BOND OF BUNDLED PRESTRESSING STEEL STRANDS

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The present investigation of totally 62 pull-out tests with strands prestressed and without prestress was conducted for the clarification of the influence of bundling of strands on bond. The effect of prestress and deterioration on bond between bundled and not bundled strands in different positions along the developing length at slow and fast releasing of the prestressing force after the concrete had hardened were also studied.

The results indicate that bundling of strands does not reduce the bond capacity. The splitting tendency of the concrete is slightly reduced instead of being spread along the expected spliting crack as it is the case when the strands are in one plane. Prestressing of strands during casting and hardening of concrete increases the bond slightly. The fast release of prestress increases slightly the slip for bundled but not for spaced strands, but does not affect the bond capacity.

Key words: Concrete
Prestress
Anchorage
Bundling

1. INTRODUCTION

The Finnish Code approve of the bundling of prestressing strands over each other in groups of two or three in concrete beams until 28.2.1981. At present only two strands can be bundled. In Sweden, bundling in zones where bond stresses are low, is accepted in practice. In anchorage zones the strands must be spread about and every strand has to be anchored individually taking into consideration minimum spacing requirements. The acceptance of bundling in anchorage zones in Finland is contrary to Swedish practice and seems illogical especially as no known tests performed support it and as the level of the design and the concrete workmanship in both countries is very equal.

The comparative test series with bundled and not bundled strands were performed in an attempt to obtain more knowledge of bond action, deformations, slip between strand and concrete and of failure loads. The tests were carried out as comparison tests on pull-out specimens instead of expensive beam anchorage zone tests because the purpose was to compare particularly the bonding properties of a single and bundled strands. The pull-out specimens are easy to manufacture and load. A large number of specimens can be made and the influence of several parameters on bond studied.

The effect of the prestress and the deterioration on bond between bundled and not bundled strands in different positions along the developing length at slow and fast releasing of the prestressing force after the concrete had hardened were also objects of interest. The eventual damage to bond at fast releasing of the prestress is dependent on the mass of the concrete specimens. A heavier mass will result in increased damage. Therefore the pull-out cubes 300 mm in side length were chosen, FIG 1, and represented the heaviest mass, which could be handled in the testing equipment. However, this mass will still not be heavy enough to study the influence of the chock on bond due to fast releasing of the steel strands. Therefore, the same prestressing steel strands joined with stiff connections were passing through the individual cube moulds in order to make up a heavier mass representative of the mass of a concrete beam. The order of cutting the steel strands determined the degree of damage on the bond in each specimen.

The bond length in the middle of the pull-out specimens was chosen to be 150 mm. At this length a uniform bond stress distribution along the strand could still be expected. The strands outside the bond length were insulated from the concrete using plastic sleeves individually fixed on each rope, FIG 2.

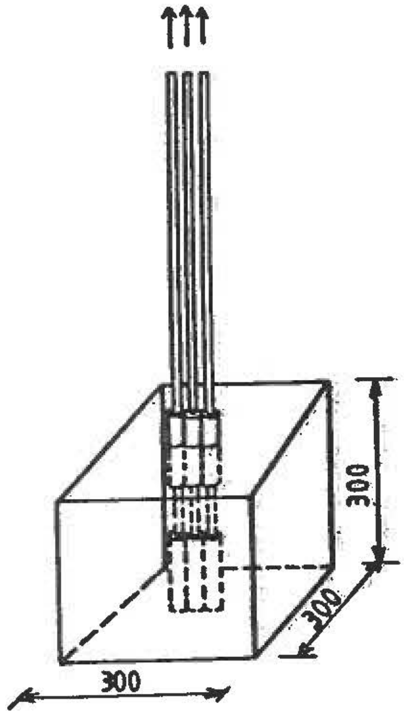

FIG 1. Pull-out specimen. Bond length 150 mm in the middle of the cube.

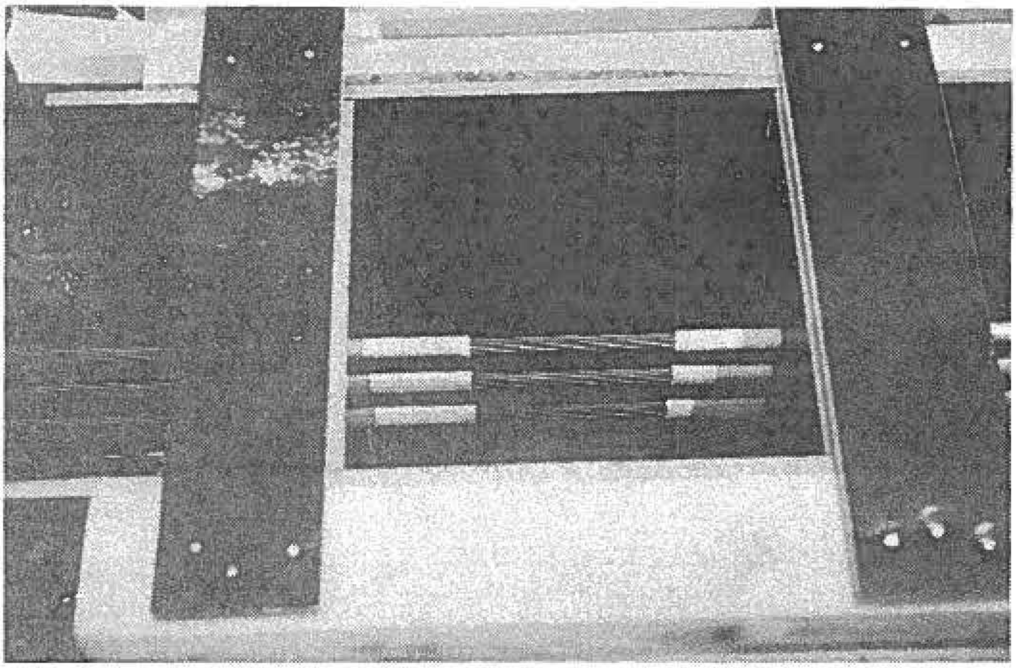

FIG 2. Mould for a pull-out specimen. The three steel strands have the bond length 150 mm and are situated in the middle of the concrete cube.

2. TEST PROGRAM

The test program included 62 pull-out specimens. 30 specimens were manufactured without prestressing the strands and 32 with prestressed strands.

The test specimens without prestress were of 5 different types, designated A, B, C, D and E, as presented in FIG 3. Type A had a single strand, type B had two strands with free space of 37.5 mm in between, type C had two strands bundled over each other, type D had three strands in a vertical plane with free space of 37.5 mm in between and type E had three strands close together in a vertical plane. 6 specimens of each type were manufactured.

The test series with the specimens without prestress made if possible to compare the bond capacity of bundled strands with that of not bundled ones and also with the bond capacity of a single strand forming the basis for the comparison and representing the highest possible bond capacity of a strand.

The test specimens with prestress represented only the pull-out specimens of type D and E according to FIG 3. The specimens were manufactured along two prestressing lines as shown in FIGS 4 and 5. Along both lines 8 specimens of respective type (two indentical with each other) were produced. After casting and hardening of concrete the prestress of line 1 was released very fast and the prestress of line 2 was released slowly. These arrangements enabled a comparison between the bond capacity of three bundled and that of three not bundled strands, which had prestress during the manufacture of the specimens. A comparison could also be possible between specimens where the bond has been severed differently by the varying chocks in the different ways of release of the prestress in the strands, and between specimens in different positions along the bond developing lengths.

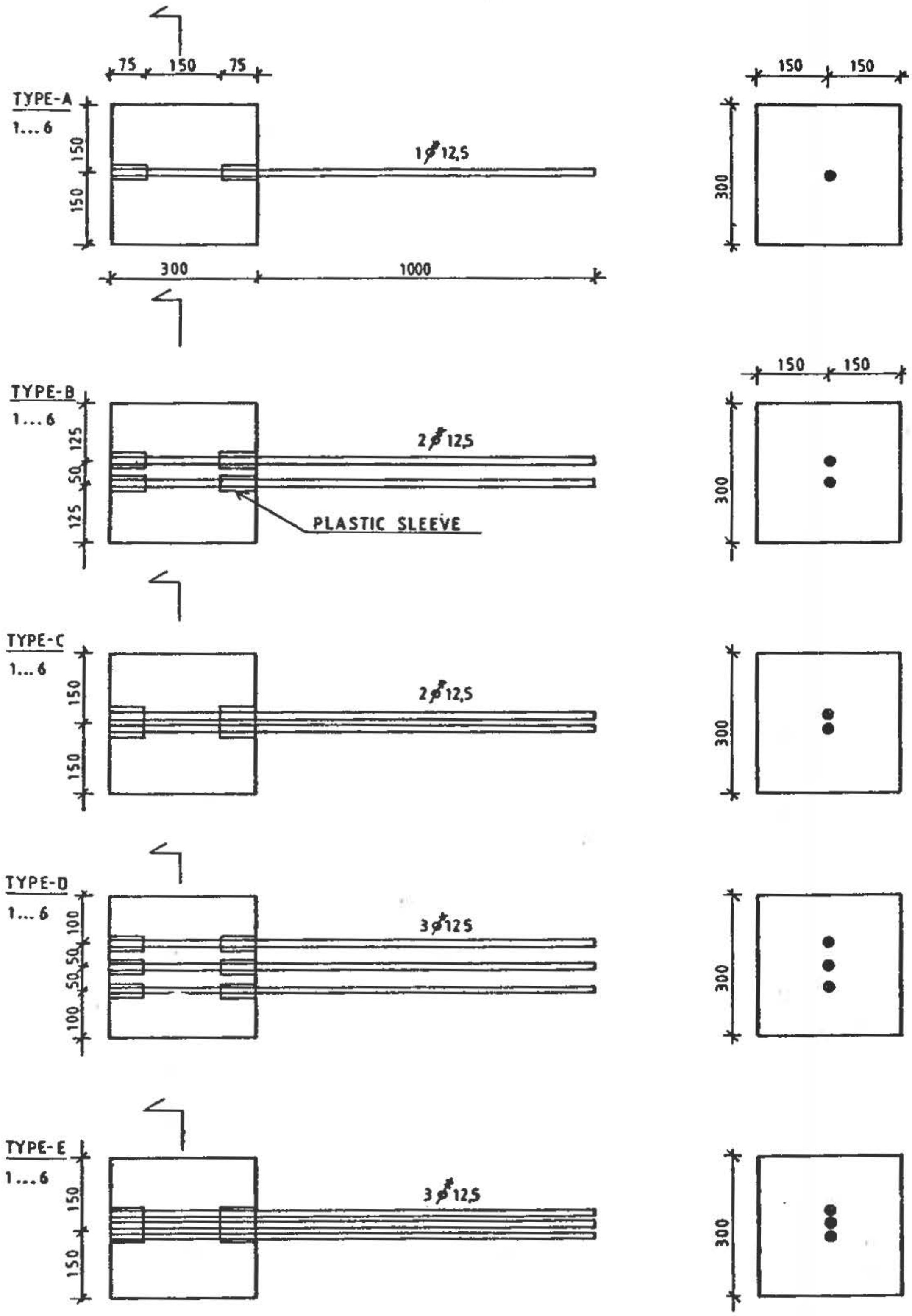

FIG 3. Pull-out specimens with bond length 150 mm in the centre of the cube.

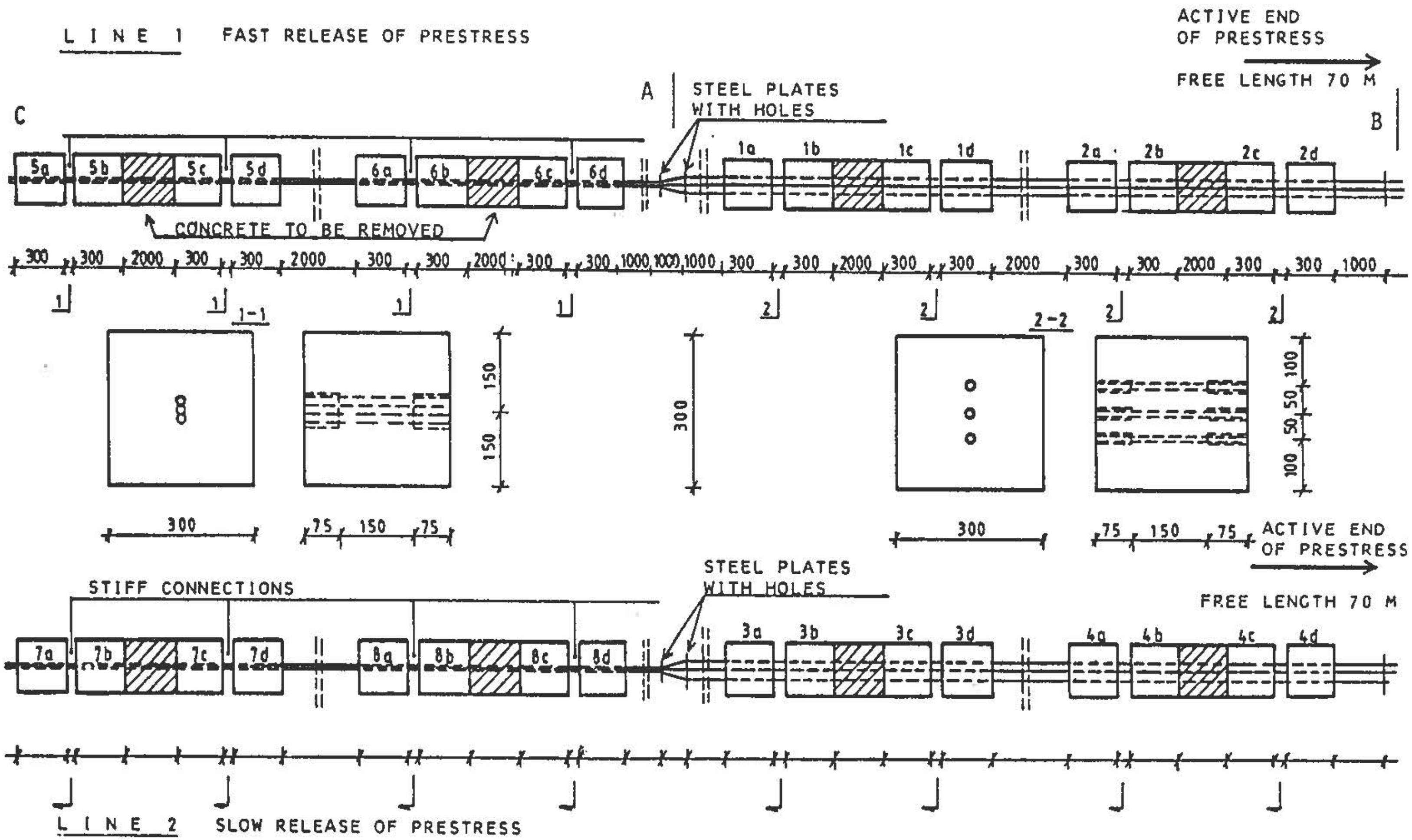

FIG 4. Pull-out specimens with prestressed strands cast along the prestressing lines.
At fast release of prestress the cutting of the strands was done in the order of a, b and c.

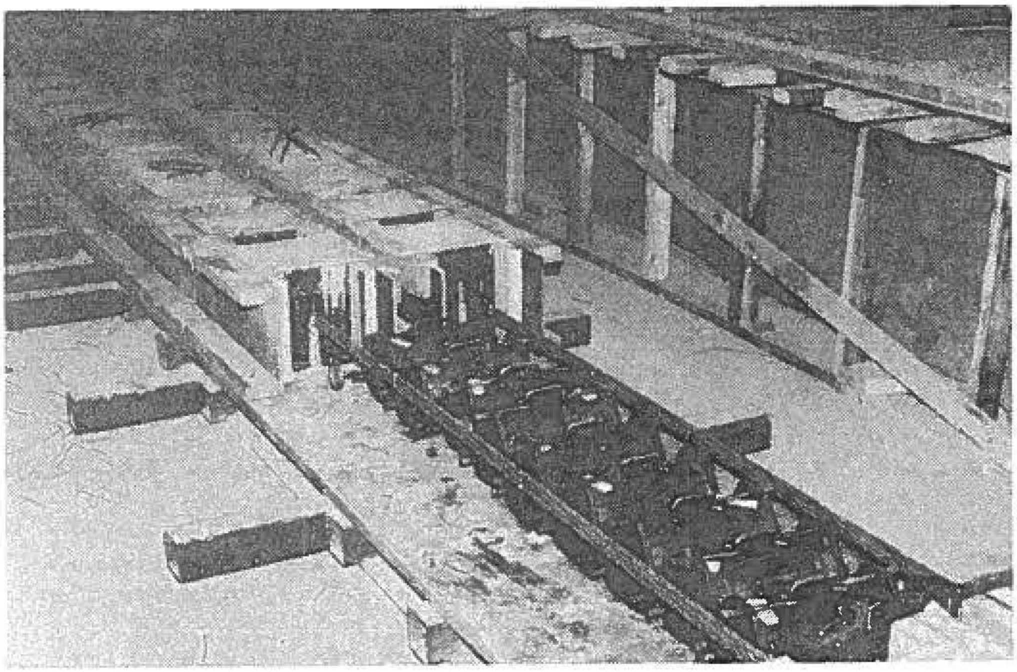

FIG 5. One of the four groups of pull-out specimens after casting together with the concrete cylinders.

3. MANUFACTURE OF SPECIMEN

The pull-out specimens were manufactured with the strands being horizontal and placed over each other in a vertical plane if there were more than one strand. The strands outside the bond length were protected against the concrete by thin stiff plastic sleeves close to the perimeter of the strands. The plastic sleeves did not space the bundled bars more than 2 mm apart. The direction of casting of the concrete was transverse to the location of the strands and thus simulated the situation at casting of a prestressed beam. The concrete was compacted by a poker vibrator.

At the casting of the specimens also standard cylinders ø 150 x 300 mm were cast for determination of the strength of concrete at releasing of the prestress. The concrete cylinders were stored nearby the pull-out test specimens and covered by plastic sheeting.

4. RELEASING OF PRESTRESSING FORCE

The strands were prestressed up to 1360 MN/m^2 in the two lines about 108 m in length. Before releasing the weight of the concrete elements with a mass of 7500 kg was placed on the pull-out specimens along every line. In spite of this, the specimens at release did slip slightly. The sequence of the releasing of the prestress for each line is presented in FIG 4. At slow release the total elongation of 560 mm was reduced step by step by 30 to 60 mm in turn for each strand.

The specimens faced towards the first cutting sections of the strands at fast releasing received chocks which deformed the strands as shown in FIG 6.

5. PROPERTIES OF STRANDS

The prestressing strands were British Bridon low relaxation prestressing strands with nominal diameter 12.5 mm and steel area 94.2 mm^2. The breaking stress was 2012 N/mm^2, elongation to fracture 6.2 %, stress at 1 % extension 1852 N/mm^2, 0.2 % proof stress 1900 N/mm^2 and the modulus of elasticity 198500 N/mm^2. The strands were made up of 7 wires with 4.1 mm diameter.

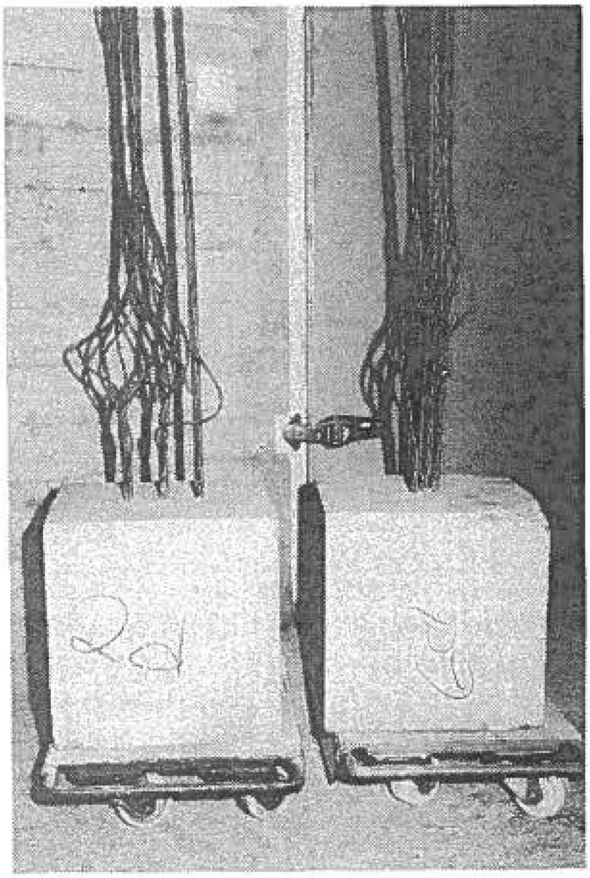

FIG 6. Specimens with twisted strands due to chock at fast release of prestress.

6. PROPERTIES OF CONCRETE

The concrete was proportioned for the strength class K 50 with rapid hardening Portland cement 490 kg/m^3, water cement ratio 0.43 and maximum aggregate size of 16 mm. The consistence of the concrete corresponded to 1-2 Vebe (s).

The strength of the concrete was determined on cylinders ϕ 150 mm x 300 mm after 4 days at the releasing of the prestress from the strands and at the beginning of the testing time after 13 days and at the end of it after 17 days. The test results are presented in Table 1, where also corresponding cube strength is given for cubes 150 mm in side length.

Table 1.

No.	Age days	Cylinder strength MPa	(Corresponding cube strength Side length 150 mm MPa)
A1	4	35.0	(43.0)
A2	4	38.5	(46.5)
A3	4	29.5	(37.5)
A4	4	35.0	(43.0)
Mean	4	34.5	(42.5)
B1	13	44.0	(49.0)
B2	13	44.0	(49.0)
B3	13	43.5	(51.5)
Mean	13	43.8	(49.8)
B4	17	44.5	(52.5)
B5	17	45.5	(53.5)
B6	17	-	(-)
Mean	17	45.0	(53.0)

7. TESTING EQUIPMENT

The pull-out tests were performed in a 200 kN hydraulic testing machine, FIG 7. The pull-out specimens were supported against a steel-plate with wood fibre board in between. The first tested specimens (A1, A2, A3, B1, C1, D1, D2 and E1) had an insertion of a 5 mm thick rubber plate. This plate due to excessive transverse deformation under compressive load contributed to the splitting of the pull-out test cubes. Therefore the rubber plate was exchanged for a wood fibre board. The strands were fixed to the pulling head of the machine by wedge locks, FIG 8. The bundled strands were kept in the position by a special device so as to prevent disturbing forces on the specimen caused by divergency of strands. The locking system gave an even load distribution on all pulled strands. The free strand end slip relative to the concrete was registered using one electronic gauge and two dial gauges, FIG 9.

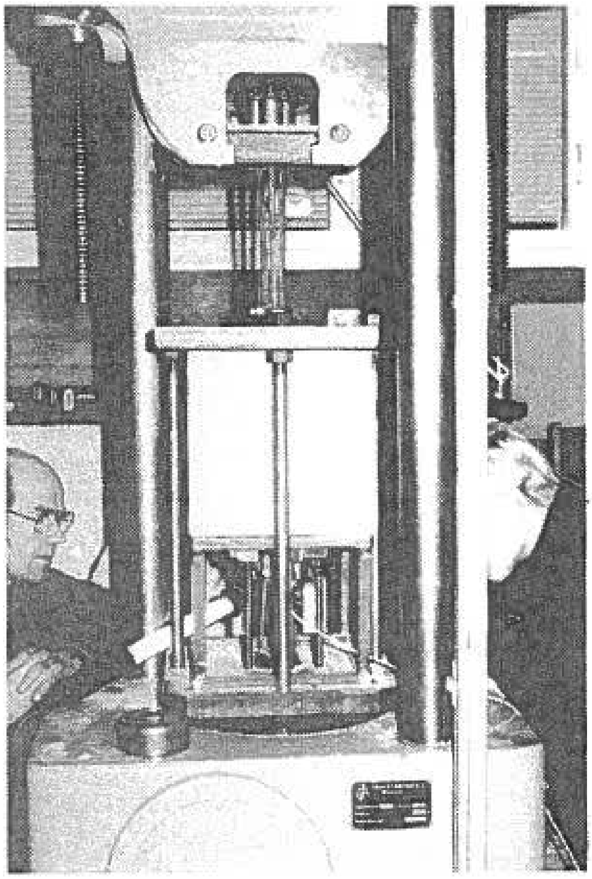

FIG 7. Pull-out test in a 200 kN hydraulic testing machine.

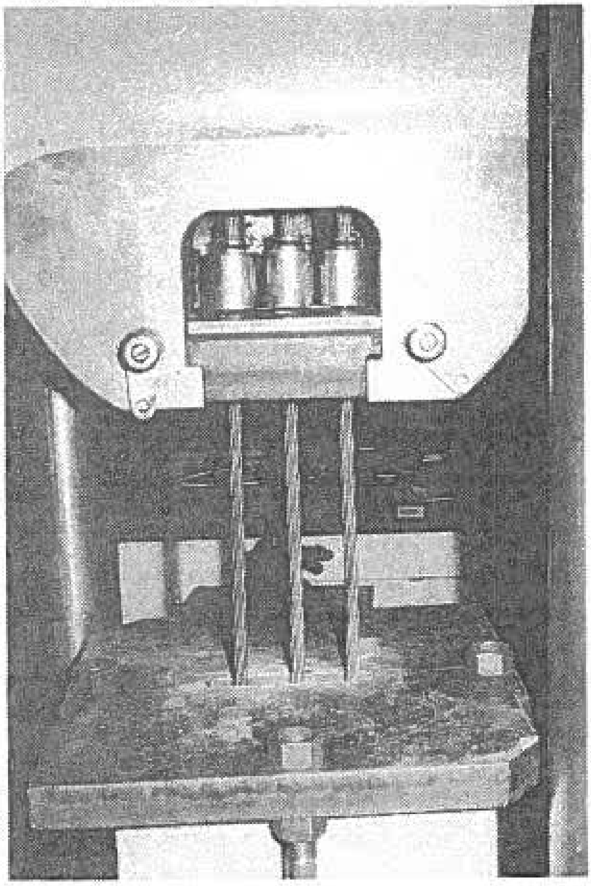

FIG 8. Anchoring of the strand ends to the pulling head of the hydraulic testing machine.

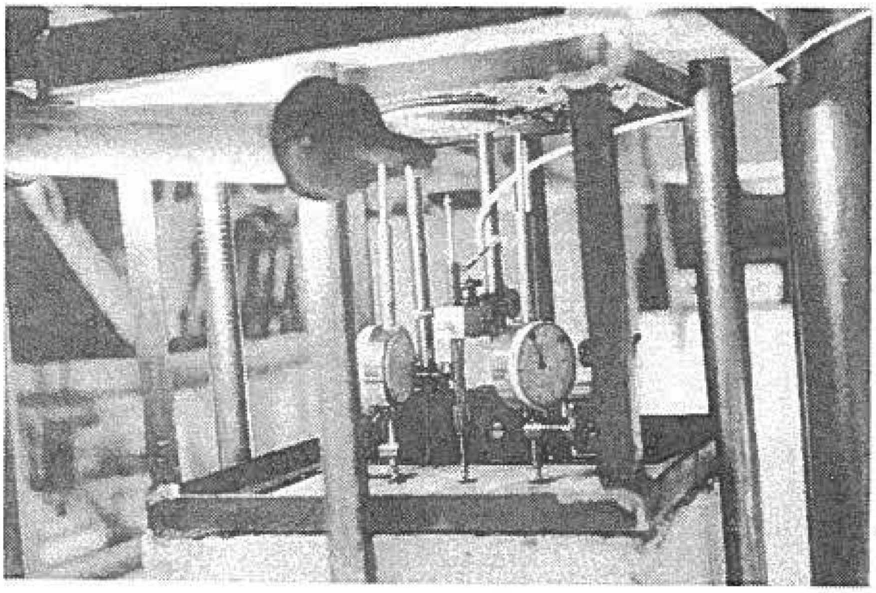

FIG 9. Registration of the free strand end slip by one electronic gauge and two dial gauges.

8. TEST RESULTS

The test results obtained are presented in tables and diagrams.

The results from pull-out tests without prestressed strands are gathered in Table 2. In the table the tensile force of all the strands is given at slips of 0.01, 0.1, 1, 10 mm and at failure for individual strand. Mean values of the six specimens of equal design are calculated. The specimens A1, A2, A3, B1, C1, D1, D2 and E1 were tested with a rubber plate used as a support between the concrete cube and the testing machine. As the transverse deformation of the rubber under load is greater than that of concrete, the cube loaded by transverse friction of the rubber plate resulted in an earlier splitting of the cube. For the purpose of excluding the splitting force transfer from the rubber plate the rubber was replaced by wood fibre plate. The change in the arrangement increased the splitting failure loads by about 20 %.

Mean failure loads with supporting wood fibre plate are given at the bottom of Table 2. The mean load values on different levels of slip include specimens with the wood fibre plate as well as with the rubber plate, because the rubber plate is considered to influence only the failure load.

The results from pull-out tests with strands prestressed during the casting, are presented in Table 3. In the table the specimens, with 3 strands in each, are divided into specimens with bundled and not bundled strands. Then the specimens are divided into such groups, where the prestress in the strands was slowly released and into such groups, in which the release of the prestress was fast. Finally the specimens were arranged in such a way that they were directly exposed to the chock of the release of the prestress or that they were indirectly affected. The results from the 4 individual specimens mentioned at each column heading are arranged in lines 1, 2, 3 and 4

Table 2. Results from not prestressed specimens. Tensile force of the strand/strands.

	SPECIMEN	TENSILE FORCE IN STRANDS, kN										
		A type one strand	B type two strands		C type two strands		D type three strands			E type three strands		
			not bundled		bundled		not bundled			bundled		
		1	1	2	1	2	1	2	3	1	2	3
At slip of 0.01 mm kN	1	102,0 1)	51	34	24,5	46,5	93	82	79,5	78	91	127
	2	32,5	47	30	59	65	97	108	72	105	68	110
	3	36,2	62,5	75	55	59	44	101	106	37	43	73
	4	55	50	95	68	70	129	102	82	88	88	113
	5	32,0	35	55	67	65	66	103	82	80	108	129
	6	36,0	58	82	37	43	61	86	83	57	79	116
Mean value	$\bar{x}$	49.0	51,4	54,3	56,3	57,8	71,8	101,5	87,4	73,2	79,5	111,3
			52,9		57,0		86,9			88,0		
At slip of 0.1 mm kN	1	-	67	50	40	60	104	107	95	98	108	134
	2	-	60	52	78	77	124	128	95	117	80	124
	3	46	79	79	70	78	63	110	119	76	88	100
	4	40	68	56	99	80	83	139	120	96	110	145
	5	39	47	70	80	75	88	114	101	98	118	148
	6	42	72	95	52	65	85	106	104	76	94	122
Mean value	$\bar{x}$	41,8	65,5	67,0	69,8	72,5	91,2	117,3	105,7	93,5	99,7	128,8
			66,3		71,2		104,7			107,3		
At slip of 1.0 mm kN	1	107 2)	98	91	72	85	163	157	139	142	156	168
	2	53	94	85	111	107	172	171	155	162	120	159
	3	60	112	111	102	102	113	145	150	120	120	154
	4	56	96	92	125	119	137	167	157	145	150	188
	5	48	86	92	108	105	136	152	145	160	170	192
	6	54	107	115	95	106	136	148	146	124	137	147
Mean value	$\bar{x}$	54,2	98,8	97,7	102,2	104	142,8	156,7	148,7	142,2	142,2	168,0
			98,3		103,1		149,4			150,8		
At slip of 10.0 mm kN	1	-	162	162	166	175	-	-	-	-	-	-
	2	90	152	148	-	-	-	-	-	-	-	-
	3	112	175	173	214	214	-	-	-	-	-	-
	4	98	145	139	223	218	-	-	-	-	-	-
	5	89	157	160	191	187	248	-	248	-	-	-
	6	80	190	193	218	218	230	230	-	220	226	227
Mean value	$\bar{x}$	93,8	163,5	162,5	202,4	202,4	-	-	-	-	-	-
			163,0		202,4		239			224		
Maximum value kN	1	160 g)	206,5 s)		203,5 s)		233 s)			178 s)		
	2	139,3 s)	234,0 s)		270,0 s)		173,5 s)			298 s)		
	3	174,5 1)	248,0 s)		296,0 s)		262,0 s)			299 s)		
	4	148,0 g)	277,0 s)		271,0 s)		294,5 s)			293 s)		
	5	179,0 1)	266,0 s)		279,0 s)		291,5 s)			301 s)		
	6	151,0 g)	277,5 s)		290,0 s)		276,0 s)			258,5 s)		
Mean value	$\bar{x}$	159,3	260,5		281,2		281,0			289,9		

g) slip failure
s) splitting failure
1) failure of strand
2) excluded from the mean value

The specimens A1, A2, A3, B1, C1, D1, D2, and E1 have supporting rubber plate and are excluded from the maximum mean value load.

Table 3. Results from prestressed specimens. Tensile force in all three strands.

NOT BUNDLED STRANDS

	Strand	Slow releasing of stress: 3a,3d,4a,4d 1	2	3	3b,3c,4b,4c 1	2	3	Fast releasing of stress: 1a,1d,2a,2d 1	2	3	1b,1c,2b,2c 1	2	3
At first slip kN	1	55	120	102	92	95	107	106	100	152	100	118	131
	2	101	116	103	72	133	97	82	102	138	77	120	130
	3	85	107	107	65	89	102	88	100	50	47	95	109
	4	103	123	118	85	106	100	65	114	93	104	138	104
Mean value	$\bar{x}$	86,0	116,5	107,5	78,5	105,8	101,5	85,3	104,0	118,3	82	117,8	118,5
		103,3			95,3			102,5			106,1		
At slip of 0.1 mm kN	1	69	130	116	113	105	128	113	107	160	130	140	138
	2	120	130	120	86	150	120	90	123	150	90	125	140
	3	100	127	120	85	116	119	112	117	98	52	110	120
	4	117	135	126	114	122	119	74	118	96	125	155	122
Mean value	$\bar{x}$	101,5	130,5	120,5	99,5	123,3	121,5	97,3	116,3	126,0	99,3	132,5	130
		117,5			114,8			113,2			120,6		
At slip of 1.0 mm kN	1	116	178	168	152	157	163	127	144	180	164	167	170
	2	160	166	161	140	182	160	135	180	188	156	165	167
	3	152	168	160	140	158	154	190	193	124	90	146	144
	4	153	166	154	151	157	155	100	126	107	164	164	180
Mean value	$\bar{x}$	145,3	169,5	160,8	145,8	163,5	158,0	138,0	160,8	149,8	143,5	160,5	165,3
		158,5			155,8			149,5			156,4		
At slip of 10.0 mm kN	1	-	-	-	242	243	244	208	208	216	-	-	-
	2	-	-	-	-	-	-	240	250	-	-	-	-
	3	-	-	-	-	-	-	188	188	182	-	-	-
	4	212	213	216	-	-	-	162	188	158	-	-	-
Mean value		-	-	-	-	-	-	199,5	208,5	185,3	-	-	-
		-			-			198,9			-		
Maximum value kN	1	273 s)			264,5 s)			260 s)			260 s)		
	2	250 s)			278 s)			269 s)			269,5 s)		
	3	281 s)			269 s)			258 s)			266 s)		
	4	277 s)			266 s)			275 s)			254,5 s)		
Mean value	$\bar{x}$	270,3			269,4			265,5			262,5		

BUNDLED STRANDS

	Strand	Slow releasing of stress: 7a,7d,8a,8d 1	2	3	7b,7c,8b,8c 1	2	3	Fast releasing of stress: 5a,5d,6a,6d 1	2	3	5b,5c,6b,6c 1	2	3
At first slip kN	1	118	175	150	63	140	127	25 1)	82	-	118	90	143
	2	90	97	187	85	107	163	129	113	155	101	120	150
	3	119	130	157	101	120	153	143	96	156	95	90	139
	4	143	115	148	91	95	142	-	-	-	38	100	153
Mean value	$\bar{x}$	117,5	129,3	160,5	85	115,5	146,3	136	97	155,5	88,0	100,0	146
		135,8			115,0			124,8			111,4		
At slip of 0.1 mm kN	1	135	184	166	77	159	142	-	107	-	147	111	160
	2	109	116	198	104	118	175	146	-	-	120	140	162
	3	146	150	200	118	136	165	162	120	176	123	104	150
	4	153	129	159	110	113	149	-	-	-	53	113	162
Mean value	$\bar{x}$	135,8	144,8	180,8	102,3	131,5	157,8	151	114	176	118,8	117,0	158,5
		153,8			130,5			147,2			128,8		
At slip of 1.0 mm kN	1	195	220	213	123	188	180	64 1)	142	-	182	156	178
	2	181	174	240	150	160	198	181	163	168	162	178	191
	3	200	190	230	164	180	196	211	180	216	170	154	183
	4	186	172	195	157	159	174	-	-	-	85	150	183
Mean value	$\bar{x}$	190,5	189,0	219,5	148,5	171,8	187,0	196	161,7	192	149,8	159,5	183,8
		199,7			169,1			183,1			164,3		
At slip of 10.0 mm kN	1	-	-	-	248	-	-	205	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	245	-	-
Mean value		-	-	-	-	-	-	-	-	-	-	-	-
		-			-			-			-		
Maximum value kN	1	300 s)			277 s)			269 m) 1)			275 s)		
	2	295,5 s)			314,5 s)			276 s)			286,5 s)		
	3	300 s)			263 s)			302,5 s)			282 s)		
	4	297 s)			287 s)			-			276 s)		
Mean value	$\bar{x}$	279,0			285,4			289,3			279,9		

1) not included in mean value $\bar{x}$

s) splitting failure

m) grip failure in machine

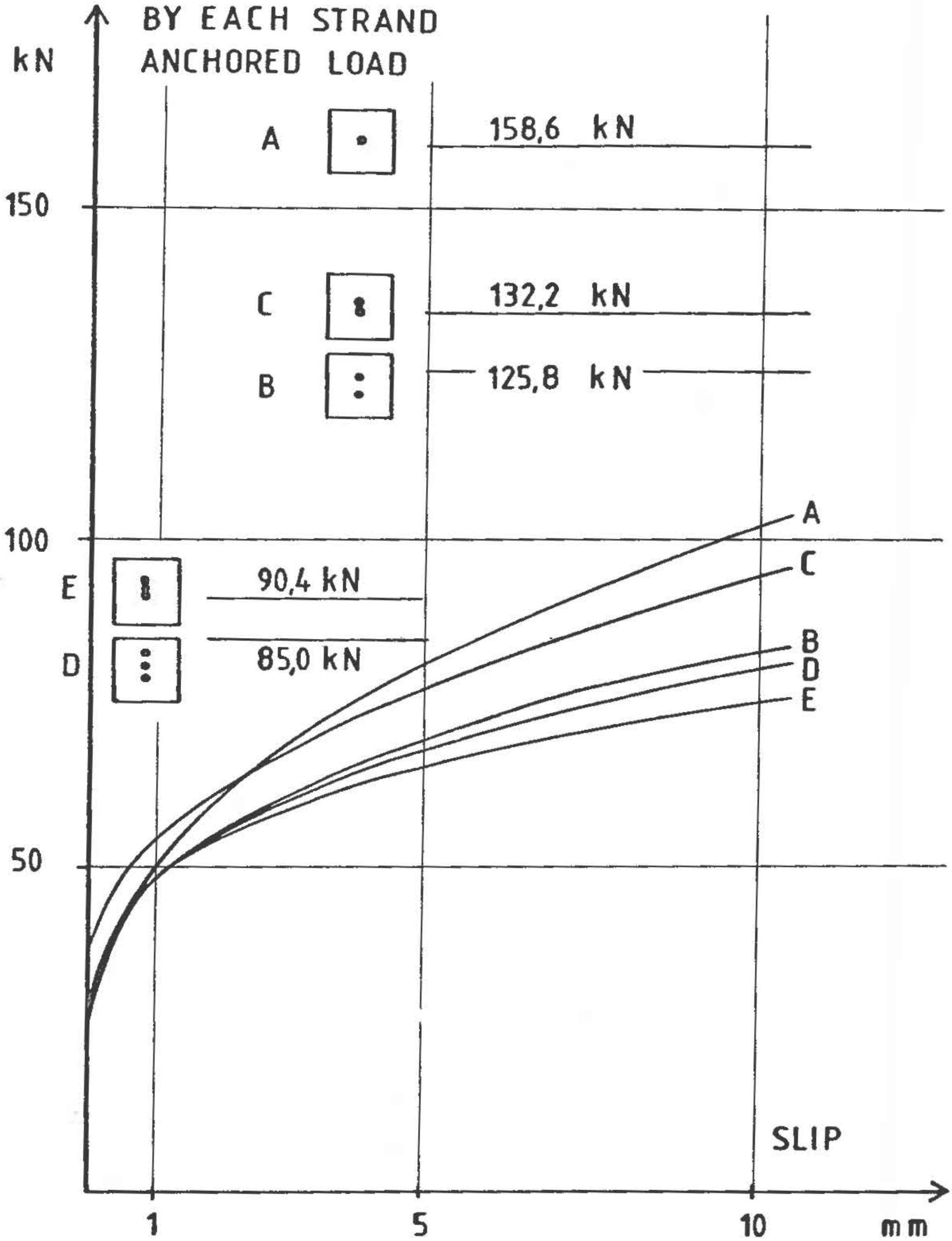

FIG 10. Load-slip curves for pull-out specimens without prestressed strands. The curves represent mean registrations for the 6 equal specimens.

in the same order as at the heading. The loads taken by all three strands, 1, 2 and 3, at the first slip and at slips of 0.1, 1.0 and 10 mm for individual strands are given. Number 2 always represents the total load at a certain slip of the strand in the middle. The mean values of the load taken by the strands are calculated for the 4 equal specimens.

The mean values of the load taken by the strands from the pull-out tests without prestressed strands are compared in Table 4. The comparison is done between specimens with bundled and not bundled strands at different slip values. The results are also shown in diagram, FIG 10. It must be noted that the specimens with two and three strands failed by splitting of the surrounding concrete and not by bond. The splitting forces resisting concrete mass is about the same for all specimens and is naturally cause for about equal ultimate load on the strands. It can be noted that all of the ten comparisons except one at different slip values and at failure gave higher failure load for bundled strands. Obviously, the splitting forces have about 5 % greater effect if they are spread along the line of the expected crack than if they are concentrated near the centre of the cube. This fact is important because it was believed that the splitting effects of the anchored strands were reduced if the strands were spread about in the concrete. Probably this would be the fact if the three strands were spread about so that they would not act together on the formation of the same crack. This means that no more than two strands should be in the same plane.

In Table 6 the coefficients of variation are calculated for the series of six equal specimens, which are compared. The coefficients of variation have about the same magnitude on every certain level of slip for the series with 2 and 3 strands respectively. Therefore a comparison between specimens with bundled and not bundled strands is possible. The coefficients of variation show a decrease with an increasing slip. The specimens with one strand show the lowest coefficients of variation at low slip values but not at failure.

The tests with one strand only, type A, gave different reasons for failure. 3 specimens failed due to bond at mean strand load of 153 kN and corresponding mean bond stress of 26.0 MPa. 2 specimens failed because the strands were broken. The mean load was 177 kN, and the mean ultimate tensile stress of the strands was 1878 N/mm^2. The specimen A2 failed due to splitting of the cube under a rather low load. The supporting rubber plate used in this specimen, must have influenced considerably the splitting force during testing. In all tests, the bond stress at failure exceeded the bond stress at splitting failure for specimens with two and three strands.

The mean values of the loads taken by the three strands, which were obtained from the pull-out tests with prestressed strands at casting, are compared in Table 5. The comparison is done between specimens with bundled and not bundled strands at slow and fast releasing of prestress. The results are also shown in diagram, FIG 11. All specimens except one failed due to splitting of the concrete cube caused by anchorage forces. The failure of the one deviating specimen was a result of a grip failure in the loading machine. This value is excluded from the analysis. All specimens were supported against wood fibre plate.

Table 4. Anchored force by each strand in pull-out specimens without prestressing. Mean values of results from six equal specimens.

Anchored force at	A	B	C	D	E	C/B	E/D
First slip kN/strand	38.3	26.5	28.5	29.0	29.3	1.08	1.01
Slip of 0.1 mm kN/strand	41.8	33.2	35.6	34.9	35.8	1.07	1.03
Slip of 1.0 mm kN/strand	54.2	49.2	51.6	49.8	50.3	1.05	1.01
Slip of 10 mm kN/strand	93.8	81.5	101.2	79.7[1]	74.8[1]	1.24	0.94[1]
Maximum value kN/strand	159.3	130.3	140.6	93.7	96.6	1.08	1.03

[1] only a few values

Table 5. Anchored force by each strand in prestressed pull-out specimens. Mean values of results from four equal specimens.

Anchored force at	NOT BUNDLED				BUNDLED			
	Slow releasing of prestress		Fast releasing of prestress		Slow releasing of prestress		Fast releasing of prestress	
	3 a,d 4 a,d	3 b,c 4 b,c	1 a,d 2 a,d	1 b,c 2 b,c	7 a,d 8 a,d	7 b,c 8 b,c	5 a,d 6 a,d	5 b,c 6 b,c
First slip kN/strand	34.4	31.8	34.2	35.4	45.3	39.3	39.1	37.1
Slip of 0.1 mm kN/strand	39.2	38.3	37.7	40.2	51.3	43.5	49.0	42.5
Slip of 1.0 mm kN/strand	52.8	51.3	49.8	52.1	66.6	56.4	61.1	54.8
Slip of 10 mm kN/strand	–[1]	–[1]	65.9	–[1]	–[1]	–[1]	–[1]	–[1]
Maximum value kN/strand	90.1	89.8	88.5	87.5	93.0	95.1	96.4	93.3

[1] The anchored force could not be registered.

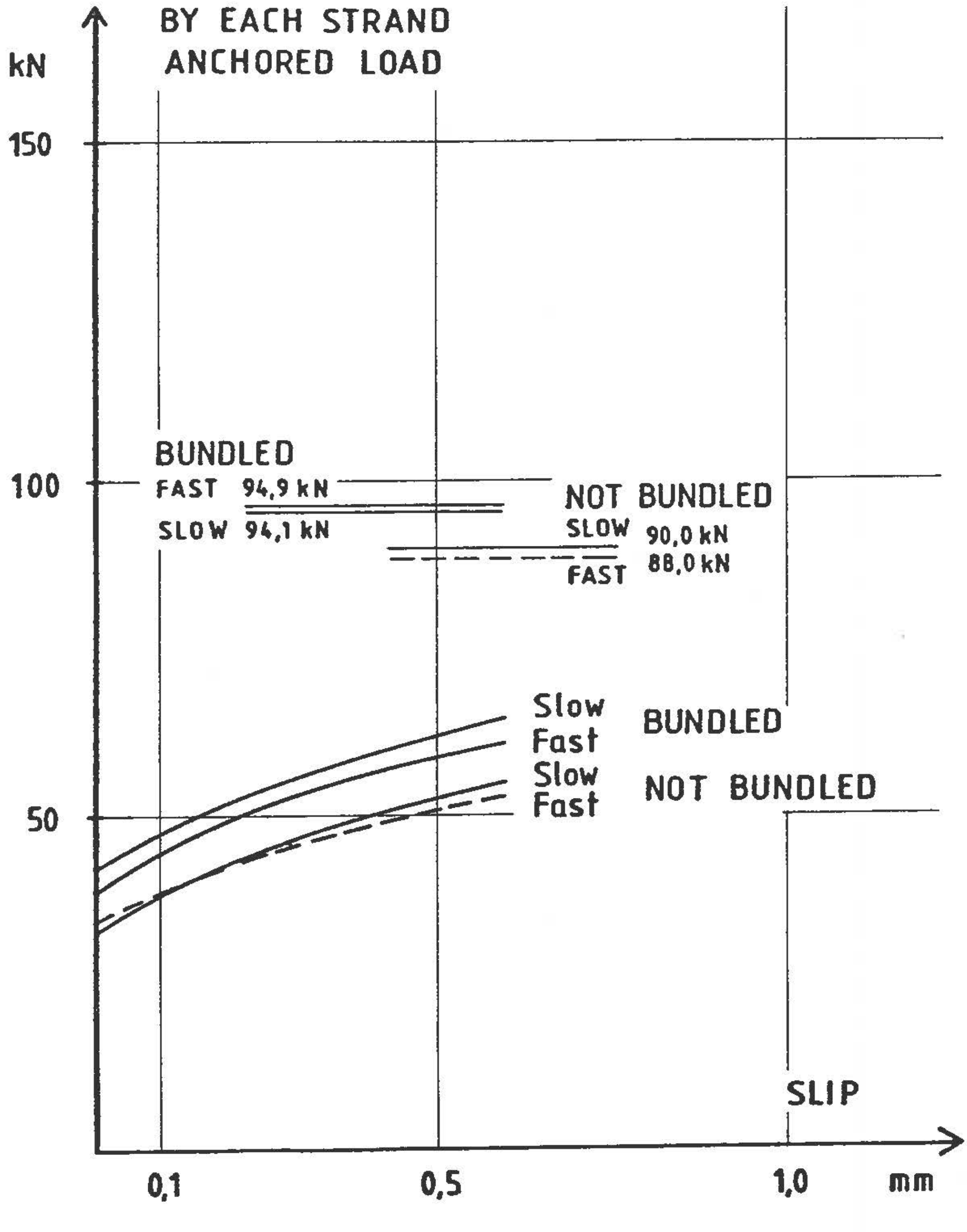

FIG 11. Load-slip curves for pull-out specimens with strands prestressed during casting and hardening of concrete. The curves represent mean registrations for 8 specimens.

The failure loads for all specimens are of about the same magnitude due to the splitting resistance of the concrete cube. The failure load is also the same as stated for specimens with three not prestressed strands at casting. The mean bond stress at splitting failure is from 15 to 20 MPa for the tests as shown in Table 5.

Table 6. Coefficients of variation in percentages for specimens without prestressing.

	TYPE OF SPECIMEN				
	A	B	C	D	E
At first slip	9.2	29.7	31.6	23.3	30.6
At slip of 0.1 mm	7.4	21.3	21.5	17.5	20.4
At slip of 1.0 mm	8.1	10.6	13.7	9.8	14.3
At slip of 10 mm	12.8	10.4	10.2	-	-
At maximum load	10.7	7.31	4.10	5.35	6.14

From the comparison of the failure loads and the loads at certain slips presented in Table 5 it can be stated that the bundled strands did split the cube later than the three strands distributed in a plane, and also the slips are smaller at corresponding loads. The bundling of bars did not lower the anchoring capacity of the strands anyhow. The load-slip curves and failure load levels are shown in diagram, FIG 11. In the figure the mean data of all the 8 tests under slow and fast releasing of prestress respectively are given for bundled and not bundled strands respectively. A slight increase in the slip is observed in the case of the bundled strands at fast release of prestress in relation to those at slow release. As regards the not bundled strands the slip seems not to be affected by the way of releasing the prestress.

In Table 7 the coefficients of variation are calculated for all series of equal specimens on different levels of slip. With regard to the failure load the coefficients of variation are determined for all the 8 specimens with slow and fast releasing of prestress respectively for bundled and not bundled strands respectively. The coefficients of variation are of about the same magnitude on each level of slip and slightly higher for the specimens with fast release of prestress. The coefficients of variation decrease when the slip increases and have their lowest magnitude for the failure loads. Here, however, the coefficients of variation are lower for specimens with fast releasing of prestress. It must be observed that the failure load is determined by the splitting resistance of the cube and not directly by bond.

Table 7. Coefficients of variation in percentages for prestressed specimens.

	NOT BUNDLED				BUNDLED			
	Slow releasing		Fast releasing		Slow releasing of stress		Fast releasing of stress	
	3 a,d 4 a,d	3 b,c 4 b,c	1 a,d 2 a,d	1 b,c 2 b,c	7 a,d 8 a,d	7 b,c 8 b,c	5 a,d 6 a,d	5 b,c 6 b,c
At first slip	17.9	18.3	23.1	23.9	21.8	26.2	23.1	29.5
At slip of 0.1 mm	15.1	15.2	21.2	22.5	19.3	22.0	19.5	24.7
At slip of 1.0 mm	9.7	7.0	23.1	14.8	10.9	12.6	14.6	17.2
At slip of 10 mm	-	-	14.6	-	-	-	-	-
At maximum load	3.7		2.6		5.4		3.7	

9. CONCLUSIONS

The conclusions are for specimens without prestressed strands:

- Concentration of strands in bundles of two and three strands does not increase the splitting tendency of the anchorage zone.
- According to the splitting effect it seems to be favourable not to place spaced strands in layers, where the splitting forces work together in forming a splitting failure crack.
- Bundling of strands does not lower the capacity of anchorage and the slip is increased only slightly. This is valid up to a bond stress level of 29 MPa for two strands and 20 MPa for three strands and concrete cylinder strength of 50 MPa.

The conclusions are for specimens with prestressed strands at casting:

- Prestressing of strands during casting and hardening of concrete increases slightly the bond of the strands in pull-out tests in comparison with those without prestress.
- Bundling of strands does not lower the capacity of anchorage and reduces the slip between concrete and strands in comparison with not bundled strands.
- Fast release of prestress increases the slip slightly for bundled strands but not for not bundled ones and does not affect the bond capacity up to the load at which the pull-out cube specimen was split.

10. REFERENCES

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