PUSH-OUT TEST FOR ASSESSING THE BOND STRENGTH OF PRESTRESSING TENDONS

Matti V. Leskelä
Academy of Finland, the Research Council for the Technical Sciences
PhD (Eng.), Senior researcher

ABSTRACT

The push-out test is a new type of method for testing the anchorage bond of pre-tensioned strands. The difference with respect to traditional methods is that only a small specimen is used and the strand is pushed with respect to the concrete. The idea was introduced to one concrete factory some nine years ago, and the first efforts to prove its validity were made about six years ago. Two years ago systematic experimental research was commenced to study the possibilities which the test offers, and this work is still going on.

So far, the results have proved that the test could be used as a standard method for quality assurance in the production of the pretensioned concrete elements, since all the properties of pretensioned members are closely connected to the existence and level of the anchorage bond.

The article introduces the testing method and describes the experiments performed with it. Factors affecting its reliability are discussed.

Key words: Anchorage failure, Bond strength, Testing method, Prestressing strands.

1. INTRODUCTION

One of the critical modes of failure in prestressed hollow core slabs is the shear-bond failure, involving one or two major diagonal cracks at such a distance from the support that they can cause an insufficient anchorage length of the tendons to develop in order to resist the increasing stress resultant. Thus the failure of the slab is governed by a mechanism in which flexural equilibrium cannot be maintained when the loading is increased because of the excessive slipping of the tendons (FIG. 1).

Although the exact deformation theory applying to the case is not a simple one, an average, conservative estimate can easily be obtained for the minimum anchorage capacity of the tendons required in order to eliminate the possibility of the shear-bond failure or to reach a given ultimate load level in spite of it.

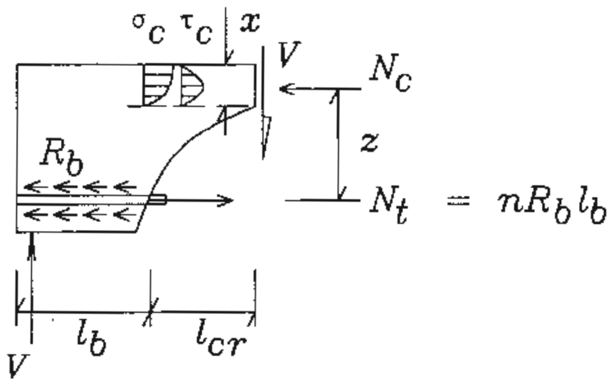

FIG. 1. The equilibrium mechanism involved in the shear-bond failure

The notations used in the following brief consideration of shear-bond failure are shown in FIG. 1. Equilibrium is maintained in the vertical direction by the shear couple V (ultimate value V_u). The aggregate interlock on the inclined crack surface is not allowed for, because it must be supposed that the cracks open so wide that no effective interlocking can be maintained at the moment of failure. The horizontal equilibrium of the forces acting on a free body as discussed here takes the form of equality between the stress resultants N_t and N_c,

$$N_t = N_c,$$

$$N_t = n l_b R_{bu}; \quad N_c = 0.67 \sigma_c bx \Rightarrow$$

$$bx = n l_b R_{bu}/(0.67\sigma_c), \qquad (1)$$

where n is the number of strands in the slab and the other symbols are as shown in FIG. 1.

The flexural equilibrium includes consideration of the shear resistance V_u involved in the case.

$$V_u(l_b + l_{cr}) = N_c z = 0.67\sigma_c bxz;$$

$$z = d - x/2 \approx 0.9d \Rightarrow x = 0.2d; \Rightarrow (\sigma_c \le f_c)$$

$$V_u \le 0.12 f_c bd^2/(l_b + l_{cr}). \qquad (2)$$

The estimate (2) looks convenient, but it includes one indeterminate factor, the length l_{cr}, which is one part of the lever arm of the force couple V_u. Furthermore, equation (2) does not consider the effect of the anchorage resistance and thus one can conclude that it gives only the upper-bound limit for the shear resistance with or without the possibility of shear-bond failure.

The effective compressive area obtained from the horizontal equilibrium condition is therefore used in connection with the failure consideration at the edge of the diagonal crack. It is assumed that the failure takes place when the principal tensile stress in the uncracked zone is equal to the tensile strength of concrete, f_{ct}

$$f_{ct} = -\sigma_c/2 + \sqrt{(\sigma_c/2)^2+\tau_c^2} \qquad (3)$$

The compressive normal stress σ_c is estimated to be f_c and the shear stress τ_c is calculated according to a parabolic distribution,

$$\tau_c = 1.5V_u/bx \Rightarrow ((1) \text{ and } (3))$$

$$V_u \le nl_bR_{bu}\sqrt{(f_{ct}/f_c)^2+(f_{ct}/f_c)}. \qquad (4)$$

Since the ratio of the strengths f_{ct}/f_c normally varies in the range 1/8 ... 1/12, a simple rule (5) is obtained

$$V_u \le (0.375 \ldots 0.300)nl_bR_{bu}, \qquad (5)$$

where n is the number of strands in a cross-section, l_b is the anchorage length and R_{bu} is the average anchorage resistance of one strand per unit length. To obtain an understanding of the level required for a specific value of V_u, the following example is given.

6-strand slab (n = 6),

V_u to be reached = 170 kN,

l_{bmin} = 600 mm, =>

required min. R_{bu} = 170000/(0.3*6*600) = 157.4 N/mm.

It has been observed in various test loadings of slabs that premature shear-bond failure can be avoided if the anchorage resistance of the strands satisfies the above principle. The only difficulty is how to predict conveniently the ultimate resistance of the strands of a given slab. There are a number of different traditional tests for doing this, but no single easy one. It is for this purpose that *the push-out test* has been introduced.

The idea of the test arose from the need to asses the quality of slabs during production so that the anchorage properties can be adjusted whenever there might be a possibility of some inadequacy occuring. The compressive strength of the concrete in slabs is monitored continuously, but this does not guarantee the quality of the bond, which also depends on the properties of the machines producing the slabs. Thus the anchorage characteristics also need to be monitored.

2. TYPES OF TEST FOR ASSESSING ANCHORAGE STRENGTH

Two types of set up have been used to test the anchorage characteristics of reinforcement and prestressing strands, (1) pull-out tests with a direct tensile load introduced onto the reinforcement, and (2) flexural tests in which tensile load is imposed on the reinforcing steel by means of flexural moment. These types have also been used with pretensioned strands, although a number of difficulties arise from the procedure of preparing the specimen:

- In order to prepare a specimen of a prestressed hollow-core slab, one must first separate a block with one tendon from the slab, then peel the strand free from the concrete in order to take a grip on it.
- It is not very easy to prepare a specimen without causing some extra cracking in the concrete which cannot be detected directly from the outer surfaces.
- The lever arm in a flexural test must be determined exactly in order to provide a satisfactory estimate for the tensile force acting on the strands.

Pull-out tests also involve a number of parameters that affect the strength:

- embedment length,
- the restraint on the bearing surface,
- a possible arching effect that induces transverse compressive stresses in concrete. This may result in extra strength which is only fictive and cannot be found in real structures.

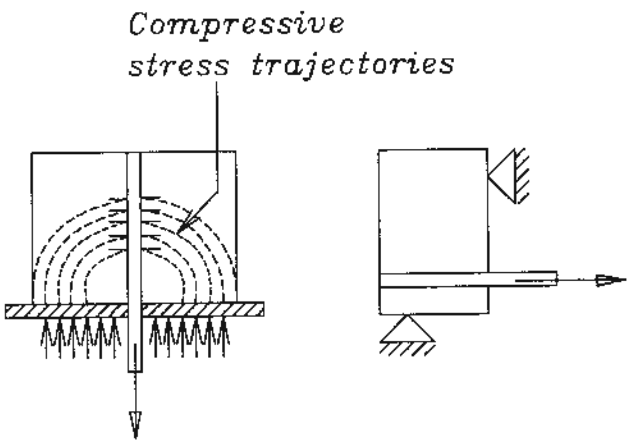

FIG. 2. Pull-out set ups for anchorage tests

The normal, straightforwarded idea in the above tests is that of applying a tensile force to the tendon. No other possibilities have even been considered. It is for this reason that the opposite idea, of pushing the strand with respect to the concrete, faced much resistance among researchers when the author suggested it in the early 1980's. It does enable many of the draw-backs of traditional tests listed above to be avoided, however some new problems may naturally arise. These are discussed in detail in the following chapters.

3. DEFINITION OF THE PUSH-OUT TEST

The push-out test for tendons or strands as presented here does not require a large specimen or high load levels (normally, < 30 kN) and is intended primarily for steels with plain or slightly deformed surfaces. The test could also be developed for ribbed or deformed reinforcing bars, but this has not been considered up to now.

The data recorded in the test include the indenter load and the slip of the tendon with respect to the concrete. This information yields the required characteristics of the bond.

The specimen is prepared by cutting a slice of thickness l_b from the end of a prestressed or reinforced member and separating a block that contains one tendon. When using the test at the site of hollow-core slab production, no extra tools are required, the sawing being done along with the other cutting operations involved in the production procedure. A brick cutter can be used to separate the T-rib from the cross-sectional slice.

The loading system (FIG. 3) is designed so that the strand should be able to move axially and concrete should not be subject to any tensile effects other than those splitting forces caused by the movement of the strand with respect to it. The block to be tested lies on a dome ring bearing which should eliminate most of the eccentricity effects caused by the irregularity of the supporting suface (no preparation work is done to make the surface more planar than that produced by the diamond saw cutting).

It is not so easy to prove analytically that the load-slip characteristics obtained from the test represent the same universal bond law that can be found in real structures, but this must be assumed to be so, as is also the case when using other types of test. Experimental validation has been sought by means of the flexural test (FIG. 4), which should describe the anchorage behaviour of the bond in by far the best way, and the effects of some of the most important factors that can influence the results have also been considered. These include:

- length of the specimen (the embedment length),

- indenter head shape,
- accuracy of placement of the indenter on the strand cross-section,
- irregularities on the bearing surface (distortions of the plane),
- friction on the bearing surface,
- loading rate and displacement rate.

It is obvious that there will be a certain amount of scatter among the results, but this is also the case with the other types of test. It is recommended that two sequential slices should be used, to ascertain whether the values differ widely from each other. In this way major errors can be avoided. So far, the scatter among push-out tests has not been found to be any greater than that among the other types discussed /2/.

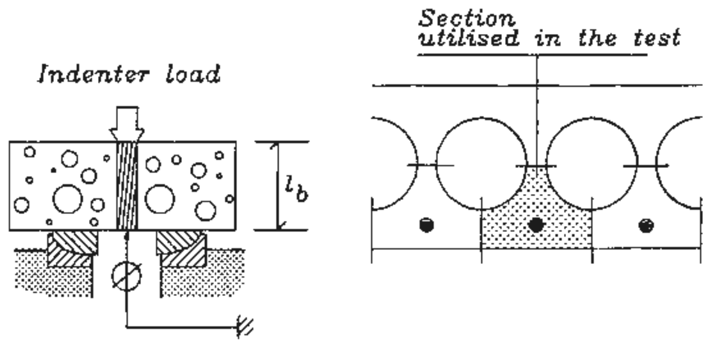

FIG. 3. Principle of the push-out test on hollow-core slabs

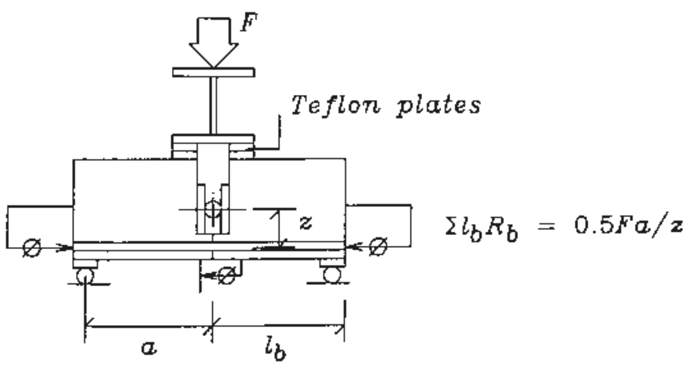

FIG. 4. The flexural pull-out test applied to a hollow-core slab

3.1 The load-slip relationship

Three main types of load-slip curve (FIG. 5) can be found when using the push-out test, type (1), resembling the stress-strain curve of a mild steel with a prominent yield stress, type (2), resembling the stress-strain curve of a cold-formed steel in which yielding is shown only as a softening arc after the linear section, and type (3), in which the curve is liable to fall after the peak, which is reached directly at the end of the linear section. The type that emerges depends on the surface properties of the strand, its diameter, and its minimum concrete cover.

Type (1) applies to a small diameter strand with an effective concrete cover. Failure may take the form of excessive slipping, without any splitting of the concrete. Type (2) can also be found among small diameter strands. Failure may be caused by splitting of the concrete after a smaller slip than in case (1). Type (3) concerns strands of greater diameter and concrete cover which is not capable of resisting the splitting of the cover in more than one direction.

The surface condition (deformed - plain) does not correlate directly with any one of the three types, but it is evident that a deformed surface provides a higher strength and thus an accentuated possibility of splitting.

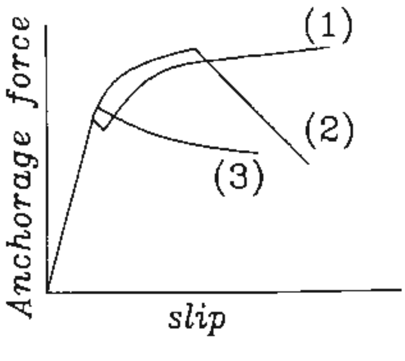

FIG. 5. Types of load-slip curves found in push-out tests

3.1.1 Adhesive bond

When considering the load-slip relationship, the anchorage bond mechanism can be divided into two phases, (1) the adhesive bond, and (2) the frictional resistance. The adhesive bond resistance is influenced by the characteristics of the bonding surface and compression perpendicular to the surface. The deformation required to break this resistance is not high, but the load applied may be, so that the stiffness of the mechanism may be prominent. The ultimate bond stress f_{ba} upon the adhesive bond failure has normally been found to be in the limits $(1.0 \ldots 1.5)f_{ct}$, where the tensile strength of concrete is calculated by the formula (K being the cube strength of concrete)

$$f_{ct} = 0.25K^{2/3}.$$

This failure causes 'yielding' of the anchorage, whereupon the slipping rate becomes higher. The anchorage resistance will now depend on the frictional mechanism.

3.1.2 Frictional resistance

It is the failure of the adhesive bond that first produces pronounced slipping between the strand and concrete. Thus the mortar particles become wedged between the steel surface and the surrounding concrete. These stresses will then become more prominent due to the 'lack of fit' phenomenon (Stocker & Sozen 1969 /3/), which arises from the irregularities in the cross-sectional shape of the strand, i.e. it will not fit exactly into the new position when sliding along the embedment channel. There are also other effects that cause high radial pressure on concrete (den Uijl 1983, /1/).

The softening part of the load-slip curve thus depends on the characteristics of the friction between the strand and concrete. The effect of radial pressure is often modelled with the aid of a thick-walled cylinder having an internal pressure. In an elastic material, the highest tangential stresses are found in the inner surface of the tube, and in concrete these stresses will cause radial cracks initiating from the channel of the strand. If these cracks split the concrete cover, the frictional anchorage cannot be maintained and ultimate failure will ensue.

Radial cracking will reduce the internal pressure and thus the frictional resistance. If a stable equilibrium can be reached, in which the frictional pressure requires no extra cracking, the strand slips maintaining the load. This may be the situation when small diameter strands are used and the concrete cover is adequate.

3.2 Embedment length

At the time when the push-out test was first introduced for the local needs of one concrete element factory in Oulu, an embedment length of 70 to 80 mm was recommended intuitively. The effect of the length was not considered at all at that stage, as there seemed to be good agreement between the results of full-scale flexural slab tests and the push-out test. The first attempt to investigate the effect of length was made in 1984, using anchorage lengths from 50 to 100 mm. No clear evidence could be obtained that R_b (anchorage force per unit length) was in any way related to the length of the specimen.

This series of tests was repeated later on with another type of strand. A slab with 5 strands was sawn into successive slices, marked A, B, C and D having embedment lengths 50, 70, 90 and 110 mm, respectively. A similar series of slices E, F, G and H was prepared from the same slab, and three extra slices of length 50 mm were sawn, marked I, J and K. The nominal diameter of the strand was 9.3 mm. All the slices were tested using the equipment capable of controlling the rate of loading and the rate of slipping. The measurements were recorded on the same computer that controlled the loading.

For the analysis of the results, it was necessary to define two load levels, termed the *anchorage yield* and *anchorage failure* loads. The anchorage yield load is reached when the load-slip curve sets out obviously in a new direction from the elastic linear line, or when no definite yield point can be seen, a slip of $\sqrt{l_b}/35$ has been reached. The initial non-linearity of the curve is extracted prior to defining the yield point. This non-linearity is due to the irregularities in the bearing surface and consequently it must be removed. The anchorage failure load is defined as the load at the moment of splitting, or when the specimen fails through excessive slipping of the strand, as the load at the moment when a slip of 2 mm is reached.

Of the five strands, two failed regularly without splitting, through excessive slipping, and three by splitting. Again, analysis of the overall results gave no clear indication that the embedment length had any evident effect on the result. Test data on the strand 5 are reported in figures 7 ... 9, and similar graphs can be drawn from the data for the other strands.

3.3 The indenter and the bearing

One crucial point in the push-out test is how to set the indenter load on the strand cross-section. It seemed obvious from the very beginning that at least the indenter diameter had a clear effect on the test result. To avoid the fictive strength increment caused by an indenter that also loads the concrete surface, the indenter diameter $\varnothing_i$ was set at

$$\varnothing_i \leq 2.3\varnothing_1,$$

where $\varnothing_1$ is the diameter of the wires of the strand. Furthermore, a central cavity of $\varnothing_1$ can be used on the indenter head, so that only the wires in contact with the concrete are loaded.

As the area in which the indenter is placed is small, it requires careful and accurate operatives to carry out this job correctly. This problem can be overcome by developing tools for locating the indenter, or by considering some reduction in the interpretation of the results.

The bearing system consists of a dome ring bearing, the ring area being used directly as a supporting surface. The dimensions of the ring were chosen so that the mean contact pressure on the ring area does not normally exceed the limit $0.5f_c$. This does not seem to be of any critical importance, however.

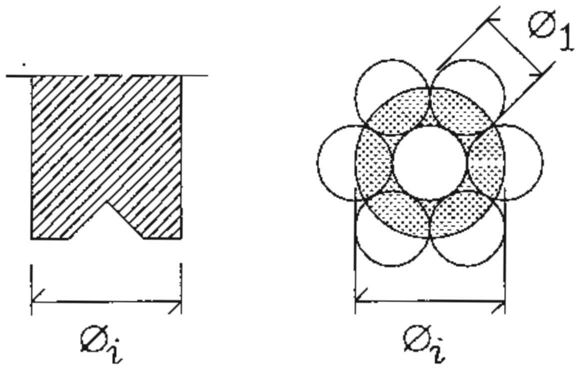

FIG. 6. Indenter requirements

3.4 Irregularities in the supporting surface

The surface produced by the diamond saw is used directly as a supporting plane, with no finishing. Normally the quality of the surface is adequate, so that it will not have an effect on the test result. There are two parallel surfaces available, and either can be selected as a support. The properties of the supporting area do not seem to have any critical effect on the test data (Järvinen /2/, 1990), the main reasons for the use of the dome ring bearing being the elimination of flexural effects and the eccentricity of the strand with respect to the supporting surface.

3.5 Friction on the bearing

Friction on the bearing is not eliminated and thus it may have some restraining effect on the concrete and prevent radial cracking. Consequently higher strengths might be expected when friction is effective. This may be the situation when using a deeper specimen.

The effect could not be detected in the test series reported in chapter 3.2, however (Figures 7 ... 9). As the embedment length is increased, the ultimate total load is increased accordingly, assuming the coefficient of friction to be constant. At higher loads, some local plastic deformations may occur on the bearing surface, due to irregularities in the shape. Thus the relative constraint on the surface may then be higher.

Consequently, if the constraints are clearly higher in tests made with a deeper specimen, the results should also be seen in the profiles according to Fig. 8. Two successive series of different lengths did not yield identical profiles in any cases in these series. If a tendency for an increasing strength relative to specimen length occured, the same maximum strength could also be obtained from the beginning of the next series (the shortest specimen), after which the successively increasing lengths could be associated with decreasing stength (strands 2, 3, 4). On the basis of this discussion it may be said that the strength profiles obtained from the tests explained in 3.2 may show the average strength flow along the tendon rather than the influence of the constraining effect of friction.

4. VALIDITY OF THE PUSH-OUT TEST

When first introducing the push-out test to some researchers dealing with bond phenomena of tendons, the author encountered clear accusations of invalidity. At the same time, comparison of the results of flexural tests on given slabs with those of push-out tests yielded satisfactory level of agreement.

Validity comparisons with flexural tests (FIG. 4) have recently been made by the author, and with pull-out tests by M. Järvinen /2/ (both pretensioned and non-tensioned strands). When the ultimate anchorage load per unit length was considered, the strengths shown in different types of tests were found to correspond well. The highest anchorage forces were obtained from the non-tensioned strands and the lowest values from the direct pull-out tests, the push-out test always giving intermediate results /2/.

Comparison of the push-out test with the flexural test provides an opportunity to use the same material in both ways. Altogether 16 hollow-core slab units of total length 850 mm have been investigated, 10 taken from the production line ends of a concrete factory and 6 cut from uncracked parts of slabs tested flexurally in other connections (slabs for standard quality assessment).

For the push-out test, two slices of nominal thickness 50 mm were cut from each end of the slab and marked as 1L, 2L, 1R and 2R. The slabs were then divided into parts having 2 or 3 strands and these units tested according to FIG. 4. The load was first raised until a crack was detected on the cross-section through the hinge, whereupon it was dropped to zero and then increased at a constant rate with concurrent recording of deformations in the crack and the ends of the strands. Loading was continued up to failure of the anchorage.

Typical data from these tests (concerning the slab identified as V51) are shown in the table on the next page. The symbols 'L' and 'R' refer to the left and right ends of the specimen.

Flexural test/id V51:

Strand no	1	2	3	4	5	6
Failing end	L	L	L	R	R	R
R_{bu} (N/mm)	308	362	311	323	363	363

Push-out test/id V51: R_{bu} (N/mm)

1R	374	452	393	***310***	***458***	***313***
2R	338	396	425	***330***	***488***	***356***
1L	***334***	***314***	***372***	439	383	462
2L	***274***	***332***	***372***	320	473	334
mean value of the failing end results	***274***	***332***	***372***	***320***	***473***	***334***

The italicised values for the push-out tests refer to the end at which the failure took place in the flexural tests. Since there is some uncertainty in dividing the total tensile stress resultant of the flexural test among the strands, it is more convenient to compare the sums. The sum of the mean values of the failing end (written in italics) are used for the push-out test:

- Flexural test: ΣR_{bu} = 2030 N/mm,
- Push-out test: ΣR_{bu} = 2105 N/mm.

The agreement was not so perfect in all the test slabs as it was in specimen V51. Part of the test material consisted of slabs with a very poor bond and it was difficult to handle these blocks sufficiently safely. They already had cracks along the strands, and this seemed to produce a greater scatter in the data.

Another difficulty in the comparison concerned those slabs which had a very high anchorage resistance, in that some of the blocks tested by the flexural method sheared longitudinally before the anchorage failure could be reached. In these cases the push-out results clearly showed that this was to be expected anyway.

4.1 Conclusions

The specimen used in the push-out test gives rise to following notes:

- The prestress and Poisson's effect in the strand have relaxed and radial contraction has been released. This is a factor that might increase the radial pressure against the concrete.

- Since the embedment length in the specimen does not affect the value of R_{bu}, it is recommended that lengths ≤ 70 mm should be used as the indenter should be kept elastic.

- Frictional constraint on the bearing surface was not found to give any clear increment in strength.

- Strands with plain or slightly deformed surfaces have been tested so far.

- The method is suitable for quality assesment of bond. To obtain a reliable result, at least two samples should be tested.

- In the case of more than one strand in a specimen, the result of the first strand tested is reliable. Due to the evident cracking induced by the first test, the others will yield lower values.

- It was assumed that the modulus of rupture of the concrete could have some correlation with bond resistance. The idea was tested using the concrete blocks left out of push-out specimen, but no confirmation was obtained for the idea. A block with fairly poor concrete quality (low modulus of rupture) can have a good bond, and vice versa. It may instead be the compaction around the strands that will prove to be correlated with the quality of the bond.

From the data collected so far, it is evident that the test can have a variety of uses for investigating the bonding properties of strands. The natural requirement for the use of the test is that the strand to be tested should have uniform properties of a kind which can be identified in the length used in the test.

One use for the test should be continuous quality control on production lines, so that products not satisfying the bond requirements could be detected directly.

5. ACKNOWLEDGEMENTS

Special thanks are extended to the Tauno Tönning Foundation and the Foundation for the Advancement of Technology, which supported this research financially. Grateful thanks are also expressed to the staff of the Structural Engineering Laboratory at Oulu University for their assistance in preparing the samples and handling the data.

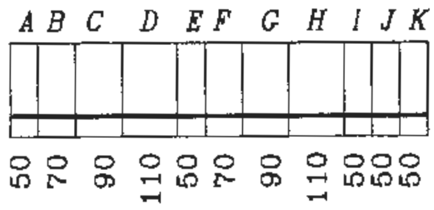

FIG. 7. Series of slices of a V6 hollow-core slab used to study the effect of embedment length on bond strength. The cross-section of the slab contains 5 strands having a nominal diameter of 9.3 mm.

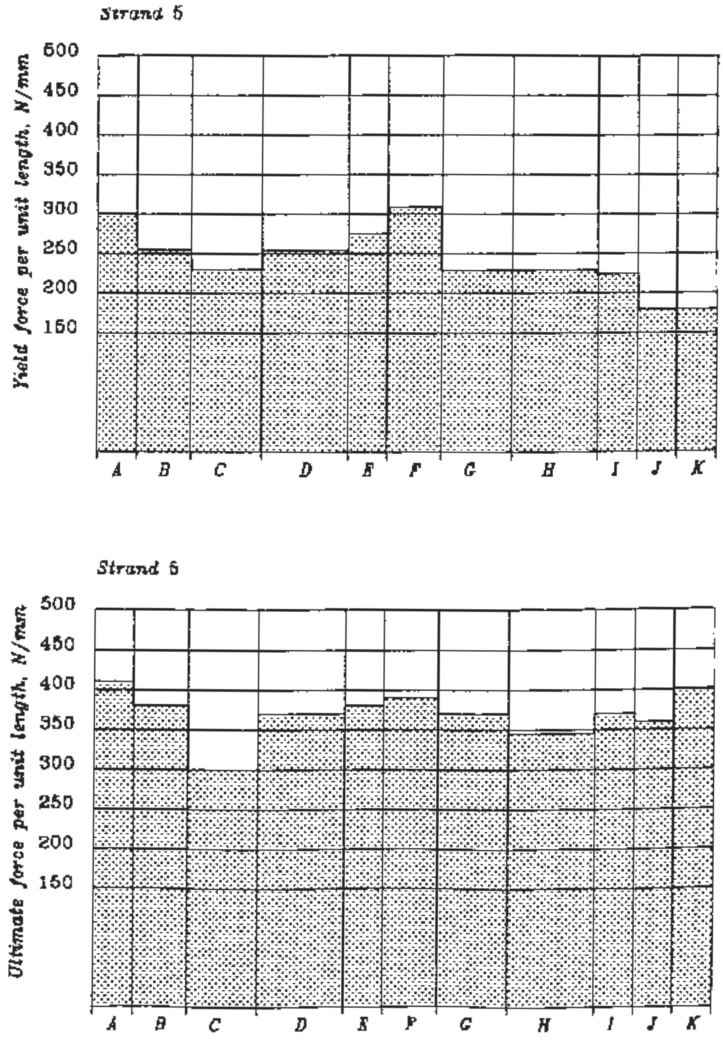

FIG. 8. Profiles of test results concerning the effect of embedment length: strand 5. Since the peak values are situated randomly in all strands, it can be assumed that the lengths used give similar results. It is not possible to use greater lengths because of yielding in the indenter and strand head.

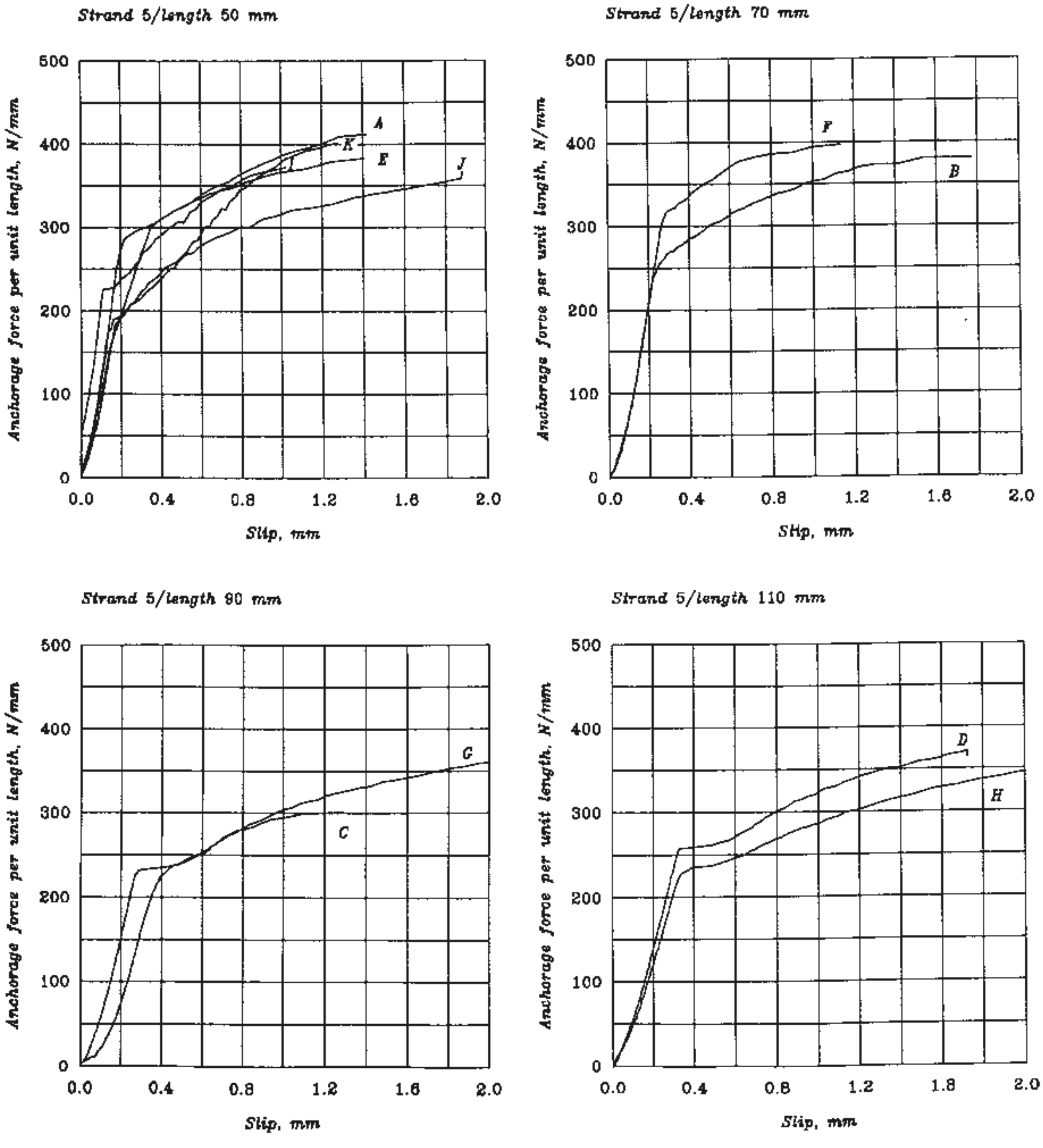

FIG. 9. Load-slip curves for tests A - K: strand 5

6. REFERENCES

/1/ den Uijl, J. A., "Tensile stresses in the transmission zones of hollw-core slabs prestressed with pretensioned strands", Report 5-83-10, Delft University of Technology, Stevin Laboratory, Concrete Structures, 1983.

/2/ Järvinen, M., "Korkealujuuksisen betonin ja jännepunostyypin vaikutus punostartuntaan", Teknillinen korkeakoulu, Rakennus- ja maanmittaustekniikan osasto, 1990 (The Effects of High Strength Concrete and the Type of Prestressing Strand on the Bond between Concrete and Strand. Helsinki University of Technology, Department of Civil Engineering and Surveying. Thesis submitted for the degree of M.Sc in civil engineering).

/3/ Stocker, M. F., Sozen, M. A., "Bond Characteristics of Prestressing Strand", University of Illinois, Structural Reseach Series no. 344, 1969.