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A LITERATURE SURVEY
ON INDUSTRIALIZED BRIDGE CONSTRUCTION

by

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PREFACE

This literature survey was undertaken to aid the writer in understanding and retaining material in preparation for a project on the Industrialization of Bridge Construction. Numerous references were reviewed in addition to those included in the survey.

Innovation in industrialized bridge construction is presented. Included also are a limited summary and a conclusion based on the author's knowledge of industrialized construction obtained from conducting the survey. The author regrets any misplaced emphasis that may have derived from his lack of experience in the field.

Any constructive criticism or other contribution to the work is welcomed.

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INTRODUCTION

Attempts have been made to develop industrialized procedures and prefabricated components which result in a reduction in bridge construction time, provide safer and more comfortable working conditions, and increase efficiency of construction. Quick erection results in reduced construction time which is especially important in urban areas where any inconvenience affects many motorists. Recent revisions in safety standards have increased the cost of providing adequate safety for on-site construction. Satisfactory safety and working conditions are more economically achieved in the factory than in the field. Labor costs are reduced as employees can work on a year-round basis. Industrialized procedures which provide for quick erection and better working conditions result in increased efficiency in bridge construction.

Transportation and erection costs, in addition to fabrication cost, must be given major consideration in the development of industrialized procedures and prefabricated components. These costs are a function of the weight, shape, and design of individual pieces and the total number of pieces necessary for construction. Connections also affect the cost of erection and in addition influence prefabrication methods and costs.

Theoretically, there are designs and industrialized procedures that provide for safety and service in the structure and efficiency in construction while requiring a minimal costs and erection time. The desired industrialized bridge system may well be complex. However, complex designs can be achieved at minimal expense under factory working conditions. High strength to weight ratios tend to reduce transportation and erection costs. Factory production facilitates the use of pre-and posttensioning and high strength concrete necessary to achieve the desired ratios. The optimum industrialized bridge system is the most efficient combination of components, joints, and production, transportation and erection equipment. Factory conditions lend themselves to the production of the optimum section, regardless of size, shape, material type, and structure.

This literature survey presents the important innovative attempts to achieve a desired industrialized bridge system. For the purpose of clarity, innovation in each of the parts of the bridge system is presented and discussed separately. The paper begins with a presentation of design criteria. The succeeding sections of the paper are presented in light of design criteria favoring safety, service, efficiency in prefabrication and transportation, and minimization of erection time and total costs. Materials to be used in construction are discussed in the following section in which emphasis is placed on combinations of concrete and steel. Superstructure geometry, the most flexible part of the bridge system, is treated, in the next and largest section of the paper. Geometry ranges from simple solid slabs to highly complex transverse segments. Connections and ties are then discussed. In the next section, transportation and erection are presented together because they are affected similarly by design. The short section on prefabrication which follows serves only to mention fabrication problems associated with different designs. Variation in design technique is presented in the next section merely to show its existence (a corresponding discussion is beyond the scope of this paper). Next, a section on substructures is presented, with various substructure geometries and connections being discussed. The final section of the paper presents some examples of innovative prefabricated bridge structures to reveal some of the achievements that have been made. Many of these structures are the results of a far more complex, industrialized bridge system than the optimum one that is to evolve from the study that has been initiated by this literature survey. The paper ends with a summary of important parts and a conclusion about the optimum industrialized bridge system. An appendix contains pictures of various geometries, connections and bridge projects discussed in the paper.

DESIGN CRITERIA

Industrialized bridge construction is plagued by conflicting design criteria. Obviously, a safe bridge is the number one item. Serviceability is nearly as important. Both are more important than cost. To be satisfactory, design must provide for safety and serviceability at a minimal cost. Interchangeable parts would increase efficiency of fabrication, transportation, and erection and therefore minimize cost, but they would not be serviceable for custom bridges. A system must be selected that is safe and serviceable but at the same time increases efficiency and minimizes erection time and total cost. Expensive formwork and scaffolding are eliminated with factory production. Quality control is facilitated. However, prefabrication introduces the extra cost of plant overhead, hauling, and erection. Quality concrete and construction efficiency must offset this cost.

The application of industrialized procedures to bridge construction has been investigated by a number of engineering and consulting organizations. Improvements have been suggested for fabrication, hauling, and erection. AASHO and the Prestressed Concrete Institute have worked together to maintain workable standards.(1) However, industrialized bridge systems are in need of additional development and improvement.

The optimum industrialized bridge system must be the fastest, most efficient and most economical system that will meet minimum standards of safety and serviceability. To achieve the optimum system, necessary tradeoffs must be made among the following characteristics, all of which are desirable:

1. Safety and serviceability in the structure
2. Efficiency in fabrication and transportation
3. Minimal erection time and inconvenience in the surrounding area
4. Minimal cost
5. Minimal maintenance
6. Aesthetically pleasing appearance

MATERIALS

The development of high strength steel, wide flanges, thin webs and cover plates is evidence that steel design has approached its limit of efficiency.(2) Traditional bridge construction incorporates these multiple advantages. However, no major efforts to develop industrialized steel bridge systems are under way in this country, although considerable success has been experienced in other countries.(3)

Traditional steel bridges have concrete floors, although other types may be more efficient, depending on dead load, traffic, and site conditions. Other types such as steel girder, armor, steel plate, and timber have been used.

Orthotropic bridges are economical for short spans of 80 to 120 ft. as well as for long spans.(4) Orthotropic cross sections have a smaller depth than both non-composite and composite construction with steel and concrete. Concrete deck deterioration is a considerable problem whereas orthotropic steel deck bridges need little maintenance. "Tests have shown that corrosion damage is not a significant factor in steel bridge design".(5)

Welding increases the cost of orthotropic design. However, tremendous savings are achieved in larger spans with reductions in substructure cost. Improvements in bridges may well lay hidden in undiscovered combinations of materials. Industrialized construction increases the range of material combinations that may be economically used.

Concrete bridge design has not completely reached its limits of development, although improvements in design have been made through the years. Standard AASHO beams are now cast with 5,000 psi concrete and Washington State beams are fabricated with 6,000 to 10,000 psi concrete.(6) Modern sections such as the bulb tee beams are cast with 8,500 psi concrete.(7) High strength concrete combined with pre-and posttensioning can result in the maximum development of concrete potential. Concrete has the advantage that it can be molded into any shape, however, precasting is the only economical way to achieve the required high quality and precision. Traditional bridge design cannot economically incorporate the full benefits of concrete design. The industrialization of bridge construction can result in the achievement of optimum efficiency in concrete bridge design.

Numerous studies have been and are being conducted on the use of various materials for industrialized bridge construction. Purdue University has constructed test bridges to determine if precast decks of high quality concrete provide improvements in traffic performance and durability. The Virginia Highway Research Council is considering concrete, timber and steel as possible materials for precast bridge construction.(8) Extensive tests should be conducted to determine the full benefits of using lightweight concrete for industrialized bridge construction. The use of lightweight concrete can result in tremendous savings because of reductions in prestressing steel, reinforcing steel, substructure costs, and transportation and erection costs.(9) Certain site conditions may require the use of lightweight concrete for prefabrication to be feasible. As an example, lightweight concrete was used in the precast bridge over the Solleks River in Washington because 77.5-ft. girders were to be transported by truck up mountain roads.(10)

Optimum structural design reduces weight to a minimum. The use of low density materials to achieve weight reduction often leads to a low modulus of elasticity. Also, the use of high strength materials results in an extremely flexible structure. Forms must be devised which will allow the geometry of the structure rather than the quantity of material to resist deformation.(11) Among the materials that have been used experimentally is paper. A bridge weighing 20% of an equivalent concrete design was constructed from paper and transported to the site by a helicopter.(12) Although such use of paper stretches the use of feasible materials beyond normal limits, the experiment indicates the range of materials that have been explored. "Optimization requires that every field of technology be utilized".(13)

"The steel and concrete industries are developing standard bridge units that can be transported and erected in a minimum of time with a minimum of field connections and a minimum of construction equipment".(14) Research may well open similar developments in other industries. The time is appropriate for the Virginia Department of Highways to take advantage of existing developments in prefabricated steel and concrete and to research possibilities of using other materials.

SUPERSTRUCTURE GEOMETRY

Introduction

Bridge superstructures may be successfully prefabricated in numerous shapes from a variety of materials. The geometric forms normally include solid slabs, slabs with voided areas, combinations of beams and slabs, box beams, and box girders. The prefabricated sections may be longitudinal components that have a length equal to one span or transverse segmented components that have a length equal to the bridge width. For continuity, longitudinal components are usually posttensioned transversely whereas transverse segmented components are posttensioned longitudinally. Bridge superstructures have been prefabricated from longitudinal components, transverse components, and from combinations of the two types (see Figure 1).*

Traditional industrialized bridge construction has used longitudinal sections or a combination of components for short and medium length spans and segmental construction for longer spans. The use of conventional erection techniques has resulted in much of the economic advantage of longitudinal sections for short span lengths. The tremendous weight of longitudinal components for longer spans has resulted in transportation problems, which have been offset by the use of combinations of longitudinal and transverse components. However, as length increases the number of pieces increases and erection cost increases. Combinations of components are presently economical only for medium length spans, and segmental construction is necessary for longer spans.

Advancements in industrialized bridge construction may well result in the use of segmental construction for all span lengths. Transverse segments can be mass produced for any span length, while longitudinal sections are limited to short spans. Industrialized construction is improved by repetitious erection techniques. The use of segmental construction may take precedence for all span lengths with future refinements in prefabrication and erection techniques.

The Virginia Department of Highways uses traditional cast-in-place bridge construction for all span lengths, however, the Department is considering prefabricated box culverts for small stream crossings. Precast solid slabs and abutments should also be considered for short spans. Slab decks with voided areas become economical for longer spans because of the need for weight reduction. Further weight reduction can be achieved by precasting a slab in sections. As an example, Massachusetts has used prestressed, precast, 4 ft. wide slab units containing large tubular voids to construct bridges up to 40 ft. in length.(15) Beam and slab construction is ideal for spans approaching 100 ft.(16) Transverse segmented box beam or box girder sections are more economical for longer spans.

Concrete companies have developed various shaped deck components. Some examples are channels, double tees, flat slabs, modified tees, single tees, and beams (see Figure 2). Steel companies have developed numerous orthotropic and composite bridge deck sections. Steel tee beams embedded in concrete decks appear to be competitive with prestressed box beam construction.(17) Obviously, a tremendous selection of prefabricated bridge components are available. Research is necessary to determine the design that would best suit the needs of the Virginia Department of Highways.

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* See Page 35 of Appendix

Five designs of precast bridge superstructures have been presented in a study conducted by T. A. Hanson & Associates. (18) The various superstructures included longitudinal and transverse hollow slab sections, longitudinal and transverse modified tee beam sections, and a composite steel stringer concrete deck section.

Obviously, efficiency in industrialized construction is improved by repetitive construction. However, the mass production of bridge components is hindered by numerous variables which include horizontal and vertical alignment, superelevation, grade, crown, span length and number of spans. "The adaptability of systems bridges is measured by how well they can satisfy the range of geometric factors". (19) Hanson suggests restricting variables to fixed increments. For example, skew could be restricted to 15 degrees and span length could be restricted to 5 ft. increments. (20) Limiting variables to fixed increments increases repetition but reduces versatility. Repetition of components may not be feasible.

Lev Zetlin suggests that geometric form should be a function of the needs of industrialized bridge construction. He suggests that a study of needs be made before a design is selected. (21) Needs include a reduction in skilled labor, efficient use of labor, simplicity of design, and a large tolerance of error. (22) Other industries and various materials should be researched. The optimum design must be the result of a complex study. Repetition of fabrication and erection techniques rather than repetition of components may be necessary. The optimum industrialized bridge system may be the most efficient way to prefabricate and erect a custom bridge. Early stages of development might best be limited to smaller spans to reduce innovation expense and to facilitate the use of existing knowledge, transportation and erection equipment, and manpower.

The following sections present some of the combinations of longitudinal and/or transverse components used in prefabricated bridge superstructures.

Longitudinal Components

Longitudinal component design for bridges evolved from refinements in traditional simple span construction. Void areas were cast into slabs for short spans to reduce weight. As spans became longer, voided slabs became too heavy to haul, which required that the slab be cast in two parts, or in multiple longitudinal components as span length continued to increase. Other shaped sections were developed to improve the strength to weight ratio for longer longitudinal components. These included the double tee, channel, single tee, and modified tee.

Studies of longitudinal component construction began with the use of precast, prestressed channels connected with a cast-in-place concrete deck. To develop satisfactory design criteria, various research has been conducted to determine the differential deflection, stress and strain distribution, and slip and separation of the channels.

The Missouri Highway Department has conducted extensive tests on a bridge system consisting of precast-prestressed inverted concrete channels, interior void forms, and a top slab of cast-in-place concrete. A standard channel section was recommended as a result of the study (see Figure 3).(23) The following recommendations also resulted from the tests:(24) (1) changes in channel depth should be used to resist variations in moment, (2) metal arches should be used to form the void space, (3) variations in width should be taken up by overhangs on the edge of the deck, and (4) additional channels can be added to accommodate variations greater than 3 feet. Tests showed that span lengths are limited by allowable deflections in addition to transportation restrictions, with economical span lengths ranging from 30 to 80 feet for channel depths up to 3 feet. (25) Results further revealed that channel cost accounted for approximately 45% of the total bridge cost. (26) Finally, design procedures were found to be adequate and the behavior of the system predictable by conventional concrete theories. (27)

"An 18-foot long 12'6" wide model bridge span consisting of five prestressed channels and cast-in-place top slab was also constructed for analytical analysis by the Missouri Highway Department (see Figure 4). Composite action was observed and failure resulted from compression crushing of the top slab in the vicinity of the load line". (28) Tests also revealed that the bridge exhibited essentially elastic behavior, the dead load is supported by the channels alone, and "wheel load distribution is comparable to that exhibited by monolithic concrete box girders". (29) Tests further showed that contact between two channel legs increased when the slab was deflected. As a result the stiffness of a channel is increased and the total deflection is reduced by 50% of the single channel deflection, which is much less than that exhibited in composite I-beam construction. (30) "The wheel load distribution of this type of bridge is comparable to that of a voided continuous slab as given by the 1969 Edition of the AASHO Standard Specifications for Highways Bridges". (31)

Totally precast bridge superstructures with longitudinal adjacent components have been developed from the above studies. The structures have joints parallel to the traffic flow, which allows for smooth rides. Longitudinal joints accommodate future widening and facilitate replacement of damaged sections. Members can be segmented from pier to pier to accommodate horizontal curves. (32) The members may be precast concrete or composite design. When shear connectors are provided in the composite design the top flanges of the steel beams can be eliminated.

A disadvantage of longitudinal components is the transportation and erection problems caused by the weight and length of long members. As a result linear component construction with "T" or inverted "U" shape sections is recommended for spans up to 50 feet. (33) Also, "up to the present precast components have proven more economical in the short span range". (34) Therefore, longitudinal members of precast concrete or composite girders placed adjacent is felt to be the best design for secondary bridge construction. (35)

An experimental bridge of longitudinal construction is being considered for construction under the supervision of the Virginia Highway Research Council.

The asymmetric cross section of the members does not facilitate the widening of the bridge. The exterior section cannot be removed easily because by design it is grouted into position. In addition, the experimental sections present a weight problem. The 8-foot wide units will reach the transportation load limit. A more efficient section would be desirable for this bridge and for future industrialized bridge construction. Superior quality bridge construction in Virginia can be obtained through the optimum design of every component.

Longitudinal and Transverse Components

Numerous precast-prestressed concrete members have been developed for longitudinal placement in a bridge superstructure. The members are usually spaced a standard distance apart and are covered by either a doubly reinforced cast-in-place slab or precast transverse segmented panels. The former design is similar to traditional bridge construction with the exception that precast concrete members replace steel beams. The latter design is a first step in the transition to industrialized construction. Diaphragms are used as necessary in both designs to provide for uniform deflection of the members.

Precast-prestressed concrete bridge beams have been produced in a variety of shapes and sizes to accommodate various superstructure designs and span lengths. Standard inverted tee shapes have been used for either the formation of a composite voided slab structure when the flanges of the tees are connected or to provide for composite beam and slab construction when the flanges are not connected (see Figure 5). (36) For both designs a doubly reinforced top slab is cast over the inverted tee beams. Standard I-section beams have been used with deck slabs and concrete diaphragms to overcome the high cost of transversely reinforcing box sections. (37) Standard AASHO girders employing pretensioning have been developed for economical use in 50 to 90-foot spans. (38) However, most "precast I-girders are not adequate for spans greater than 120 feet," (39) although Anderson refers to a Washington State beam, which utilizes both pre-and posttensioning, that is economical for 75 to 145-ft. spans. (40) "A bulb-T section was developed in 1959, followed by the development of the decked bulb-tee in 1969," (41) which completes the transition in prefabricated bridge design from spaced longitudinal beams to adjacent longitudinal components mentioned in the previous section.

Various research has been conducted to determine the composite action of bridge superstructures consisting of precast beams and cast-in-place decks. The structural laboratory of the Portland Cement Association has tested several models of a concrete bridge made of precast-prestressed I-girders spaced at 6' - 6" on center beneath a cast-in-place deck. (42) A one-half scale model of plexiglas, and a 1/13 scale model of prestressed mortar were tested. (43) Results from the tests were correlatable and in good agreement with design laws. (44) Massachusetts has constructed several bridges in which prestressed-precast, posttensioned I-shaped beams 58 to 67 feet in length support a cast-in-place deck. (45) A slab haunch (see Figure 6) is recommended in this type of construction to account for variations in camber between the deck and the supporting precast beams. (46)

The Texas Highway Department tested a model bridge consisting of "precast prestressed panels spanning between precast-prestressed girders, and serving both as a form for cast-in-place concrete and as bottom reinforcing for the bridge deck". (47) Also, a composite deck section consisting of precast panels and cast-in-place deck is being studied by the University of Florida. (48) Results have shown that crack patterns in the cast-in-place deck coincide with the joints in the precast prestressed supporting panels. (49)

Surface joints also become a problem when precast transverse deck sections are placed on longitudinal beams. Tests have been conducted to determine the desirability of this type of bridge superstructure. Purdue University studied a bridge deck consisting of precast prestressed panels 4 ft. wide and 6 in. thick with a length equal to the bridge width. The panels were fastened to the supporting beams and posttensioned longitudinally after a sealer was placed in the joints. (50) The study found that a leveling material may be necessary to fill spaces between the deck and beams caused by beam camber. (51) Also, transportation is facilitated because of separate transverse and longitudinal components; however, to achieve good performance at a minimum cost, concrete decks should be composite with steel beams. (52) Composite action is difficult to achieve with transverse components resting on longitudinal beams. (53)

Three combinations of bridge superstructures have been listed under the category of longitudinal and transverse components. These include cast-in-place decks supported by precast beams, cast-in-place decks supported by transverse precast panels and longitudinal beams, and precast panel decks supported by longitudinal beams. Each type of construction requires diaphragms for uniform deflection of the beams. Diaphragms may be constructed from reinforced concrete or from standard steel sections. If diaphragms are not used, the deck must be designed to resist the moments caused by differential girder deflection. This requires that the deck be thicker and have more reinforcing steel. It is worthy to note that the AASHO code requires that decks be designed for use without intermediate stiffners. Regardless of the type of superstructure that is designed, "precast and prestressed concrete beams for highway bridges are commonplace throughout the U. S. A.". (54)

Transverse Components

Segmental construction is recommended for long span prestressed precast concrete bridges because of the transportation and erection problems caused by the tremendous weight of longitudinal components. Numerous structures are evidence that segmental construction is effective in the 100 to 500-feet span range. (55)

Segmental construction favors mass production because the same section can be used for a wide range of spans. A standard depth section can be used for spans up to 250 ft. (56) Material economy has a greater weight than production economy for longer spans. A consideration of appearance may reduce the maximum economical length for which a standard depth section can be used.

Fabrication, handling, erection, and connection requirements rather than just service requirements are considered in the design of precast girder sections for long spans. Length and weight must be chosen for economy in prefabrication, transportation and erection. One piece costs less to fabricate than two pieces, therefore, within transportation and erection weight limits, pieces should be designed as large as possible to reduce the total number. A standard 10 ft. wide section has been shown to be economical for most situations. (57)

The design of segmental components is complicated because handling stresses are often greater than service stresses. (58) The requirement for fine tolerances in prefabrication presents another problem. Finally, transverse segments do not facilitate the widening of a bridge and are uneconomical for short spans.

Segmental precast box girder construction involves the prefabrication, erection, connection, and posttensioning of transverse sections. "This form of construction results in a very compact structural member, which combines high flexural strength with high torsional strength". (59) There are three basic designs of box girder construction: single cell, a pair of single cells connected by a deck slab, and multicell. (60) Single cell box girders are economical for narrow bridges. (61) Other designs are more economical as width increases. (62) For wide bridges with limited pier cap width, multicell boxes are most desirable. (63)

The Hammersmith Flyover bridge represents a fourth type of box girder that has been used. Three inches of cast-in-place concrete joins the various segments of this alternating design (see Figure 7). (64)

Numerous bridge structures are evidence of the success of segmental box girder construction. "The Mancunian Way, Manchester comprises a pair of single cell box girders, jointed by a cast-in-place median strip" (see Figure 8). (65) "The Oleron Viaduct in France is a single cell box girder bridge" (see Figure 9). (66) The Choisy-le-Roi Bridge in Paris is an example of two single cells connected by a deck slab (see Figure 10). (67) The Commonwealth Avenue Bridge in Canberra, Australia is a three cell box girder (see Figure 11). (68) Figure 12 shows the profiles of the longitudinal cables used in the Commonwealth Avenue Bridge and the Choisy-le-Roi Bridge. (69) "Some 7 miles of 6-span continuous prestressed concrete box girder sections supported on precast concrete columns were used for a monorail vehicle at the Walt Disney World in Orlando, Florida". (70) The versatility in design that can be obtained with segmental construction is clearly demonstrated by the hollow girders that were prefabricated for the horizontal and vertical curves of the monorail. The girders were 26" x 80" at the ends and gradually tapered to 26" x 48" at midspan (see Figure 12). (71)

CONNECTIONS

The adequacy of connections determines the success of precast-prestressed concrete bridges. To be adequate a connection must at least be structurally sound enough to satisfy code requirements. A connection should facilitate prefabrication and erection. Material economy is also desirable. Finally, a connection should provide for a pleasing structural appearance.

Generally, connections are used to secure components, to stabilize the structure against movement caused by thermal changes, shrinkage and design loads, and to insure composite action. Numerous types of connections that have been developed to satisfy these requirements are presented on the next few pages. Obviously, economy in connection is favored by simplicity and repetitiveness in design and large tolerances of error.

Joint Types

A reinforced concrete joint maximizes the tolerance of error but represents the least industrialized connection of the joint types available. Little consideration must be given to the tolerance of error when high strength concrete is poured over reinforcing bar extending from the ends of precast sections being joined. Also, a cast-in-place top slab can provide adequate connection for longitudinal supporting members. However, the large amount of site construction time required is undesirable. The development and use of quick setting cements may be necessary for the economical use of the reinforced concrete joint.

Numerous studies have been conducted to determine the composite action obtained in reinforced concrete joints. The model bridge tested by the Texas Highway Department utilized "reinforcing bar shear connectors extending into the cast-in-place concrete to completely tie the beams, cast-in-place concrete, and precast panels into an integral composite deck unit" (see Figure 14). (72) The Missouri Highway Department recommended a bridge design consisting of a continuity joint formed by using cast-in-place concrete to fill the gaps between and tie together longitudinal precast channels which had U shape reinforcing bars extending from the legs. (73) The Missouri Highway Department also studied a similar bridge in which precast-prestressed channels were to be cast in an inverted position. Joint steel for the bridge consisted of 1/2" angles welded to number 3 reinforcing bars and cast into the channel legs. Shear connectors were later welded to the angles (see Figure 15). (74) Variables affecting joint continuity are degree of roughness of contact surfaces, length of shear span, the percent of steel in the joints, distance of the joint from the neutral axis, and compressive strength of the concrete. (75) Results indicate that sections act compositely provided adequate shear connectors are employed between components. (76) The reinforced concrete joint is adequate structurally but reduces prefabrication to a minimum.

Bolted and welded connections, when used without cast-in-place concrete, represent another type of joint. The usefulness of several types of bolted connections is illustrated by the development of precast bridges in Alberta. One-inch diameter bolts were used to connect the longitudinal panels of the first precast units developed there. (77) Later, steel connector channels were cast into the sides of adjacent units and bolted together. (78) Prestressed and pretensioned concrete channels connected by grout keys and bolts were developed in 1963 and are in use in Alberta today. (79) Spring clips and bolts anchored in concrete form a connection suitable for securing slabs to supporting beams (see Figure 16). (80) Hanson suggests that the optimum connection for industrialized bridge construction would be of a dowelled or bolted gravity type. (81) The future use of bolted connections will depend on innovation.

The unreinforced concrete joint is a third type of connection. Construction consists of pouring concrete between closely spaced components which have irregular surfaces that serve as keys. Unreinforced concrete joints have been used in segmental construction involving erection on falsework. (82) The joint reduces steel costs and eliminates problems associated with strict error tolerances. However, site construction time is prolonged when the joint is used. Quick setting cement could be used to minimize site construction time.

The groove joint, a fourth type of connection, consists of a tongue or key on one section which fits into a groove on an adjacent section. Reinforcement perpendicular to the joint is used to hold the connection together. The groove joint has been used in both transverse and longitudinal construction. Various materials and grouts have been used in the joint.

Research has been conducted to determine the adequacy of the groove joint. A study (83) conducted by the Louisiana Highway Department indicates that "the groove joint for lateral transfer of live load shear is 90% efficient even though the joints do not completely bear against each other". Tests showed that 2 to 2 1/2 slab widths support an interior loading and 1 1/2 slab widths support a loading on an outer edge. The study concluded that the use of high strength tie rods or grouting of the joints would not improve the connections significantly. As a result of the study fabrication tolerances for precast sections have been increased. (84)

Purdue University tested various shaped joints and various types of joint materials and found that a flat tongue and groove joint separated by a 1/16" neoprene pad produced the lowest stress concentrations of the joints tested. (85) However, "under conditions of high load a partial circle joint was found to be most effective" (see Figure 17). (86)

Clearly, groove joints are structurally adequate for transverse and longitudinal design. However, the prefabrication of components is hindered by joint tolerance. Also, site construction time is increased when grouting is used. Groove joints were eliminated in Alberta in 1952 because of grouting problems. (87) The joint may be considered at most a serviceable joint for industrialized bridge construction.

The dry joint, a fifth type of connection, is formed when sections are merely placed in contact. (88) Shear keys located in the sides of adjacent members could be used to transfer shear. "A dry or preformed shear key could be plastic, neoprene, aluminum, or other such nondeteriorating material". (89) A groove joint without grout would be a dry joint. The joint clearly reduces site construction time to a minimum. However, the fine precision necessary for success increases prefabrication costs. The future use of the dry joint will depend on refinements in prefabrication techniques.

The mortar joint represents a sixth type of connection. The joint requires that a thin layer of high strength cement mortar be applied to adjacent members. The problems associated with achieving a uniformly thick layer of mortar have resulted in the disuse of the joint. (90) However, the joint was used to connect the flanges of the longitudinal composite sections of a prestressed and precast concrete bridge located in Washington State. (91)

The epoxy joint is the final type of connection to be considered. The joint has been successful when a perfect match has been achieved between the segments being joined. A thin film of epoxy resin serves only to join the surfaces and shear keys must be used to transmit vertical shear forces as the resin sets. (92)

The epoxy joint is recommended for segmental construction, especially where sections are cast next to each other. Epoxy resin drys fast and is favored in cantilever erection. (93) The epoxy joint reduces site construction time to a minimum. The successful use of the joint rests with precision in prefabrication.

Ties

Seven types of joints, most of which require steel ties, have been presented on the preceding pages. Steel ties are not required for bolted and welded connections. Other types of connections require some type of steel to resist moments perpendicular to the joint.

Noncorrosive ties are desirable to eliminate the need for grouting. Ties that are not grouted can easily be removed if additional sections must be added later. Corrosion is inhibited by the use of a greased, plastic coated cable tie.

Numerous types of industrialized bridge construction require longitudinal ties. Long prestressing cables are necessary for continuous construction. Longitudinal posttensioning is required in segmental construction. Two sets of prestressing cables must be used in the cantilever construction of box girders. (94) One set must be used in the deck to resist negative moment during construction and another set must be placed in the lower slab for positive moment resistance. Posttensioning cables are used to stabilize precast transverse slab sections that are placed on beams. Longitudinal reinforcement in the top of channels improves composite action and helps to stop the propagation of flexural cracks. (95) Furthermore, longitudinal reinforcement must be provided to prevent a "negative moment" type of failure. (96)

Transverse ties are required in most types of longitudinal precast component construction. Prestressing strands were placed in the cast-in-place deck of the Missouri test bridge. (97) The Missouri study also recommended that reinforcement be placed in diaphragms and channel legs. (98) To facilitate repetition in production, transverse steel in diaphragm positions of box beams should be skewed to the beams and paralleled to abutments in skew bridge construction. (99) However, for skewed T-beams, the axis of the transverse steel should be paralleled to the face of the beam. (100) The adequate use of ties is necessary for the success of industrialized bridge construction.

Summary on Connections

Various types of joints have been discussed. The reinforced concrete joint, for example, requires considerable site construction time but eliminates problems associated with error tolerance. The epoxy joint requires a precise fit between components but expedites erection. Clearly the perfect connection has not been developed.

Numerous criteria need to be satisfied. Adequate connection between longitudinal precast members which have been spliced in positive moment areas eliminates length restrictions caused by transportation and erection. To overcome severe losses due to damage in transportation and other handling operations, a connection that provides for interchangeable components is desirable. The extremely fine tolerances necessary for precise fit are possible with today's modern factory casting methods. (101) However, economy must be considered in the choice or development of the optimum connection.

TRANSPORTATION AND ERECTION

The feasibility of industrialized bridge construction depends much on transportation and erection costs. Both transportation and erection costs are a function of the design, weight, and total number of pieces. Precast members with a high strength to weight ratio reduce transportation and erection costs. Components designed for nesting during shipment reduce transportation costs. Components designed with a large tolerance of error reduce erection costs. Self-supporting members reduce propping and shoring costs. High performance precast components are a product of industrialized fabrication. Industrialized construction is necessary for economy in transportation and erection, and economy in transportation and erection supports industrialized construction.

Component size is limited by truck capacity, crane capacity, hauling restrictions, and site conditions. Truck and crane capacities are limiting variables only when adequate equipment is not available locally. Hauling restrictions are placed on vehicles with a total length greater than 110 ft. A 25-mile hauling limit is placed on vehicles with a total length between 111 and 125 ft.(102) Hauling restrictions limit axle weight to 18,000 pounds, however, existing bridges may reduce the allowable axle load. "Greater axle loads require a special permit".(103) Extra axles can be added to reduce the load per axle. Site conditions usually don't present a problem unless adequate equipment is not available locally. Special erection equipment can be obtained for extremely heavy pieces or unusual site conditions. However, erection costs are increased by the use of special equipment. Likewise, transportation costs are increased by the use of extra axles, tariffs, flagmen, and pilot cars.

Erection costs are also a function of erection technique and the corresponding equipment costs. Transverse segmental components may be erected on falsework or with a crawler crane when the underlying area can be utilized. However, segmental bridges are most efficiently erected by cantilever construction.(104) Cantilever construction requires prestressing as each symmetrical pair is placed in position. A center segment is later dropped into position and secured with epoxy cement mortar and stressed tendons. The entire operation takes place without disturbing the underlying area. Cantilever erection is required when intermediate support cannot be obtained, however for short spans erection on a falsework truss is more economical. (105) Cantilevering from abutments can be accomplished if the abutments are designed for the unbalance during erection. (106) Lifting hooks cast into segments can be burned off after erection.

Erection may require falsework, hydraulic jacks, cranes, specially designed launching equipment, surveying equipment and/or other equipment. Cranes may be of the crawler, truck or floating types. The following examples reveal the versatility of existing erection equipment. "The maximum weight of the precast components was restricted by the available capacity of the tower crane" used to construct the Queensway Hotel in Gibraltar. (107) Hydraulic lifting jacks positioned on top of existing towers were used to lift precast runway sections into place to form a ski jump in Finland. (108) Precision survey instruments were used to obtain a true position tolerance of 0.1 inch in the erection of the Walt Disney Monorail. (109) Hydraulic jacks placed at the ends of the girders of the monorail were used to stress the posttension cables. (110)

PREFABRICATION

Prefabrication costs are a function of component design and fabrication technique. Designs that facilitate mass production reduce fabrication costs. Repetitiveness in fabrication procedures also reduces costs. The extra costs caused by variations in component shape and size can be compensated for by repetitiveness in procedures. An adjustable form may facilitate the production of nonstandard components and also provide for repetition in fabrication procedures.

Variations in component design are necessary to facilitate skew, crown, horizontal and vertical curves, and other geometric variables. Adjustable forms made of steel for maximum reusage would provide for skewed ends and variations in component depth. (111) Crown can be achieved with the application of an asphalt surface. However, asphalt traps moisture and hides the concrete surface and also increases site construction time. A tradeoff between adjusting forms in the factory and applying an undesirable asphalt surface at the site must be considered. Computer cards and station marked forms would reduce fabrication errors associated with form adjustments. (112) Factory prestress or loading can be used to camber concrete components for small degrees of horizontal and vertical curvature. Steel beams in composite design can be deflected prior to casting the concrete flange to form vertical curves, or camber can be rolled in steel beams during fabrication. Transverse segments can be cast to fit any degree of horizontal and vertical curvature with proper adjustment of forms. "The secret to the success of industrialized construction is to be able to make different shapes in the same form, using the same labor, with repetition". (113) Clearly geometric factors must be satisfied for the universal use of prefabricated bridges. Therefore, procedures rather than products must be repetitive.

In certain cases longitudinal components would best be fabricated in straight sections with skewed ends and segmented from pier to pier around horizontal curves. Other items such as rails would also be more interchangeable if cast in short, straight sections.

Rapid turnover is essential in industrialized construction, therefore prestress is often transferred at 50% ultimate strength, which limits stress levels to 0.6 f'c. (114) However, the use of pre-and posttensioning can eliminate the problem of limited stress and also increase section modulus to area ratio. (115)

Components to be joined with epoxy must be fabricated with a high tolerance of error. Accuracy can be obtained by casting the segments next to each other ("match-casting"). Repetition in procedures and slip forming can result in satisfactory accuracy and efficiency in prefabrication. However, a standard form capable of producing interchangeable components would be desirable to alleviate the problems associated with a damaged component. The success of industrialized bridge construction rests with efficiency in prefabrication.

DESIGN TECHNIQUES

A comprehensive study of design techniques is beyond the scope of this paper. Therefore, the subject is merely mentioned here to reveal the following: prefabricated products are designed by various techniques, many techniques have been tested to verify the design assumptions, and new design techniques are under development.

Continuous design reduces the bending moments, lessens the deflection, reduces the depth, decreases the number of joints, and improves the appearance of a superstructure. Posttensioning provides for continuous design in precast construction.

The Missouri Highway Department has designed precast longitudinal channel sections by assuming a simple support of dead load and a continuous support of live load. Their study of the sections revealed that standard prestressed-pretensioned design procedures are adequate for channel design. (116)

The Texas Highway Department has tested several prefabricated bridge structures to determine the validity of the design assumptions. The structures consisted of longitudinal precast beams, precast transverse panels, and a cast-in-place top slab. (117) "Slab design was in accordance with AASHO 1957 Standard Specifications", (118) assuming simple support for dead loads and continuous support of a composite deck for live loads. Strain gauges were used to determine the composite action of the transverse panels and cast-in-place slab. (119) Test results verified design assumptions and indicated the ability of the system to transfer loads across panel joints.

Purdue University studied a prefabricated bridge constructed from precast transverse panels placed on precast longitudinal beams and posttensioned in the longitudinal direction. (120) Results of the study indicated that a concentrated load is supported by one prestressed panel or two-adjoining panels when joints are loaded.

Numerous design techniques have been developed for box sections with various end conditions, diaphragm situations, stiffness properties, etc., however, no design methods are available for precast transverse segmental box girders. (121) Innovation is clearly needed here.

"A limit design for prestressed concrete bridges has been developed. AASHO specifications do not allow the design, however, the procedures can be used to obtain a more accurate reflection of actual conditions". (122)

The weight of longitudinal precast components presents a transportation problem. A function which systemitizes length, width, weight, and cost to produce the optimum combination would be desirable for the design of longitudinal components.

Precast design is a function of many variables, some of which are often not given adequate consideration. Satisfactory design techniques are necessary for the success of industrialized bridge construction.

SUBSTRUCTURES

Bridge substructures are normally designed for safety, service, and appearance. A prefabricated substructure, like a prefabricated superstructure, must also be designed to facilitate fabrication, transportation, erection and connection. In addition, site conditions must be considered. Substructures are rarely prefabricated because the design and construction are often controlled by site conditions. (123) Some form of custom prefabrication may be required for the factory production of substructure components.

A minimum of 2 abutments is required to support a bridge superstructure. Some type of intermediate support is also necessary for bridges covering more than one span. The intermediate support may include single piers, double piers, multiple piers or inclined struts.

A single column pier has numerous advantages and disadvantages for industrialized construction. Advantages include the following: Fewer pieces to fabricate, transport, erect and connect, fewer obstructions in a median, adaptability to any skew, and attractive appearance. On the other hand, a 1-column pier results in heavier pieces to transport, erect and connect. Also, a single column must be designed for unbalanced moments caused by single lane loading. Furthermore, the large column width occupies more median space, creating a safety hazard. Finally, the 1-column pier does not provide for the widening of a bridge.

Two-column piers and multiple column piers have one disadvantage — more pieces to fabricate, transport, erect and connect. However, the advantages of 1-pier per lane construction are numerous. First, individual pieces are lighter. Secondly, a bridge can be widened while in use by erecting a new pier and cap for each new lane. In the third place the columns can be adapted to any skew. Finally, the design moments are small and the corresponding column size presents little safety hazard to median areas.

Inclined struts have been developed to eliminate the bad appearance caused by the close spacing of 2 sets of intermediate supports placed in a standard 40 ft. median. The number of safety hazards in the median is also reduced by the use of inclined struts.

Geometric factors are easily satisfied by prefabricated substructures. It has been mentioned that skew can be facilitated by placing the substructure on a skew. Substructure caps can be tilted to provide for superelevation, grade, and vertical curvature. Adjustable forms are necessary to provide the necessary slopes in the substructure caps.

Adequate connections are necessary for the success of prefabricated substructures. Few attempts have been made to provide the necessary connections. Some examples of the successful use of connections are presented on the next few lines. Adequate connection between the rock foundation and the precast columns of the Walt Disney Monorail was achieved by inserting projecting reinforcing bars into grout-filled holes that were drilled in the rock. (124) Pin connections were used to secure the inclined struts to ravine sides and to the girders of a precast lightweight concrete bridge used to span the Solleks River in Washington. (125) Steel locating shoes were used to provide column-to-column connections between H-frame units in the Queensway Hotel in Gibraltar. (126) The shoes were site welded for fixity. Similar shoes might provide adequate pier connections.

The optimum connection for industrialized bridge construction has not been developed. Bolts, welds, pins and tongue and groove joints have been tried by various industries. Further innovation is necessary for the success of prefabricated bridge substructures.

The development of prefabricated bridge substructures is just beginning. Innovations in design, prefabrication, and erection are needed at this time. A study of other industries may benefit the corresponding research. The success of industrialized bridge construction may depend on the development of satisfactory prefabricated bridge substructures.

INNOVATIVE BRIDGE STRUCTURES

Numerous structures are evidence of the advancement, success, and versatility in industrialized bridge construction. Prefabricated structures have been erected throughout the world.

"The first prestressed concrete bridge in Canada was built in British Columbia in 1952". (127) Since then Canada has made considerable progress in the development of prefabricated bridge structures, using shallow box sections, channel units, I-beams, T-beams, and deep box sections. Recently a 288 ft. structural overpass was constructed in Alberta from precast-prestressed pier and deck components. (128) The erection of the structure is typical of the success of substructure prefabrication.

"An impressive ski jumping hill of prestressed-precast concrete has been built in Lahti, Finland. The majority of the runway is made of prestressed-precast concrete double T-beams and cross beams". (129) Clearly vertical curves present no fabrication problem in precast bridge construction. Prefabricated concrete is extremely versatile.

"The Fawr Bridge in Wales is a continuous three span prestressed box girder 470 ft. long with spans of 127 ft., 216 ft., and 127 ft.". (130) The cantilever erection of this bridge is typical of the advancements that have been made in segmental construction.

Several states in the United States have made considerable advances in industrialized bridge construction. "The Mississippi Highway Department has developed and now erects a precast short-span bridge on all their secondary roads". (131) The bridge consists of precast deck sections, caps, and abutment wings. Clearly, the successful precasting of the entire structure of a bridge is possible. In Michigan, four prestressed-precast concrete, double T-beam deck planking units 5 ft. wide, 77 ft. long and weighing 43 tons each were used to span the Pigeon River. (132) This structure is evidence of the effectiveness of longitudinal T-beam construction for spans less than 120 ft. The Mississippi Bridge and the Pigeon River Bridge, constructed from longitudinal precast components, are typical of the success of the prefabrication of short and medium length bridges. The achievements in segmental construction for longer spans are just beginning in the United States.

SUMMARY

Industrialized procedures and prefabricated components reduce site construction time, provide for better working conditions, and increase the efficiency of bridge construction.

Industrialized bridge costs are a function of design, materials, fabrication, transportation, erection and connection. Theoretically, there should be structural designs and industrialized procedures that provide for safety and service in the structure and efficiency in construction while requiring minimal costs and erection time.

Industrialized construction increases the range of material combinations that may be economically used. Traditional steel bridge design has approached its limit of efficiency. However, concrete design has not completely reached its limit of development. Numerous other materials have not been researched. Factory conditions facilitate the production of high performance components. Improvements in bridges may well lay hidden in undiscovered combinations of materials.

Bridge superstructures may be successfully prefabricated in numerous shapes from a variety of materials. The geometric form normally includes solid slabs, slabs with void areas, combinations of beams and slabs, box beams or box girders. Concrete companies have developed various shaped deck components. Some examples are channels, double tees, flat slabs, modified tees, single tees, and beams. Steel companies have developed numerous orthotropic and composite bridge deck sections. Bridge superstructures may be prefabricated from longitudinal components, transverse components, and from combinations of the two types. Longitudinal sections or combinations of components are traditionally used for short and medium length spans and segmental construction is utilized for long spans.

Precast concrete and composite sections have been developed for longitudinal construction. Joints are parallel to the traffic flow, which allows for smooth rides. Longitudinal joints accommodate future widening and facilitate the replacement of damaged sections. Members can be segmented from pier to pier to accommodate horizontal curves. The disadvantages of longitudinal construction are the transportation and erection problems caused by the weight of longer sections.

Bridge superstructures with both longitudinal and transverse members have been designed usually with longitudinal components spaced some standard distance apart and covered by either a doubly reinforced cast-in-place slab or multiple precast transverse segmental panels. Precast-prestressed concrete bridge beams have been produced in various shapes and sizes to accommodate various superstructure designs and span lengths. However, designs are limited because most precast girders are not adequate for spans greater than 120 ft. Also, surface joints become a problem when precast transverse deck sections are placed on longitudinal beams.

Segmental construction involves the fabrication, erection, connection, and posttensioning of transverse sections. Segmental construction is recommended for long span prestressed-precast concrete bridge construction. Segmental construction favors mass production because the same section can be used for a wide range of span lengths. However, fabrication, handling, erection and connection requirements must be given major consideration in transverse segmental component design. Also, transverse segments do not facilitate widening or the replacement of damaged sections. Finally, transverse segments are not presently economical for short spans.

Connections are used to secure components, to stabilize the structure against movement caused by thermal changes, shrinkage and design loads, and to insure composite action. A connection should facilitate prefabrication and erection by providing for a large tolerance of error. A connection must also satisfy code requirements for strength and stability and have a pleasing appearance.

Numerous types of joints have been developed. The reinforced concrete joint, for example, eliminates problems associated with error tolerance but requires considerable site construction time, although quick setting cements can be used to minimize the time. The epoxy joint expedites erection but requires a precise fit between components. Each of the other joints discussed, bolted and welded, unreinforced concrete, groove, dry, and mortar, is also limited in adequacy for industrialized bridge construction.

Steel ties are required to resist moments perpendicular to joints. Non-corrosive ties are desirable to eliminate the need for grouting. Longitudinal ties are required for continuous and transverse construction. Transverse ties are required for longitudinal construction.

The feasibility of industrialized bridge construction depends much on transportation and erection costs. Both transportation and erection costs are a function of the design, weight, and total number of pieces. Erection costs are also a function of erection technique and the corresponding equipment costs. Erection may require falsework, hydraulic jacks, cranes, specially designed launching equipment, surveying equipment and/or other equipment. Special equipment increases erection costs. Component size is limited by truck capacity, crane capacity, hauling restrictions, and site conditions. Transportation costs are increased by the use of extra axles, tariffs, flagmen, and pilot cars.

Prefabrication costs are a function of the component design and fabrication technique. Obviously, efficiency in industrialized construction is improved by repetitiveness. However, the mass production of bridge components is hindered by geometric variables. Limiting variables to fixed increments reduces the versatility of industrialized construction. Adjustable forms which facilitate the production of custom components with repetitive procedures would satisfy design criteria at a minimum cost. The success of industrialized construction rests with efficiency in prefabrication.

Satisfactory design techniques are also necessary for the success of prefabricated structures. Prefabricated structures have been designed by various techniques, many of which have been tested to verify the design assumptions. New design techniques are under development.

Bridge substructures are designed for safety, service, and appearance, Prefabricated substructures, like superstructures, must also be designed to facilitate fabrication, transportation, erection and connection. In addition, site conditions must be considered. Substructures are rarely prefabricated because design and construction are often controlled by site conditions.

Prefabricated structures erected throughout the world are evidence of the advancement, success and versatility of industrialized bridge construction.

CONCLUSION

Obviously a tremendous selection of prefabricated bridge components are available. Research is necessary to determine the design that would best suit the needs of the Virginia Department of Highways. However, repetition of components may not be feasible. Repetition of fabrication and erection techniques may be necessary. The optimum industrialized bridge system may be the most efficient way to fabricate and erect a custom bridge.

Relative to concrete components, steel components offer some favorable attributes for urban areas, such as reduced weight and ease of handling. It is generally believed that current research on industrialized construction has failed to give adequate consideration to steel, and therefore immediate research is warranted in order that the potential of steel is not overlooked.

Advancement in industrialized bridge construction may well result in the use of segmental construction for all span lengths. Transverse segments can be mass produced for any length. Industrialized construction is improved by repetitious fabrication and erection techniques. Segmental construction may take precedence with future refinements in prefabrication and erection techniques.

Longitudinal construction is limited to short spans because of weight. The universal use of longitudinal sections requires the development of a satisfactory intermediate span connection.

An adequate connection for industrialized construction has not been developed. A connection which facilitates the use of interchangeable components is desired. Overall economy must be considered in the development of the optimum connection.

Precast bridge design is a function of many variables, all of which must be given adequate consideration to prevent costly mistakes.

The development of prefabricated substructures is just beginning. Innovations in design, prefabrication, and erection are needed at this time. Some method of custom prefabrication may be required for the factory production of substructure components.

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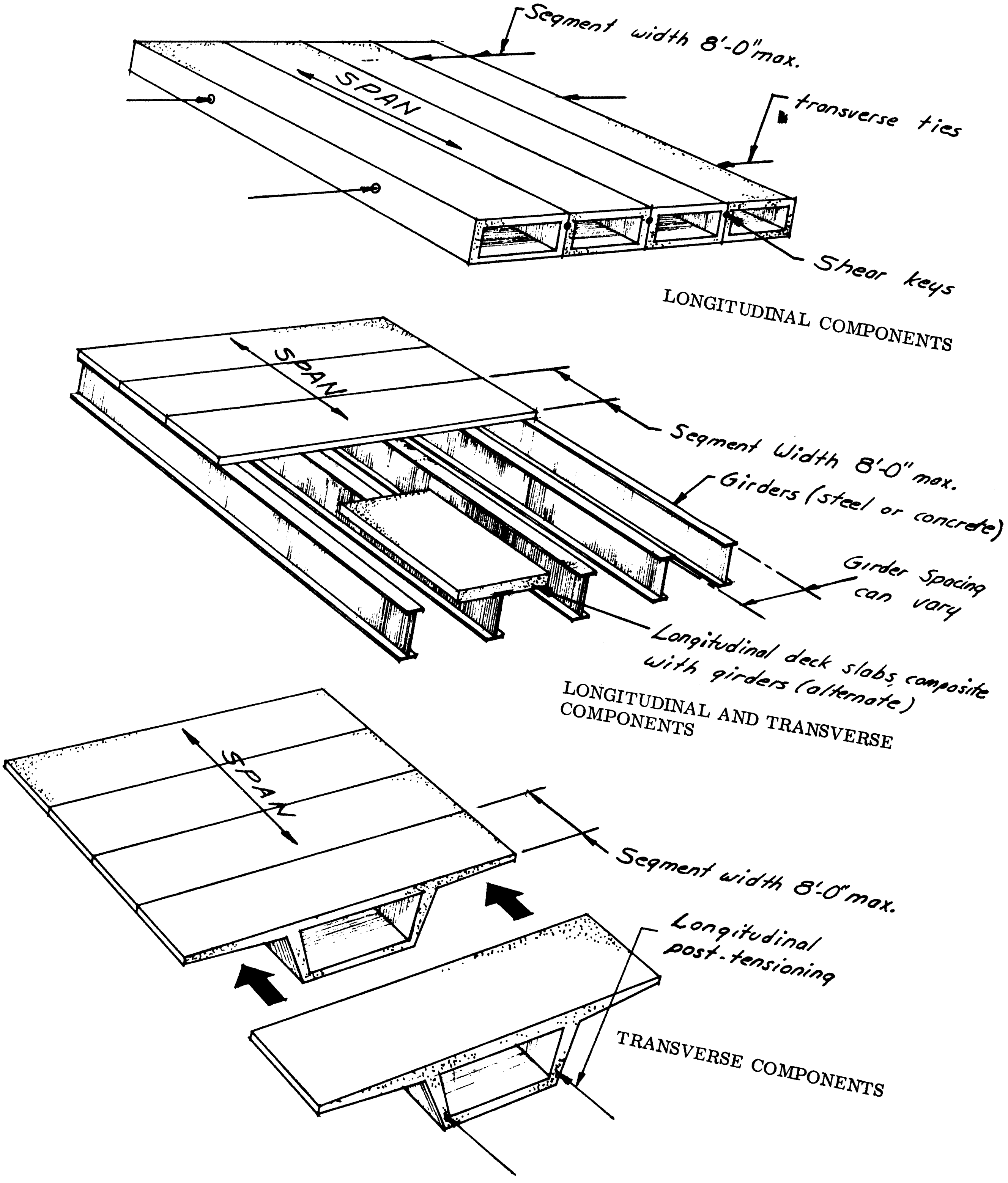
APPENDIX

To enhance the reader's understanding of this survey, the following pages contain pictures of various geometries, connections and bridge projects discussed in the paper.



LONGITUDINAL COMPONENTS

LONGITUDINAL AND TRANSVERSE COMPONENTS

TRANSVERSE COMPONENTS

Figure 1. Bridge superstructure types.(133)

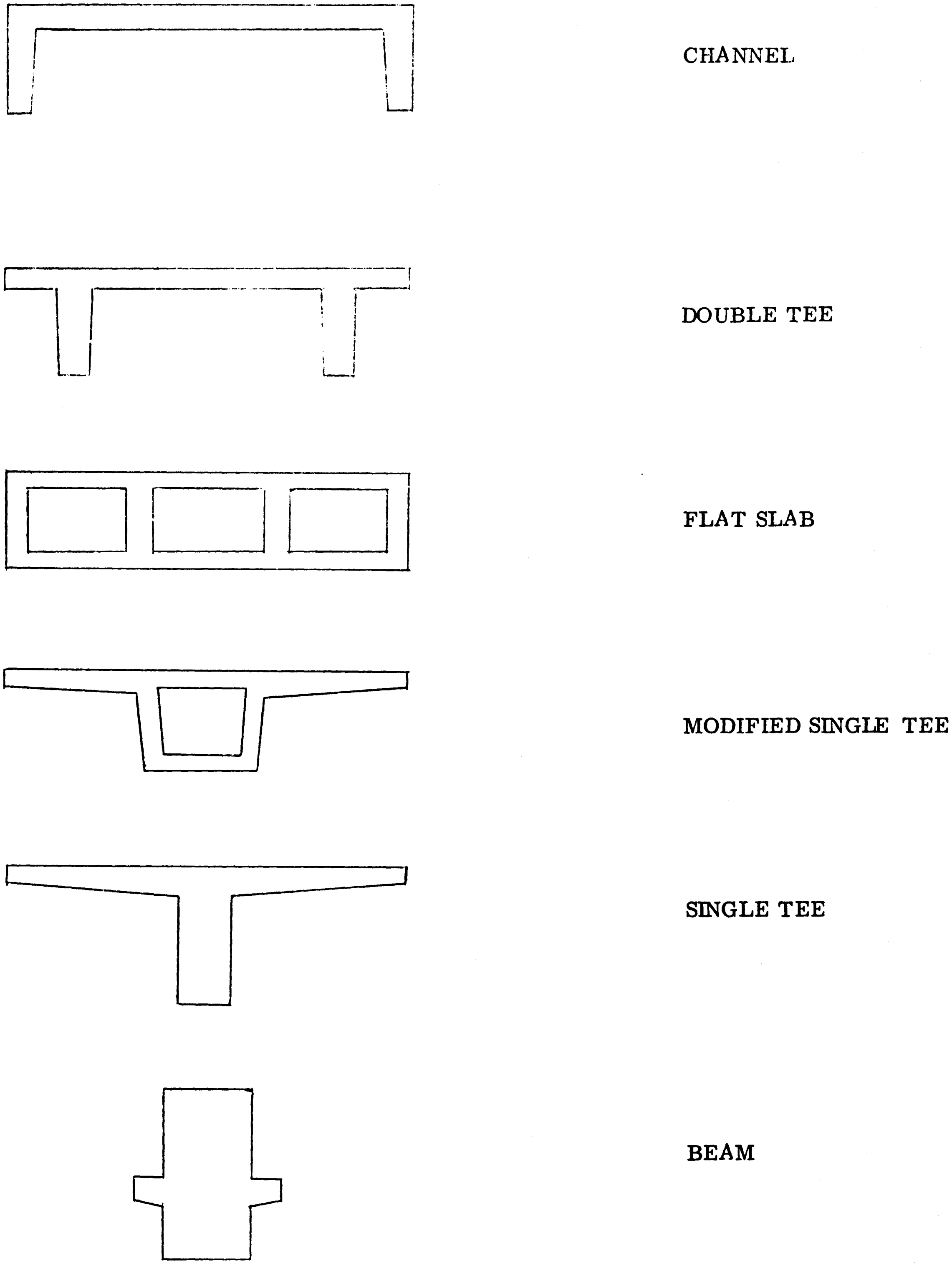
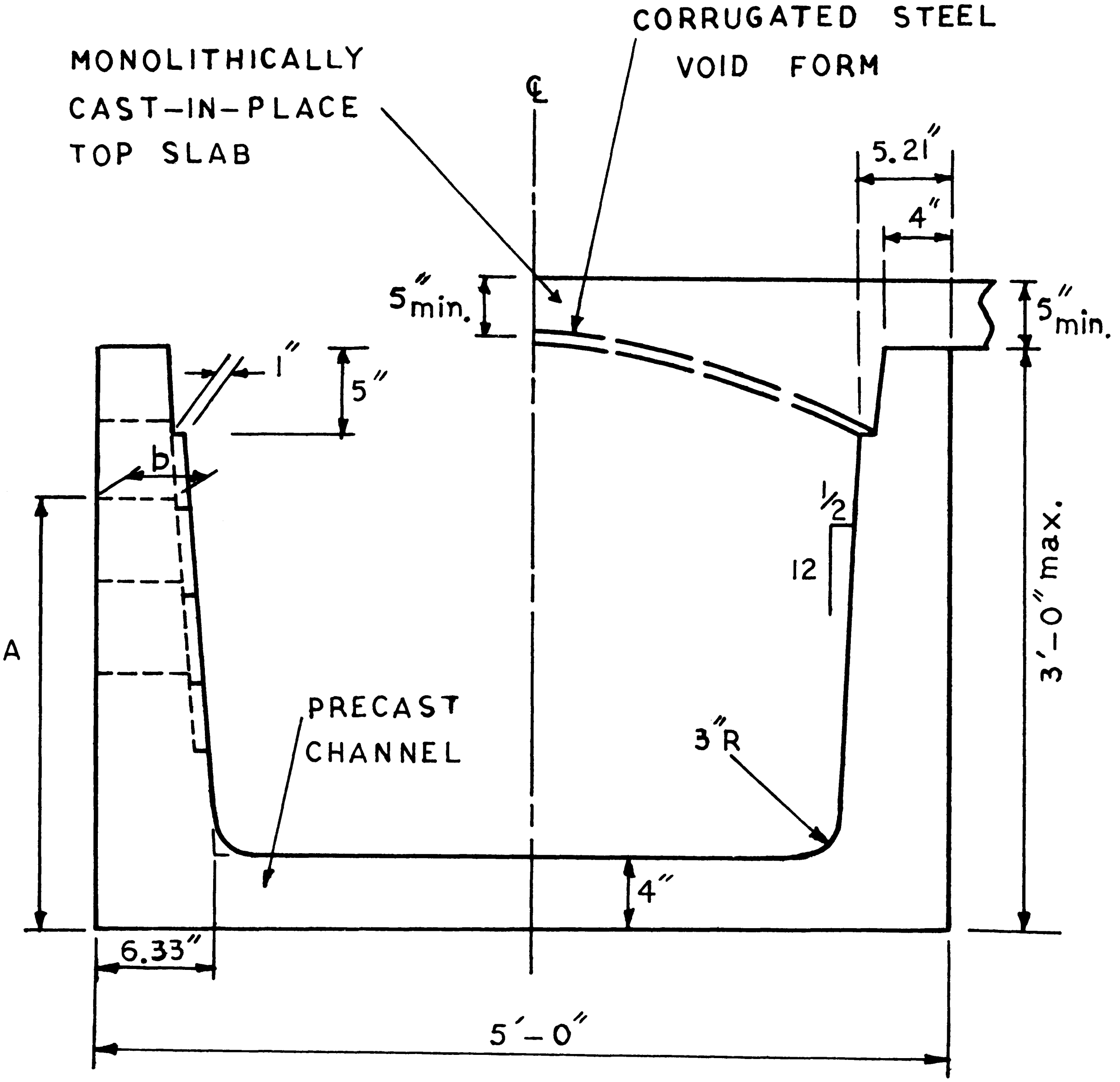


Figure 2. Precast concrete deck components.



A	20"	24"	28"	32"	36"
b	4.67"	4.50"	4.33"	4.16"	4.00"

Figure 3. Standard channel section recommended by Missouri Highway Department.(134)

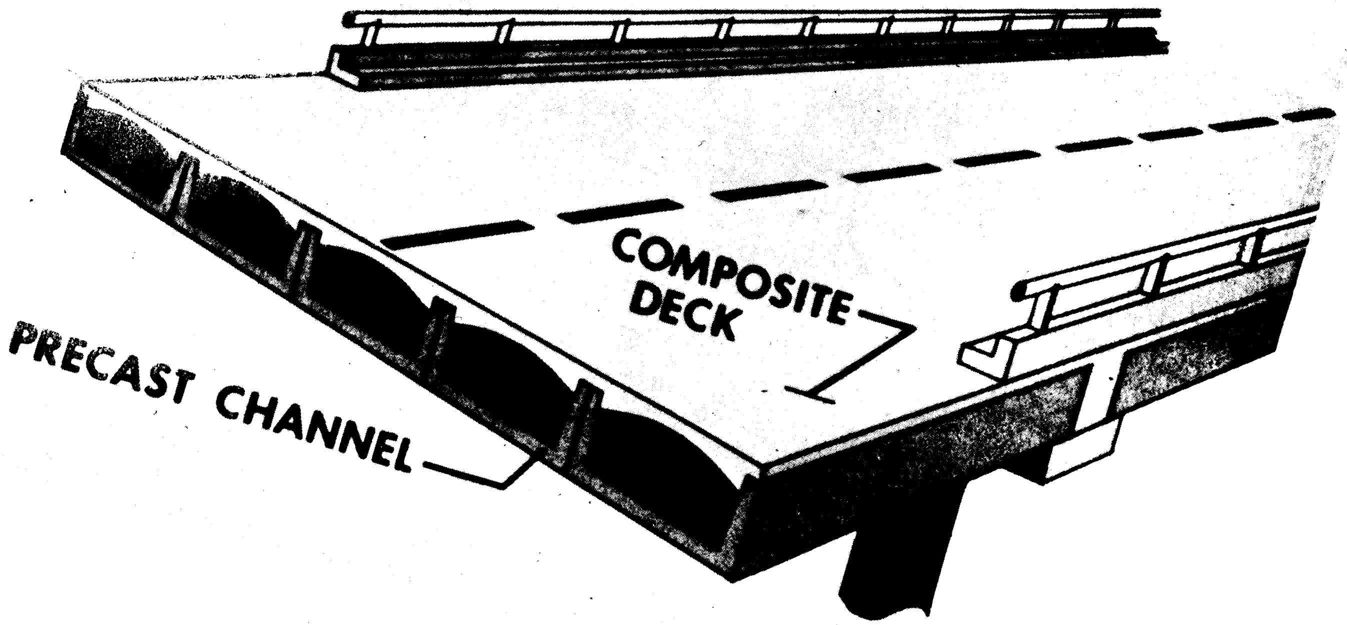


Figure 4. Precast channel bridge system proposed by Missouri Highway Department. (135)

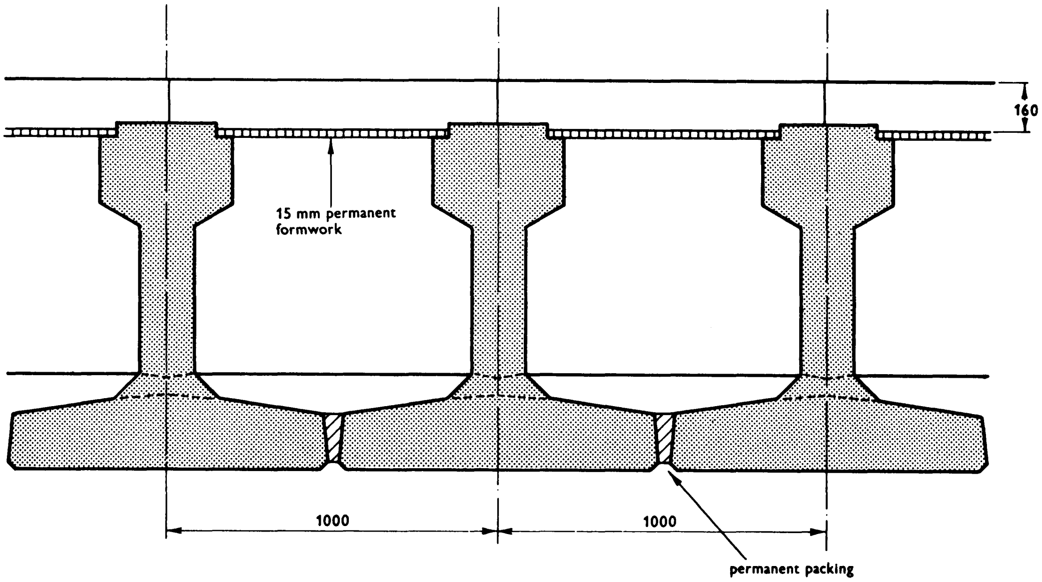


Figure 5a. Composite voided slab construction.

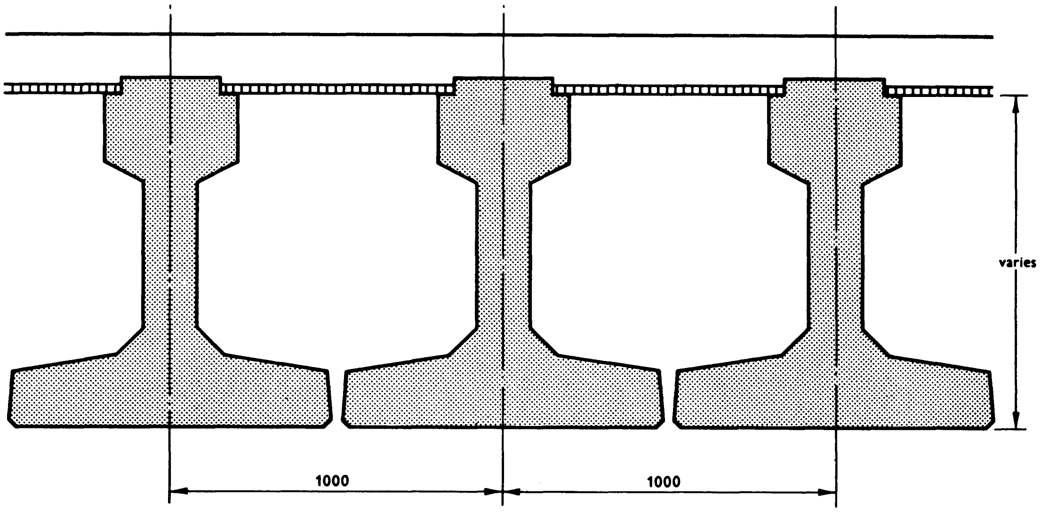


Figure 5b. Composite beam and slab construction.

Figure 5. Composite construction.(136)

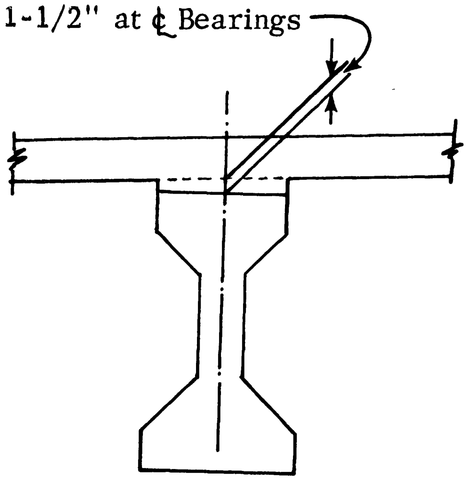


Figure 6. Recommended slab haunch detail (137)

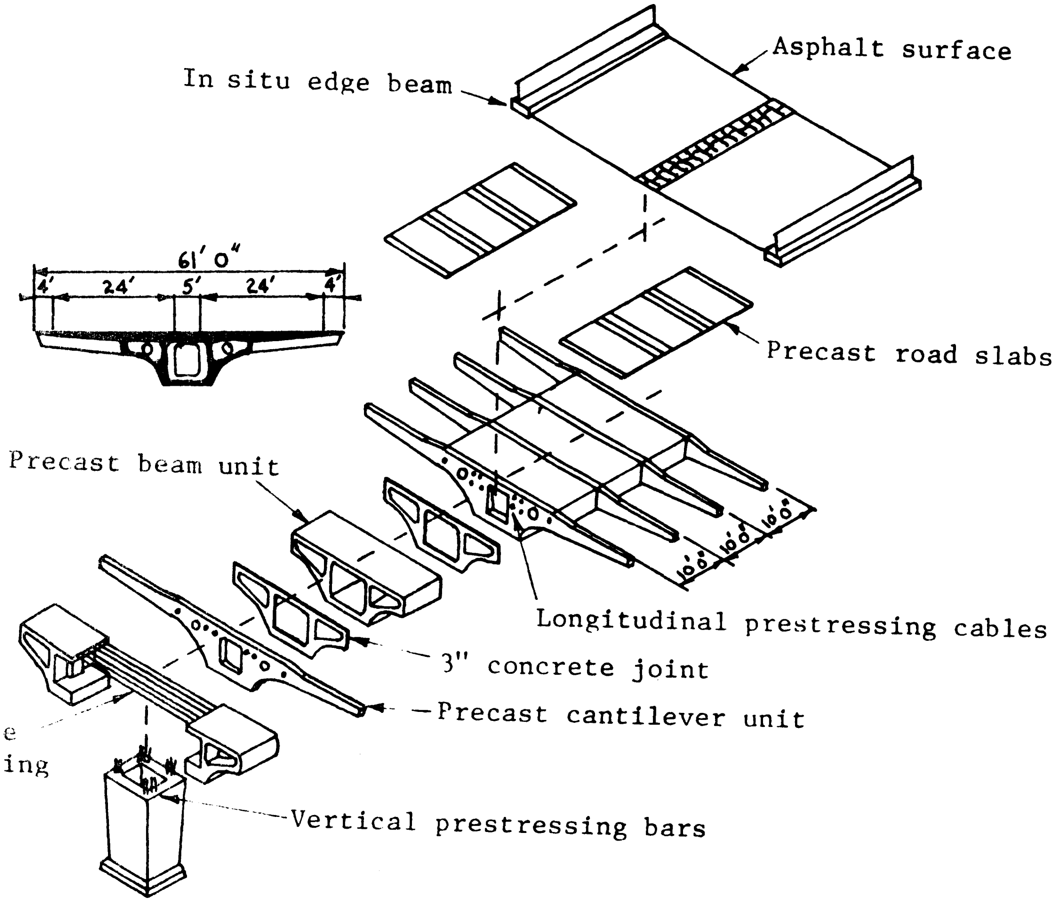


Figure 7. Hammersmith Flyover, London. (138)

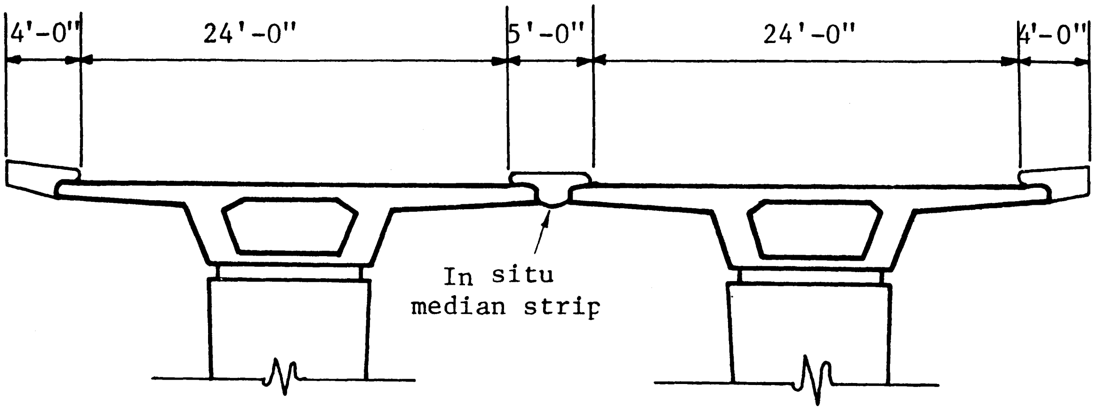


Figure 8. Mancunian Way, Manchester.(139)

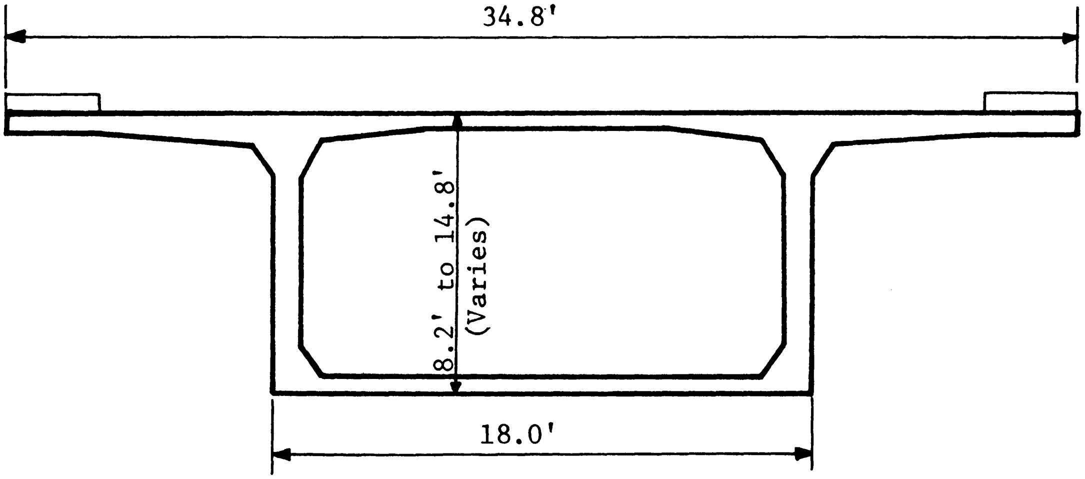


Figure 9. Oleron Viaduct, France.(140)

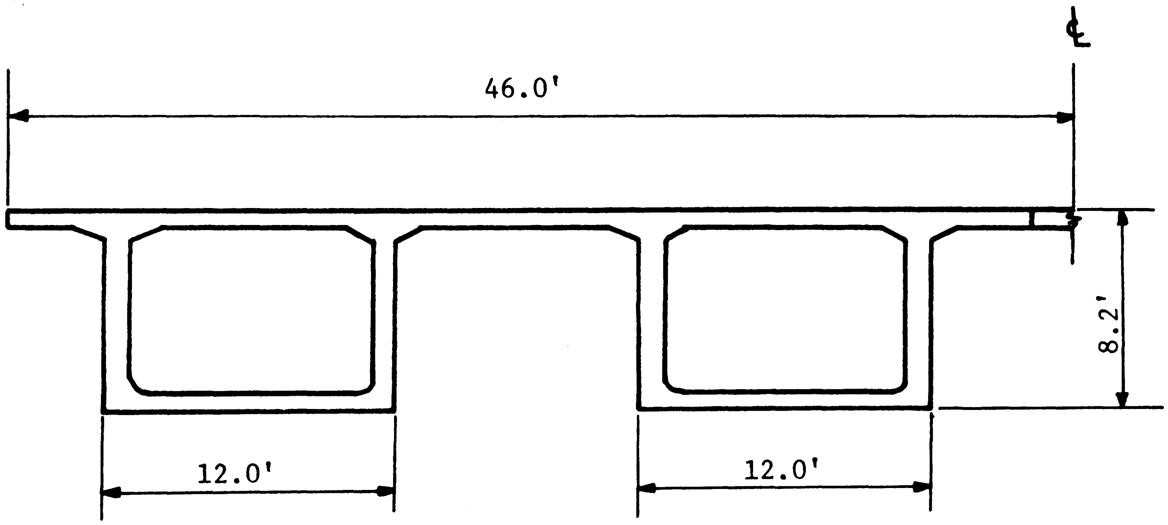


Figure 10. Choisy-le-Roi Bridge, Paris.(141)

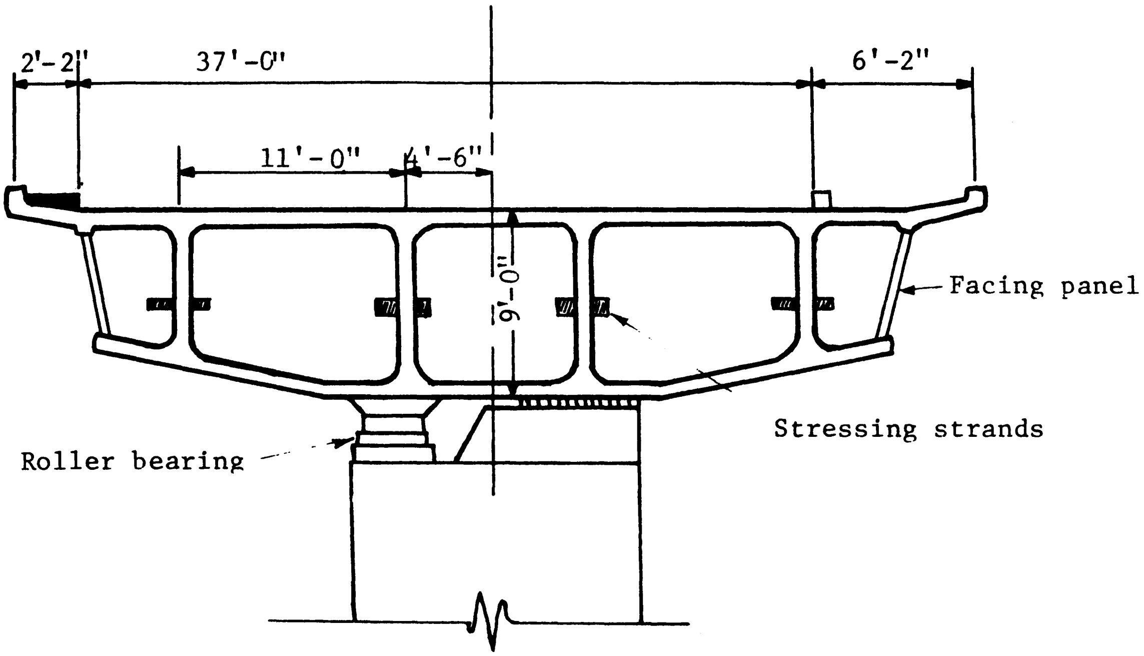
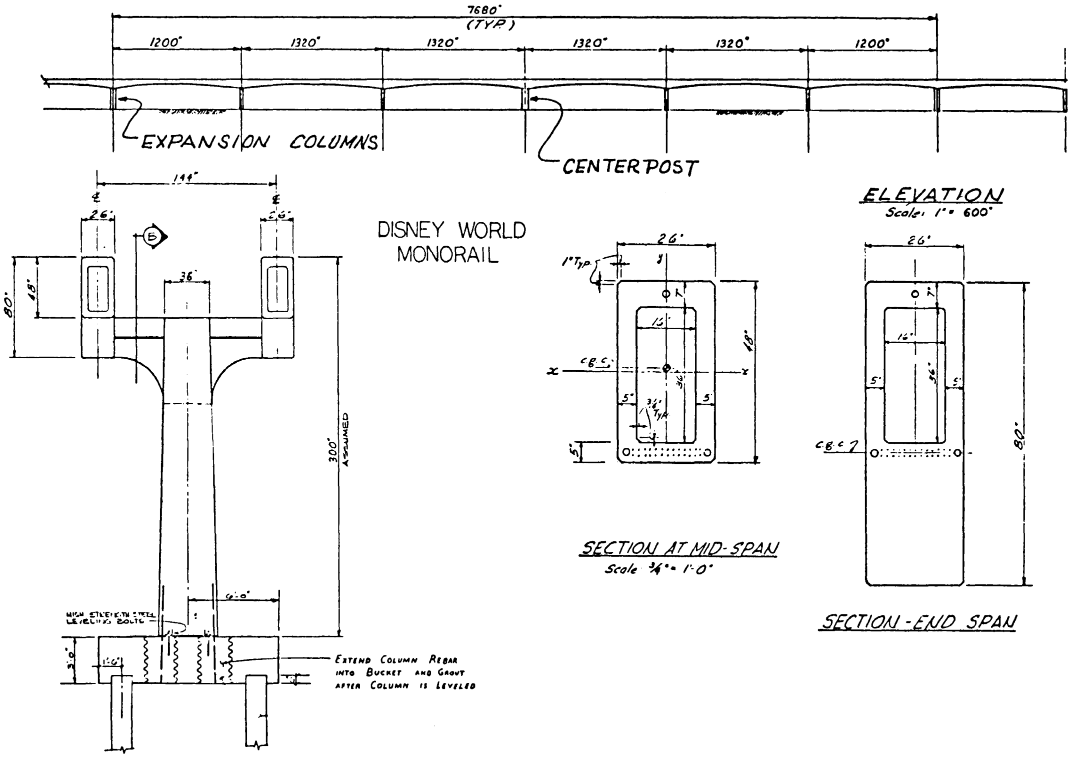
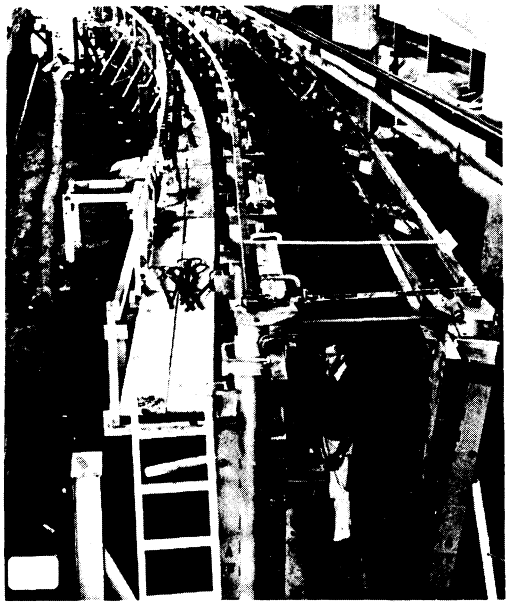


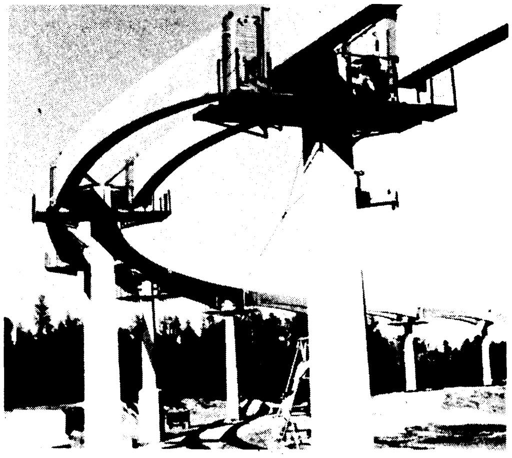
Figure 11. Commonwealth Avenue Bridge, Canberra.(142)



Structural details of Disney monorail guideway (all dimensions in in.).



Variations in horizontal, vertical, and superelevation permitted by adjustable forms for curved sections of monorail



Cable ducts coupled by sleeves and gap between girders filled with cast-in-place concrete (6 girders connected into continuous spans)

Figure 12. Disney monorail.(143)

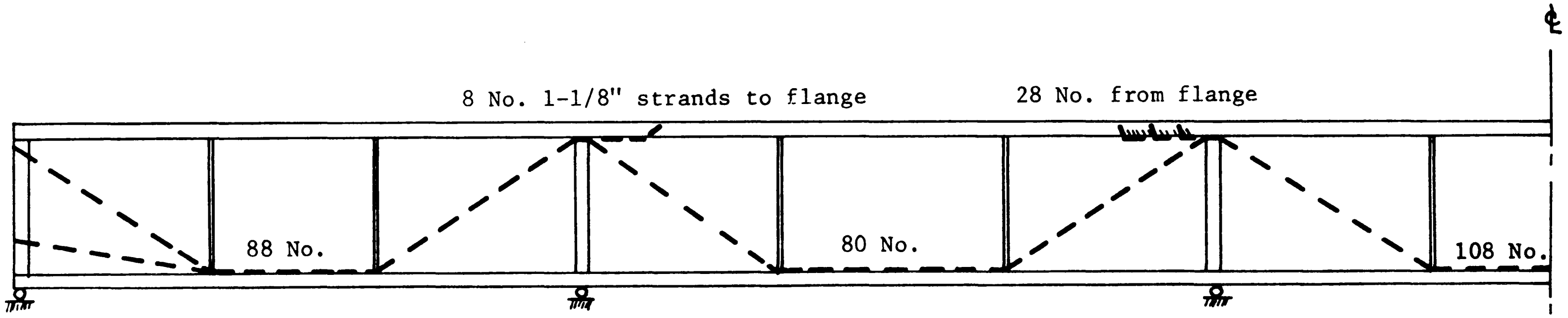


Figure 13a. Commonwealth Avenue Bridge — longitudinal cable profile.

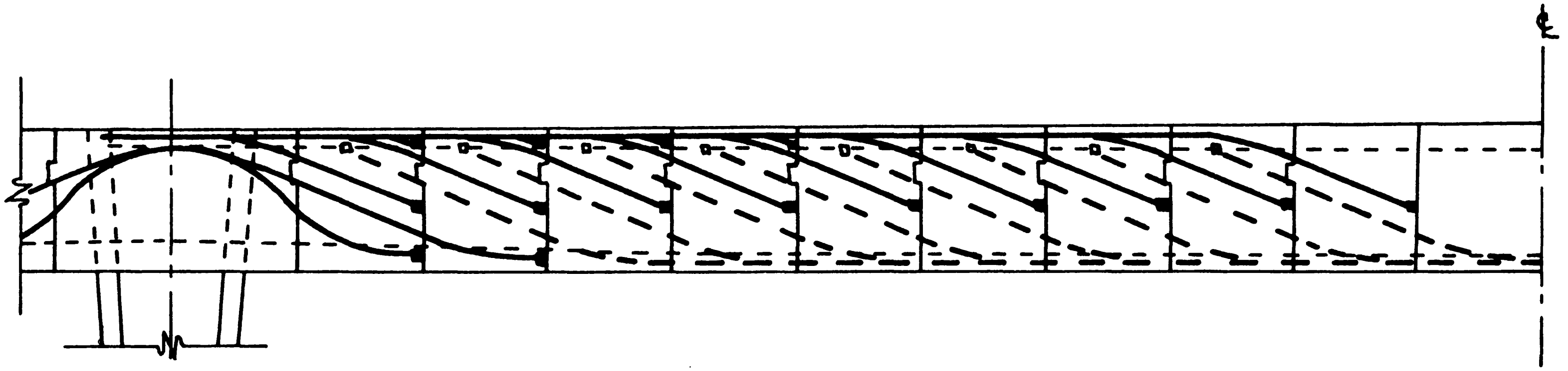
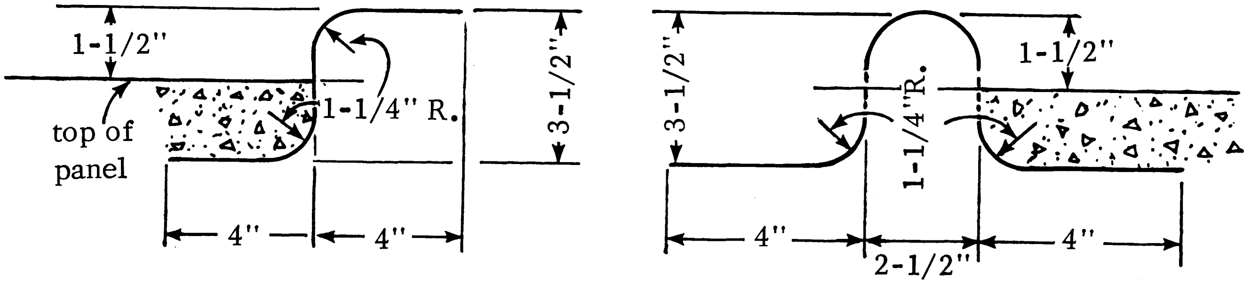


Figure 13b. Choisy-le-Roi Bridge — longitudinal cable profile.

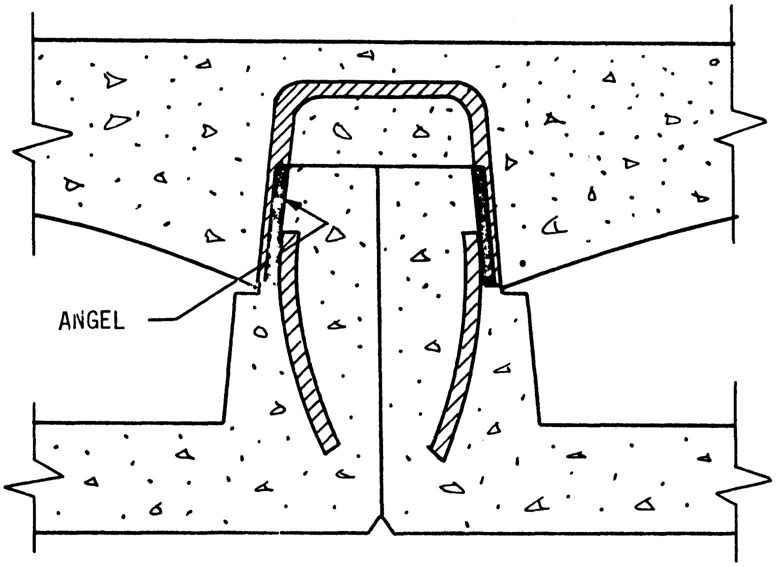
Figure 13. Longitudinal cable profiles.(144)



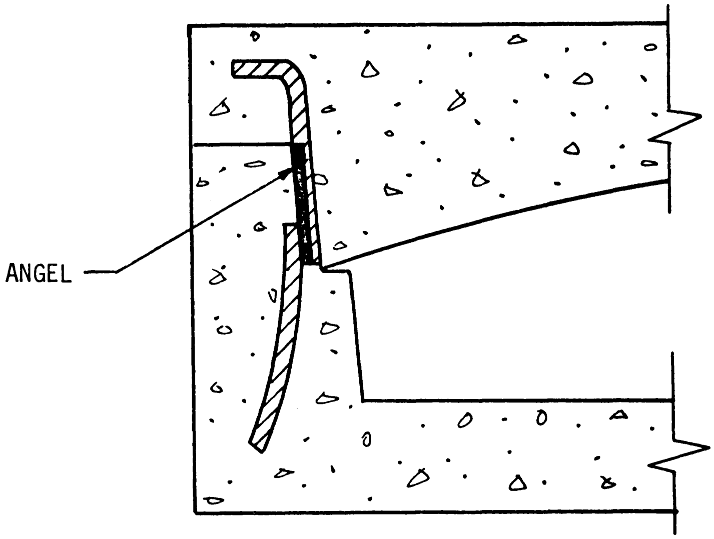
Bar Z (#4 Bar)

Bar U (#4)

Figure 14. Reinforcing bar shear connectors used in Texas Highway Department model bridge (145)

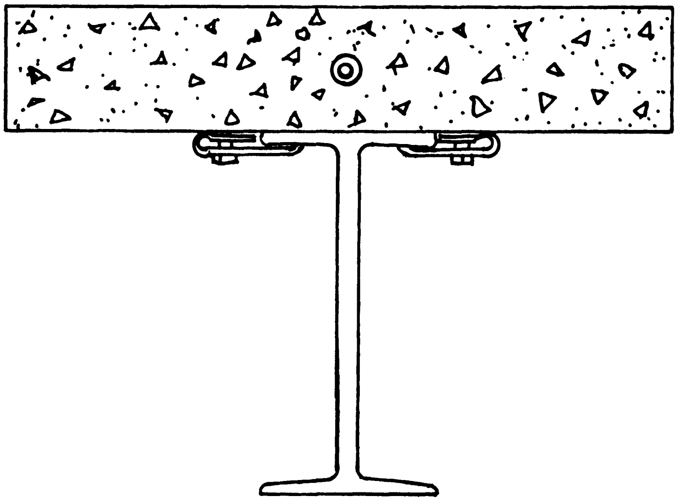


At interior joint



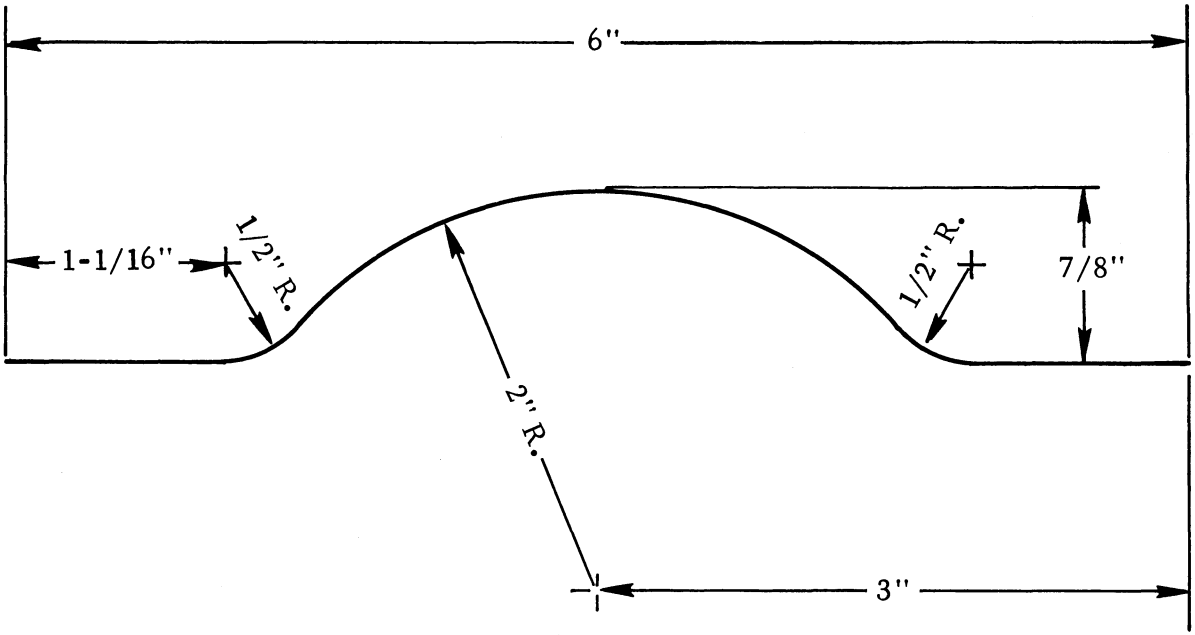
At exterior joint

Figure 15. Proposed joint steel for Missouri test bridge.(146)

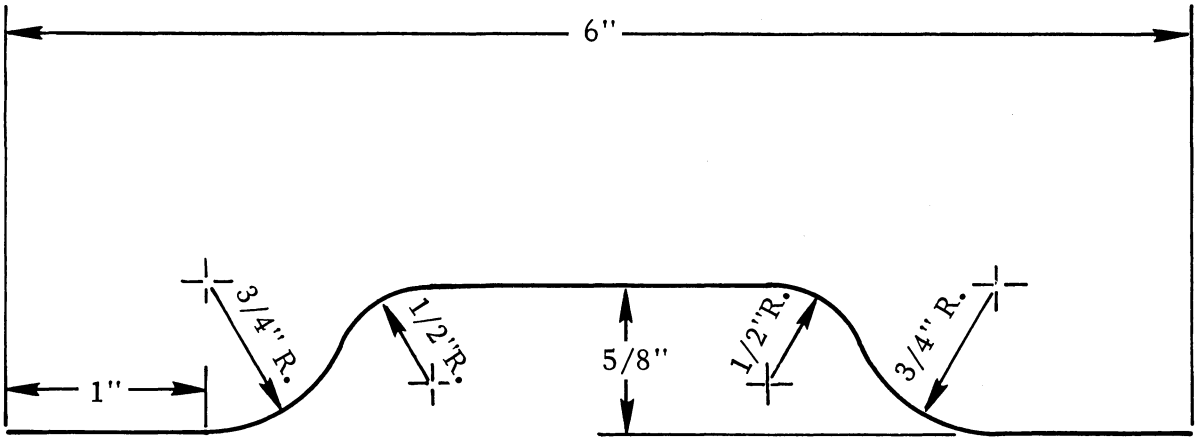


(147)

Figure 16. Spring clips and bolts for beam and slab construction



Partial-circle joint



Flat, key-type joint

Figure 17. Joints recommended by Purdue University.(148)