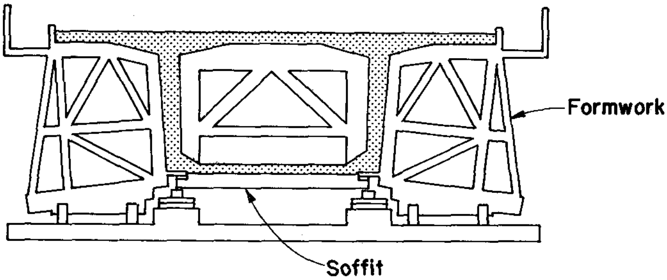

Fig. 1a. Cross section of formwork using long-line method.

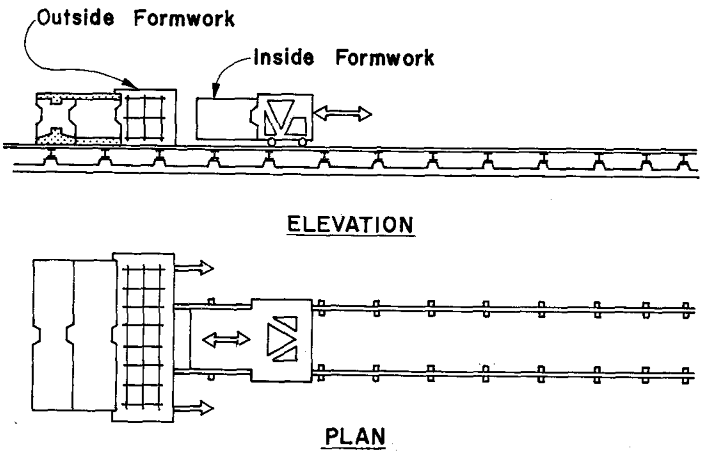

Fig. 1b. Start of casting (long-line method).

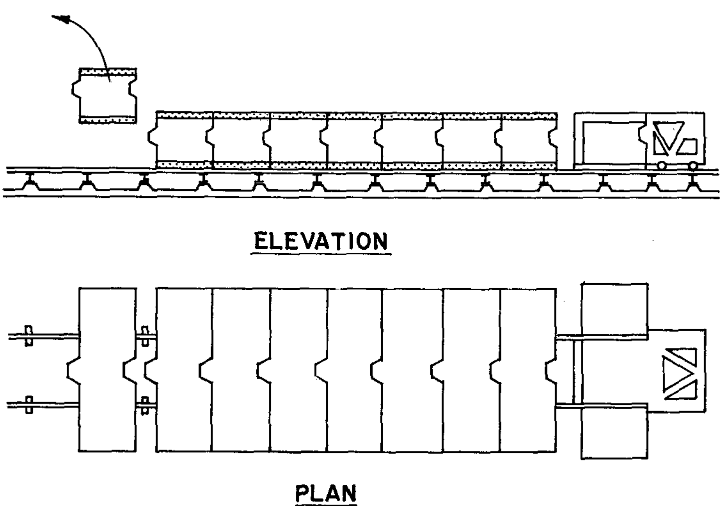

Fig. 1c. After casting several segments (long-line method).

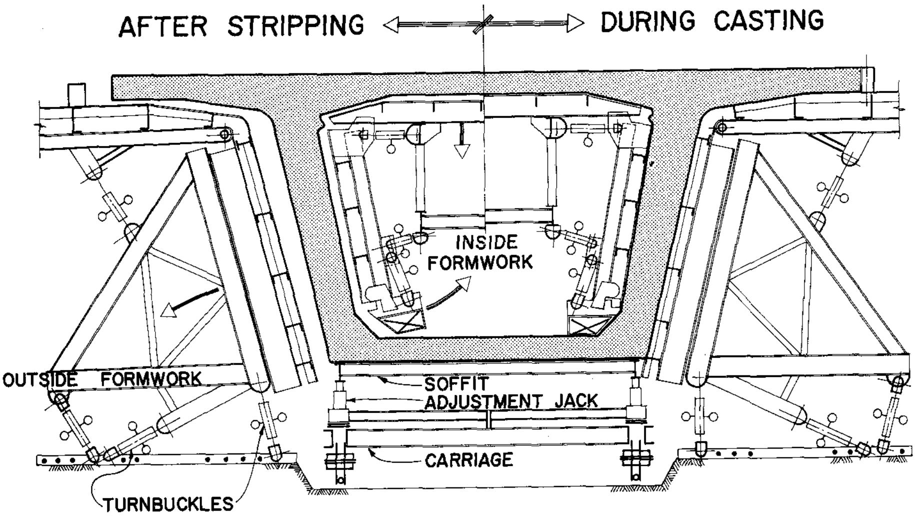

Fig. 2a. Formwork for short-line method.

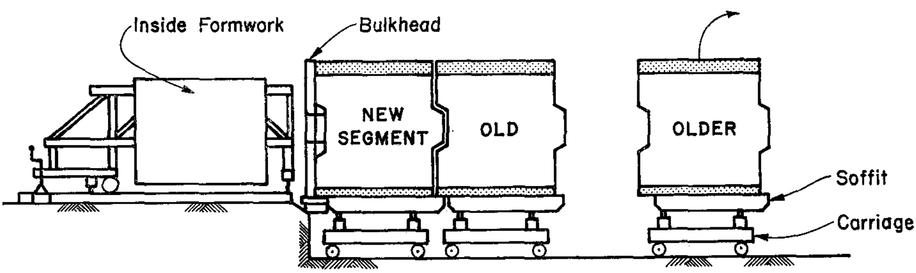

Fig. 2b. Just before separation of segments (short-line method).

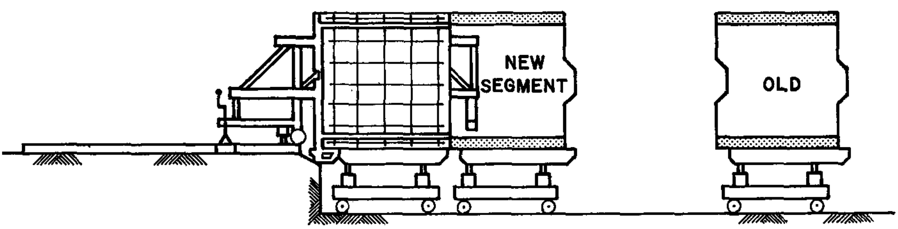

Fig. 2c. Just before casting next segment (short-line method).

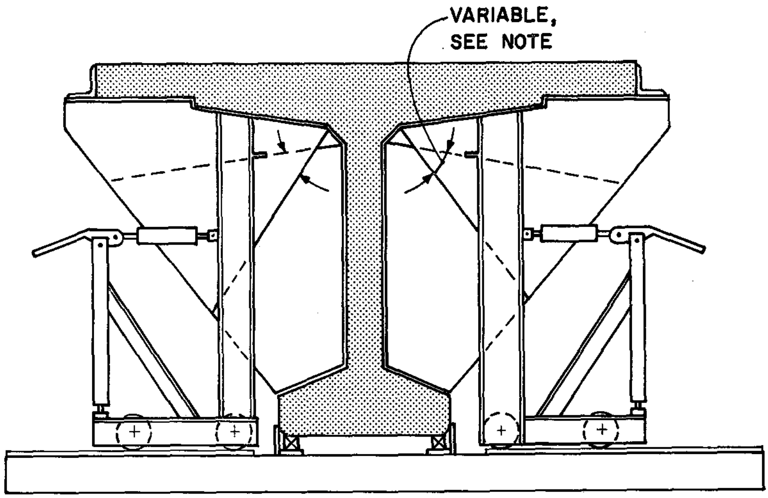

Fig. 3. Form to construct I-shaped girder segments. (Note: Plane of deck may be varied with respect to web of I-beam).

Fittings must not interfere with stripping of the forms.

If accelerated steam curing using temperature in excess of approximately 160 F is foreseen, the influences of the deformations of the forms caused by heating and cooling must be considered, in order to avoid development of cracks in the concrete.

External vibrators must be attached at locations that will achieve maximum consolidation and permit easy exchange during the casting operations. Internal vibration may also be required.

2.3.2—Provisions for tendons

Holes for prestressing tendons may be formed by:

(a) Rubber hoses which are pulled out after hardening of the concrete.

(b) Sheathing which remains after hardening of the concrete. Flexible sheathing made out of spirally wound metal is usually stiffened from the inside by means of dummy cables, rubber or plastic hoses, etc. during the casting operation.

(c) Rigid sheathing with smooth or corrugated wall may be used that will not deform excessively under the pressure of wet vibrated concrete and for which there is no danger of perforation.

(d) Movable mandrels.

Holes must be accurately positioned, particularly when a large number of holes is required. Further information on forming holes for tendons and tendon anchorages is presented in Chapter 5.

2.3.3—Provisions for supplemental reinforcement

Supplemental reinforcement is used to resist forces either not covered or not fully covered by prestressing. Requirements for supplemental reinforcement are listed in Chapter 6.

2.3.4—Tolerances

Formwork that produces typical box girder segments within the following tolerances is considered good workmanship.

Width of web	± ⅜ in.
Depth of bottom slab	+ ½ to 0 in.
Depth of top slab	± ¼ in.
Overall depth of segment	± ¼ in.

Overall width of segment . ± 1/4 in.
Length of match-cast
segment .... ± 1/4 in.
Diaphragm dimensions ... ± 1/2 in.
Grade of roadway and
soffit .... ± 1/8 in.

Depending upon the detail at bridge piers, the tolerances for the soffit of a segment may need to be limited to ± 1/16 in. The tolerance of a segment should be determined immediately after removing the forms. If specified tolerances are exceeded, acceptance or rejection should be based on the effect of the over-tolerance on final alignment and on whether the effect can be corrected in later segments.

In match-cast construction, a perfect fit is established between segments. Limits for smoothness and out-of-squareness of the joint should be established. Where wide joints are used, the tolerance in out-of-squareness may be that which can be accommodated in the joint thickness.

2.4—Concrete

Uniform quality of concrete is essential for segmental construction. Procedures for obtaining high quality concrete are covered in PCI and ACI publications.[1,2]

Both normal weight and structural lightweight concrete can be made consistent and uniform with proper mix proportioning and production controls. Ideal concrete for segmental construction will have as near as practical zero slump and 28-day strength greater than the strength specified by structural design. It is recommended that statistical methods be used to evaluate concrete mixes.

The methods and procedures used to obtain the characteristics of concrete required by the design may vary somewhat depending on whether the segments are cast in the field or in a plant. The results will be affected by curing temperature and type of curing. Liquid or steam curing or electric heat curing may be used.

A sufficient number of trial mixes must be made to assure uniformity of strength and modulus of elasticity at all significant load stages. Careful selection of aggregates, cement, admixtures and water will improve strength and modulus of elasticity and will also reduce shrinkage and creep. Soft aggregates and poor sands must be avoided. Creep and shrinkage data for the aggregates and/or concrete mixes should be available or should be determined by tests.

Corrosive admixtures such as calcium chloride should not be used. Water-reducing admixtures and also air-entraining admixtures which improve concrete resistance to environmental effects such as deicing salts and freeze and thaw actions are highly desirable. However, their use must be rigidly controlled in order not to increase undesirable variations in strength and modulus of elasticity of concrete.

The cement, fine aggregate, coarse aggregate, water, and admixture should be combined to produce a homogeneous concrete mixture of a quality that will conform to the minimum field test and structural design requirements. Care is necessary in proportioning concrete mixes to insure that they meet specified criteria. Reliable data on the potential of the mix in terms of strength gain and creep and shrinkage performance should be developed for the basis of improved design parameters.

Proper vibration should be used to afford use of lowest slump concrete and to allow for the optimum consolidation of the concrete.

Consideration should be given to delaying erection of segments until their internal moisture is reduced to a level that subsequent drying will not produce excessive deformation.

2.5—Joint Surfaces

Requirements concerning surface quality must be stricter for match-cast joints than for wide joints filled with mortar or concrete.

2.5.1–Orientation

Surfaces should be oriented perpendicular to the main post-tensioning tendons, to minimize shearing forces and dislocation in the plane of the joint during post-tensioning. Inclination with respect to a plane perpendicular to the longitudinal axis is permitted for joints with assured friction resistance. The inclination should generally not exceed 20 deg. Larger inclination, but not more than approximately 30 deg, may be permitted if the inclined surface area is located close to the neutral axis and does not exceed 25 percent of the total joint's surface area.

2.5.2–Quality

For match-cast joints, the surface, including formed keys, should be even and smooth, to avoid point contact and surface crushing or chipping off of edges during post-tensioning.

For wide joints, rough surfaces are preferable, as they produce better bond between segment and filling material.

Since it is difficult in normal practice to produce perfect sharp edges, it is advisable to make joint surface edges slightly rounded or chamfered. Although this will tend to make joints visible, it will also reduce the contrast if neighboring segments have slight color variation. Rounding or chamfering of edges should not decrease the joint surface area by more than approximately 2.5 percent.

2.5.3–Holes for tendons and couplers

Holes or sheathing for tendons must be located very precisely when producing segments joined by post-tensioning. Care is required to prevent leakage or penetration of joint-filling materials into the duct, blocking passage of the tendons.

2.6—Bearing Areas

Bearing areas at reactions should be even, without ridges, grooves, honeycomb, etc., to assure uniform distribution of bearing forces. It may be desirable to place bearing elements like pads or steel plates in the forms before casting. Otherwise, cement mortar or epoxy may be required on contact surfaces.

CHAPTER 3—TRANSPORTATION AND ERECTION OF PRECAST SEGMENTS

3.1—Plant Handling and Transportation

Segments should be handled carefully, without impact, in a manner that limits stresses to values compatible with the strength and age of the concrete. It should be verified that the segment weights are less than the capacity of the lifting equipment. Highway and site transportation may produce dynamic stresses which need to be considered. Special care of cantilever projections is often needed to prevent cracking. Location of lifting hooks and inserts should be determined carefully to avoid excessive stresses in the segment during handling, and they should have an adequate safety factor.

Storage of units at the site should be arranged to minimize damage, deflection, twist, and discoloration of the units. Stockpiling should be limited to avoid excessive direct or eccentric forces. Special precautions may be required to avoid settlement.

Inserts, anchorages and other embedded items may need to be protected from corrosion and from penetration of water or snow during cold weather.

Segments of decked I-beams, without pretensioning, may be transported and assembled up to about 100 ft.

3.2—Methods of Erection

3.2.1—Assembly on ground

Settlement of the segments during their assembly must be prevented. Handling and lifting equipment should be removed from the segments at the completion of each operation. The segments should be stabilized and braced to resist lateral forces, wind, earthquake, and impact. Potential difficulty in gaining access for handling the final member should be considered.

Before delivery to the site or before erection, sheathing should be cleared of all obstructions. Restraint of the segments against shortening must be prevented during post-tensioning operations. Consideration of subsequent change in forces at supports due to camber and redistribution of dead load may be required. Stability due to prestressing should be checked.

3.2.2—Assembly on scaffolding

Settlement and shortening of scaffolding due to dead load of segments as well as construction loads must be considered. Segments need to be carefully aligned and leveled before forming joints and post-tensioning.

Shortening of the segments and jointing materials due to temperature, settlement, or change in loading conditions should be checked before post-tensioning of the structure. If joints separate due to the above causes, the post-tensioning may cause uneven distribution of stresses, grout leakage, etc.

3.2.3—Balanced cantilever construction

By this method, segments are erected successively on each side of a central pier. Mobile cranes, winch and beam mechanisms or launching gantries are used to raise the segments. Temporary supports or struts may be needed. Care must be exercised to maintain compression, by means of temporary post-tensioning, over the entire joint area until the permanent tendons are stressed. The magnitude of stresses must be evaluated at all stages of construction.

3.3—Erection Tolerances

Maximum differential between outside faces of adjacent units in the erected position should not exceed ¼ in.

The most important item of tolerance or acceptance is the final geometry of the erected superstructure. The elevation of the deck surface of each segment used in the cantilever portions of the bridge superstructure, measured after closure sections are in place, must not vary from the theoretical profile grade elevation by more than that specified for the project. The gradient of the deck surface of each segment should not vary from the theoretical profile gradient by more than 0.3 percent. More liberal tolerances may be acceptable if the design incorporates a wearing surface.

CHAPTER 4—JOINTS

Depending on their width, joints may be cast-in-place with concrete, dry packed with mortar, or grouted. The joint surfaces must be clean, free from grease and oil, etc. and preferably wire brushed or sand-blasted. Prior to construction of the joint, the adjacent concrete surface should be kept thoroughly wet for approximately 6 hours or a bonding agent should be applied. Match-making joints are normally bonded with epoxy.

4.1—Cast-in-place Joints

The design width of a joint must allow access for coupling of conduits, welding of reinforcement, and thorough vibration of concrete. Typical joint widths are twice the thickness of the web or one-half the flange width, but not less than 4 in.

The compressive strength of the concrete at a specified age should be equal to the strength of the concrete in the adjacent precast segments. High early strength portland cement may be used. Aggregate size should be selected to ensure maximum compaction.

The height of each concrete placement or lift must be limited so that the concrete can be properly consolidated. Ports are normally provided for inspection.

Formwork must prevent leakage of concrete during and after its placement. Adequate curing is necessary to reach the design strength of the concrete.

4.2—Dry-Packed Joints

The concrete mortar must have a compressive strength equal to the concrete in adjacent segments, or at least 4000 psi. Good mortar should be thoroughly mixed and have zero slump. Maximum aggregate size normally does not exceed 3/16 in. Mortar should be rammed into place using a heavy hammer and a wood ram.

The width of dry-packed joints should not exceed approximately 2½ in. Mortar should be introduced into the joint in small quantities or batches not exceeding 10 lbs by weight. Each batch must be thoroughly tamped and packed before the next batch is placed. Containment may be necessary, particularly at the bottom of the joint.

4.3—Grouted Joints

The width of grouted joints should not exceed approximately 2 in. Grouted joints may be made with either gravity or pressure methods. In either case, provisions must be made to contain the grout.

The compressive strength of the grout at a specified age should equal that of the concrete in adjacent segments, or be at least 4000 psi. In some cases it many be difficult to attain a grout strength equal to that of the adjacent concrete. Nonmetallic grout mixes should be used when the grout will be exposed to weather.

To assure filling of the joint when gravity grouting is used, rodding or tamping should be used to consolidate the grout. Practical problems may be encountered with gravity methods, particularly on thin horizontal joints. For this purpose the grout should consist of approximately one part of cement, one-third part of clean sand passing a #16 mesh screen, and a water-reducing agent which preferably minimizes sedimentation. The total water content should be kept as low as practical.

Pressure grouting of joints requires equipment in good condition and adequate preparations. The joint must be tightly sealed in order to sustain the pressure. Pressure grouting is particularly effective when forms or gaskets can be easily used. Formwork must be vented at the top. At the conclusion of the grouting operation, the vent should be closed, and the pressure increased to a minimum of 15 psi at the vent. Twenty-four hours after grouting, the vent should be opened and filled if sedimentation has occurred.

4.4—Epoxy-Bonded Joints

It is particularly important that the adjacent surfaces are solid, clean, and free of dust and grease. All remnants of formwork oil, grease, soap talcum, powder, etc. must be taken away by proper washing or sandblasting. Sandblasting should be required when joints will be subjected to tension.

4.4.1—Selection of epoxy

The compressive strength of the epoxy should equal that of the concrete in adjacent segments under any environmental condition that may be encountered during the life of the structure.

Only highly cross-linked adhesives should be used that have been thoroughly tested in accordance with current ASTM and industry standards whenever applicable. Information which should be obtained from the manufacturer, or be determined by test, includes:

(a) Pot life and "open time" at various temperatures.

(b) Compressive strength and modulus of elasticity at various temperatures after curing for at least 7 days at 68 F (20C).

(c) Direct shear strength of bonded concrete prisms at various temperatures, with notation of whether failure occurs in the joint or in the concrete.

Data should be available on the resin/hardener system used in formulating the adhesive, including creep behavior and performance of bonded concrete prisms.

4.4.2—Application

The adhesive should be supplied in preweighted packs or cans of resin and hardener component. Resin and hardener should have different colors.

Components of the epoxy mix must be proportioned and mixed thoroughly until a uniform color is obtained, following the instructions of the manufacturer. Each batch should be assigned a number. The adhesive must be applied immediately after mixing, and the joint surfaces brought together before the pot life expires. A record of the location of the joint where the batch of epoxy is used, weather, temperature, and observed pot life should be maintained.

The concrete surfaces which are to be bonded should not be wet; a damp but not dark, shiny surface is permissible. To get rid of a wet surface, the concrete may be dried with hot air just before applying the adhesive.

The adhesive should be applied in a uniform thickness to both surfaces. Care must taken that no epoxy mix enters the ducts for the tendons. After joining the segments the tubes must be checked to be sure they are not blocked by the adhesive. Some post-tensioning must be applied within the "open time" of the adhesive. If the correct amount of adhesive has been used, a little will extrude from the joint when pressure is applied. It is recommended that a minimum of 30 psi (2 kg/cm^2) be applied to the joint.

In case of unforseen interruptions, the "open time" may have expired before the segments are fully joined. Then the epoxy has to be removed with a spatula and the remainder washed off with solvents according to the instructions of the manufacturer. Sandblasting will be necessary. Particular care is required in cold weather.

In case corrections in the alignment are anticipated, it is recommended that wire mesh be embedded in the epoxy layer.

4.4.3–Testing on site

If desired, test specimens can be made at the site to later verify the properties of the epoxy. These may include prisms of adhesive to test the compressive strength and diagonally cut concrete cylinders or prisms bonded together with the epoxy to indirectly test shear strength by compressive loading.

If necessary, concrete cores may be drilled through the bond line and tested in compression.

A record of the testing should be compiled.

4.5—Metal Joints

Metal joints in the form of mating pairs of steel plates which are welded together, or pin connected metal hinges, etc. may be used. However, they are classified more as connections than as typical joints between precast elements in segmental structures. Special attention is required for welded joints to prevent cracking or spalling of the concrete and to prevent staining of adjacent surfaces.

CHAPTER 5—POST-TENSIONING TENDONS

Background information on various post-tensioning systems and their applications is given in the *PCI Post-tensioning Manual.*[3]

5.1—Sheathing

Sheathing is used to form the holes or enclose the space in which the prestressing steel is located. It may be located inside or outside of the concrete section. Sheathing materials are listed in Section 2.3.2.

The prestressing steel can be placed with the sheathing, or installed after the concrete is placed. The cross section of the sheathing must be adequate to allow proper installation of the prestressing steel and to provide enough passage area for filling the tube with grout subsequent to stressing. The ratio of the net area of the prestressing steel to sheathing cross-sectional area should comply with the PCI Guide Specification for Post-Tensioning Materials in Reference 3.

Sheathing must have sufficient grouting inlets, vent pipes for escape of air, shut-off valves, and drains to allow proper grouting and to avoid accumulation of water during storage, Inlet and/or vent pipes should be located at all high points of the tendon profile and, if necessary, at low points. The distance between inlet and/or vent pipes should not be more than approximately 100 ft.

Sheathing placed inside the concrete must be resistant to irreparable damage caused during installation and placing of the concrete. It must prevent leakage of concrete into the void, and must be secured against buoyancy.

When semi-rigid sheaths are used, they must bend sufficiently to follow the required tendon profile. Flexible sheaths need to be tied securely to auxiliary reinforcement to minimize wobble of the tendon.

In certain applications, the sheaths are arranged outside the concrete section, either in voids of the section or along the outside of the concrete cross section. In addition to the requirements listed above, they must be protected against corrosion.

Special attention must be given to the alignment of the sheathing. At the joints, accurate placing is mandatory. Sharp curvature must be avoided or difficulty may be encountered in threading tendons through the sheathing.

Sheathing may be connected at joints by:

(a) Telescopic sleeves pushed over the protruding ducts.
(b) Screw-on type sleeves.
(c) Rubber or plastic sleeves.
(d) Gaskets.

For joint types (a), (b), and (c), leak tightness must be assured to avoid the entrance of jointing materials into the sheaths, causing possible blockage. Also, gasket joints must offer the same leak tightness as the rest of the sheathing.

5.2—Anchor Plates

The anchor plate is the component of a post-tensioning system which transmits the prestressing force from the tendon anchoring device directly to the concrete. Its function is to distribute the concentrated force from the anchoring device over a larger bearing area to the concrete.

The anchor plate must be of such shape and dimensions as to limit the bearing stresses to those specified in the *PCI Post-Tensioning Manual*[8] or in applicable codes.

5.2.1—Cast into precast segment

This is the most commonly used procedure. The concrete must be thoroughly vibrated behind the bearing plate to avoid honeycomb and to achieve proper strength.

5.2.2—Placed against precast surface

When the bearing plate is placed against the hardened surface of the precast element, dry-packed mortar should be used between the plate and the concrete. The strength of the mortar should not be less than the concrete strength on which it bears, and the thickness of the joint should be limited to 2 in.

The reinforcement of the concrete underneath the dry-packed mortar should be the same as if the plate was cast into the precast segment.

5.2.3—Placed against cushioning materials

Cushioning material may be used under a bearing plate when special circumstances require a highly uniform stress distribution between bearing plate and concrete. The cushioning material must not creep after final load. Very careful attention to details is required.

The cushioning material must be chemically stable and must not change physical properties with time and/or under load. It must also be compatible with the concrete and the bearing plate material. When metals are used as cushioning material, special attention must be given to the possibility of corrosion due to electrolysis.

5.2.4—Surface under anchor plate

The preparation of the surface under the bearing plate will depend on the type of plate and placing procedure used.

If the bearing plate is not cast into the concrete, the bearing surface must be approximately perpendicular to the prestressing steel to minimize shear stresses. The surface must be clean and free from foreign matter. The surface should be wire brushed to remove all laitance and loose concrete chips. If the bearing plate is to be grouted, the surface may be roughened by chiseling.

5.3—Tendon Layout

Attention must be given to the tendon layout, to make it compatible with:

(a) Sequence of the segmental construction.

(b) Progressive and subsequent load conditions which the segmental structure will undergo while being erected.

It is important to anticipate the secondary effects (stresses due to restrained deformations) which post-tensioning may have on the structure, and how these effects can be influenced by slight changes in the tendon profile.

Couplers and splices of post-tensioning tendons should preferably not be located in areas where yielding may occur under ultimate load conditions.

5.4—Placement and Stressing of Tendons

When tendons are installed in the segments before casting, they are usually subsequently coupled together at each joint. This construction method permits stressing of part of a tendon, after installing one or more segment, before the full length is completely installed.

Tendons may also be installed after casting and erection in partial lengths and coupled together at special openings. Usually, however, these tendons are installed full length. It may be noted, though, that this procedure permits intermediate stressing of portions of the structure, by using tendons of variable lengths, stressing the short ones first and long ones later.

Special attention must be given to the corrosion protection of the post-tensioning steel which, at any stage of construction, has to be unbonded. If a tendon which contains couplers is to be stressed over the full length, the couplers must be able to move.

5.5—Grouting

The purpose of grouting is to provide corrosion protection to the prestressing steel, and to develop bond between the prestressing steel and the surrounding concrete. To accomplish this, the grout has to fill all the voids in and around the post-tensioning tendon for its entire length. Grouting procedures should follow the *Recommended Practice for Grouting of Post-Tensioned Prestressed Concrete*[4] wherever applicable.

Grouting is preferably done from the lowest points of the tendon, toward the higher points, where vent pipes must be installed. The grouting must be done gently and slowly to assure the displacement of the air. Highly pressurized grout may mix with the air, creating entrapped air bubbles.

The tendon can be flushed with water before grouting, to avoid blockage when injecting the grout. The water can be blown out with pressurized air, or displaced by the grout. Sufficient purging must be allowed, but not less than 1 minute per tendon.

Grouting must not be done if the temperature in the duct is less than 35 F or if the surrounding concrete temperature is less than 32 F.

With vertical tendons, segregation is greater than with horizontal tendons.

Precautions must be taken to eliminate the danger of blockage of grout due to the couplers. Couplers are generally housed in a special, enlarged encasement, which should:

(a) Have the same open cross-sectional area for passage of grout as the rest of the tendon.

(b) Be provided with a grout inlet and/or vent pipe.

5.6—Unbonded Tendons

Unbonded tendons may be used in segmental construction, provided the structural requirements of the post-tensioning steel are also met by the tendon anchorage. In unbonded post-tensioning, a corrosion protection system must be provided, which must assure at least the same degree of corrosion protection as grout. This can be achieved by using a protective coating on the prestressing steel, and enclosing the coated tendon in an encasement to protect the coating during handling, installation and stressing of the tendon.

If unbonded and unprotected tendons are used, construction details must prevent accumulation of water in the ducts.

CHAPTER 6—DESIGN CONSIDERATIONS

6.1—General

Analysis and design of segmental structures is essentially the same as for monolithic prestressed concrete structures. Design should be based on two main considerations: acceptable behavior of the structure at all stages of construction and under service load, and adequate ultimate strength. Special consideration should be given to redistribution of forces in structures erected by the balanced cantilever method.

Provisions of the ACI Building Code[5] and the AASHTO Specifications[6] intended for non-segmental prestressed construction are generally applicable. Additional useful information is contained in the *PCI Design Handbook.*[7] Unless special consideration is given to crack control and to prevention of corrosion, it is recommended that flexural or principal tension not exceed the allowable tensile strength of the concrete under service loads. Use of a waterproof membrane on the top surface may assist in preventing corrosion or deterioration.

6.2—Design of Segments for Box Girder Bridges

For constant depth segmental bridges, span-to-depth ratios from 18:1 to 25:1 are currently considered practical and economical. Variable depth bridges may have span-to-depth ratios of 40 to 50 based on the depth at the center of the span.

It is recommended that single cell box girders, including cantilevers, not exceed 40 ft in width or a width-to-depth ratio of 6:1 unless special attention is given to the design. For wide segments, multiple cells are desirable and the webs should be located to reduce moments in the top slab and to minimize transverse bending of the webs. Generally, these moments are computed with sufficient accuracy by considering the top slab and webs as a rigid frame with fixed column bases.

Fillets should be used in the interior corners of box sections to improve the flow of stresses. They also provide additional room for tendons.

Vertical diaphragms are normally required at abutments, piers, and points of articulation.

6.3—Design of Segments for Decked I-Beams

The spanning capability of typical I-shaped sections is extended when the beam and deck are precast integrally. Reference 8 describes methods of design for segmental AASHTO Type III and Type IV sections for spans up to 180 ft.

6.4—Force Transfer Between Segments

The joints between segments should be capable of transferring the compressive, shearing, and torsional forces required by the design. Normally, tension is not permitted between segments under any stage of erection or service loading. However, if an epoxy or grout is used in the joint that has a tensile strength at least equal to that of the concrete, the allowable tensile stress under service loading may be the same as for nonsegmental construction.

6.4.1—Keys

Keys in the webs of segments are useful to facilitate alignment and to transfer shear during erection. It is recommended that the keys be proportioned for erection loads so that the bearing stress does not exceed $28\sqrt{f'_c}$ and the shear stress on the gross section of the key does not exceed $2\sqrt{f'_c}$.

6.4.2—Compression

As indicated in Sections 4.1 through 4.4, the compressive strength of material in a joint should be at least equal to that of the concrete in adjacent segments. If a dry joint is used, consideration should be given to the prevention of spalling around the edges of the contact area. It is recommended that dry joints be used only when verified by previous acceptable performance with regard to transfer of prestressing force and long-term weathering.

6.4.3—Shear

Shear in a joint is normally considered to be resisted by friction. Considering the magnitude of the resultant compressive force across the joint and a conservative estimate of the coefficient of friction between the surfaces, the available shear resistance should be at least twice the applied shear at service loads. At ultimate load, the available shear resistance should be at least equal to the applied shear. Diagonal web tendons across a joint may be used to increase shear capacity.

If the shear is not considered to be resisted by friction, simple or multiple keys[9] are required.

Wide grouted joints should contain nonprestressed reinforcement equivalent to that in adjacent segments.

6.5—Supplemental Reinforcement

Supplemental reinforcement to at least meet minimum requirements is normally required in segments for:

(a) Transverse bending moments.
(b) Shear.
(c) Torsion due to curvature or eccentric loading.

(d) Concentrated forces at reactions and due to tendon anchorages.
(e) Thermal and volume change forces.

Additional supplemental reinforcement may be required for:

(a) Longitudinal and lateral forces on the superstructure.
(b) Temporary forces imposed during fabrication, transportation, or erection.
(c) Local forces due to changes in shape of cross section, addition of curbs and parapets, use of diaphragms, connections for utilities, etc.
(d) Severe environmental exposure.

To decrease the possibility of damage to segments during post-tensioning due to accidental poor quality or uneven surfaces, or during handling of segments, supplemental reinforcement may be desirable immediately adjacent to the joint surface. This reinforcement typically consists of ¼ in. diameter wires spaced in two directions at 2 to 3-in. intervals or of comparable mesh.

Horizontal and vertical reinforcement may also be placed between segments in wide joints filled with mortar or concrete when the transverse thickness of the joint is more than 2 in.

Since too many reinforcing bars may cause difficulty in placing concrete, the arrangement of reinforcement in congested areas should receive special attention.

Special consideration must also be given to the effects of severe environmental exposure. For example, it may be essential to increase cover of steel, use coatings such as epoxy on reinforcement, or provide other protection.

6.6—Bearing and Anchorage

Bearing areas may be subjected to large concentrated forces; they may also need to accommodate substantial movement due to volume changes and thermal effects.

Post-tensioning tendon anchors are located in end block or anchorage areas. Their purpose is to safely transfer anchorage forces into the structure during all loading stages, including time of initial post-tensioning. End blocks may not be required if the stresses in the anchorage area are not excessive.

When all tendons extend the full length of the structure, the end blocks are located in end segments of segmental structures, which, in a simply supported beam system, will also be the bearing or the support segments. In some cases, however, anchorage areas may be located in intermediate segments (continuous beam or cantilever structures with segmental tendons distributed according to the moment or shear diagram) or in non-bearing end segments (cantilever structures).

Special attention should be given to proper reinforcement of bearings and anchorages. They should be provided with minimum reinforcement. In particular, anchorage zones should contain sufficient horizontal and vertical stirrups or grill reinforcement placed in the plane parallel to the end surface. Closed stirrups or ties should be used, or preference may be given to grills or welded wire mesh.

Generally three different areas of diagonal splitting and cracking can be identified in anchorage areas which require reinforcement:

(a) Under end surfaces, not more

than ¾ in. deep, to control possible surface cracking around anchorages.

(b) Internally, to prevent splitting of separate anchorages. Size and location of this area and of the magnitude of splitting (bursting) force depends on the type of anchorage and the force in the post-tensioning tendon, and should be investigated individually for each type of anchorage.

(c) Internally, to prevent tearing between groups of anchorages (not distributed on bearing surface uniformly). For each case, the tearing force and necessary reinforcement should be defined separately for the vertical and horizontal directions.

Concrete which is placed around anchorages, after post-tensioning, should be provided with reinforcement to assure that it will not spall.

6.7—Couplers

Couplers should be designed to develop the full ultimate strength of the tendons they connect. Adjacent to the coupler, the tendon should be straight for a minimum length of 12 times the diameter of the coupler. Adequate provisions should be made to assure that couplers can move during prestressing. The void areas around a coupler should be deducted from gross section areas when computing stresses at the time of prestressing.

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5. ACI Committee 318, *Building Code Requirements for Reinforced Concrete (ACI 318-71),* American Concrete Institute, Detroit, Michigan.
6. *Standard Specifications for Highway Bridges,* Eleventh Edition, American Association of State Highway and Transportation Officials, Washington, D.C., 1973.
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9. Muller, Jean, "Ten Years of Experience in Precast Segmental Construction," PCI JOURNAL, Vol. 20, No. 1, Jan.-Feb. 1975, pp. 28-61.

Discussion of this report is invited. Please forward your discussion to PCI Headquarters by August 1, 1975.