APPLICATION AND DESIGN OF PRESTRESSED DECK PANELS

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The purpose of this paper is to review the development of precast prestressed concrete panels as permanent structurally interacting forms in the construction of reinforced concrete decks for stringer type bridges. This system was used on the Illinois Toll Highway in 1957. In 1963 Texas constructed three bridges in this manner. Many bridges have been subsequently completed using this slab construction technique. Precast prestressed concrete panels are placed to form a deck between adjacent stringers. A mat of reinforcing steel is placed and concrete is cast-in-place on top of the panels. The panels support the weight of the wet concrete and then act compositely with it to resist subsequent live loads. Design of the panel deck system is explained and several aspects of fabrication and construction are reviewed.

Early in the modern era of bridges, it became apparent that construction is simplified considerably by using preformed beams (stringers), to span from bent to bent. These stringers usually can be manufactured under a more sheltered environment, delivered to the bridge site by some common mode of transportation and erected without the use of expensive falsework or shoring. First it was timber that was the most readily available stringer material, then steel became economical and lately precast prestressed concrete beams have been developed to accomodate spans of over one hundred feet. A deck must be constructed to span the space between stringers, adjust elevation differences and provide a smooth riding surface. Timber decks were used originally with timber and some steel stringers, but the most popular deck soon became reinforced concrete because of its workability, smoothness and durability. However, construction of a concrete deck has never been easy. Forms must be tight, supported sturdily from the stringers and adjustable for line and grade. The concrete must be strong and durable and it must be placed and consolidated properly. Expert finishing is required to achieve a good riding surface. Early on, the deck would cost half as much as the stringers beneath. This ratio has continued to rise until, in 1977, the decks cost as much as the stringers on Texas bridges. Naturally, there have been attempts to reduce this cost by devising more efficient systems for construction of bridge decks. There have been better forming procedures developed, including stay-in-place metal forms, admixtures introduced to improve the workability of the concrete without injuring the strength and durability, and bigger and better finishing machines marketed to replace the skill required for producing a good surface. One system, which appears to be coming into more widespread use in this country, uses precast prestressed concrete panels to serve as forms and act with a thin cast-in-place slab to provide a bridge deck of sufficient strength to carry the live load (Figure 1).

This development did not occur overnight. As early as 1957 some of the bridges on the Illinois Toll Road were constructed with prestressed panel decks (1). No further activity was reported until 1963 when Texas constructed three grade crossing structures utilizing prestressed concrete panels. Another five year gap in experience followed, broken in 1968 with the letting of Texas' Trinity River Bridge near Trinidad (Figure 2) and others amounting to a total of 130,200m$^2$ (1,400,000 ft$^2$) of panel deck let during the four year period ending in 1971. During this time research began with an investigation of the 1963 Texas bridges (Figure 3) and continued through 1975 with projects conducted by Texas A & M University, the University of Florida and Pennsylvania State University on various phases and details of panel deck construction (2). Another two year lapse ensued during which the Texas research was culminated (Figure 4) and some of the restrictions governing panel use imposed by the FHWA were overcome. Since 1974 there have been a steady number of bridges constructed in Texas using prestressed concrete panel decks. Other states have also constructed panel decks lately and inquiries indicate that still others are seriously contemplating their use. It appears that the prestressed deck panel method has become acceptable for construction of decks on prestressed concrete stringers.

The purpose of this paper, after having reviewed the background of panel deck construction, is to briefly recap the design concepts and then discuss various manufacturing and construction problems that influence the economy of the system.

Design of prestressed panel decks is the same as for conventional slabs on stringers, except for consideration of the prestressed member as it carries the entire deck dead load and then acts compositely with the cast-in-place slab to resist the live load (Figure 7). The selection of prestressed panel thickness is not vital to the structural design. It can be as thin as possible to contain a layer of seven wire strands or as thick as practical to allow a slab with the necessary cover to an imbedded reinforcing steel grid. The Texas approach was to maintain the total panel plus cast-in-place thickness the same as for a full depth reinforced concrete slab, with the panel thickness in one quarter inch increments, approximately one half the total thickness. This has lately been considered a mistake because of the multiplicity of panel thickness which require different side forms. Often two or three different thicknesses would be required for one project or even one bridge due to the variation of stringer spacing.

Once the panel thickness is selected and the topping thickness estimated, the design can proceed to the calculation of required prestressing, mild steel reinforcing and evaluation of the thicknesses selected. A unit strip of panel is analyzed as a plain rectangular beam for stresses due to simple beam moments caused by the weight of the panel plus cast-in-place slab. Live load moment on the unit strip is calculated, using the regular slab on stringer distribution formula of A.A.S.H.T.O. Article 1.3.2(C) and the 80% continuity factor. A rectangular section of the total panel and cast-in-place thickness is analyzed for stress due to this moment. The sum of these two stresses, less any tension allowable, must be counteracted by the prestress. Thus strand size and spacing may be determined. Since there has been some question about the ability of strands to develope themselves for resistance of ultimate moment in the relatively short length of the panels, Texas has always used 9.5mm (3/8" Ø) strands. Research has indicated no problem with development length, however, and a check of the ultimate moment resistance of the positive moment portion of the panel deck will indicate more than adequate strength using the stress that can be developed according to the formula in A.A.S.H.T.O. Article 1.6.18. The negative portion over the stringers is analyzed as a plain reinforced concrete beam for the live load moment as calculated above. The size and spacing of transverse mild steel in the top of the cast-in-place slab is thus calculated. Concrete stress will not be critical at this point. The strength of the panel concrete is higher than for the usual conventional slab and it has been verified by research (3) that compression in the panel due to prestressing does not have to be added to the beam compression due to live load in establishing the required concrete strength. If the results are reasonable and compatible with the original assumptions, the design is complete. Otherwise new thickness assumptions are made and the system re-analyzed until satisfaction is achieved. The amount of reinforcing perpendicular to the prestressing strands is nominal as is the longitudinal reinforcing in the cast-in-place portion, except that temperature requirements must be satisfied. Texas maintains a fairly high amount of longitudinal reinforcing 13mmØ @ 230mm (#4 @ 9") because there is a history of fine transverse cracking with panel decks and since the most conclusive research used this amount of steel. Composite behavior of the panel and cast-in-place slab, with or without steel across the interface has been verified by tests (3,4). The same research failed to disclose any problem with composite action of the deck with the stringers. Consequently, stringer design can be the same with panel decks as with reinforced concrete deck if the two are of the same thickness.

Panels may be designed to extend past the outside stringers into the overhang also (Figure 2). Openings in the panel are provided over the outside beam to match the beam stirrups in order to achieve the composite tie. This system was used in Texas on a few bridges but has since been abandoned due to construction problems considered not justified by the advantages thereof.

Current details for prestressed precast concrete panel deck used in Texas are shown in Figure 8.

Structural design of the panels has been adequately verified by research and use. Problems in manufacture and construction continue to be studied so that the cost of adequate panel decks can remain competitive.

Panel decks are not automatically less expensive than conventional wood formed decks. Prices have fluctuated so that it is impossible to establish the economy of the panel deck without actually taking bids on an alternate or optional basis. Until 1974 the panel deck was offered for an alternate bid on selected Texas projects. The alternate bid items were slab concrete, reinforcing steel and prestressed concrete panels. During the four big years of 1968-71 prices ranged from $1.15 per square foot for panels to $1.53 and from $63 per cubic yard for concrete to $80. In 1974 a large project was bid for $.75 per square foot with $135 concrete but in 1975 another project was bid at $2.58 - $134. During this period panel deck construction was not used by the low bidding contractors on several other projects. Projects selected were usually those with considerable repetition of details and also high above the ground or over water where form removal is more difficult and dangerous.

Manufacturing problems have influenced the cost of panel decks to some degree. Early problems involved the reinforcing that protruded from the top of the panels. In the beginning there were "Z" shaped bars on 457mm (18 in) centers each way, one leg of which was in the plane of the strands under the transverse bar mat with the other leg 38mm (1 1/2 in) above the top of panel (Figure 5). These bars had to be tied in place before concreting, because of being under the top mat, and they interfered with the finishing of the top of the panel. Some fabricators tried leaning the "Z" bars enough to screed over the top and then lifting them to position and patching the tear left in the concrete. Others tried to finish in between bars. Another problem involved removing splashed concrete from the protruding "Z" bars. They always got a liberal coating of concrete, which took too many man hours to remove. These problems were solved by one fabricator by using multiple loop "U" bars that could be tied more securely than the "Z" bars and employing external form vibrators to level the concrete instead of a screed (Figure 6). The rough top finish required to facilitate bond with the cast-in-place deck was provided with a stamp made of expanded metal lath. Currently the rough finish is accomplished with a stiff broom.

On the first project using panels extending past the outside beam into the overhang, there was a considerable problem due to mislocation between the stirrup bars protruding from the beam and the hole in the panel through which these bars were supposed to be grouted. Where the holes did not match it was necessary to cut off the stirrup bars and drill and grout an anchor bar into the beam to match the hole location. Two other projects did not exhibit the problem, but items that were necessary to cast into the edge of the panels, such as rail parapet bars, anchor bolts, light brackets and deck drains discouraged the use of panels in the overhang. Also, vertical offset between bottoms of adjacent panels made the overhang somewhat rough in appearance. Although overhang panels have proven to be structurally adequate, they are no longer used in Texas.

A nagging problem that continues to occur is cracking of the panels during handling. The panels are weak in the direction parallel to the prestressing strands, since they are thin and have the reinforcing steel in the middle. There is even less than the gross concrete section resisting moment since the strands form a weakened section and may even create a certain amount of splitting stress themselves, as reported by Pennsylvania (4). There have been projects with as many as 10% of the panels rejected because of cracking, but there have been others with practically no rejects. It is possible to deliver crackless panels but very careful handling is required. The method of lifting must not induce severe bending stresses. Panels are usually stacked five or six high for delivery. Four point or two line resilient blocking, properly located, that bears evenly on upper and lower panels must be provided, along with straps or tie-downs located immediately over the blocking. Care is still required by the carrier to avoid unnecessary roughness. It has been necessary to develop acceptance criteria whereby some cracking parallel to strands is permissible.

With the use of panels on more and more projects, the problem caused by several different designs to fit various beam spacings became apparent. Not all projects are big enough to pay for different side forms and pulling heads. A constant panel thickness and strand spacing became highly desirable so that a more permanent type bed could be provided. Texas' standard details have been revised to meet this requirement (Figure 8). It was considered and calculated to be structurally sound to use 102mm (4 in) thick panels with 9.5mm (3/8" Ø) strands on 152mm (6 in) centers for all beam spacings. This represented a departure from original design controls, primarily in the allowance of some tension in the panel under design loads. The thicker panel allowed the transverse mild steel to be placed below the strands without violating cover requirements. Both the thickened panel and bottom reinforcing are expected to reduce the susceptibility to cracking. Mild steel in the form of wire mesh under the strands will overcome another problem caused by the requirement that no form oil be allowed on the strands. Other revisions were made to the details in order to improve production economy, including allowance of saw cutting square panels to form skewed ends.

In addition to fabrication problems, there are some construction problems that have been encountered with panel decks. Texas has always used constant thickness fiber board strips at the beam edges on which to bed the panels. Early attempts to glue this material on the beams in the fabricating plant were unsuccessful. Placing the strips immediately before erecting the panels is more practical (Figure 9). Rough beam tops can close the opening between the panel and slab so much that grout will not flow in for bearing. It was established by trial that grout from regular deck concrete would flow into a 3.2mm (1/8 in) space. On one early project the beam tops were too rough to let grout enter when 13mm (1/2 in) thick strips were used. The thickness of the strips was doubled. On subsequent jobs the tops of the beams outside of the stirrup bars have been trowelled smooth for better grout penetration. The portion within the limits of the stirrup bars is left rough to provide bond between beam and slab. The gap left between bedding strips to allow air escape has sometimes allowed mortar to escape also. This is corrected by placing a short bedding strip behind the gap to block the mortar exit while allowing the air to escape.

After the panels are erected, extensive grading is required (Figure 10). Because the panels on the constant thickness strips follow the camber of the beams, it is necessary to adjust to finished grade by placing a variable thickness cast-in-place slab, usually thicker nearer the bearings and the minimum design thickness in the span center. This extra thickness occurs through the entire width and most of the length of panel deck and can amount to a sizeable increase in concrete quantity. It is desirable to keep this overrun to a minimum, so bottom of panel elevations are taken for several spans ahead of the concrete placement, if practical. Grade lines and slopes can then be adjusted slightly if necessary to provide minimum concrete over the high points while minimizing the extra thicknesses required near the bents. A computer program has been provided to assist in these deliberations. Initially, Texas paid for this extra concrete at bid prices. Then the specifications were changed to pay only invoice price for the extra concrete since forming and placing costs were hardly affected. Now the decks are bid by the square foot so the overrun is not paid for directly. Pennsylvania reported bedding the panels on variable thickness strips of grout in order to reduce the cast-in-place slab thickness. Sealing of the joints between panels has not been a problem. They usually fit together closely so that only a little tape or caulking is necessary to make them mortar tight.

Just prior to placing concrete the panels are cleaned by high pressure water. There should be no free water standing on the panels when concrete is placed. This poses no particular problem and this type of cleaning appears to be sufficient. Occasionally there may be laitance or even adhered pieces of curing fabric which will require sandblasting to remove prior to concrete placement. No grout or paste is required to be scrubbed in before placement (Figure 11). Placement and finishing of the concrete is very similar to the conventional slab except that it doesn't last as long because of the reduced thickness (Figure 12).

In 1975 prestressed panel decks began to be offered as options to conventional decks rather than alternates. Payment was made on the basis of the plan quantities for the conventional deck. This allowed more projects to have panels because it was not necessary to prepare complete plans and calculate accurate quantities for the panel deck. In 1977 Texas published a specification that provided for bridge decks to be bid and paid for by the square foot, with the Contractor having the option to form conventionally, use stay-in-place metal forms or provide a prestressed concrete panel deck. This makes allowance of panels very easy from the plan preparation stand point and has greatly increased the number of projects with panel options. Under this system bridges are built all three ways. Most are still conventional wood formed decks, but some are metal deck and an increasing number seem to be prestressed concrete panel decks. They continue to be favored for long, repetitive bridges, although safety requirements for solid deck over traveled ways have increased their desirability for shorter structures. It is anticipated that even further usage will occur when the advantage of the current details are fully realized.

In summary, the development of prestressed concrete panels has been reviewed, structural design procedures given, fabrication and construction problems discussed and the latest improvements presented. It appears that panel decks are here to stay. Now is the time for someone to develop an adequate and economical full depth precast deck for stringer bridges.

## References

1. Bender, M. E. and J. N. Knoerle, "Prestressed Concrete Bridges for the Illinois Toll Highway," World Conference on Prestressed Concrete, Paper A-11, 1957.
2. Transportation Research Circular Number 181, September 1976.
3. Furr, Howard L. and Leonard L. Ingram, "Cyclic Load Test of Composite Prestressed-Reinforced Concrete Panels," Summary of Research Report 145-4F, Texas A&M University (December 1972)
4. Barnoff, Robert M. and James A. Orndorff, "Construction and Testing of an Experimental Prestressed Concrete Bridge," Research Project #71-8, Report #1, Pennsylvania State University (March 1973).

Figure 1. Prestressed Concrete panel deck schematic.

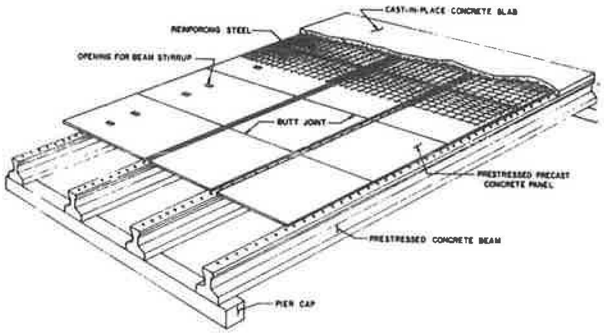



Figure 4. Full size prestressed concrete beam span with panel deck tested at the University of Texas.

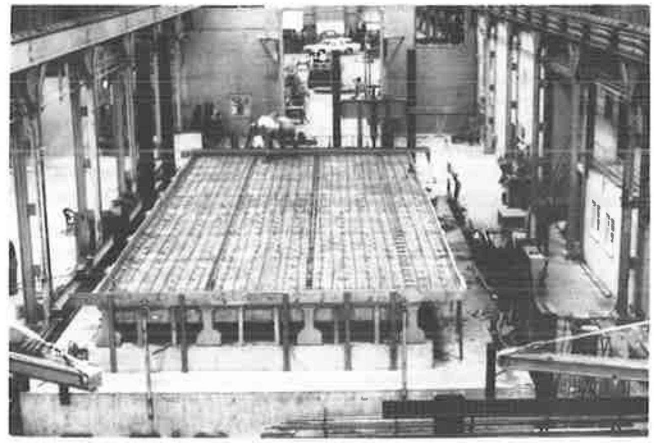


Figure 2. Trinity River Bridge near Trinidad.

Figure 5. "Z" Bars were difficult to place.

Figure 3. Core from 7 year old panel deck.

Figure 6. "U" Bars with external vibration are better.

Figure 7. Structural analysis of a panel deck.

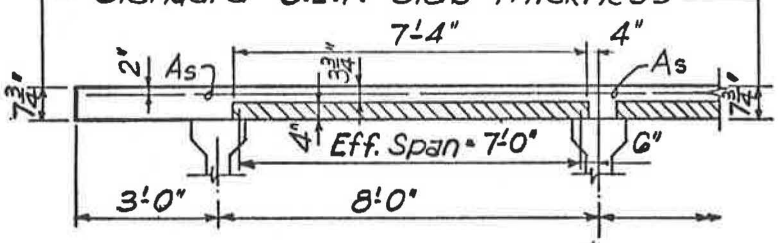
DESIGN R.L.R. DATE 6/26/78
CK. DSN. ........ DATE ........
DESIGN FOR PRESTRESSED PANEL DECK

TEXAS
STATE DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION
BRIDGE DIVISION

COUNTY ........
CONTROL ........
I.P.E. ........
HIGHWAY ........
SHEET ........ OF ........

HS20 Loading — 8'-0" Beam Spacing

Standard C.I.P. Slab Thickness




Try Standard Panels
4" Thick
$f'_{ci} = 4000$ p.s.i.
$f'_c = 5000$ p.s.i.
$\frac{3}{8}$"$\phi$ 270K Strands @ 6" c.c.
Cast-in-Place
$f'_c = 3000$ p.s.i.
$f_y = 60$ k.s.i.

$DLM = \frac{1}{8} \times .0969 \times 7^2 = 0.59^{K'}$

$LLM = \frac{.8(7+2)}{32} 16 \times 1.3 = \pm 4.68^{K'}$

Panels:

DL $S = \frac{12 \times 4^2}{6} = 32 \text{ in}^3$

DL $f_c = \frac{.59 \times 12000}{32} = -221$ p.s.i.

LL $S = \frac{12 \times 7.75^2}{6} = 120 \text{ in}^3$

LL $f_c = \frac{4.68 \times 12000}{120} = -468$ p.s.i.

Design Total $f_c = -689$ p.s.i.

Prestress $= \frac{16{,}100 \times .8 \times 2}{4 \times 12} = +538$ p.s.i.

Final Panel $f_c = -151$ p.s.i.

Allow. $= 6\sqrt{5000} = -424$ O.K.

Cast-in-Place Slab:

Req'd d (Overhang) $= \sqrt{\frac{4.68}{.197}} = 4.87"$
$\quad + 2.$
$\quad = 6.87"$

Provided 7.75" O.K.

$A_s = \frac{4.68 \times 12}{20 \times .875 \times 5.75} = .558\ \square"$

#5 @ $6\frac{1}{2}$" c.c. O.K.

Check Ultimate Moment: +M

$f_{su}^* = f'_s\left(1 - .5\frac{p^* f'_s}{f'_c}\right)$ AASHTO 1.6.9(C)

$= 270\left(1 - \frac{.5 \times .0854 \times 2 \times 270}{5.75 \times 12 \times 3}\right) = 240$ ks.i.

or

$f_{su}^* = \frac{L}{D} + \frac{2 f_{se}}{3}$ AASHTO 1.6.18

$= \frac{44}{.375} + \frac{2 \times .7 \times 270 \times .8}{3} = 218$ k.s.i. Use

$M_u = A_s^* f_{su}^* d\left(1 - \frac{.6 p^* f_{su}^*}{f'_c}\right)\phi$ AASHTO 1.6.9(A)

$= 2 \times .0854 \times 218 \times \frac{5.75}{12}\left(1 - \frac{.6 \times .0854 \times 2 \times 218}{5.75 \times 12 \times 3}\right).9$

$= 14.3^{K'}$

Check Ultimate Moment: −M

$M_u = A_s f_y d\left(1 - \frac{.6 p f_y}{f'_c}\right)\phi$ AASHTO 1.5.32(B)

$= .567 \times 60 \times \frac{5.75}{12}\left(1 - \frac{.6 \times .567 \times 60}{5.75 \times 12 \times 3}\right).9$

$= 13.2^{K'}$

Req'd $M_u = 1.3(DLM + \frac{5}{3}LLM)$
$= 1.3(.59 + 1.67 \times 4.68) = 10.9^{K'}$
O.K.

Standard Panels Adequate

one foot (') = .3048 m, one inch (") = 2.54 cm, one square inch (□") = 6.45 cm²
one kip foot = 1,356 Nm, one pound per square inch (p.s.i) = 6.895 kPa
one kip per square inch (k.s.i.) = 6.895 MPa

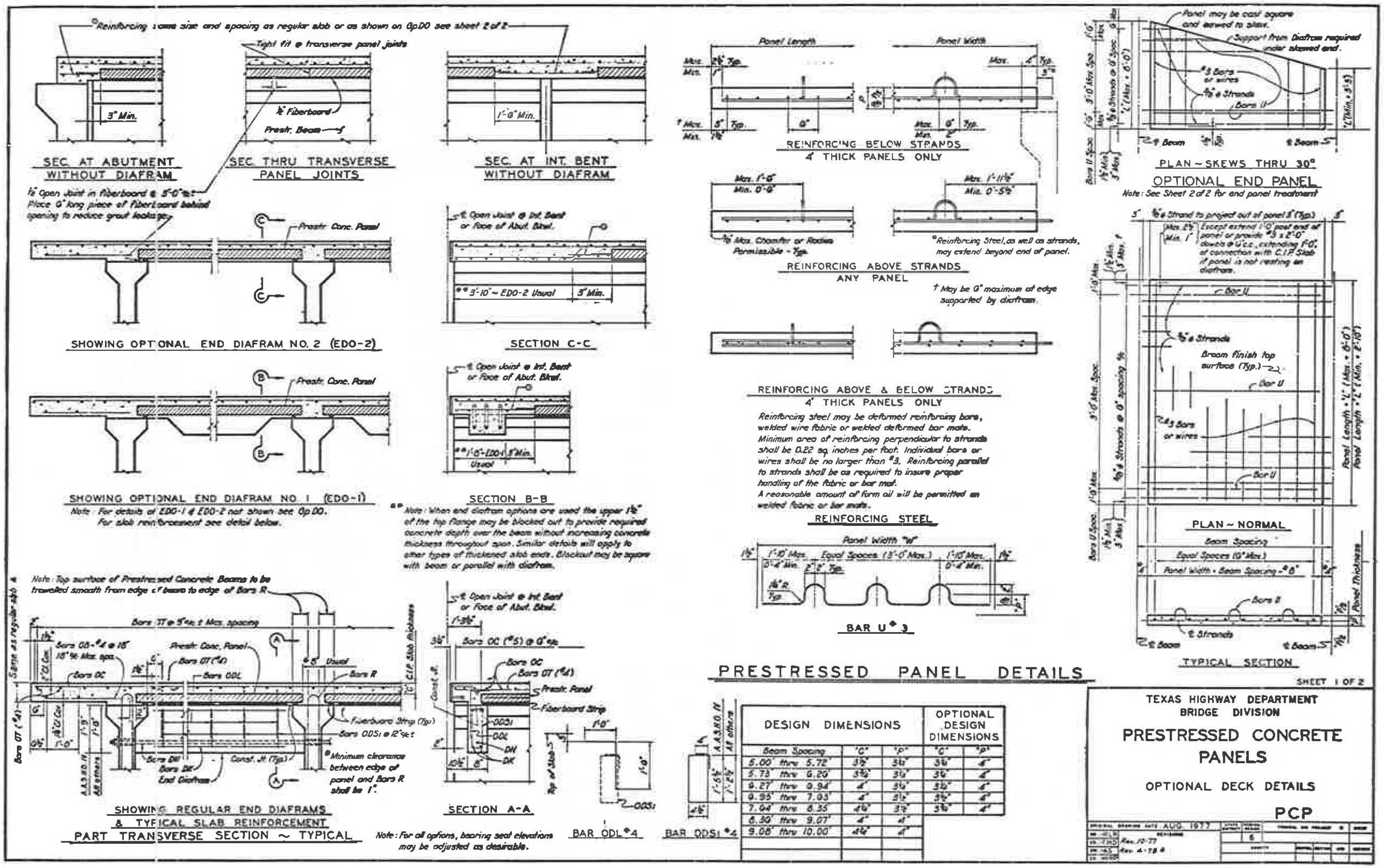



Figure 8. Current Texas standard panel deck details.

Figure 9. Panels being placed on fiberboard strips.

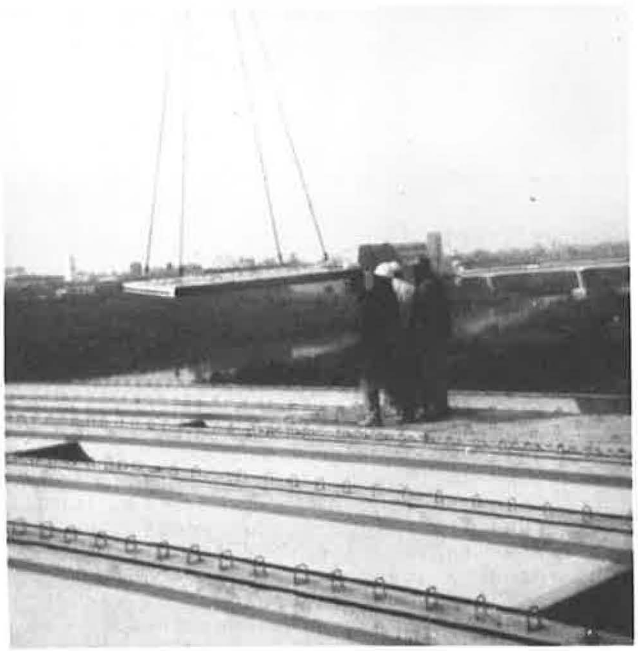


Figure 11. Concrete placement.

Figure 10. Grading the deck after erection of panels.

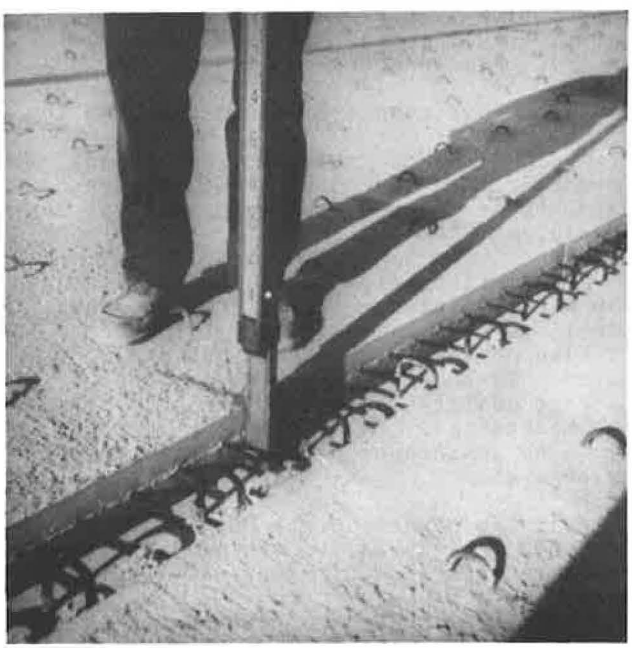


Figure 12. Concrete finishing.