New engineering solutions

Trihedral 10-wire compacted strand

Most of prestressed concrete items and constructions use reinforcement without anchor grips or other joints for fixation after manufacture. Furthermore, it's impossible to realize fixation joints in semi-dry casting which is one of most common technologies for manufacture of hollowcore slabs, piles and other widespread items.

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End slip of PC strands (fig. 1) is one of serious factors limiting abilities of such prestressed concrete items and constructions. This effect means that most of prestressed concrete constructions are particularly unloaded (fig. 2) in the end parts [1-6].

This specificity of PC strands generates a variety of technical problems, complications and limitations – but it is considered inevitable. As ends of concrete items (hollowcore slabs for example) are not prestressed – even slabs from one forming can have different tensioning and curvature.

Furthermore, there are many precast concrete items – bridge girders, piles, railway sleepers etc., which are manufactured in one line with separate molds – often the slip of strands in these items can even not detected. PC strand with indented wires has higher and more stable bond to the concrete – but it's more expensive, with lower corrosion, elasticity and relaxation characteristics. And its bond isn't principally higher – such strand can be pulled through all length of hollowcore slab in case of overload.
Since 2003 engineer Lev M. Zaretsky and professor Veniamin A. Kharitonov developed new engineering solutions in PC strand area which could decide most of these problems by extra-high bond to the concrete and, accordingly, extra-short transfer area length.

This PC strand should meet several difficult and conflicting requirements:
- extra-high and stable bond to the concrete;
- high and stable elasticity modulus;
- high fatigue and corrosion resistance;
- high relaxation stability;
- exception of strand jamming between previously laid strands;
- guarantee of concrete flowing anywhere between strand and tendon;
- exception of adverse effects.

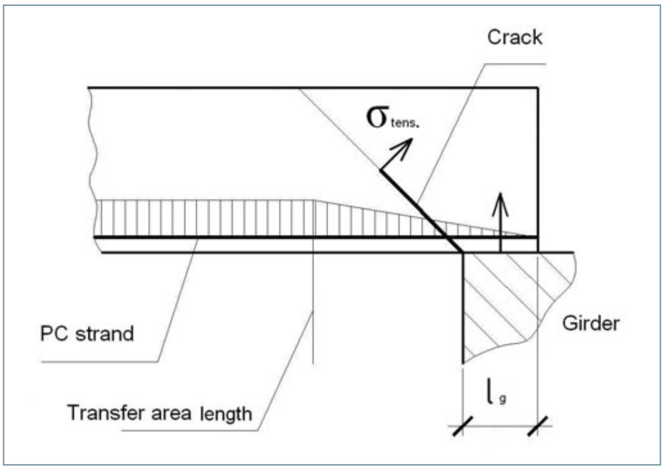

Fig. 2: Epure of longitudinal force fsi in the concrete slab.

That's why the strand must meet following requirements:
- external surface with strongly pronounced inclined planes and periodical (indented) profile – to except both longitudinal and helical movement without total destruction of concrete item;
- indented profile on the external surface only to prevent decrease of corrosion resistance;
- flattened areas in each contact between two wires – for high relaxation stability, high elasticity modulus, high fatigue, better redistribution of tension between wires and coefficient of wire strength use.

So it's possible to make something similar to usual 7-wire strand in these requirements, but they found a very convenient solution for bonded reinforcement – trihedral 10-wire compacted strand with periodical profile on the external surface [7] (fig. 3).
This solution isn't absolutely new – there were similar developments in 60th years of XX century [8] but the predecessors didn't decide

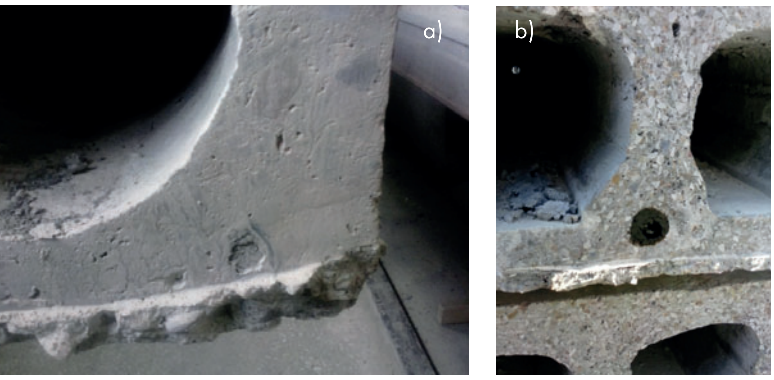

Fig. 1: Slip of PC strands in the hollowcore slab: a – acceptable, b – invalid.

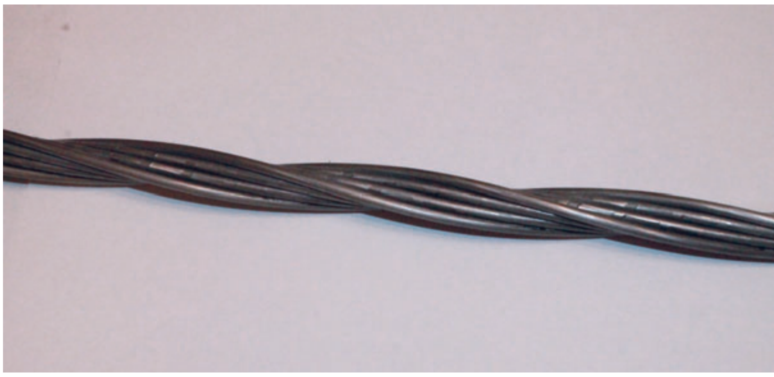

Fig. 3: Physical appearance of trihedral 10-wire PC strand.

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the structural sustainability problem of complicated strand, so the solution wasn't realized.

They decided this problem by some technological solutions and added some important details of configuration:

- periodical indented profile on the external surface of wires for mechanical bond to the concrete in helical direction;
- tight structure for high fatique resistance, high relaxation stability high and stable elasticity modulus.

Such configuration provides much more pronounced relief of the external surface of PC strand and much larger gaps between PC strand itself and its cylindrical generatrix in comparison with commensurate standard "round" 7-wire PC strand (fig. 4).

First tests of trihedral PC strands were realized at Chelyabinsk precast concrete plant #1. These were laboratory comparative tests of pullout force for standard and trihedral PC strands.

The samples of 10-wire PC strand for these tests were not stabilized yet – they were processed only by low temperature tempering, without tensioning – preproduction party was manufactured only several days before this test. So these samples were fixed by wires, which were situated out of concrete – on the back side of cubes.

Fig. 4: Comparison with commensurate standard PC strand.

They tested bond to the concrete by pulling out of 250 mm (10 in) cubes of 50 MPa concrete, without measuring of strand displacement from the back side. Tests were realized with 2 samples of 7-wire strand with 9,0 mm diameter, 140 mm lay and 2 samples of 10-wire strand with 11,5 mm outer diameter (analogue of 9,0 mm 7-wire strand), 145 mm lay.

They received the following results:

- 1st sample of 7-wire strand pulled out of cube at 65 kN,
- 2nd sample (the adjacent part of the same strand) began to pull out at less than 20 kN, max. load was 43 kN.

- 1st sample of 10-wire strand was damaged in the process of casting (approximately 130-140 mm of strand were pushed through formwork bottom into the vibrating table, lost its wire knot and destructed into quasi-round structure with "birdcage" defect because of insufficient tempering) - it was pulled out at 86 kN. Lower – destructed – part of strand (approx. 140 mm) slipped out of lower part of cube, upper – trihedral – part of strand crushed upper part of cube (fig. 5).
- 2nd sample was broken in the clip at 92 kN (its nominal breaking tension - 90 kN or more) without pulling out of cube. This cube remained undamaged (and even previous cube – with damaged strand – was undamaged at 65 kN load - maximum of 7-wire strand).

So Zaretsky and Kharitonov established a very large advantage over standard PC strand in bond to the concrete and couldn't even quantify this advantage. Furthermore, they discovered that not only value of bond differs – but its character too: overloaded standard PC strand moves by slipping, overloaded trihedral 10-wire strand crushes the concrete cube.

Therefore, they were required to ensure no adverse effects of such bond character in real objects – or to make sure their presence. They had severely limited resources for tests also. So they decided to realize the next stage of tests – the field tests of real prestressed concrete items, which are more convenient to identify adverse effects and more interesting for potential customers, instead of further laboratory testing.

Fig. 5: Broken cube of trihedral PC strand.

Fig. 6: Dry casting line with combined reinforcement.

Zaretsky and Kharitonov chose hollowcore slabs for this work, because these slabs have porous concrete and small distance between PC strands and borders of concrete – so, if they wouldn't find adverse effects in hollowcore slabs, they could be sure in their absence. But there was a serious problem: how to ensure a correct comparison between hollowcore slabs reinforced by standard and experimental PC strands. Variety of factors, which can increase/decrease bond to the concrete, could invalidate the result of testing.

The right solution was found by the business partner, engineer Andrey Zaitsev: he offered to make hollowcore slabs with combined reinforcement – several standard PC strands and several trihedral PC strands. Such solution ensures work of compared strands not even in identical according to the documents, but in the same concrete.

Therefore, they casted and cut short line of hollowcore slabs with combined reinforcement: 3 trihedral PC strands Ø 11.5 mm in stabilized performance, 2 standard PC strands Ø 9.0 mm with plane wires and 1 standard PC strand Ø 9.0 with indented wires – in the lower part of slab; 2 wires Ø 5.0 mm in the upper part of slab. The test was realized at Tyumen concrete plant #1 (fig. 6).

The line was cut at 28-36 MPa of concrete strength for 2 slabs with 5.4 m length (for further test program) and 3 slabs with 1,8 mm length (for end slip measuring only).

The depth of slip was:

- about 0,05-0,2 mm for trihedral PC strands;
- about 0.2-0.4 mm for 7-wire PC strand with indented wires;
- from 2.0 and up to 5,5 mm for 7-wire PC strand with plane wires.

On 13.08.2015 they tested one of these hollowcore slabs with 3 standard strands on the right side (in direction of extruding) and 3 trihedral strands on the left side.

SLAB PB54-12-10.5 K7

- Strength of concrete R_{cp} = 560 kg/cm^2 (55 MPa)
- Manufacturing date: May 18, 2015
- Testing date: August 13, 2015
- Reinforcing: 6 x Ø 9 mm PC strands in lower zone, 2 x Ø 5 mm wires in upper zone, 3 strands of experimental 1+6+3 trihedral configuration (with cross-section similar to standard 9 mm strand), far standard strand – in profiled version.
- Grade of concrete: 450 (B35)

- Strength at the time of cutting R_{cp} = 60 %.
- Tension on strands Q = 11400 kg/cm² – approx. 1120 MPa (by INK-2.4 device)

According to drawings IZH 509-05 "NIIMosstroy" under the guidance of V.S. Schukin, load capacity of slab is 10,5 grade (1050 kg/m²), based on the dependencies "load-length". Breaking, rigidity and crack resistance loads were estimated by linear interpolation between "10" and "12.5" grades:

- P_r = 890 kg/m²
- deflection f_c = 8 mm
- P_{cr} = 1050 kg/m² without cracks (a = 0)
- P_b = 1630 kg/m²
- P_{b2} = 1910 kg/m²
- The loading area S = 6.15 m², load unit = 320 kg.

The results of test are described in the Table 1.

So the slab had twice higher deflection on the right side, its breaking force was more than 20% higher than usually. And it was broken when all 3 trihedral strands were riven and all 3 standard strands, including strand with indented wires, were pulled out of concrete into central crack.

Zaretsky and Kharitonov received additional information about work of trihedral strand in the concrete:
- it has no adverse effects, such as crushing of concrete, in overloaded hollowcore slab;
- it doesn't move along the slab under any load

So they supposed that trihedral strand has inclination mechanism of bond to the concrete and very short transfer area length – and it

Table 1. Test of hollowcore slab with combined reinforcement

Load percent	P theor.	P fact.	Number of units	Deflections, centimeters 1st (trihedral strand side)	2nd (standard strand side)	Bearing	Remark
20% P_{cr}	210	208	4	0.095	0.190	0.06	
40% P_{cr}	420	416	8	0.215	0.360	0.115	
60% P_{cr}	630	624	12	0.320	0.524	0.158	
80% P_{cr} = P_r	840	884	17	0.465	0.768	0.198	
P_{cr}	1050	1092	21	0.588	1.028	0.238	No cracks
Pause 30 minutes, after that precision deflectometers are turned off							No cracks
P_{cr} + 10% P_{b2}	1241	1249	24				No cracks
P_{cr} + 20% P_{b2}	1432	1457	28	1.0	2.0		No cracks
P_b	1630	1629	32	a = 0.4	a = 0.5		First cracks in central part
P_{cr} + 40% P_{b2}	1821	1837	36				3 cracks on both sides
P_{b2}	1910	1925	37	f = 10 cm	f = 20 cm		Another 3 cracks, width 0.25 mm on 1st side, 0.5 mm on 2nd side
110% P_{b2}	2101	2185	43	rip	Pulling out		Slab settled on insuring support, all 3 standard strands pulled out of concrete

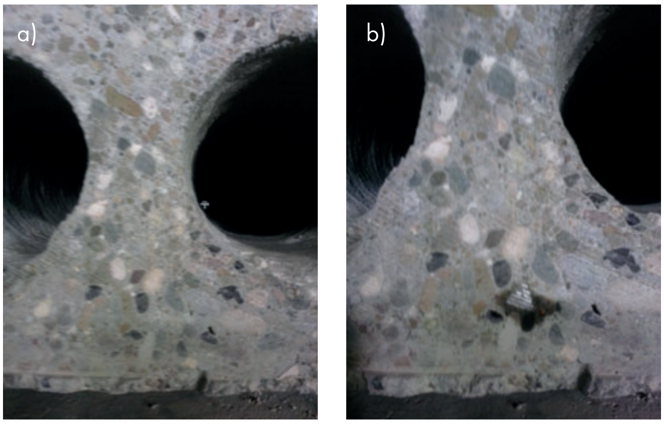

Fig. 7: The appearance of strand flange with zero slip at the end of slab: a – dry, b – wet.

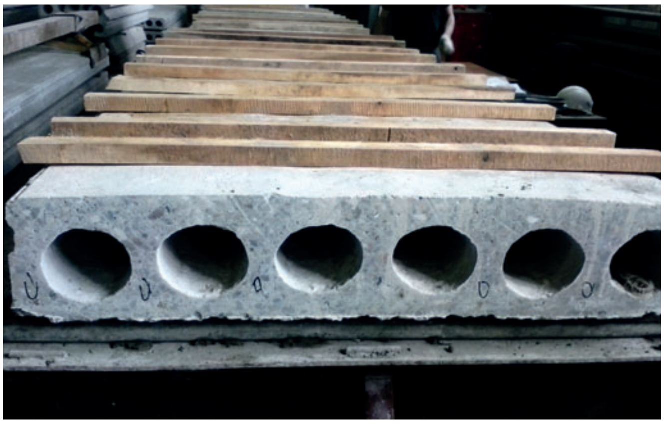

Fig. 8: End of slab with measured depth of strand slip

must have increased crack resistance because of short parts of strand slipping into the beginning crack.

The prime cause of these results is differing mechanism of strands' bond to the concrete: Standard 7-wire strands use adhesion largely – 10-wire strands use inclination. So 7-wire strands load the enveloping contour by the shear stress – 10-wire strands load the volume of concrete by the support reaction.

But they had to make and test hollowcore slabs with complete trihedral slab reinforcement to check this assumption. From 08.2015 to 05.2016 there were manufactured 3 lines of hollowcore slabs with 10-wire strand reinforcement at "Kulonstroy" precast concrete plant in Kazan.

At first stage they manufactured full line with 3 trihedral 10-wire PC strands Ø11.5 mm and 1 standard PC strand Ø9.0 mm, 980 MPa tensioning of all strands, no reinforcement in upper zone, B15-B40 concrete with crushed stone and crushed pebble inert fill. Line was cut into slabs with different strength of concrete with 4.8 m length and one slab of B40 concrete with 6.0 m length.

Zaretsky and Kharitonov decided to test this weakly reinforced long hollowcore slab – and it showed enough rigidity and crack resistance for its length, despite the fact that had to have 6 strands with the same tension. Of course, its load capacity was lower than standard. First cracks were registered at more than 90% of breaking load.

After this test they decided to decrease strength of concrete because of potential economy reasons. They casted full line with 6 trihedral 10-wire PC strands, tension 1100 MPa, no reinforcement in upper zone, B25-B35 concrete with pebble and crushed pebble inert fill;

Also they casted full line with 7 trihedral 10-wire PC strands, tension 1200 MPa, no reinforcement in upper zone, B25-B35 concrete with pebble and crushed pebble inert fill.

Both of these lines were cut to 6.6 m hollowcore slabs – such standard slabs are reinforced by 8 standard strands with 9500-1100 MPa tension. All slabs with 7 strands and slabs with 6 strands after two weeks were tested successfully. All trihedral PC strands in all these tests showed depth of slip from zero to 0.2 mm (fig. 7-8).

So they received interesting product, which is able not only to decrease costs of prestressed concrete manufacturers, but to expand the boundaries of what is possible.

Of course, new product needs in serious work: certification, approbation, manufacture of anchor grips etc. For example, they realized 1st and 2nd stages of tests with standard 3/8' anchor grips, but

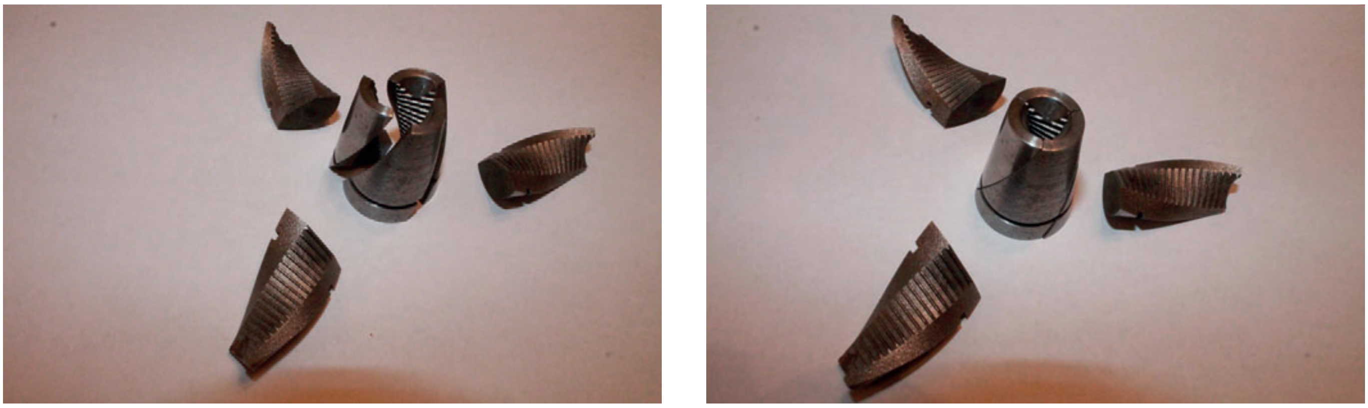

Fig. 9: 1st version of anchor grip for trihedral PC strand.

their colleagues from precast concrete plants asked to develop new configuration of anchor grip, because existing grip isn't reliable in work with the trihedral strand.

So Zaretsky and Kharitonov developed a new configuration of anchor grip (fig. 9) which surface answers to surface of strand – but they decided that this design is too expensive.

So now they are testing another idea of anchor grip. Of course, all received results are only a new piece of science now. They have to realize design of reliable and cheap anchor grip, certification of new strand for the key world's standards and manufacture of both products.

But sometimes this trihedral 10-wire PC strand could become the same world standard, as usual 7-wire PC strand now.

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