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Preliminary report

Testing bond behaviour of an innovative triangular strand: experimental setup challenges and preliminary results

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1 Introduction

In the beginnings of prestressed concrete, a smooth prestressed wire made of hardened, high-grade steel was first used. The quality of the material was of the utmost importance due to the possibility of applying greater forces and a lower relaxation loss. Over time, it has been shown that smooth prestressed wire, in the case of force transfer by direct bond, has certain shortcomings in terms of bonding only through adhesion and friction, which is disrupted during the first slips. To improve these shortcomings of the wire, a solution was reached in the form of a strand woven from wires of smaller diameters. The improvement is reflected in the capacity of the bond, where it can be seen that when the strand slips, the bond resistance remains constant or increases. This desired behavior of the strand is attributed to the mechanical locking, i.e. wedging, which does not exist in the case of smooth wires. Thus, today, the strand for prestressing means the conventional 7-wire (7-w) strand.

In the case of pre-tensioned beams (force transfer by direct bond), the most important connection is the bond between the strand and the concrete. Thus, a difference in the bond was observed in the zones of the beam ends and the central zones. End-zones of the girder are called the anchorage zones into the concrete structure (transfer length zones). The development length I_d of the prestressing force is the superposition of the transfer length I_t and the flexural bond length I_{fb}. The bond of the transfer force from the strand to the concrete during release is called the "prestress transfer bond." During the bending of beam elements, when cracks appear, the bond between strands and concrete plays an important role in the subsequent behavior of the elements. The bond that is activated as a result of bending,

ABSTRACT

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The use of the seven-wire strand in pretension structures so far has shown that such strands have a relatively long development length. An attempt to reduce the development length is reflected through the idea of a different strand geometry that has a more favorable shape. This new shape should have a greater inclination of the outer wires, increasing the resistance that occurs when moving through the concrete. The idea is primarily about the triangular distribution of wires in the cross-section of the strand. This paper reviews tests related to the use of innovative, triangular, and ten-wire strands. The tests exclusively relate to the strands formed by the use of steel wires.

and which has a significant role in the continuity of the prestressing force transfer, is called the bond due to bending or "flexural bond."

Long-term experimental research [1, 2, 3, 4, 5, 6, 7] has shown that the transfer length and the development length of the prestressing force are influenced by several important parameters. If the diameter of the strand increases, the value of It and Id also increases. The characteristic 28-day strength of concrete has little effect on It, while its increase results in a reduction of Ifb, and thus a reduction of Id. However, with higher initial concrete strength at the point of releasing strands, there is a reduction in It. An increase in prestressing forces, after losses, results in a higher value of It, but also in a lower value of Ifb. The technological process of releasing the strands also plays a significant role. Gradual and controlled strand release has up to 30% shorter development length than sudden strand release (partial mechanical or temperature cutting) [8,9]. The surface conditions of the strand have a significant influence on the bond characteristics, such as, for instance, mild surface corrosion, which causes lower lt values.

The transfer length I_t , according to the observations so far and as a function of the previously mentioned parameters, ranges between approximately 500 and 1200 mm. This means that by applying a 7-w strand, the full input of the prestressing force is moved from the shear span. The motivation for the use of a new geometric shape is to reduce I_t and ensure the contribution of prestressing force to the shear capacity of the girder. Therefore, replacing the standard 7-w strands with a new geometric shape of the strand may lead to an improvement of the bond connection as well as an increase in the shear capacity. Previous assumptions are the main goal of the scientific contribution

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within this research and, as such, they must be experimentally approved or disapproved.

For many years, there have been no attempts to improve the bond of the 7-w strand from the view of the geometric change of the cross-section, and thus the wavelength (360° stroke). In the 1960s, the idea of a sharper polygonal crosssection of prestressing strands first emerged. Polygonal shape refers to the regular and linear arrangement of the outer wires arranged around the leading, central wire. The proposal primarily concerned the triangular distribution of wires in the cross-section of the strand. This cross-sectional structure allows a greater inclination of the outer wires, improving the resistance that occurs when moving through a concrete tunnel. To ensure the compactness of the windings when constructing triangular strands with linear contact, which are wound from wires of equal diameter during one technological operation, it is necessary to provide two basic conditions:

 The wires of any concentric winding (twisting) must touch each other and the wires of the adjacent winding;

 The wires must touch the entire length of the strand with the same winding step for all windings (subject to the previous condition).



Figure 1. Schematic of innovative, triangular, 10-wire strand [10]

At the time this idea was proposed, it was not technologically possible to produce such a strand with

sufficient precision. Only at the beginning of the 21st century, based on the previously proposed solution, patent US2012 / 0240548 A1 was recognized for a geometrically innovative, 10-wire (10-w), and triangular strand (Figure 1). Soon after that, a prototype smooth strand of triangular cross-section, which is the subject of this research, was produced.

It is expected that application of this type of strand will improve the bond behaviour in pre-tensioned structures in which the transfer of force takes place exclusively through the direct bond. The assumption is that the new triangular strand should have a better bond connection due to its geometric shape. The triangular spiral forms a wide periodic profile (360°) continuously. This allows extremely long concrete ribs to be formed, and thus the stress is distributed efficiently over the entire volume. The contact area on those hills has smaller ribs formed in between wires perpendicular to the concrete hills. On the other hand, the surface of the 7w strand is similar to a circular cross-section, but it has small grooves in which concrete ribs are formed. These ribs have a limited resistance caused by the movement of the strand during higher loads, and the conventional 7-w strand has relatively large end slip.

The first model of the new triangular strand is shown in Figure 2.



Figure 2. Ribbed innovative, triangular, 10-wire strand [10]

Improving the bond between the strand and concrete should reduce the slippage and transfer length, as shown in Figure 3. This is directly related to the higher shear capacity due to the greater contribution of the applied prestressing force. However, the set assumptions need to be experimentally verified, and on the basis of the test results, a model of the bond behavior of a triangular strand should be proposed.



Figure 3. Schematic presentation of the expected contribution of the triangular strand compared to the standard one

2 Experimental program

The testing program is divided into several phases, including pull-out tests of untensioned strands, push-in and pull-out tests of pretensioned strands [11], transfer length tests [12], and shear beam tests [13]. Pull-out tests of untensioned strands are presented in this work.

2.1 Materials

The strands used in the experimental program are shown in Figure 4:

- 7-wire strand, configuration 1 (d = 3.2 mm) + 6 (d = 3.05 mm), with a tensile strength of 1860 MPa;

- 10-wire strand, configuration 1 (d = 2.6 mm) + 6 (d = 2.6 mm) + 3 (d = 2.6 mm) with tensile strength of 1770 MPa;

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Figure 4. Geometry of tested strands: (left) standard, seven-wire; (right) ten-wire

Self-compacting concrete (SCC) of class C40/50 was made with the mixture proportion given in Table 1. The same concrete mixture was applied in all tests. Casting of concrete samples was performed in the laboratory of IGM "KABAS" in Teslić, where all other tests will be performed. Based on properly stored material and data on the surface moisture of each of the aggregate fractions, an identical mix for concrete samples was applied in the laboratory in Teslić.

Table 1. Concrete mixture proportion

Class: C40/50			
The origin of the aggregate	Aggregate fractions (mm)	Percentage participation (%)	Dosing for 1 m ³ of concrete
Stone pit "Dobrnja" Banja Luka	0-2	38	629 kg
Stone pit "Dobrnja" Banja Luka	0-4	22	367 kg
Stone pit "Dobrnja" Banja Luka	4-8	12	196 kg
Stone pit "Dobrnja" Banja Luka	8-16	28	463 kg
		Total:	1655 kg
Cement	CEM II/B-N	/(S-LL) 42.5 N	420 kg
Water	City wa	City water supply	
W/C	0.393	Residual air	1.70 %
Chemical additive	HRWRA	0.71 %	4.05 L
Mineral additive	F	Fillers	
Consistency		SF2	

Testing of concrete component materials and characteristics of fresh concrete SCC C40/50 was performed in the laboratory of the concrete factory "BINIS" in Banja Luka.

The characteristics of fresh concrete that are tested are shown in Table 2. Results of the slump-flow test, "V" funnel test, and "L" box test are shown with obtained values and adequate class in the standard (EN 206, reference). After casting, the concrete cube specimens (15x15 cm) were protected with a plastic sheet to prevent the premature loss of moisture. Specimens were stored in the Laboratory for 24h. After that, they were demolded and then placed in the water to be cured by the time of examination.

The measured compressive strengths of SCC C40 / 50 concrete are given in Table 3.

2.2 Pull-out test of untensioned strands

Pull-out tests of untensioned strands were performed on large concrete blocks with a size of 611x450x450 mm (length, width, and height). Each block had 6 strands of which 3 were 7-w and 3 were 10-w strands. Two different surface conditions of strands were tested: AR-as received and W-weathered (Figure 5). Strands were debonded on both sides of the concrete block to a length of approximately 5 cm. Specimens were demolded and mounted on previously ready steel frames where tests will be conducted 24 hours following casting. Pull-out tests were accessed 3 and 7 days from the day of pouring the blocks: the pull-out force was applied on one side of the specimen (active side) and gradually increased over a period of 120-180 seconds until the bond fracture appeared. When the force/slip line reaches the horizontal position parallel to the X-axis, the bond fracture appears, indicating that there is no longer any resistance to the slipping.

The keys to the test were:

- a) <u>Measuring points</u>:
 - Values of pull-out force;
 - Slip of the strand on both sides (active and passive);
 - Rotation of the strand on the passive side.
- b) Test method:
 - Applying pull-out force on the strand constantly for a period of 120-180 seconds;
 - Equipment used for applying pull-out force was a hydraulic hollow jack with a capacity of 40 tons;
 - Hydraulic jack was placed on top of the concrete blocks.
- c) Measuring equipment:
 - For force, oil pressure sensor capacity 500 bar;
 - For displacement, 2 x LVDT sensors on both sides of the concrete block (active and passive ends of the strand);
 - For rotation of the strand rotary encoder was placed on the passive end.

Table 2. Results of SCC C40/50 fresh concrete tests

Test	Class	Values accor. to class	Obtained value
Slump-flow test	SF2	660-750 mm	710 mm
"V" funnel	VF2	9-25 s	10 s
"L" box	PL2	≥ 0,80 with 3 rebars	0,83

Table 3. SCC C40/50 compressive strengths

	Concrete	Complete	Dimensions (mm) —	2 days	7 days	14 days	28 days	
		Samples		Stress (MPa)	Stress (MPa)	Stress (MPa)	Stress (MPa)	
C40/50	C40/50	1	150x150x150	36.34	52.56	61.77	66.52	
		2	150x150x150	35.98	51.80	62.01	65.82	
		3	150x150x150	35.58	52.20	61.56	67.14	



Figure 5. Strand specimens preparation (left) and surface conditions - remains on paper (right)

The schematic presentation of the planned setup with a block specimen that has multiple strand samples is shown in Figure 6. The first used setup of the pull-out test with untensioned strands is called the A setup. The concrete block, with a size of 1240x450x450 mm, was originally planned. Due to the capacity of the mixer, this concrete block was reduced to the size of 611x450x450 mm (Figure 7) to enable the casting of a whole specimen from one mixing.

Figure 8 shows test arrangement and position of the sensors for measuring pull-out force (pressure sensor – S0) and displacement sensors for strand slipping on both sides of the concrete block (1 + 1 LVDT - S1 and S2).

Setup A had imperfections that affected the logic and accuracy of the test results, such as (Figure 9):

- The steel device shown in Figure 9-right, which rested over the anchor chuck taken at one point, had a rotation in both directions when pulling the strand. This was happening in the process of "tuning", so measuring with only one displacement sensor in this way was very unreliable. At least one more displacement sensor must be introduced. - The height of the steel device itself introduced additional unknowns. The steel device should essentially have a previously tested stiffness, the values of which could be used to compensate for any unwanted measurements in the pull-out test. By removing such a high steel device, a lot of unwanted factors have been eliminated.

At the passive end, the displacement sensor was set according to Fig.9-left. The way that the sensor made contact from the bottom, perpendicular to the cross-section of the strand, introduced potential problems that can manifest themselves in the form of sensor displacement and sliding during rotation of the strand caused by slipping through concrete.

Magnetic holders can additionally affect the measurements if they are not strong enough and do not lie on a solid surface. In the new arrangement (setup B), the sensors will be attached directly to the strands according to Figure 10.



Figure 6. 3D schematic presentation of the block with multiple strand samples



Figure 7. Reduced concrete block specimen with a position of strands – setup A



Figure 8. Test arrangement and position of the sensors (left) and concrete specimens with numbering (right)



Figure 9. Setup A imperfections on the passive side (left) and active side (right)



Figure 10. Setup B active side (upper side) and passive side (lower side)

The new setup B was first tested on test specimens, in order to eliminate new unpredicted situations. The specimens were tested according to the previously defined procedure, in order to determine the closest possible moment to full "clamping", i.e. to reduce free movement due to the mutual adjustment of the strand (wedges in the sleeve) and the piston of the cylinder.

The setting of the sensors at the active end is shown in Figure 10-upper side. It can be seen that 2 displacement sensors LVDTs (1 inductive and 1 potentiometer) with a range of 50 mm are placed on each side. Both are mounted directly on the test strand via an aluminum holder (Fig. 10). By pulling the strand out, the strand also rotates. In order for the sensors attached to the strand to rotate freely and together with the strand, it is necessary to reduce the friction in contact with the concrete to a minimum value. This is achieved through glass plates that are placed over the strand and glued to the concrete surface. The contact between the top of the LVDT and the polished glass surface has negligible friction, so it is considered that the LVDT will rotate smoothly with the strand.

On the passive side, the setting of the measuring instruments is shown in Figure 10-lower side. It can be noticed that the setting is completely the same as on the active side (1 inductive and 1 potentiometer LVDT), with the addition of the encoder for measuring the rotation of the strand. The encoder has a range of 2000 impulses. A shaft with a diameter of approximately 8 mm passes through the encoder, which is attached to the headrest. The headrest is attached to the strand. This headrest slides freely over the shaft in the direction of the strand slipping. During the rotation of the strand, the strand can slide upwards without hindrance, and at the same time it does not drag the encoder with it. A glass base was placed over the strand, and on the concrete surface, which enabled uninterrupted rotation of the LVDTs together with the strand (same as the active end).

The force was measured as mentioned via a pressure sensor placed between the cylinder and the oil supply.

The complete final setup of the experiment is shown in Figure 11.

In this approach, the imperfections detected in the setup A were successfully resolved in setup B. Moreover, some fine preparations were performed in setup B which are shown in Figures 12 and 13.



Figure 11. The complete setup B of the pull-out test



Figure.12. Fine preparation of supports on concrete surface

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Figure 13. Leveling position of the LVDT's on the active side

3 Experimental results and discussion

The specimen's identification procedure is shown in Table 4 and Figure 14.

Table 4. Summary of the testing program and research variables

	Type of strand	Strand condition	Concrete class	Time	Number of large beam samples
	7	٨	C40/50	3 days	
		A		7 days	
7 W -	В	C40/50	3 days	4	
			7 days		
10w -	^	C40/50	3 days		
	A		7 days		
	B	C40/50	3 days		
			7 days		



Figure 14. Identification procedure for the block specimens

So far concrete block specimen C50-A-3d was tested with the previously described setup B. The strands were pullout from the blocks with the procedure described in chapter 2.2. A pull-out force/slip relationship is shown in Figure 15. Dot lines represent the active side, and continuing lines represent passive side results.

As was shown in [14], it was expected that measurements on the active end of the strand (the side on which the force is applied) differ from those obtained on the passive side. This difference is in higher values of slips at lower forces, which is caused by the way the strand is fixed (slip of wedges in the sleeve) and by elastic elongation of the unsupported part of the strand. As a consequence, the active side curve will always have a smaller slope to the horizontal axis. From the moment when the strand completely slips (the strand begins to move through the concrete along its entire length), the curve changes from a linear behavior to a nonlinear behavior. At this point, the connection has been plasticized all the way to the breaking moment by slipping.



Figure 15. Pull-out force versus Slip response: 1-3 (10-w strands); 7-9 (7-w strand)



Figure 16. Pull-force versus Strand rotation response: 1-3 (10-w strands); 7-9 (7-w strand)



Figure 17. Slip versus Strand rotation response: 1-3 (10-w strands); 7-9 (7-w strand)

From the beginning of plasticization, the slips on the active and passive sides are equalized, i.e., the curve of the active side is parallel and offset by the values of the initial slips. The same behavior was obtained in this test (Figure 15): on the passive side, there is no slip until the moment when the bond plasticization occurs. After that, the strand begins to move completely through the concrete and the slip on the passive side appears.

It can be seen in Figure 15 that 7-w untensioned strands had dominantly higher pick bond strengths than the 10-w strands. Individual results of the 7-w strands are less uniform with respect to 10-w strands. Besides, the AS-01 strand showed measuring imperfections in the range of 20-25 kN. These imperfections are caused by the current fine-tuning of the measuring instrument.

Figure 16 shows the relationship between pull-out forces and strand rotations. It can be noticed that 10-w strand results have very good uniformity in comparison to 7-w strands. Figure 17 presents the results of slip versus strand rotation. The results of the PS-03 strand deviate from other 10-w strand results, which was caused by the dirty shaft of the encoder and its inability to rotate freely. Other results show constant uniformity, which instills confidence in the accuracy of the results.

4 Conclusion

All the tests presented in this paper were non-standard and performed completely innovatively with self-made devices and setups. Initial tests indicate a justified need to investigate the bond characteristics of the innovative triangular 10-w strand.

The pull-out test results obtained on specimen C50-A-3d allowed a comparison of 7-w and 10-w strand bond behavior. Firstly, the results showed logical bond behavior for both strand types. Secondly, 7-w untensioned strands had dominantly higher pick bond strength than 10-w strands, contrary to expectations. Individual results of the 7-w strand

were however less uniform in comparison with 10-w strands. Due to the sensitivity and accuracy (3.5%) of the oil sensor pressure used in this test, the results need to be taken with some reserve. In order for the results to be more accurate, it is necessary to have a high degree of repeatability.

Previous observations define the next steps in the pullout test of the untensioned strand. Instead of the pressure sensor, a calibrated load cell with a capacity of 500 kN will be used. After the pull-out test of untensioned strands is successfully completed, including different specimens' ages and surface conditions, the focus will be moved to the next phase. Further test phases mentioned in the paper, which are part of the Ph.D. thesis of the first author, should give a clear picture of the behavior of the bond connection between the 10-w strand and concrete, as well as its contribution to the shear capacity of the beam elements.

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