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Centrifugally-cast concrete poles with non-metallic reinforcement

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Research Paper

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The article describes the testing of poles for electric power transmission lines, which are made of centrifugally-cast concrete and ultra-high strength concrete, and which are prestressed with Carbon Fibre Reinforced Polymer bars (CFRP). The presented results of pole ultimate load testing suggest the potential for usage of this construction product, particularly in aggressive environments with high probability of steel corrosion. Part of the tested poles had shear reinforcement in the form of confined Glass Fibre Reinforced Polymer (GFRP) grid, while one share of samples had no shear reinforcement, but the concrete matrix was strengthened with synthetic macro fibres. A review is given on similar product testing, calculation methods, and guidance is provided for further research.

Key words:
non-metallic reinforcement, Carbon Fibre Reinforced Polymer (CFRP), centrifugally-cast poles, prestressing, ultimate load testing, bending testing

Prethodno priopćenje

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Centrifugirani betonski stupovi armirani nemetalnom armaturom

U radu se prikazuje ispitivanje stupova namijenjenih elektrodistribuciji, koji se proizvode postupkom centrifugiranja, od betona vrlo visoke tlačne čvrstoće i koji su prednapeti šipkama od polimera armiranog ugljičnim vlaknima (Carbon Fibre Reinforced Polymer - CFRP). Prikazani rezultati ispitivanja stupova savijanjem do sloma upućuju na mogućnost primjene ovog građevnog proizvoda, napose u okolišu u kojemu dolazi do pojačane korozije konvencionalne čelične armature. Dio ispitanih stupova imao je posmičnu armaturu u obliku ovijene mrežice od polimera armiranog staklenim vlaknima (Glass Fibre Reinforced Polymer - GFRP), a dio je uzoraka bio bez posmične armature, ali je betonska matrica ojačana sintetičkim makro vlaknima. Dan je osvrt na dosadašnja ispitivanja sličnih proizvoda, na metode proračuna, kao i naznaka smjernica za daljnja istraživanja.

Ključne riječi:
nemetalna armatura, ugljičnim vlaknima armirani polimer, CFRP, centrifugirani stupovi, prednapinjanje, ispitivanje do sloma, ispitivanje na savijanje

1. Introduction

Concrete reinforced with steel bars, widely known as material that is currently predominantly used in the construction of various civil engineering structures [1], is a combination of two materials having different mechanical characteristics, which jointly participate in the transfer of load. Many reinforced-concrete structures realised in aggressive environments are susceptible to reinforcing steel corrosion, and to consequential damage leading to expensive repairs and limitations regarding the use of such structures. The problem of durability is especially pronounced in aggressive environments so that, in some situations, strengthening with fibre reinforced polymer (FRP) is used instead of steel reinforcement.

After decades of testing and limited use in construction elements and products, it can be stated that the new material has found its market niche, although its wider application is still somewhat hindered by the absence of a standardized calculation procedure (although some guidelines have been in use for quite some time) and by the lack of extensive practical experience. Centrifugally cast FRP prestressed concrete poles, destined for the long distance distribution of electricity, are certainly one of the products that have proven their efficiency and cost-effectiveness in a number of practical situations. Such products are also fabricated in Croatia, where they are used in the electricity distribution network thanks to cooperation between a motivated manufacturer and its client who is faced with speedy deterioration of traditional poles in coastal environment. This study has been initiated through a direct initiative of the manufacturer and it constitutes, in our regional setting, a rare and praiseworthy endeavour. Centrifugally cast concrete poles with non-metallic reinforcement are construction products in the sense of the applicable Law [2], which means that they are factory manufactured and placed on the market for the purpose of permanent incorporation into a structure, and their properties have an effect on the properties of the structure as related to basic requirements. An appropriate European standard [3] has been adopted in Croatia for centrifugally cast concrete poles, and internal regulations of the client [4, 5] and [6] for placing the product on the market are also in force, and so it can reasonably be stated that this is a standardised product. Investigations conducted so far have shown that FRP prestressed centrifugally cast poles for electricity transmission lines can have a competitive edge on the market. However, standardised calculation procedures for dimensioning such elements have not as yet been developed, and the current testing basis is quite modest. One of significant but insufficiently investigated problems is the anchoring of FRP reinforcement. The issue treated in this paper is expected to contribute to the field of experimental investigations of the described construction product.

2. Overview of development of concrete elements with composite reinforcement

Composite FRP bars are produced by pultrusion of high strength-stiffness fibres that are impregnated with polymer resin. In addition to being resistant to corrosion, these materials are also characterized by high strength, good behaviour under dynamic load, and low unit weight. Their deficiencies are an elastic behaviour until failure, small total deformation, inhomogeneity, drop of cable strength at bending point, and failure under long-term load close to strength limit [7].

These materials have been used in air navigation industry since the second world war, but the strengthening of civil engineering structures with FRP was not considered cost-effective as no commercial products were available until 1970s [8]. By 1990, commercial use of the FRP strengthening could mostly be observed in Japan where it was used on more than one hundred projects. The use of FRP in Europe started in Germany by construction of a FRP prestressed bridge in 1986 [9]. At the same time, the use of this material was increasing in Canada and the USA, mainly because of the start of industrial production of FRP strengthening. Development of bars, meshes, strands, and cables fabricated out of this new material was followed by intensive scientific research about the properties of materials, products and structural elements of FRP strengthened concrete. The new material was initially applied in structures that had to be reinforced with non-metallic reinforcement for some specific reasons, i.e. in hospitals with the equipment sensitive to electromagnetic phenomena. Later on, its use has extended to maritime structures, airport runways, and bridges. Thus, already at an early phase of its use, the fact that the material does not conduct electricity has been recognised as an advantage of FRP use on some structures.

Because of specific properties of FRP strengthening, it is used to reinforce all kinds of concrete featuring either normal, high, or ultra high strength. Compressive strength of concrete varies from 20-40 MPa for normal strength concrete, 80-100 MPa for high strength concrete, and 150 MPa for ultra high strength concrete (UHPC). FRP is fabricated out of glass (G), aramid (A) and carbon (C) fibres, bonded with epoxy resin, polyester or vinyl ester, with moulding and pressing. From the engineering point of view, fibres can be differentiated according to their mechanical properties such as strength, stiffness, density, and diameter. The main deficiency is that such products are not ductile, i.e. there is no pronounced yield at a certain stress, as for instance in steel [1]. Considering their higher price, these materials are used in specific types of structures where durability is of high significance. Commercial cables are wrapped on the outside with quartz sand so as to ensure proper adhesion between the cable and concrete.

In most research endeavours, researchers use thin (30 mm and more) CFRP cable prestressed elements made of high to ultra high strength concrete (5 to 100 N/mm^2). Although CFRP cables can be somewhat more expensive when compared to other available fibre reinforced polymer products, they are more resistant to fatigue, they exhibit smaller creep and smaller losses due to relaxation after prestressing, and they are more durable in alkali environment i.e. in concrete [10]. General characteristics of bars, cables and strands vary to a great extent as they can be adapted to many different uses – and this is the property by which these products greatly differ from reinforced steel whose physical and mechanical properties vary within a relatively narrow range. Commercial CFRP fabricated for reinforcing various concrete structures are usually characterized by longitudinal tensile strength ranging from 600 to 3500 MPa, their elastic modulus (along fibres) ranges from 100 to 580 GPa, and elongation until failure varies from 0.5 % to 1.7 % [11].

An extremely great number of published studies cover significant aspects of the behaviour of construction elements prestressed with cables made of fibre reinforced polymer. However, this material has not as yet found its place in design-related regulations, so that currently the use is made of guidelines, most popular being the ones published by the American Concrete Institute (ACI) [12], although first guidelines were in fact issued in Japan, and then in Canada. European guidelines were published by fib [11] and they cover calculation principles for limit states of failure and limit states that are used for concrete elements strengthened with untensioned FRP. These guidelines use similar principles for calculating limit states of failure, i.e. the limit states are derived from principles used in regulations for reinforced concrete and prestressed concrete. The presented comparison of various regulations shows great differences in recommendations that are related to limit state of use. Technical properties of commercial products are regularly calibrated through extensive laboratory tests and numerical analyses.

Resistance to bending, or bending with longitudinal force, is relevant for the design of a significant portion of concrete-made structural elements. Traditional concrete elements, reinforced or prestressed with steel based on procedures defined in regulations, are designed for yield by ductile failure via reinforcing bars. In the case of structural elements strengthened with FRP the failure via reinforcement can be described as brittle, just like the failure via concrete, and so the failure via concrete is often specified in the design as a required limit state. As to deflection, under similar conditions, the elements strengthened with FRP develop greater deflections than comparable traditional elements, which can be explained by smaller elastic modulus of the FRP reinforcement, but also by the yield of the concrete – reinforcement connection [13].

Although it can be said that the behaviour of elements prestressed with FRP (CFRP) cables has been properly investigated, the details of such structures are still the object of studies because an appropriate variation of properties of concrete and reinforcement offers an opportunity for development of products with even better properties.

3. Testing reinforcing bars made of fibre reinforced polymer

Reinforcing bars made of fibre reinforced polymer are supplied as a finished factory-made product with declared properties, which vary from one manufacturer to another. FRP bars can be designed and produced so as to meet requirements for specific applications. Available design parameters include selection of components (fibres and polymer matrices), volume of fibre and matrix fraction, orientation of fibres, and manufacturing process.

Preliminary testing of bars was conducted for pole testing purposes. Tensile properties of five samples of CFRP bars were tested, i.e. the testing involved polymer reinforced with carbon fibres, 4.2 mm in effective diameter, i.e. 5.4 mm in diameter with the wrapping (Figure 1). Test results are presented graphically (Figure 2) and in Table 1.

Figure 1. Testing bars made of fibre reinforced polymer [4]

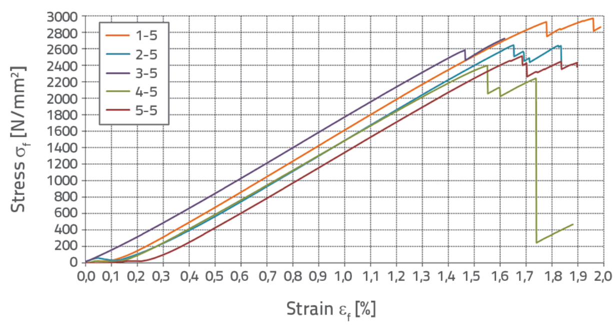


Figure 2. Test results for bars made of fibre reinforced polymer

Table 1. Tested mechanical properties of reinforced CFRP bars

Designation of samples (D = 4.2 mm)	Maximum load [kN]	Tensile strength [N/mm²]	Relative strain at failure [%]	E - modulus [N/mm²]
1-5	40.5	2926.6	1.77	185500
2-5	36.6	2644.1	1.65	180400
3-5	35.8	2584.9	1.46	183000
4-5	33.2	2397.2	1.55	177000
5-5	34.8	2511.5	1.68	179300

Test results point to linearly elastic behaviour until failure, where an average tensile strength at failure of CFRP bars amounted to f_{sr}=2612,9 MPa while the mean elastic modulus was E_{sr}= 181,0 GPa, which is in accordance with the data declared by the manufacturer.

4. Preliminary testing of poles

Centrifugally cast reinforced-concrete poles of circular cross-section, strengthened with FRP reinforcement, have been a subject of study since 1994, and first experimental poles were included in the electricity network of a Swiss electricity supplier in 1998 [14, 15]. Such poles are primarily used in electricity transmission networks for the distribution of electric energy, and as lighting poles (Figure 3).

Figure 3. Traditional pole used in electricity transmission network

In many cases, reinforced-concrete poles are installed at locations that can be characterized as aggressive environment, whether referring to soil or atmospheric exposure (Figure 4). Circular cross-section of centrifugally cast poles dictates their manufacturing method, Their advantages lie in even and smooth surface and a favourable aesthetic effect. Specific requirements of purchasers of such structural elements make the use of this non-metallic (i.e. not able to conduct electricity), corrosion resistant reinforcement very interesting. Experimental production of FRP reinforced poles started at the time when stringent regulations for the design of concrete structures were introduced in response to requests for increasing thickness of the protective layer of concrete, making traditional poles impractical due to an increase in their dimensions and mass. Various types of high strength concrete poles, reinforced with FRP (most often with CFRP), have been developed since that time.

FIgure 4. Damage to reinforced-concrete powerline pole – typical cracks in aggressive environment

As the described poles are a product that is appropriate for industrial production and as it can be competitive on the market (especially when taking into account its longer service life and lower weight, which is significant in relation to transport costs), it is not surprising that it has been the subject of extensive testing campaigns. The strength, deflection and resistance to bending values of centrifugally cast poles, destined for use in power transmission, and prestressed by CFRP material, are experimentally and numerically analysed in [16]. It was established that, when properly reinforced, these elements have satisfactory bending properties, including ductility. The influence of reinforcement method (longitudinal and transverse) on the cracking, deflection and yield – failure mode of these poles was also studied. The resistance to fatigue of poles prestressed with CFRP reinforcement was investigated in [17] where an emphasis was placed on the loss of adhesion between cables and concrete. It was established that this loss of adhesion will be of decisive influence on their deterioration. The link–adhesion between prestressing CFRP cables and concrete is considered in [18] as behaviour of structural elements is greatly defined by this property (sliding of cables). The CFRP cable anchoring system as related to prestressing of concrete elements is considered in [19] as these cables are normally prestressed up to 40 % of their failure strength. It was established that more efficient cross-sections can in fact be obtained by increasing the prestressing force, and that this can primarily be achieved through improvement of anchors.

5. Calculation model

The lack of an accepted formal standard for the design of this material constitutes a significant barrier to a more widespread use of concrete reinforced with FRP bars. The first regulation draft was published in Japan [20], and was followed by European recommendations issued based on the EUROCRETE project [21], and then by a Canadian regulation [22] and by the most widely used guidelines (recommendations) issued in the USA by ACI [8]. Several European countries have issued their own recommendations for the use of FRP reinforcement either in concrete structures or for the strengthening of structures [21].

Following many years of work by numerous experts, an appropriate working group of the fib (International Federation for Structural Concrete) published the fib Bulletin 40 in which the issue of FRP reinforcement in concrete structures is considered [11]. Numerous results of experimental research have shown that the resistance of elements subjected to bending load can be determined according to the procedure similar to that used for dimensioning elements strengthened with steel reinforcement. More specifically, it could be said that it has generally been accepted that basic rules for the analysis of cross-sectional resistance to bending of traditional reinforced concrete elements are also applied to elements reinforced with FRP.

If an element fails due to bending, the element yields either by concrete crushing in the compression zone or by FRP reinforcement breaking in the tensile zone [23]. The framework given in HRN EN 1992-1-1 [24] for assessing moment at failure of a cross-section reinforced by FRP has been adopted in publication [11]. Equations and calculation diagrams for defining moment at failure are given for the case of failure by concrete crushing in the compression zone. When the failure due to bending occurs due to breaking of FRP reinforcement, the publication offers an iterative process for assessing the moment of failure.

The dimensioning of FRP reinforcement for centrifugally cast hollow circular poles is quite a complex task. The calculation is based on the analysis of curvature of the cross-section under study. To determine the curvature, one has to know the position of the neutral axis, which is determined by iterative procedure in the scope of which the position, i.e. the depth of the neutral axis, is defined for an assumed relative deformation of concrete at the compression edge of cross-section. At the same time, the value of relative deformations of reinforcement in tension must correspond to the force in concrete so that the cross-section equilibrium equations can be satisfied (Figure 5). The calibration of the design model of the centrifugally cast cross section of the pole prestressed with FRP reinforcement will be the subject of analysis conducted further on in this paper. Simplified calculation models did not provide the results that would deserve to be presented in this paper, as the focus of the paper is on informing the professional community about valuable testing of a genuinely Croatian construction product.

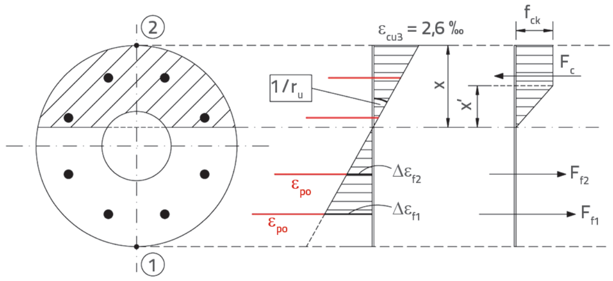
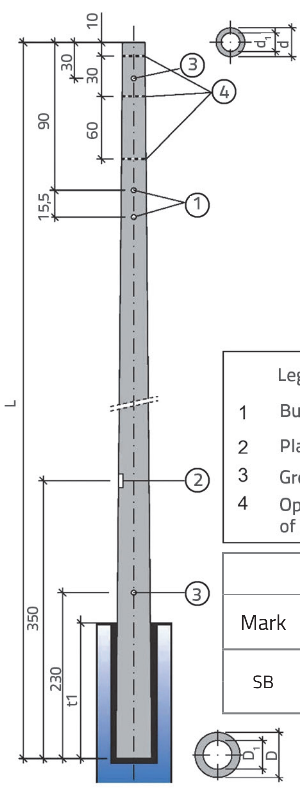


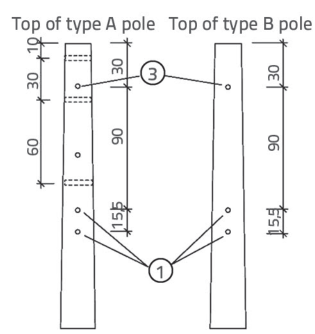
Figure 5. Stress – strain ratio in circular and hollow cross-section reinforced with prestressed FRP bars

6. Testing poles until failure

6.1. Basic requirements

Centrifugally cast reinforced-concrete poles are placed on the market as construction products that are fabricated in accordance with the adopted European standard HRN EN 12843:2004, Precast concrete products – Masts and poles [3]. This standard defines requirements for precast concrete poles (masts) fabricated in one piece or in segments, that can





Legend:

1 Bushings 2xM10 for fastening the public lighting lamp
2 Plate with basic information about the pole
3 Grounding nut M12
4 Opening 18 mm in diameter for installation of low voltage equipment

Pole type			Total length [m]	d [cm]	D [cm]	Depth under ground [m]
Mark	Force F (daN)	Type of pole top				
SB	315	A or B	9	14,0	27.5	1.6
			10		29	

Figure 6. Geometry of testing pole marked SB 315/10

be either reinforced or prestressed, solid or hollow, and can have a connection, or can include other elements (cross beams, platforms, etc.). These poles can be used as posts for carrying overhead electricity or telecommunication lines, as posts carrying electricity lines for supplying power to railway vehicles, as lighting posts, etc.

As structural elements made of concrete, the poles are checked for limit states in accordance with relevant design standards [24, 25]. In addition, the poles must comply with internal regulations of the Croatian Electric Utility (in Croatian: Hrvatska elektroprivreda d.d. or HEP d.d.) [4-6] and, according to these regulations, they also must meet the global factor of safety: $k_{GSN} \geq 1.8$ with regard to limit state of bearing capacity.

Circular hollow poles that are most frequently used in electricity distribution have been selected for the testing, cf. Figure 6. The poles are made of concrete having very high compressive strength (C90/105) and are reinforced with CFRP (Carbon Fibre Reinforced Polymer) bars.

6.2. Samples and description of experiment

Eight poles of equal dimensions, but differing in reinforcement details, were tested on the manufacturer's test site. All these poles (samples) were produced on the spot, i.e. in the plant itself. One of the samples was reinforced traditionally – by steel reinforcement (B500B) – so as to enable control and comparison of results [26]. The data on reinforcement and concrete additives used in the tested poles are given in Table 2. All poles, marked from 2/8 to 8/8 were equally reinforced each with eight CFRP bars. The effective bar diameter amounts to 4.2 mm and the total diameter of the bar with matrix and quartz sand lining is 5.4 mm. All samples were centrically prestressed before hardening by applying the total force of P_0=110 kN. Compared to traditional prestressing with steel strands, the stressing amounted to only 40 % of the breaking strength of the bar, i.e. to $\sigma_{P,1}$= 1000 MPa. This relatively small prestressing percentage was used because of the lack of sufficient knowledge about anchoring characteristics of this reinforcement and about adhesion of bars and their prestressing, and due to scarce knowledge about reinforcement sliding hazard and about bearing capacity of the mould itself that must be capable to independently resist the total prestressing force and to rotate together with the anchoring system during application of centrifugal force. According to literature, recommended stress in FRP bars during the prestressing ranges from 800 to 1200 MPa [14, 19].

Considering that transverse reinforcing of poles with GFRP mesh is relatively complicated, it was assumed that the use of transverse reinforcement could completely be avoided, and that the pole reinforcement process would be simplified, by adding fibres in various proportions. The fibres SikaFiber® Force 60 were selected because of their favourable properties. These are polyolefin synthetic macro fibres that are used in in-situ structural concrete for the production of precast elements in order to ensure better distribution of stress and an improved load bearing capacity. These fibres can bridge cracks, increase bending and shear strength, and improve bearing capacity and ductility of concrete. The tensile strength of these macro fibres amounts to 475 MPa, the elastic modulus is 7.5 GPa, and the length is 60 mm. It will be shown below that the bearing capacity of poles made of concrete with fibres is somewhat greater then that of poles wrapped with GFRP grid, which encourages further research in this direction.

As previously mentioned, the pole marked SB 315/10 was tested because this pole type accounts for about 20 % of the total production of this manufacturer. It is a concrete pole (SB) whose nominal capacity is the resultant of horizontal forces F_n=3.15 kN (315 daN) and total length L=10 m.

The measurement setup is schematically shown in Figure 7 and on figures 8 and 9. The poles were tested in horizontal position. Bottom parts of samples were fixed to concrete anchoring blocks, while horizontal force was applied perpendicularly to the sample at the top of the pole – where free movement of the pole was allowed. A steel cart was placed below the top of the pole so that the results

Table 2. Significant properties of tested pole samples and principal test results

Designation of samples	Properties of samples			Test results			
	Longitudinal reinforcement	Shear reinforcement	Addition of fibres to concrete	δ_n [mm]	δ_u [mm]	F_u [kN]	k_{GSN} (F_u/3.15)
1/8 (control sample)	Steel bars	Spiral steel reinforcement	no	194	1950	13.8	4.38
2/8	CFRP bars (D = 5.4 mm) 8 bars in cross-section	Wrapping with GFRP mesh	no	84	1750	10.5	3.33
3/8				86	1650	10.7	3.40
4/8					2200	10.8	3.43
5/8		no	sinthetic macro fibres (SikaFiber® Force 60)	82	1900	11.3	3.59
6/8				102	1800	11.6	3.68
7/8				86	2000	11.5	3.65
8/8					1900	11.6	3.68

where:
δ_n – pole top displacement at nominal force [mm]; δ_u – pole top displacement at failure [mm]; F_u – final pole-failure force [kN]
k_{GSN} – global safety coefficient for ultimate bearing capacity

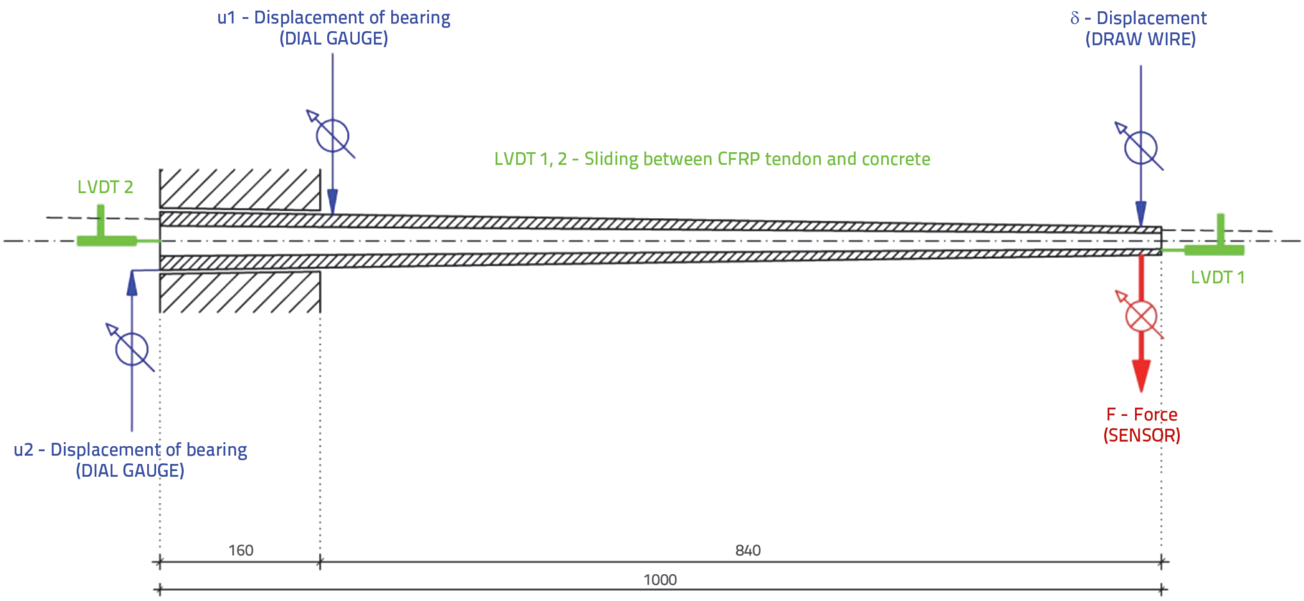


Figure 7. Pole position and measuring equipment used in testing

Figure 8. T.B.S. test site with pole prepared for testing and measuring equipment

Figure 9. Pole testing in progress

would not be influenced by gravity. The testing was conducted in accordance with [3]. The load was applied in three phases:

Phase 0: Stabilisation phase. Before the start of the measurement, the load $F_0 = 0.15\ F_n$ is applied and the pressure is then released so that the sample can be stabilised in its initial position.

Phase 1: Elastic phase.

Step 1: Application of load $F_1 = 0.5\ F_n$ followed by release of load. Deflection δ_1 is measured.

Step 2: Application of load $F_2 = F_n$ followed by release of load. Deflection δ_2 is measured.

Phase 2: Final phase. Testing continues until failure so that F_u (load at failure) can be defined.

6.3. Test results in elastic phase

The control sample, i.e. the pole strengthened with steel reinforcement, behaved as expected in the elastic phase that is characterized by approximately liner relationship between force and displacement (Figure 10).

Approximately two times smaller displacements were realized in the elastic phase for the same force on samples principally strengthened with prestressed CFRP bars, with GFRP mesh wrapping used as shear reinforcement. A typical result is shown in Figure 11.

The concrete of poles prestressed with CFRP reinforcement, but devoid of shear reinforcement, contains an additive: macro fibres ((SikaFiber® Force 60). The quantity of fibres added to

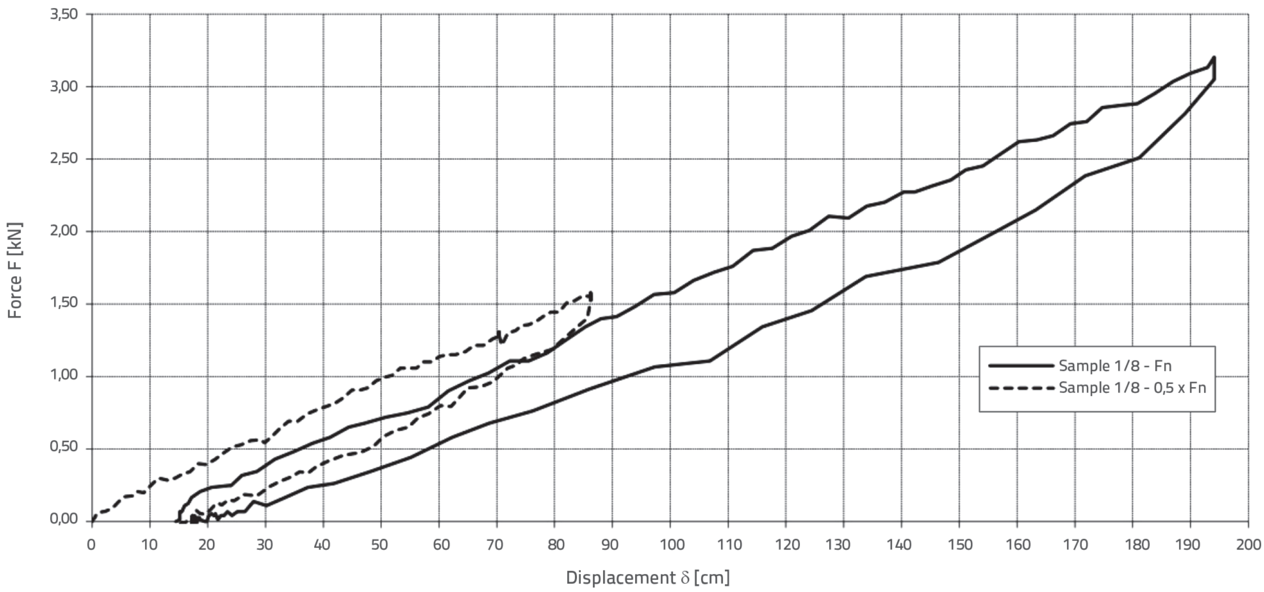


Figure 10. Force and displacement relationship in the elastic phase of testing (steps 1 and 2) of the control pole strengthened with steel reinforcement

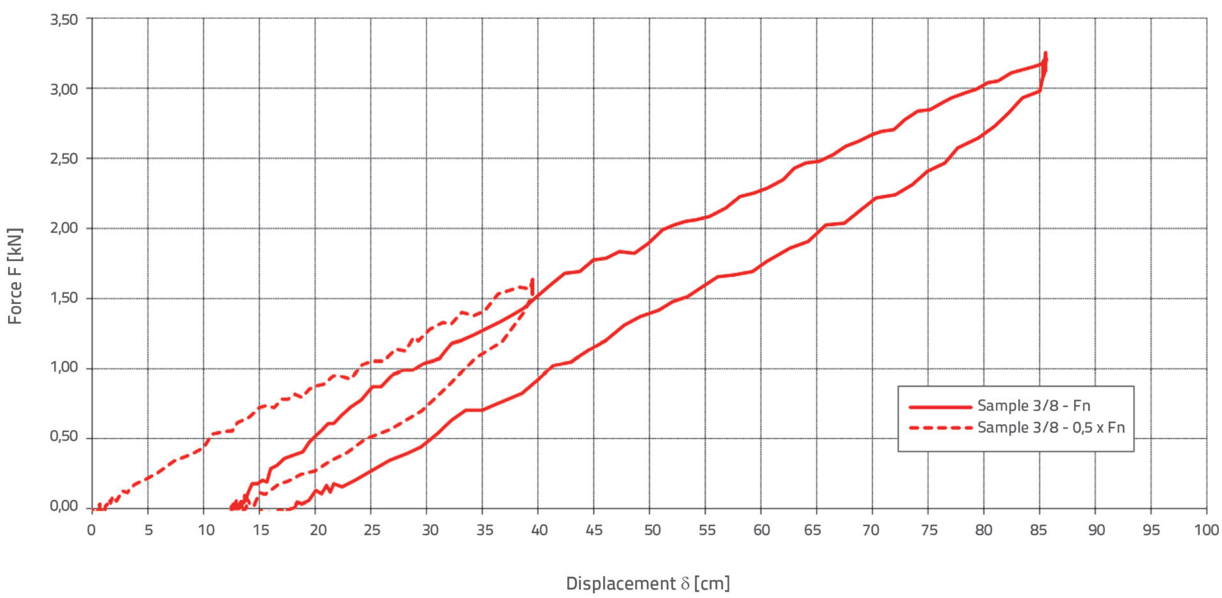


Figure 11. Force and displacement relationship in the elastic phase of testing (steps 1 and 2) of one pole sample that was longitudinally prestressed with CFRP reinforcement, while it was transversely wrapped with GFRP mesh

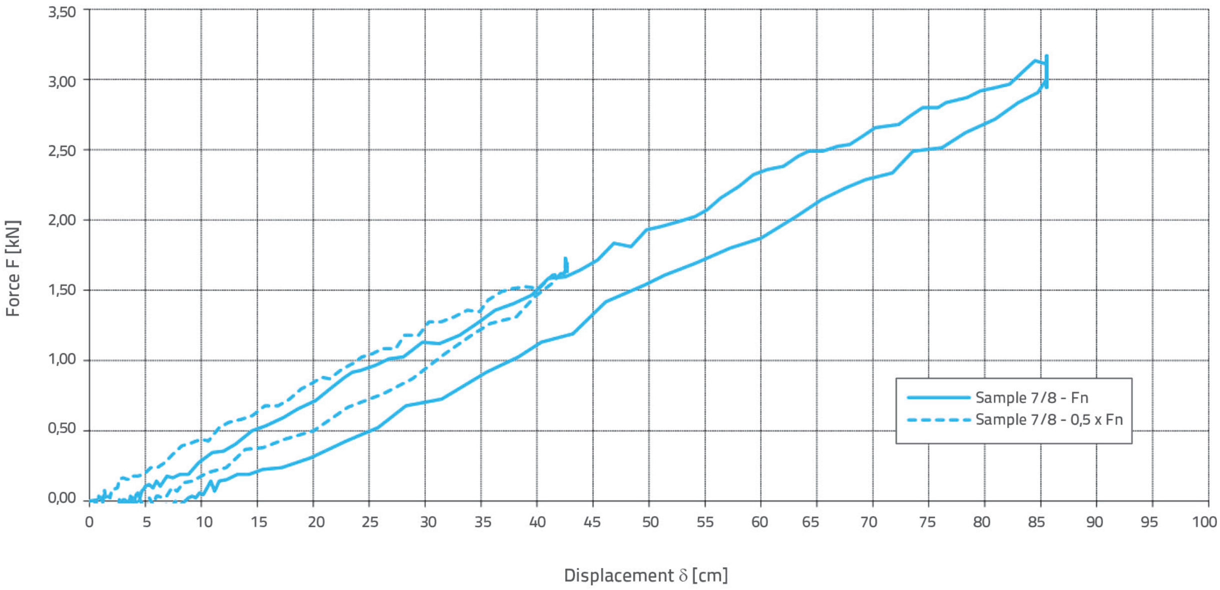


Figure 12. Force – displacement relationship for the elastic phase of testing (steps 1 and 2) of the pole sample longitudinally prestressed with CFRP reinforcement, without transverse reinforcement, but with synthetic fibres in concrete

individual samples was not constant, i.e. it varied from 1.2 kg/m3 (sample 5) to 3.8 kg/m3 (samples 6 and 7). It can be said that displacements generated in Phase 1 of the testing are equal for poles with and without shear reinforcement (Figure 12) and that an increase in the quantity of fibres in concrete resulted in somewhat smaller displacement of pole top during the bending test, while the bearing capacity remained almost identical.
One of significant indicators of the efficiency of construction elements of this type is the sliding between the CFRP bar and concrete, as this sliding can lead to the loss of load bearing capacity. In the elastic phase of testing, and in the testing until failure, the mentioned sliding was measured at the tensile side of cross-section of the CFRP bar subjected to greatest load. The results obtained by measuring bar displacement in the elastic phase of testing at top of the pole near the force application point were negligible, i.e. after relaxation of load the measured bar displacement value returned to zero. Reinforcement displacement results obtained in the phase of testing until failure varied between 0.09 mm and 0.224 mm, and so it may be concluded that no sliding of the measured bar with respect to concrete occurred at any of the tested samples. Measurable values of remaining deflections at the free end of poles occurred at all samples, and are most probably due to rotation of fixed bearing, and so they have no influence on the interpretation of results. The sliding at the fixed end of the pole, as measured in both testing phase, was equal to zero.

6.4. Results obtained by testing until failure

The reference pole sample (designation: 1/8) that was strengthened with steel reinforcement failed, as expected, by the yield of reinforcement, which was followed by the crushing of concrete. High ductility of this control sample was realized due to known toughness of steel reinforcement. The load displacement diagram is linear until occurrence of the first crack, after which it assumes parabolic shape until failure. Samples strengthened with prestressed CFRP bars failed by crushing of concrete in the compression zone, which was followed by failure of CFRP bars (Figure 13). Failure of samples reinforced with CFRP bars occurred at forces that were by 15 to 25 % lower compared to forces registered at the failure of the reference sample strengthened with steel reinforcement.

Figure 13. Typical failure of pole sample strengthened with CFRP bars and shear mesh

The analysis of results for the P-δ line of samples (load – deflection) reinforced with prestressed CFRP bars (samples 2/8 to 8/8) reveals stiffness in elastic area that is greater than that

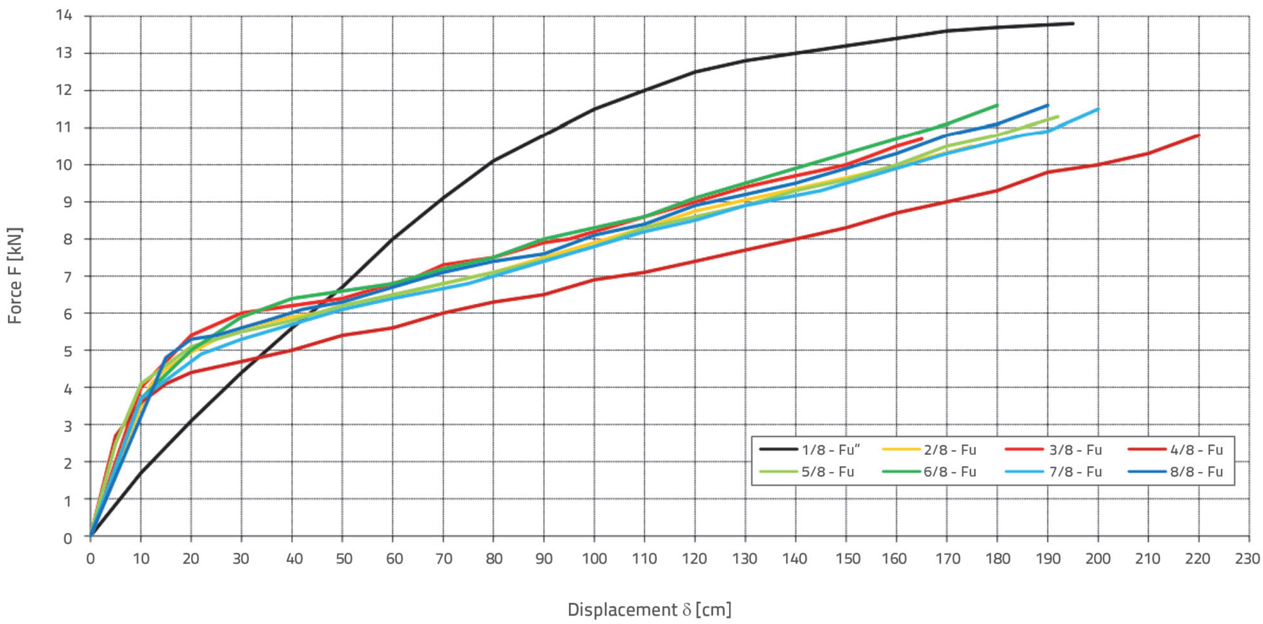


Figure 14. Overlapping load – deflection diagrams for all pole samples subjected to testing (diagram of the traditionally reinforced pole is shown in black colour)

Figure 15. Bearing capacity testing – sample 7/8 – displacement immediately before failure

of the sample strengthened with steel reinforcement. These diagrams are characterized by bilinearity that is manifested in steeper inclination in elastic area compared to the reference sample. However, after the occurrence of first crack the inclination becomes less steep, which results in the decrease of stiffness and finally in smaller value of failure force. However, even the results obtained in this way exceed by two times the bearing capacity requirements set according to internal regulations of the client [4, 5].

The comparison of load – deflection relationships of tested samples, established during bearing capacity testing, is shown in Figure 14. The force registered at the failure of the first traditionally reinforced control sample amounted to 13.8 kN. The force registered at the failure of samples reinforced with CFRP bars ranged from 10.5 kN to 11.6 kN. A considerable deformation prior to failure was registered at all samples, which shows that poles have a significant rotational capacity of cross section (Figure 15).

7. Conclusion

In the area defined by the standard [3] as elastic phase, i.e. until achievement of nominal force F_n, all tested samples exhibited linearly elastic behaviour during the bending test. At that, poles prestressed with CFRP bars exhibited greater stiffness in this area when compared to the control sample strengthened with traditional steel reinforcement. The occurrence of cracks was not registered. In phase 2, i.e. during the testing until failure, the samples reinforced with prestressed CFRP bars yielded through failure mechanism via concrete, which was expected. In the control sample strengthened with steel reinforcement, the failure occurred through crushing of concrete, preceded by the yield of reinforcement. The load to displacement relationship at the top of the prestressed pole is bilinear prior to and after occurrence of initial crack, which occurs at a load of approximately 4.5 kN.

Although CFRP is an elastic material and does not have a plastic deformation property, all samples reinforced with CFRP bars exhibited the same, very high, deformation value. This can be explained by ductility achieved thanks to high strength concrete and by low mechanical coefficient of reinforcement, due to which a considerable rotational capacity of cross-section was achieved. As good results were obtained by the bar sliding control, it can be said that the poles reinforced with prestressed CFRP bars meet requirements that have been set for the use of such products, i.e. that they can be used for their intended purpose in the same way as the poles strengthened with traditional reinforcement.
Shear reinforcement did not show any advantage over synthetic macro fibres as an addition that improves properties of concrete. Although durability properties of the new pole type have not bee tested, it can be expected that they will be much more favourable compared to the traditional product.
Additional improvement of poles reinforced with prestressed CFRP bars can be achieved by greater level of prestressing, which could be realized by improving efficiency of anchoring at the point of force application. However, this would require additional testing in laboratory.

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