

WEDGE ANCHORAGE SYSTEM FOR STRAND POST-TENSIONING

Reports on design and development of a 3-strand wedge anchor and anchorage components. This system has been applied in development of tendons with working forces from 225 to 1300 kips (100 to 600 t). Static and dynamic test results are reviewed, and use of the system in U.S. bridge and building construction is described.

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The need for a new high capacity strand post-tensioning system in the United States, was apparent by late 1967. The demand for long span, cast-in-place post-tensioned structures in the United States seemed certain to expand rapidly, and comparative costs of tendon materials indicated that strand would economically meet this growing need. Pull-through tendon systems, which require neither fixed tendon lengths nor factory-attached anchorages, have considerable cost advantages for long span cast-in-place bridges, buildings, and nuclear reactor containment structures. Existing European pull-through tendon systems were well represented in the United States and licenses were unavailable.

In response to these factors the authors began development of the S/H Wedge Anchorage System.

SYSTEM CRITERIA

Specific criteria for this system, established prior to the start of hardware development, were:

1. Tendons must develop the minimum guaranteed ultimate tensile strength of the assembled strand.
2. Anchorages for multi-strand tendons should be so constructed that, at ultimate load in the unbonded state, at least 2 percent elongation of the tendon takes place before failure of any strand.
3. Anchorages should be designed

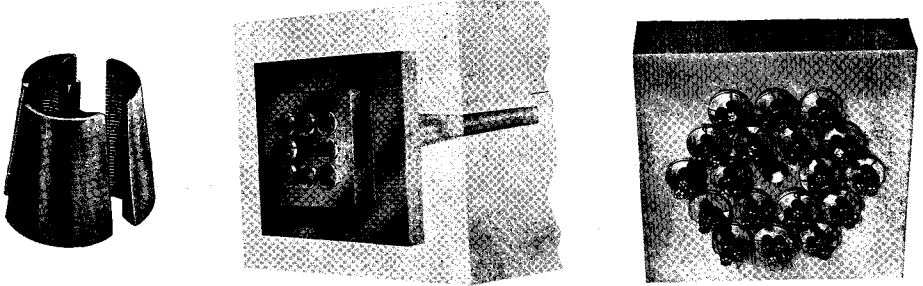


Fig. 1. Three-piece wedge anchor (left) seats in wedge plate (right), each wedge holding three post-tensioning strands

- to meet the ACI Building Code requirements for unbonded tendons for dynamic loading.
- Component parts should be designed, in size and shape, to be fabricated on existing machine tools.
 - Field placing and tensioning systems should be developed

- for maximum economy.
- Tendons should be primarily designed for use in bonded structures. Therefore, simple and efficient grouting methods were needed.
- The anchorage devices should be originally designed to use $\frac{1}{2}$ -in. (13 mm) dia. 270K (19,000 kg/cm²) ASTM A-416 strand, but should be adaptable to improvements made in this material and to larger size strands.

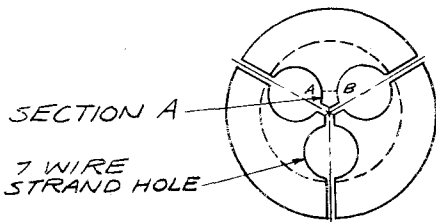


Fig. 2. Symmetrically cut wedge anchor

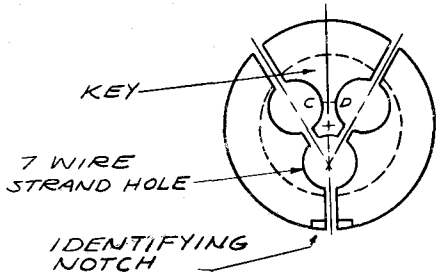


Fig. 3. Asymmetrically cut wedge anchor

SYSTEM COMPONENTS

The S/H wedge is a 3-piece slotted cone (Fig. 1) which grips three $\frac{1}{2}$ -in. (13 mm) dia. 270K (19,000 kg/cm²) strands in its serrated teeth and seats in a conical hole in a wedge plate. The strands pass from the tendon duct, through a transition cone and a splay plate, into the wedge plate where they are anchored by the wedge. By incorporating a number of these wedges in a multi-hole wedge plate, this system provides tendons in sizes ranging from 225 to 1300 kips (102 to 590t)* working force (Table 1).

*1t = 1000 kg

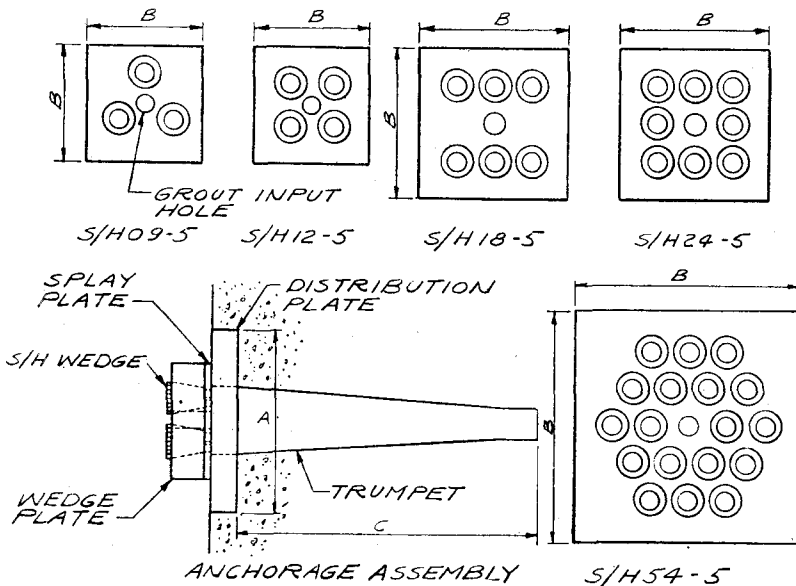
Three-piece wedge. On the basis of 15 years experience with wedge anchorages for post-tensioning bars, it was decided that the strand wedges should be no larger than the largest bar wedges. A primary design objective was to achieve a ratio between the area of the anchor plate and the number of strands anchored which would be lower than that of existing multi-strand anchorage systems. Preliminary analysis indicated

that the combination which would best achieve the most favorable ratio was the use of three strands in each wedge component. This concept was new to post-tensioning systems in the United States.

Several types of prototype anchors were initially fabricated. Under long term loading conditions, it was observed that 3-piece anchors cut symmetrically as shown in Fig. 2 have a tendency to crack across Section

Table 1. Strand tendon properties

Number of ½-in., 270K strands per tendon	Guaranteed ultimate tensile strength kips	Load, kips			Rigid sheath diameter in.	Dimensions in inches		
		0.8 f'_s	0.7 f'_s	0.6 f'_s		A	B	C
9	371.7	297.0	260.0	223.0	2⅝	11	7	18
12	495.6	397.0	347.0	297.0	2⅝	11	7	18
18	743.4	595.0	520.0	446.0	3¾	15¼	9	24
24	991.2	793.0	694.0	595.0	3¾	15¼	9	24
54	2230.0	1784.0	1561.0	1338.0	5½	20	13	36



A-B. Should the crack continue through the wedge, Section A tends to break free and, lacking positive support, creates an incipient failure condition. It became obvious that positive center support was mandatory for the new wedge. This requirement led to the asymmetric configuration shown in Fig. 3. Should a full crack occur across Section C-D in the key wedge piece, center support is maintained against each of the three strands with all wedge components, especially the small center piece of the key, remaining in compression with no loss of anchoring capability.

During machining of the wedge, a groove is cut around the outer body. This groove accommodates a neoprene O-ring, which maintains alignment of the wedge sections during shipment and field placement. An identifying notch (Fig. 3) is also machined into the wedge, between the right and left side sections, so that field crews can correctly reassemble the sections should they become separated. Wedge sections are machined to close tolerance, making comparable sections interchangeable. Each wedge is shipped as a complete unit, held together by its O-ring.

Wedge plate. Observation and study indicated that the most efficient and economical method of grouting was through the center of the wedge plate. Therefore, no separate grout input or grout vent pipes are required at the anchorage. Preliminary plate layouts were made with the wedge holes placed in a circle around a center grout hole. It was found, however, that the smallest size transition cone could be obtained only with a square configuration of wedge holes.

Wedge plates are fabricated from longitudinal standard mill flat bars or plate. Plate cutting, hole drilling, and hole reaming are done on the same manufacturing line with the same equipment as that utilized to produce anchorage plates for the bar system. Experimental analysis determined that the wedge plate material should have a higher yield point than that obtainable with rolled plate. To reduce plate deflection and provide smooth wedge holes, all wedge plates are heat treated.

Prototype anchor plates tested under simulated field conditions indicated that wedges could be placed at a minimum spacing of only $\frac{1}{4}$ in. (6.4 mm) when seated. This close spacing permits easy field placement, does not affect the strength characteristics of the tendon, and allows a close grouping of strands.

Splay plate. Since strand holes in the wedges are drilled with vertically moving equipment, the holes in the wedge are straight and parallel to its center. Strands, however, must pass from the tight area of the duct, through the transition cone, to the larger area required by the hole spacing in the wedge plate. Strands would normally enter the wedge plate at an angle not perpendicular to the plate and thus create the possibility of nonlinear stress.

To insure that the strands enter the wedge plate holes parallel to each other and perpendicular to the plate, a thin steel splay plate is placed between the bearing plate and wedge plate. It accommodates the strands from the transition area by passing each strand through an individual hole, which provides a precise guide for the correct alignment of all strands when tensioned.

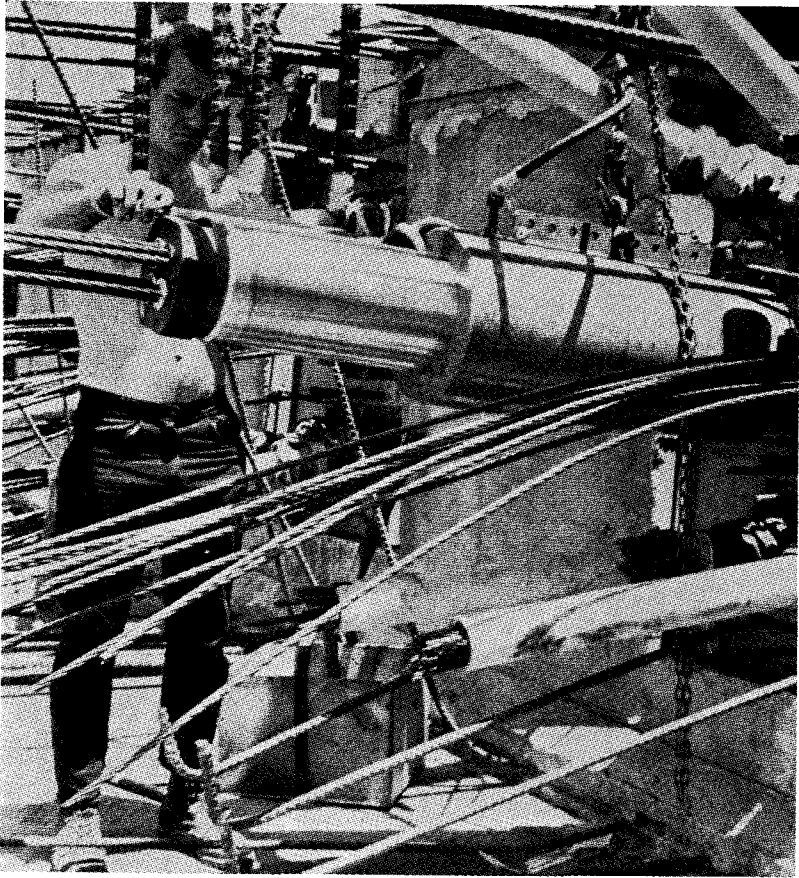


Fig. 4. Hydraulic ram, suspended by chainfall, simultaneously tensions all 12 strands of a tendon

TENSIONING METHODS

Placing and tensioning procedures developed for the 9- and 12-strand series embody no new concepts. After pulling strands through preformed ducts, the splay plate, wedge plate, and wedges are positioned. The strands are then passed through a center hole hydraulic jack, anchored at a jacking plate by the wedges, and tensioned (Fig. 4). Anchor wedges are seated, after elongation, by a secondary hydraulic

system, similar to that previously developed for seating bar wedges.

After the experience gained in tensioning 12-strand tendons, however, field personnel became concerned with the problem of handling the heavy equipment necessary to stress tendons of the 18- and 24-strand series. Preliminary studies indicated that this equipment, completely assembled with jacking chairs and pulling devices, would weigh approximately 2 tons (1.8t). Equipment of this size could

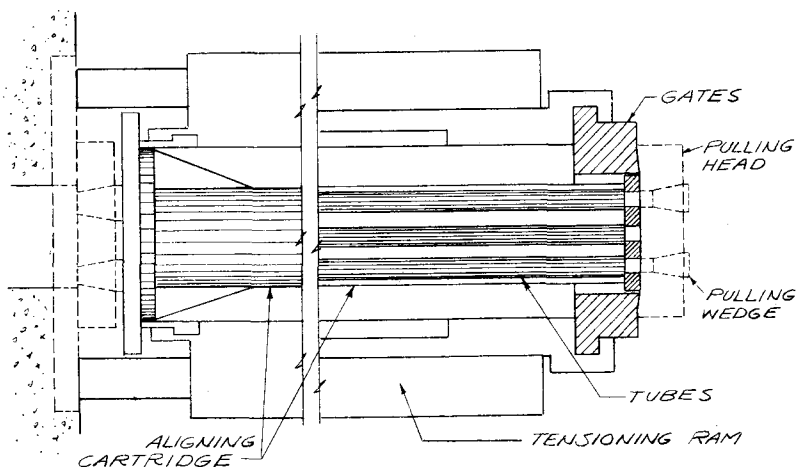


Fig. 5. Aligning cartridge used with tensioning ram

be efficiently handled only by small, long-reach cranes. Field experience with the 12-strand system indicated that 3-strand wedges were economical to place and anchor in comparison to monostrand systems. With the 24-strand system, however, the cost of crane time necessary to hold the jacking equipment in position while field crews placed stressing equipment, pulling heads and pulling wedges was so high that stressing with these large tendons promised to be uneconomical.

This problem was solved with a new approach in stressing the larger tendons. A cartridge was designed in which the strands are pre-aligned before they enter the center hole of the ram, the hole having sufficient diameter for the cartridge, pulling head and pulling wedge to pass through. The aligning cartridge consists of a series of parallel tubes (Fig. 5), each tube accepting a group of three strands. This assures that

all groups of three strands in the wedge plate are precisely aligned for gripping by the pulling head. The lightweight aluminum aligning cartridge is readily placed by hand in proper position on the stressing extension of the tendon, along with the pulling head and pulling wedges.

The center hole ram is brought over the cartridge, and gates mounted on the ram are closed ahead of the pulling head. The ram cylinder is then axially advanced, tensioning the tendon. After tensioning load and elongation are reached and anchor wedges seated, the ram cylinder is retracted and the gates opened.

The ram is then slipped off the aligning cartridge and immediately placed over the next cartridge, which has been readied for ram acceptance. With this procedure the crane no longer must hold the jack in place during the time needed for alignment of strands and the placing

of the pulling head and the pulling wedges, as these operations are proceeding in advance. Using these methods, a four man crew has stressed as many as 38 tendons of 24 strands each (912 strands) in a single working day. Without this special equipment, the maximum number of 24-strand tendons that could be stressed by the same crew would probably not be more than 12.

STATIC TESTS

Developmental tests on 3-strand anchorage. The asymmetrical nature of the 3-strand anchorage components created questions for the system developers as they sought to achieve the best possible results. Many hundreds of tests were conducted during the developmental stage using combinations of the following variables:

1. Wedge metallurgy
2. Wedge angle
3. Heat treatment
4. Configurations of gripping teeth
5. Spacing of gripping teeth
6. Length of wedge

An important conclusion from this testing was that only a very small but critical range of latitude exists in determining proper wedge angle. At one end of the range the wedge angle can be reduced to the extent that brittle shear fracture of the strand wires occur. At the other end, the angle is increased so that gripping compression is decreased and slippage of the strands result. When the final wedge angle was determined, it was found to be the same as that used for many years in the wedge anchors for high strength alloy steel bars.

A heat treatment procedure was researched to insure that the throat

of the key wedge had sufficient depth of hardness for the teeth to grip the strands and still remain sufficiently ductile to prevent cracking during tensioning and anchoring. Varying the number of the gripping teeth in the wedge from 18 to 54 threads per inch (per 2½ cm) had no discernible effect upon the performance of the wedge in ultimate strength or fatigue characteristics.

After extensive testing, never changing more than one of the variables from one test to another, the final S/H wedge was developed which now is guaranteed to provide a minimum of 2 percent elongation at the ultimate strength of the strand.

Static tests of 12 -and 24- strand tendons. The testing of 12-strand and 24-strand tendons was grouped into four phases:

1. Failure mode and/or performance of wedge plates at loads above the rated ultimate strength of the strand.
2. Testing of full scale tendons to ultimate load with parallel strands.
3. Testing of full scale tendons to ultimate load in a simulated duct-transition cone condition.
4. Testing of full scale tendons in a simulated duct-transition cone condition, using field tensioning procedures by tensioning and anchoring tendon at normal stressing load, then taking tendon to ultimate load.

Phase 1 for the 12-strand tendons was accomplished with four 1½-in. (29 mm) dia. special grade bars anchored by specially machined wedges of the same outer configuration as the 3-strand wedge. This allowed testing of the wedge plate to 1.2 times the ultimate load of the

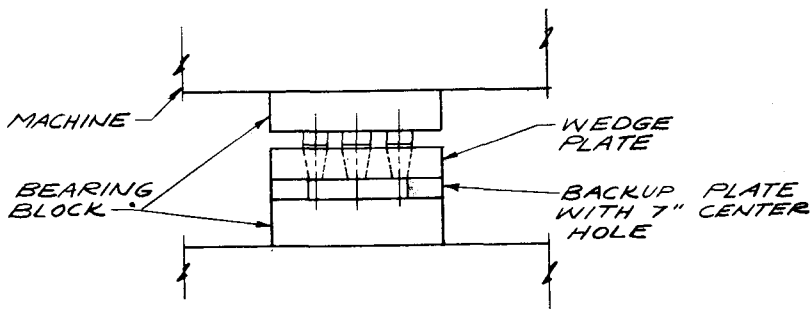


Fig. 6. Phase 1 test of 24-strand wedge plate

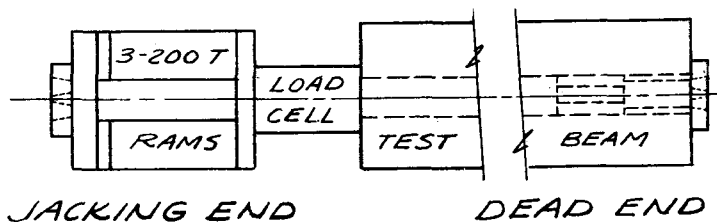


Fig. 7. Phase 3 test configuration for 24-strand tendon

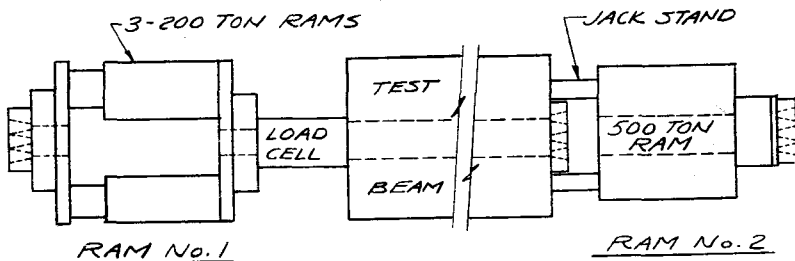


Fig. 8. Phase 4 test configuration for 24-strand tendon

strand tendon. Dial indicators were mounted on the testing machine to measure plate deformation during loading sequences. It was concluded that a 2-in. (51 mm) thick plate, properly heat treated, will effectively contain 1.2 times ultimate load of the 12-strand tendon, when used in conjunction with a 5-in. (127 mm) dia. transition cone hole and having a center hole to accommodate a $\frac{3}{4}$ -in. (19 mm) dia. grout input pipe.

Phase 1 testing for the 24-strand tendon was accomplished by placing a wedge plate between two bearing blocks and using solid steel wedges to apply 1.2 times the ultimate load with a 600-ton (544 t) hydraulic press (Fig. 6). It was concluded that a $2\frac{1}{4}$ -in. (57 mm) plate, properly heat treated, will effectively contain the above force for a 24-strand tendon when used in conjunction with a 7-in. (178 mm) dia. transition cone and

having a center hole to accommodate a 1-in. (25 mm) dia. grout input pipe.

Full scale testing for both tendon sizes was performed using a 14 x 4 ft. (4.2 x 1.2 m) concrete test beam with an 8-in. (203 mm) center hole. Tensioning was done with three 200-ton (180 t) rams placed parallel in a triangular arrangement, with a 1000-kip (454 t) load cell between the beam and the rams. Over-all tendon length, from anchor to anchor, was a minimum of 16 ft. (4.8 m).

Phase 2 tests indicated that wedge plates tested in Phase 1, when used with the already developed 3-strand wedge, will effectively contain either 12 or 24 strands at ultimate load, and develop at least 2 percent elongation.

Phase 3 testing was conducted in the same manner as Phase 2, except that a splay plate and strand transition device were added at the non-jacking end of the tendon (Fig. 7). Here, the testing was expanded to simulate elongation of the strand groups for 9 in. (23 cm) through the splay plate at 0.8 times ultimate load. This test phase resulted in the conclusions that a $\frac{3}{8}$ -in. (9.5 mm) thick plate is sufficient for 12-strand tendons and a $\frac{1}{2}$ -in. (13 mm) thick plate is sufficient for 24-strand tendons.

For the final test phase of both tendon sizes it was felt necessary to approximate actual field stressing and wedge anchoring procedures as closely as possible, and then to take the anchored tendon to ultimate load (Fig. 8). This testing phase also brought the conclusion that the sizes and configurations of splay plates, wedge plates, and wedges are such that the rated ultimate strength of the tendons and 2 percent minimum elongation can be reached.

Static tests of 54-strand tendon. In

developing the 54-strand tendon and anchorage system, by extension of work previously done with 12- and 24-strand tendons, the following steps were taken:

1. Testing for failure mode and/or performance of wedge plates at loads above ultimate load of the strand tendon.
2. Testing of full scale 54-strand tendon to ultimate load with parallel strands.
3. Testing of full scale 54-strand tendon to ultimate load in a simulated duct-transition cone condition.
4. Testing of full scale tendon under full field conditions of loading and configuration.

Before the start of this work, testing facilities had to be developed for these unusually large and heavy tendons. It was decided to construct a special test bed and static load facility for the performance of these tests (Fig. 9). This test bed consists of two hexagonal reaction blocks made of prestressed concrete. The movable block is forced away by six 225-ton, 12-in. stroke (204 t, 30 cm) hydraulic rams which develop an ultimate force of 2700 kips (1220 t). The testing of the 54-strand tendon with a minimum guaranteed ultimate strength of 2230 kips (1012 t) was well within the capacity of this machine.

The first phase of the 54-strand tendon program tested prototype bearing plates and wedge plates to 1.1 times ultimate load, or 2460 kips (1114 t). This test was performed using high strength steel bars with special wedge anchors made to fit the geometry of the wedge anchor plate. Measurements were taken of both elastic and plastic deformation. It was determined that 2-in. (51 mm) thick bearing plates and

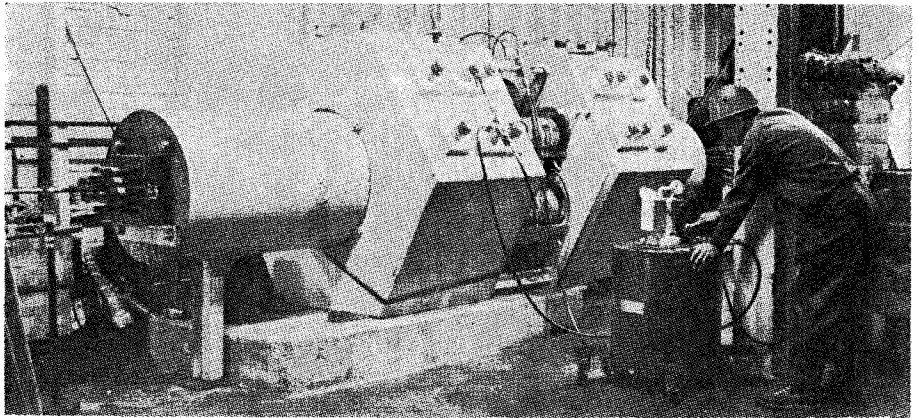


Fig. 9. Special test bed and static load facility for testing 54-strand tendon

3½-in. (89 mm) thick wedge plates meet the criteria for the system with adequate safety.

In Phase 2, full scale ultimate load tests were performed on prototype bearing plates, wedge plates and wedges. Minor modifications were made, where necessary, in these materials in order to improve the performance of the total 54-strand system.

In Phase 3, the entire tendon train using strand, duct-transition cone, bearing plate, splay plate, wedge plate and wedges, which will be used in nuclear containment construction, was subjected to ultimate load in eight tests. These tests established that the 54-tendon system will consistently develop 100 percent of the minimum guaranteed ultimate strength of the 54 strands, with an elongation at failure of not less than 2 percent (see Fig. 10). A ⅝-in. (16 mm) splay plate thickness was also determined in this test phase.

Phase 4 testing is still underway.

DYNAMIC TESTS

Numerous dynamic tests have been

performed during the development of the 3-strand wedge. The largest tendon tested dynamically, with an ultimate force of 3721 kips (168 t), is described in detail here. The purpose of this test was to determine whether the proposed new anchorage system would meet the requirements for dynamic load capability as stated in ACI 423.*

Test requirements. The specification requires that the test tendon be able to withstand, without failure, at least 500,000 cycles of stress varied between loads equal to 60 and 66 percent of the minimum tendon guaranteed ultimate tensile strength. The specification also requires that the test tendon withstand, without failure, at least 50 cycles of stress change according to the following formula:

$$R = 0.6 f'_s \pm \frac{2000}{L + 100}$$

*"Tentative Recommendations for Concrete Members Prestressed with Unbonded Tendons," ACI-ASCE Committee 423, ACI Journal, Feb. 1969, pp. 81-86.

L is the length in feet of the shortest tendon to be used in the structure. A tendon of nine strands, anchored with 3-strand wedges, was chosen for this test.

Test equipment and materials. The tests were performed on a Material Testing System (MTS) Universal Testing Machine, Model 901.83 (Fig.

11), 300,000 lb. (136 t) capacity, at the University of California's Lawrence Radiation Laboratory, Berkeley.

The strand material was ASTM A-416 $\frac{1}{2}$ -in. (13 mm) 270K (19,000 kg/cm²) special grade. Anchorage components were $7\frac{1}{4}$ -in. dia. x $3\frac{1}{2}$ -in. thick (184 x 90 mm) wedge plates; $7\frac{1}{4}$ -in. dia. x $\frac{5}{8}$ -in. (184 x 16 mm)

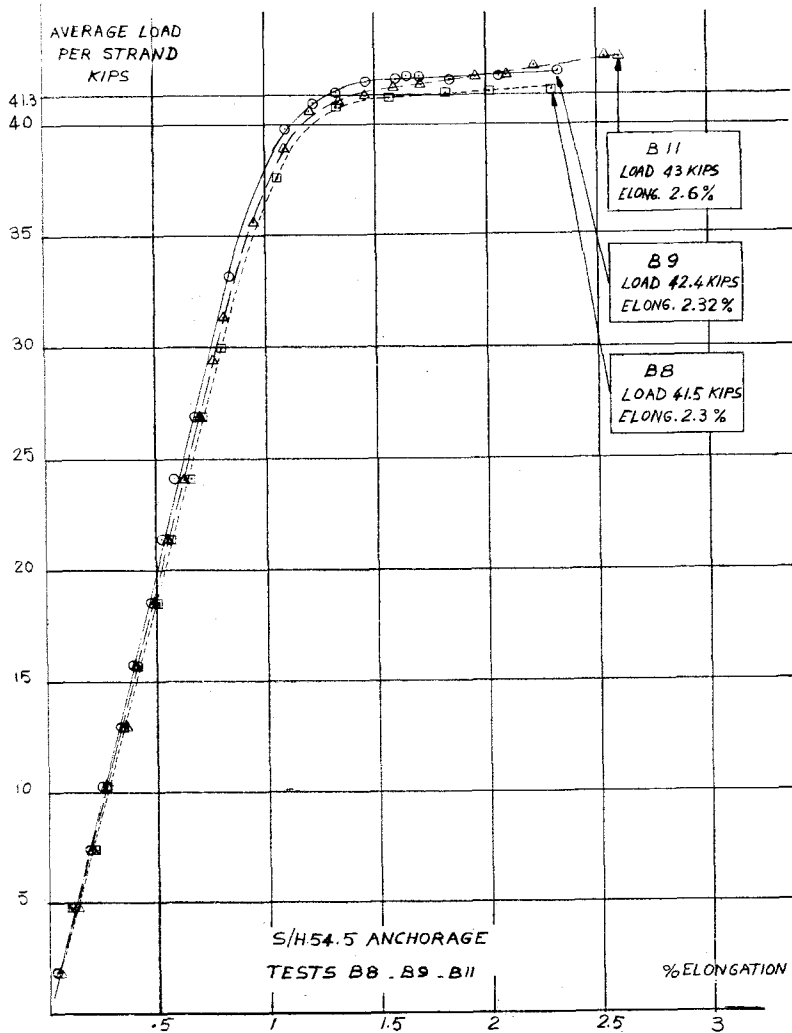


Fig. 10. Tests on three 54-strand tendon systems show good reproducibility

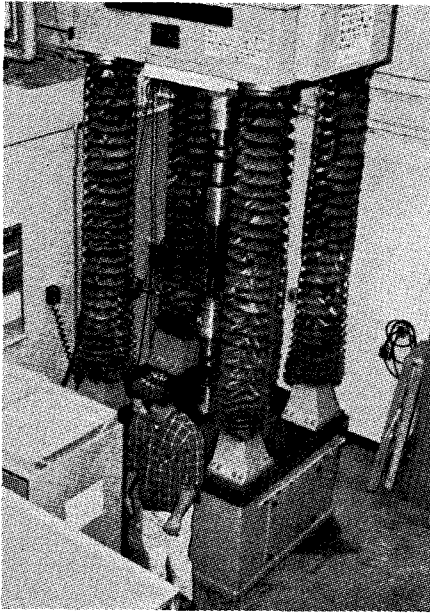


Fig. 11. Machine used for dynamic testing

splay plates; and 3-strand wedges.

In order to duplicate in this test the maximum splay angle of the strand as it emerges from the duct, passes through the transition cone and then into the anchorage, the test assembly was constructed with one wedge plate having wedge holes located at a 1¼-in. (32 mm) radius and the other wedge plate with holes located at a 2¼-in. (57 mm) radius (Fig. 12).

Procedure and results. The test unit was preassembled with ¾-in. (19 mm) bars for spacing and positioning. These were needed to insure that each of the nine strands was anchored by the wedges at the same length in this short, 21-in. (53 cm) test specimen. The test unit was mounted in the MTS machine and the ¾-in. (19 mm) spacing bars re-

moved. The machine was then adjusted to apply and record the required loads. The cycle rate was then raised to six cycles per second and the test initiated. The 500,000-cycle test was run first. Upon completion of this test, the MTS machine was readjusted for load and, without removing the test specimen from the machine, the 50-cycle test was run.

The test sample withstood the 500,000-cycle and 50-cycle tests without failure. The anchorage ends were checked before and after test. Wedge seating was normal as anticipated. There was no distortion of the wedge anchor plate, no evidence of wire slip, and no wire failure.

TYPICAL BRIDGE APPLICATIONS

Developed initially for cast-in-place post-tensioned bridges in California, the system has spread to many other states. The S/H Wedge Anchorage System has been successfully placed, stressed and grouted in over 250 bridge spans using more than 125,000 individual 3-strand wedges. All bridge tendons for the system are pulled through preformed ducts after the concrete has been placed and cured.

Post-tensioning sequence. The fast, efficient post-tensioning sequence is as follows:

1. Bearing plates and transition cones are attached to end bulkheads.
2. Rigid galvanized duct is placed in conjunction with mild reinforcing steel.
3. After concrete placement and cure, strand tendons are pulled into ducts, and splay plates, wedge plates and anchors are placed.
4. Tendons are tensioned to proper load and elongation.

5. After cutting off strand stressing lengths, grout caps are placed and tendons are grouted.

A number of these operations on a typical bridge project are shown in Figs. 13 to 17.

TYPICAL BUILDING APPLICATIONS

The S/H tendon system is also adaptable to cast-in-place building

construction. An excellent example is the 110 ft. (33 mm) square gymnasium roof of Laney College, Oakland, California (Fig. 18). Ducts were placed in the forms in correct position for the two-way grid of post-tensioning forces. After concrete had cured, the tendons were pulled through, anchorages were attached and the tendons tensioned and grouted. Some of the typical operations are shown in Figs. 19-23.

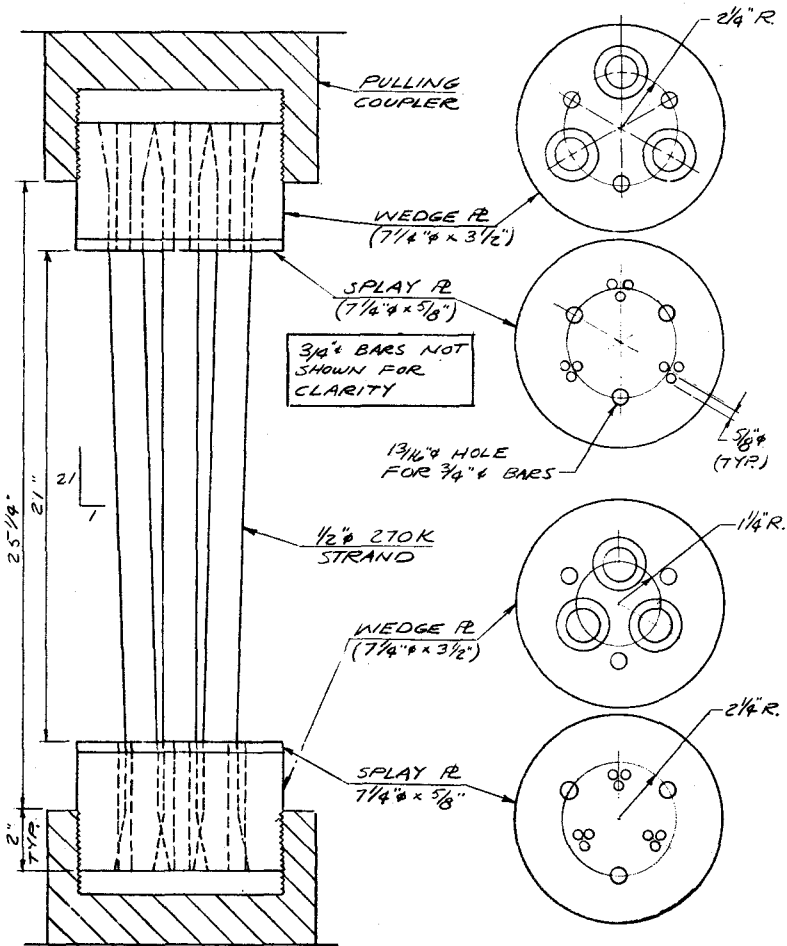


Fig. 12. Fatigue test set-up for 9-strand tendon

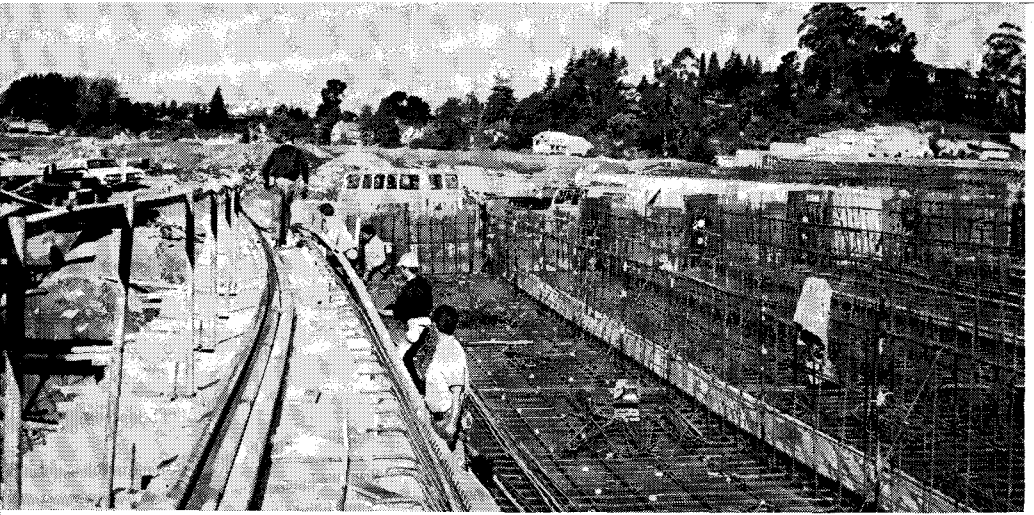


Fig. 13. In a two-span, multiple box girder bridge, rigid ducts are positioned in the webs along with shear steel.

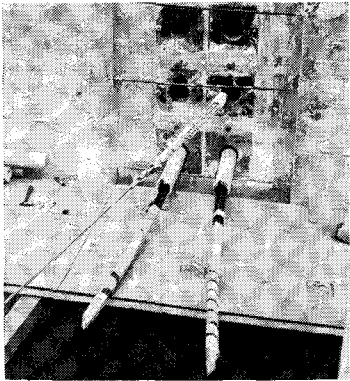


Fig. 14. Tendons are pulled through the ducts using a pulling sock.

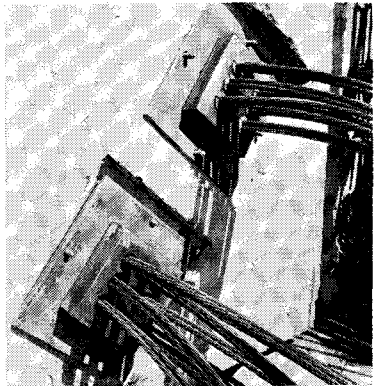


Fig. 15. Upper tendon is stressed and anchored with split wedges. The lower 24-strand tendon has wedge plate in place but is not stressed.



Fig. 16. The aluminum alignment cartridge is placed on the tendon prior to attaching the jacking ram.

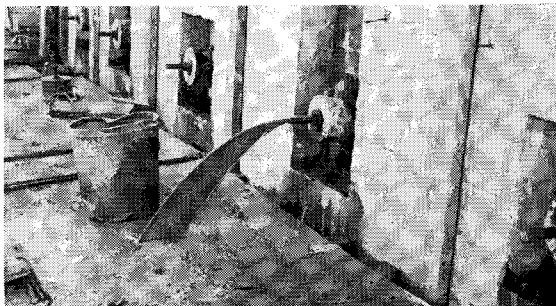


Fig. 17. Grout is pumped into the ducts at the far end until it free flows from the vent, which is then capped to build up to specified pressure.

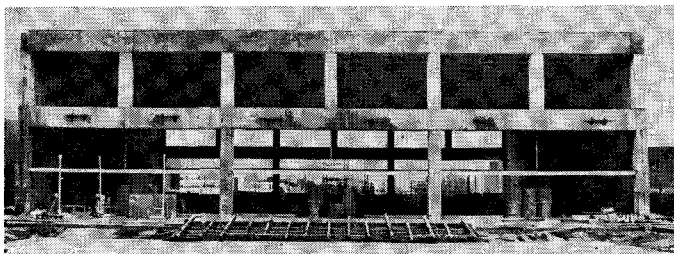


Fig. 18. Gymnasium roof clear-spans 110 ft. with a two-way, post-tensioned concrete waffle roof.

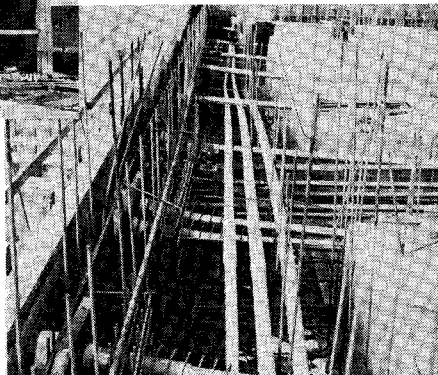


Fig. 19. Semi-rigid ducts are placed in the two-way ribs and drape up over column supports in the perimeter beams.

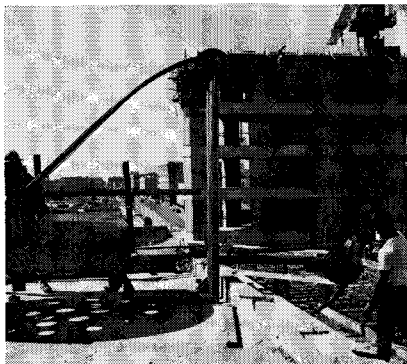


Fig. 20. After roof concrete was cast and cured, tendons are pulled into the ducts using special guides at the edge of the roof.



Fig. 21. Spray plates were placed on the tendons to separate the 9-strand tendon into three groups of 3 strands.



Fig. 22. Closeup of a fully stressed and anchored 9-strand tendon. Jack in place will stress and anchor adjacent tendon. Excess of strands are cut off with an abrasive saw.

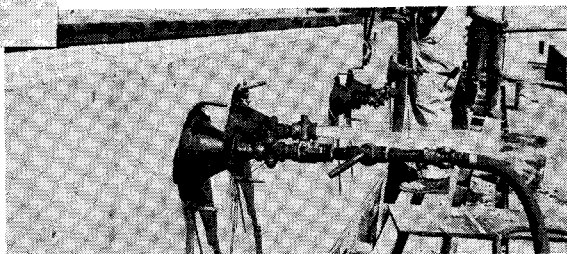


Fig. 23. For grouting, special grout caps and valves are used. The second duct is being flushed with water just prior to pumping in grout.