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THE USE OF GFRP TUBES AS LOAD-BEARING JACKETS IN CONCRETE-COMPOSITE COLUMNS

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A b s t r a c t

The paper presents the fields of applications of polymer composites in building structures. The use of composite glass fibre tubes is discussed in more detail. The laboratory methods used to test the mechanical properties of these pipes are presented. An original research program is presented, including six concrete-filled glass fibre tubes. The cylinders and columns made in this way were tested for their axial load capacity. Conclusions were formulated regarding the relationship between the load-bearing capacity of the test elements and their length, as well as the angle of glass fibres arrangement in the tube composite.

Keywords: composite structures, fibre-reinforced polymer, concrete-filled tube, column, experiment, standardisation

1. INTRODUCTION

Fibre-reinforced composites are multi-component materials used in the contemporary technology as uniform (in macroscopic terms) construction materials. Despite the use of materials for their production, which often

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significantly differ in properties, it is possible to obtain the resulting material. Due to the synergistic cooperation of all components, the resulting material may have better technological properties than the starting materials. This fact, as well as the dynamic development of reinforcement production technology, especially carbon reinforcements, and manufacturing techniques, determine the spread of this type of materials in many fields of engineering.

An example of such a market expansion and establishing a position as a structural element are Glass Fibre-Reinforced Plastic (GFRP) tubes. Their technological properties can be widely modified thanks to high flexibility of their production techniques, as well as the multitude of reinforcement types and resin types which constitute the composite matrix. Therefore, it is possible to manufacture elements tailored to specific requirements, optimized in terms of mechanical properties or chemical and thermal resistance.

The second chapter of this article describes the contemporary applications of composite materials in building structures. The focus was on the aforementioned GFRP tubes. The third chapter presents the current methods of laboratory testing of such tubes. The following two chapters present the authors' first attempts to create concrete columns with composite tubes serving as a load-bearing part of cross-section. Three short cylinders and three long columns were manufactured and tested. In both test series, the only variable tested was the winding angle of the fibres. The fourth chapter describes the tests on tube material, while the fifth chapter presents the tests on composite-concrete members. In the sixth chapter the conclusions from the tests are drawn.

2. APPLICATION OF COMPOSITE MATERIALS IN BUILDING STRUCTURES

2.1. Applications of FRP bars, strips and fabrics

The use of composite materials in the modern civil engineering is very wide. Certainly more common than GFRP tubes is the use of composite bars as concrete reinforcement. They are made on the basis of fibres, most often made of glass (Glass Fibre-Reinforced Polymer, GFRP) or, less frequently, basalt (BFRP, Fig. 1).

Fig. 1. Basalt composite bars with a visible, wound additional strand of fibres to improve adhesion to concrete

Composite reinforcing bars have been used in developed countries for several dozen years to reinforce bridge structures in order to improve their durability. Bridges, as structures exposed to atmospheric conditions, are subjected to faster corrosion degradation than other building structures. This applies in particular to countries in climatic zones with temperatures falling below 0°C. Multiple freezing and thawing of rainwater, combined with the widespread use of de-icing salts on roadways, significantly accelerates the corrosion of concrete reinforced with traditional steel bars. The advantages of using FRP composite bars in bridge construction, especially for deck plates that are mostly subjected to corrosion, were recognised in Canada, USA, Japan in the late 20th century. It was then that the first applications of this technology appeared, and the first technical standards were introduced. The American standard [4], currently in force in the design and realisation of concrete structures with FRP reinforcement, had its previous editions already in 2006 and earlier in 2003.

Besides the reinforcement of concrete structures, composite FRP materials are also often used for the strengthening of structures, especially reinforced concrete structures. The most common applications use unidirectional carbon fibre strips (CFRP) and bi- or multidirectional carbon fibre fabrics. Strips are used to strengthen beam structures subjected to bending, while fabrics are used to strengthen beam structures in the shear zones and columns by wrapping. The use of FRP strips and fabrics in building structures began at the end of the last century. In the first applications, carbon strips were used only as passively glued ones, so their excellent strength parameters were not effectively used. The strips carried only the service loads and did not contributed to carry the self-weight of the structure. Currently, technology of prestressing strengthening strips is becoming popular [12], [13], so the potential of FRP materials can be fully utilised. A modern technology of strengthening circular concrete columns is based on circumferential wrapping them with FRP woven fabrics which are then joined to the concrete surface by means of polymer glue. This solution brings with it a double benefit. Firstly, the concrete strength of the columns is enhanced because of developing a spatial state of compressive stress in the concrete core as a result of its confinement. Secondly, the failure mode of the columns changes from brittle to more ductile one, which is of great importance especially for structures subjected to seismic loads. The American standard [3], currently in force for the design and realisation of concrete structures with external FRP reinforcement, had its previous editions already in 2008 and earlier in 2002.

2.2. Applications of FRP tubes

The use of FRP tubes in concrete columns and piles provides the advantages which were already described in the above paragraph devoted to the concrete columns strengthened with hoop glued fabrics. However, while the previously discussed columns are created by strengthening the existing concrete columns, the columns fabricated with the use of FRP tubes are used in newly built structures. In the literature, the abbreviation CFFT, derived from the name *Concrete-Filled FRP Tube*, has become popular for this category of columns and piles.

Due to their low fire resistance, CFFT columns are not used in building construction. Their main advantage, corrosion resistance, would be poorly used in this construction segment. Thus, CFFT piles are mostly applied in hydrotechnical construction, where they are used to build piers, jetties and wharfs (Fig. 2).

Fig. 2. CFFT piles protecting the wharf from ships mooring at the Hadlock military port on Indian Island, Washington, USA [6], [9]

Driving of CFFT piles may take place before or after concreting. Regardless of this, the same devices are used for driving CFFT piles as for other pile types. The devices are: impact drivers and vibro hammers [8], [11]. Driving a hollow tube is provided with a conical tip ("blade") protecting the tube against destruction when it comes into contact with obstacles in the ground. When pile drivers are used, the upper surface of the piles, hit by a hammer, is secured with a thick plywood spacer. When a pile, previously filled with concrete, is driven, the damaged top of the pile is finally destroyed by means of pneumatic hammers and the top, damaged part of the FRP tube is removed. The connection of CFFT piles with a reinforced concrete cap is made by means of bars (steel or FRP) protruding from the pile core and embedded in the cap [5]. The composite material of the tubes can be cut and drilled with tools commonly available on building site such as angle grinders and drills with bits made of cemented carbide [7].

CFFT piles are used primarily as structures protecting quays against mooring ships (Fig. 3) or protecting bridge supports against vessels passing by (Fig. 4). CFFT piles are relatively rarely used for the construction of bridge supports. An example of such a CFFT application was described in [5]. One of four intermediate supports of a five-span road bridge with a total length of 85.3 m was made of CFFT piles with a diameter of 62.5 cm and a wall thickness of 5.65 mm. The 13.1 m long piles were driven to 10.2 m below the ground level, so that the remaining 2.9 m of piles could be called columns.

Fig. 3. Close-up of CFFT piles of the structure shown in Fig. 2 [9]

Fig. 4. CFFT piles protecting the intermediate supports of the bridge in Lacey Township, NJ, USA [7]

3. LABORATORY TESTS OF GRP TUBES

3.1. Content of the reinforcement in the material

The development of production technology and the popularization of Glass-Reinforced Plastic (GRP) pipes require a reliable assessment of their physical and mechanical properties, as well as the quality and durability of this products. One of the basic characteristics of all composites containing glass or carbon reinforcements is the content of the reinforcement in the material. The mass ratio of matrix (resin) and reinforcement allows to predict the properties of the material as well as assess its quality. Along with the increase in the content of the reinforcement in the composite, provided that it is properly distributed and its cohesion with the matrix is good, the value of composite strength and stiffness increases, and the value of the thermal expansion coefficient decreases. This coefficient is important in the case when the FRP composite is combined with other material, e.g. concrete. Depending on the production technology, the mass content of the reinforcement in the form of glass fibre may vary from approx. 30% for manual lamination performed by a not very experienced worker, to approx. 90% for pultrusion technology. Testing of the content of glass fibre in the composite is carried out in accordance with the guidelines of the standard [19]. It includes two methods for determining the content of reinforcement described as A-thermal and B- using chemical reagents. Due to the much greater popularity, resulting from the ease of carrying out the process, the method A will be described below.

Its idea is determining the change in mass of the tested composite sample after it has been subjected to the calcination process. This treatment is carried out in a muffle furnace at approx. 500÷650°C. Under such conditions, the polymer matrix undergoes thermal decomposition, which allows for the release of the reinforcement and a detailed analysis of its content. It is recommended not to run the process at higher temperatures. This is due to the risk of some fibres melting. The time of the calcination process, depending on the weight of the sample, is usually from 2 to 4 hours. An important factor affecting the reliability of the test result is the mass of the sample, which should be from 2 g for composites with an expected high content of reinforcements to over 10 g. In the case when many samples are calcined in the same furnace simultaneously, the amount of oxygen in the furnace may be insufficient and partial charing of the polymer may occur, which leads to contamination of the sample, mainly by the soot formed in this process. To prevent this, an additional oxygen stream should be used, fed directly to the furnace chamber. This method is also suitable for an approximate evaluation of the carbon fibre content in a composite. Carbon fibres are distinguished by excellent thermal resistance.

3.2. Assessment of fibres arrangement in the composite and local material defects

The above-described test can also be used to prepare a sample intended to assess the arrangement of fibres in the composite. To strengthen the composite pipes continuous filaments or strips are used. They are spirally wound at an appropriate angle. The angle of the winding is essential for the strength of the product. In the case when the dominant type of stress occurring during the operation of the pipe are radial loads, the aim is to arrange the fibres circumferentially, while in the case of axial loads, the direction of the fibres should be parallel to the pipe axis. In practice, in order to provide the pipe with adequate strength properties in all directions, combinations of multiple layers of reinforcement are used. Additionally, it is common practice to use in pipe fabrication so-called chopped strand mats. They consists of short fibres distributed randomly across each other and held together by a binder. Short chopped fibres may be also used without joining them into mats. In assessing the reinforcement arrangement in the composite the most commonly used method at present is calcination of the matrix and mechanical separation of individual reinforcement layers. This method allows direct access to the reinforcement layers.

Another, increasingly popular method of testing the reinforcement arrangement in the composite, is computed tomography (Fig. 5). It does not require thermal removal of the matrix. It allows, apart from the observing the reinforcement arrangement, to detect also discontinuities of the composite structure, e.g. bubbles or delamination. The occurrence of such defects is particularly dangerous due to the stress concentration around them and the initiation of a possible damage.

The presence of bubbles in composites is most often the result of errors in the laminate production process or failure to comply with a strict technological regime in the preparation of the resin. Before application, the resin is usually homogenized with modifiers: a hardener initiating the cross-linking and hardening process, catalysts accelerating these reactions, a paraffin co-reactor preventing the stickiness of the product surface, and fillers. During the homogenization of the composition of the mixture, air bubbles can easily be introduced into it. Moreover, highly surface area fillers may adsorb air bubbles which can be later released causing material defects. Due to the usually very high viscosity of polymer resins, which is advantageous from the point of view of their application technology, the bubbles trapped in the resin cannot easily diffuse towards the surface of the product. The presence of bubbles may also be the result of technological errors, especially in the case of the most commonly used unsaturated polyester resins in the production of pipes. These materials harden thanks to the cross-linking reaction with the participation of styrene. This reaction is highly exothermic, causing the composite temperature to rise. When the thickness of the laminated layer is incorrectly selected or the optimal content of initiators and catalysts for the reaction is exceeded, in the extreme case the boiling point of styrene (145°C) may be exceeded. Such a situation may lead to a local deficit of styrene in the resin and, consequently, the inability to obtain full cross-linking and obtain the expected material properties.

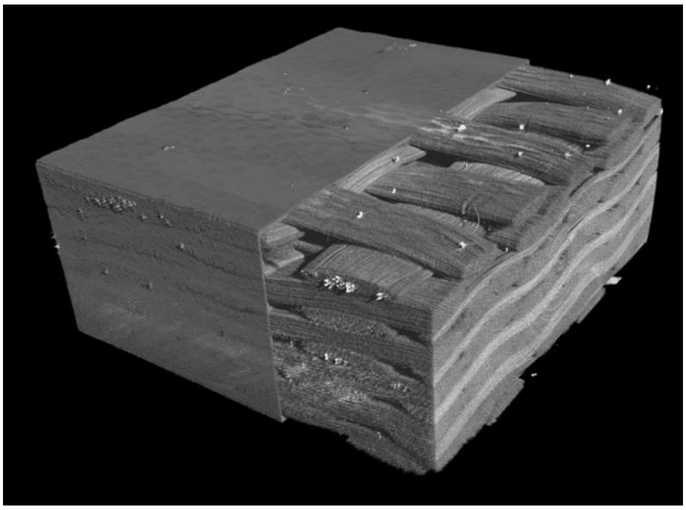

Fig. 5. View of the FRP reinforcement obtained by microtomography using a Nikon Metrology XTH 225 tomograph

Discontinuities in the composite structure may also be the result of improper oversaturation of the reinforcement by the resin. This means that in certain areas the ability of the polymer matrix to transfer stress to the reinforcement is limited. This stress transfer is the primary function of the matrix.

The above-described composite defects can be also detected in microscopic observations of the material with the use of stereoscopes.

3.3. Degree of hardening and cross-linking of the resin

The process of cross-linking the resins can be initiated by many factors. In the case of tubular polymer products, the most common of them are: a chemical reaction that occurs with elevated temperature as well as UV radiation. Other methods of cross-linking initiation are also known, but they are not applied in the industry. Regardless of the factor causing these reactions, they lead to radical changes in the properties of the resin. Moreover, the speed of the resin cross-linking process depends also on the environmental conditions in which the process is conducted. Low temperature and high humidity cause a radical decrease in the rate of the cross-linking process, also affecting the deterioration of the final properties of the product. This is especially important in relation to the most commonly used polyester resins. An important factor determining the course of the cross-linking process is also the type of chemical compounds initiating its curing and their concentration. In addition, the acceleration of the cross-linking process and the increase in resin stiffness can also be influenced by the introduction of catalysing compounds, for example cobalt compounds. As a result of the hardening process, a resin becomes a solid with increased modulus of stiffness, hardness and reduced flexibility. By quantifying these material properties, the correctness of the cross-linking reaction can be assessed.

A very good way to assess the degree of resin hardening, and thus its ability to perform its function in the composite, is to test the hardness. Due to the considerable stiffness of the resins, it is necessary to use a hardness gauge with significant penetration ability to reliably assess their hardness. A Barcol hardness tester is appropriate for this. It is a relatively small and lightweight device that allows measurements to be made even in the field. Due to the small required contact surface of the measuring element with the tested sample, it is possible to test the hardness of elements with a complex, corrugated surface, e.g. circular pipes. The hardness value increases with the passage of time from the initiation of cross-linking. Depending on the conditions surrounding the element, this process may take up to several dozen hours. The Barcol hardness test is carried out in accordance with the methodology of the standard [18]. The advantage of this method is also that there is no need to take samples, so the tested product is not cut nor drilled.

Another research device for assessing the cross-linking degree of the resin is a differential scanning calorimeter DSC. It is a very precise device measuring the heat energy flux related to all individual phase transformations, including cross-linking. Testing with this method is based on a measurement of the energy flux emitted or taken by the sample. All structural changes in the material are exothermic or endothermic, which allows the whole process to be observed and assessed on the basis of changes in the heat flux magnitude. The main advantage of this method is a very small mass of the test sample. For the evaluation of the cross-linking degree, several milligrams of resin are sufficient to obtain reliable results. Such a sample can be taken from even a very complex and responsible product without fear of its excessive weakening. In chemistry, cross-linking refers to reactions in which a large number of individual molecules are linked together to form a three-dimensional network. The network of connections can be achieved either by direct alignment of the macromolecules or by reaction between already existing polymer structures. The degree of hardening is fairly easy to estimate using the DSC method. The degree of hardening in this case is the amount of heat released during the calorimeter forced cross-linking process divided by the total enthalpy of reaction for the completely undyed resin. The value of the total enthalpy of the reaction can be read from available literature data or determined by testing the given resin sample.

3.4. Flexural strength parameters of the composite

In addition to the above-mentioned features of composite GRP pipes, the most important are the strength properties, which determine the possibility of using a given product in a specific application. One of the most important strength tests that are carried out on samples cut from the walls of fibre-reinforced pipes is the bending test. Due to the fact that in most applications of the pipes radial loads dominate over axial loads, the reinforcing fibres in the pipe are usually arranged circumferentially. Consequently, test specimens are cut in the circumferential direction, which leads to obtain the test samples in the form of an arc. Cutting the sample in the axial direction would damage the fibres, so that the sample could not bear the bending load. The recognized standards, e.g. [20] require the spacing of supports ranging from 15 to 17 times the average thickness of the tested sample. Consequently, its total length equals approx. 20 times the average thickness. In the bending test performed with a smaller spacing of supports (three-point bending), the so-called inter-layer shear may occur, which is undesirable, because brings underestimated strength results. During the bending test, the basic characteristics of the material are determined, which include: bending strength, bending stiffness modulus and deformation at the first fracture, which is a measure of the material elasticity. The bending stiffness modulus can be used to calculate the value of the so-called ring stiffness (Fig. 6).

Ring stiffness is a parameter that characterizes the resistance of a pipe to deformation under an external force acting perpendicularly to its axis. Ring stiffness is tested according to the standard [15]. The test is carried out on a pipe section of approximately 300 mm length, by compressing it with an external force, directed perpendicular to the pipe wall, in the direction of the pipe diameter, at a speed that allows for 3% deformation within 1 minute. The value of the ring stiffness can also be quite accurately calculated using for this purpose the value of the bending stiffness modulus of the pipe wall material. However, this is possible only in the case of GRP pipes with a slight deviation of the wall thickness value and a homogeneous reinforcement structure.

In case of so-called CIPP pipes (Cured In Place Pipes) the wall thickness exhibits significant fluctuations. This is a natural effect of the CIPP process. The CIPP pipes are GRP sleeves applied for trenchless renovation. During their curing at the final installation site, before the process ends, resin flows down gravitationally. As a result, the wall thickness is uneven- bigger in the bottom of pipe than in the top. In this case determining the ring stiffness on the basis of the bending stiffness modulus value obtained in the bending test may be not precise. However, it is often the only applicable method due to the difficulty of making the test sample annular.

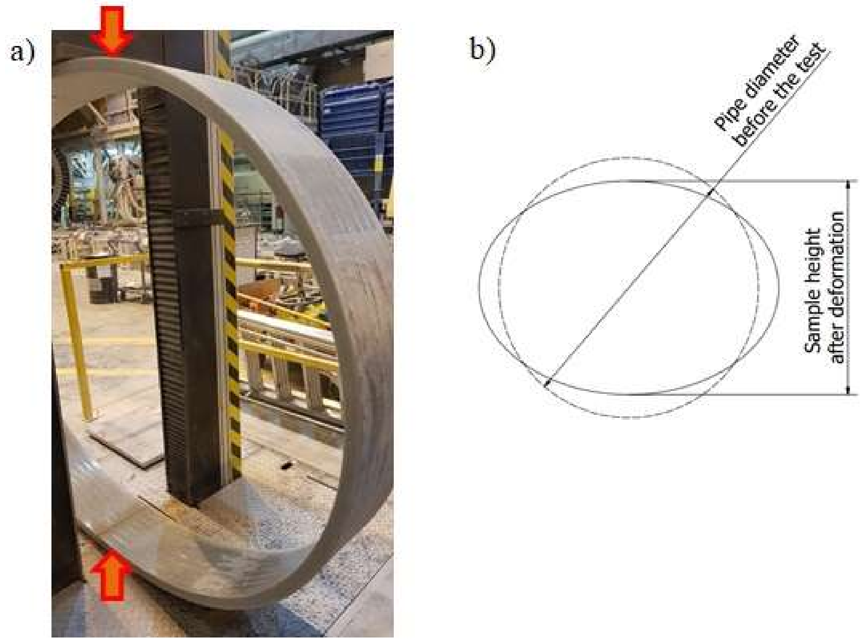

Fig. 6. a) Testing of GRP pipe ring stiffness. The arrows indicate the direction of the forces during the test. b) scheme of sample deformation during the test

The methodology of testing the ring stiffness is very similar to the method of assessing the resistance to failure of a GRP pipe in the deflection state. Also in this case, the test consists in deforming the ring sample to the shape of an ellipse. The sample is damaged during the test. GRP pipes are quite deformable: for typical, properly made pipes, it is possible to deform them by 10÷15% without symptoms of cracks or initiation of reinforcement delamination.

3.5. Tensile strength of the composite

The tensile strength test is performed for glass fibre-reinforced pipes in the circumferential and axial direction in accordance with the methodology of the standards [16] and [17]. The hoop tensile strength test can be carried out either on specimens in the form of tube rings with intentionally made weaknesses or on strip specimens in the form of circumferentially cut arcs. The first method is usually used for testing small diameter pipes (up to approx. 600 mm). More often, however, this test is performed on samples in the form of wall sections. This is done even despite the fact that lower strength values are obtained.

The underestimation of the tensile strength is a result of the significant deformation of the initial sample in the jaws of the testing machine while holding the arc sample. The complex state of stresses occurs in the sample, resulting from the simultaneous tension and bending. In laboratory practice, however, this method is generally considered an acceptable compromise between the result reliability and the test rationality. Before the test, the ends of the arc samples are strengthened in the area where the testing machine grips the sample with its jaws. This strengthening is made in the form of overlays made of resin. However, due to the lower strength of the resin used to make overlays than the tested sample (the sample is reinforced with fibres), there is a risk of shear damage to the sample at its connection with the overlays.

Using the test method with the annular samples, it is necessary to have a separate set of clamping grips adapted to each pipe of a specific diameter and wall thickness. Moreover, for the large cross-sections of the ring specimens, large forces occur. Strength machines are required, which are non-typical even for composite materials.

Determining longitudinal tensile strength (Fig. 7) is most often carried out on samples cut longitudinally to the pipe axis. A sample preparation and testing is relatively simple. In the case of pipes with large nominal diameters, above 400-500 mm, the longitudinally cut test specimen is practically a cuboid. The curvature resulting from the cylindrical form of the product is almost imperceptible. This makes it easier to mount it in the jaws of the testing machine. The standard [16] allows for carrying out tests on three types of samples: parallel-sided strips, shaped strips (dumbbell specimens) and wide plates with two notches. Obviously, the results obtained on each sample type may differ from each other. The fibres arrangement is different in the respective samples. It results in a different ability to transmit stress. Method of preparing the test specimens is crucial for obtaining the correct result. Obviously, the test specimen should have an equal width over the entire measuring section and be free from any surface defects that could initiate damage. The best method to reach this objective is machining by means of milling machines or milling plotters. Especially numerically controlled CNC machines allow to obtain the desired dimensions and surface quality. Unfortunately, due to the presence of hard glass fibres in the composite, and often mineral fillers (silica, sand, carbides), commonly used cutting tools, even those with abrasion-resistant ceramic layers, do not show acceptable performance and durability. In the authors' opinion water jet cutters should not be used to prepare the test specimens. These are modern tools for machining which use a very high-pressure jet of water, or a mixture of water and an abrasive substance. The water jet cutters are admittedly very effective and efficient, and allow to obtain the expected geometrical accuracy in the preparation of the GRP specimens, but they imprint a characteristic relief on the cut surface, perpendicular to the force applied during the test, which may result in the underestimation of the obtained results. The most effective preparation method is the machining with diamond discs capable of cutting through hard inclusions in the composite. It is especially important that the tool rotation direction is parallel to the sample axis. In this case, the created relief is parallel to the direction of the force during the test. Thus, it is not conducive to initiating cracks in the sample.

Fig. 7. Axial tensile strength test of GRP pipe

3.6. Thermal expansion of the composite

The value of the thermal expansion coefficient is very important in those applications of the composites when they are combined in a structure with other materials, e.g. metal or concrete. Thermal expansion coefficients of polymer based materials can be approximately an order of magnitude higher than for other materials used in construction. This fact may cause serious difficulties in achieving a permanent combination of polymers and other materials.

Thermal expansion coefficient of fibre-reinforced composites depends on the content and orientation of the reinforcement, which reduces the coefficient value. Fibre reinforcement enables polymer materials to be combined with steel or concrete in structural building elements. Testing the thermal expansion coefficient of composites can be carried out with the use of dilatometers, which are capable of precisely measuring changes in the size of the sample as its temperature changes. The test should be performed on samples taken in such a way that they represent all possible directions of fibre reinforcement that are expected for the tested product. The fibres arrangement noticeably influences the composite's ability to limit changes in its dimensions under the influence of temperature changes. The described principle can be abandoned for the composites in which only chopped strand mats or short chopped fibres constitute the reinforcement.

4. TESTING OF GRP TUBES IN AN AUTHORS' EXPERIMENTAL PROGRAM

In the framework of an author's experimental program [2] a series of Glass Fibre-Reinforced Polymer (GFRP) tubes was investigated. The tubes were manufactured in continuous cross-winding process. Just one parameter was a variable in the program: the angle of the glass fibre winding, so-called *beam angle*. This angle, hereinafter referred to as θ and measured with respect to the longitudinal axis of the tube, was 20°, 55° and 85° (Fig. 8). Inside diameter of the tubes was 200 mm. The nominal wall thickness declared by manufacturer ranged from 5 to 6 mm. In fact, however, the measured wall thickness of the tubes varied between 5.8 and 7.1 mm.

The glass fibres used in the production of the pipes were in the form of continuous roving with linear density 2400 g/m = 2400 tex. The roving was produced in Slovakia by an American company *Johns Manville* from E-glass fibres. The fibre content in the mass of the tube composite was 60% according to the manufacturer's declaration. In fact, the fibre content differed significantly from that declaration. The detailed data is given in the sections below.

Unsaturated polyester resin was used for the production of the tubes. The resin, with the trade name *Crystic 2-420 PA,* was produced in Croatia by a British company *Scott Bader*. Resin hardener, with a trade name *Butanox M-50*, was produced by a Dutch company *AkzoNobel*. Tensile strength of the hardened resin was in the range of 44–46 MPa according to the manufacturer's declaration. The modulus of elasticity in tension of the hardened resin was in the range of 3.03–3.68 GPa according to the manufacturer's declaration.

Filament winding machine was used to manufacture the tubes.

The manufactured pipes were subjected to comprehensive material tests. Table 1 shows the results of the testing the content of glass fibres in the composite. The tests were carried out according to the standard [19]. The thermal method was used (cf. point 3.1).

The dimension of the internal diameter of all tubes exactly complied with the manufacturer's declaration and was D_{core} = 200 mm. This fact is not surprising: the production technology was based on the continuous winding of fibres on a metal core. There were, however, significant differences in the wall thickness t of tubes from individual series (Table 2).

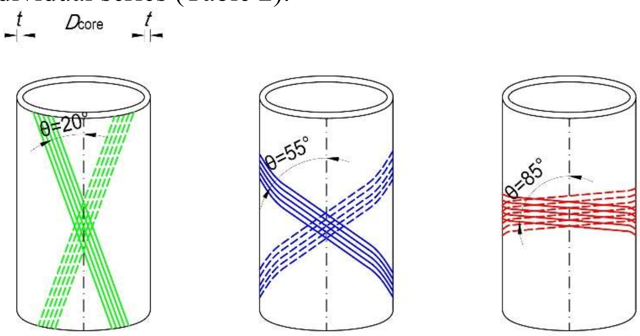

Fig. 8. Three test series of GFRP tubes

Table 1. Results of testing the content of glass fibres in the tube composite

Beam angle	Content of glass fibres [%]	
	in the composite volume	in the composite mass
20°	69.4	49.1
55°	58.4	37.5
85°	72.4	52.8

Table 2. Results of testing the wall thickness of the tubes

Beam angle	Mean value of wall thickness t [mm]
20°	7.1
55°	6.5
85°	5.8

Comprehensive strength tests of the tube composite were carried out. Longitudinal compression strength of the composite and its longitudinal compression modulus of elasticity were tested on 40 cm long tube sections (Fig. 9). In order to measure the modulus of elasticity, strain gauges were installed in the mid-height of the tube specimens in three places situated every 120° on their circumference. The results of this test are presented in Table 3.

The test of the longitudinal tensile strength of the tube composite and its longitudinal tensile modulus of elasticity were carried out according to the standard [16] (cf. point 3.5). Parallel-sided strips and shaped strips (dumbbell specimens) were used. The modulus of elasticity was measured using a mechanically attached extensometer to the dumbbell specimens. The obtained results are presented in Table 4.

Fig. 9. Longitudinal compression test of the tube composite

Table 3. Results of testing the longitudinal compression strength and compression modulus of elasticity of the tube composite

Beam angle	Longitudinal compression	
	Strength [MPa]	Modulus of elasticity [GPa]
20°	142.4	36.3
55°	78.6	14.7
85°	87.0	14.1

Table 4. Results of testing the longitudinal tensile strength and tensile modulus of elasticity of the tube composite

Beam angle	Longitudinal tension	
	Strength [MPa]	Modulus of elasticity [GPa]
20°	173.9	10.9
55°	48.6	8.0
85°	32.6	3.4

The tests of the circumferential tensile strength of the tube composite and its circumferential tensile modulus of elasticity were carried out according to the standard [17] (cf. point 3.5). Tubular rings were used with intentionally made notches weakening the samples. The modulus of elasticity was measured using strain gauges installed at the weakened places of the ring specimens. The obtained results are presented in Table 5.

Table 5. Results of testing the circumferential tensile strength and tensile modulus of elasticity of the tube composite

Beam angle	Circumferential tension	
	Strength [MPa]	Modulus of elasticity [GPa]
20°	46.1	6.0
55°	301.3	20.6
85°	692.2	46.4

Comparing the resulting strength parameters obtained for the three types of composite, it can be seen that the strongest and the stiffest in the longitudinal direction (both in terms of compression and tension) is the composite with the fibre winding angle θ=20°, while in the circumferential direction - the composite with winding angle θ=85°. This observation confirms intuition. It is also noticeable that it is impossible to draw any mathematical relationship (neither linear nor non-linear) that would describe in a universal way the relationship between the angle of the filament winding angle θ and all the tested strength parameters of the composite. This is fully consistent with the theory of fibrous composites [10], which does not provide simple dependencies between the beam angle and the mechanical parameters of the composite. These parameters are greatly influenced by other, additional factors, among which one of the most important is the adhesion of the fibres to the resin matrix [10]. It should be noted that the value of the tested characteristics was also influenced by the different thickness of the tested samples and their glass fiber content. The influence was considered to be relatively small and was not investigated.

Nevertheless, it can be noticed that as the direction of the fiber winding approaches the direction of the force acting during the test, the values of both tested material parameters (strength and modulus of elasticity) clearly increase. This allows us to conclude that it is possible to match the GRP pipe structure to the intended application in order to optimally use the potential of the composite material.

5. TESTING OF CONCRETE-FILLED GRP TUBES IN AN AUTHOR'S EXPERIMENTAL PROGRAM

Three short Concrete-Filled FRP Tubular (CFFT) cylinders and three long CFFT columns were made of the tested tubes [1]. Concrete of class C30/37 according to the standard [14] was used. Mechanical parameters of concrete were tested on cylindrical specimens ϕ150/300 mm directly before testing CFFT cylinders and CFFT columns. The concrete parameters were tested according to [21]. Average compressive strength f_{cm}=38.0 MPa and average modulus of elasticity E_{cm}=31.9 GPa were obtained.

The length of tubes used to make CFFT cylinders was 400 mm, and tubes used to make CFFT columns - 2000 mm. The length of the specimens was the only difference between the series of cylinders and the series of columns subjected to the experimental tests.

Experimental tests on the CFFT specimens were carried out using a hydraulic strength press manufactured by the Swiss company Walter + Bai AG, model 102/5000-HK4, with a load capacity of 5000 kN and a stroke of the press from 0 to 100 mm. Both CFFT cylinders and columns were axially compressed to the failure. Steel articulated joints and thick platens at both ends of the compressed members were used (see Fig. 9). When taking into account the platens thickness (40 mm), the axial height of the tested elements was 480 mm and 2080 mm for cylinders and columns, respectively. The load increased monotonically and was controlled by displacement. The piston of the hydraulic press was extending with a constant speed of 0.5 mm/min. The press equipment enables digital recording of the measurement results. The measurement of the stroke of the piston and the force values was discrete, with a time interval of a few seconds. Every test lasted several dozen minutes, including the post-critical phase. The results of the destructive force for all six test elements are summarized in Table 6.

Table 6. Results of the axial compression load capacity of CFFT cylinders and columns

No.	Beam angle	Axial height [mm]	Failure load N_u [kN]
1	20°	480	1608.7
2	55°	480	2144.5
3	85°	480	4136.7
4	20°	2080	1600.0
5	55°	2080	1406.3
6	85°	2080	1863.7

Attention should be drawn to the very high load capacity of the cylinder with a beam angle of θ=85°. The specimen failed reaching the circumferential tensile strength of the tube composite. The sample after testing was barrel-shaped. The cylinder with the beam angle θ=20° also failed reaching the circumferential tensile strength of the tube composite, but a much smaller force was required for this (see Table 5), and the shape of the sample remained cylindrical after the test.

Failure mode of the CFFT columns was different than for CFFT cylinders. Due to their slenderness, they failed by buckling. As shown in Table 6, their load capacities were no longer as different as those of the cylinders. The small number of column specimens does not allow to draw definite conclusions. However, it is worth noting that the highest load capacity in columns category was achieved for the specimen No. 6, though its tube composite was relatively weak in axial compression (see Table 3). This was probably due to the definitely highest strength and stiffness of this composite for circumferential tension (Table 5).

Just before the failure of the column or cylinder, they were subjected to high compressive stresses, both the FRP shell and (above all) the concrete core. As found in the experiments, the highest compressive stresses in the concrete core were achieved in the column and cylinder with the highest circumferential strength of the FRP shell. This was due to the greatest ability of this shell to create a spatial state of compressive stresses in the concrete core. Concrete in the spatial state of stress can be subjected before failure to the greater stresses than in the uniaxial state.

Thus the deficiency in the vertical load-bearing capacity of the composite θ=85°was covered by the increase in the load-bearing capacity of the concrete core subjected to the spatial state of compressive stresses. On the other hand, the composite of the specimen No. 4, although by far the strongest in compression, did not result in achieving the highest load capacity by this element in its category. The load-bearing capacity of the concrete core in the specimen No. 4 did not increase significantly. Its tube composite was not strong nor stiff enough in circumferential tension.

For all tested elements, the theoretical load capacities N_{theor} of their cross-sections can be easily calculated. It is enough to add the capacities of tubes (N_{FRP}) and concrete cores (N_{core}) together. The load capacities of the tubes can be calculated multiplying their cross-sectional areas (depending on the wall thickness t, given in Table 2) and the longitudinal compressive strength of the composites (Table 3). The theoretical load-bearing capacity of the concrete core is the same for each specimen, because the same concrete was used to fill the tubes, and all elements were tested at the same time. The core load capacity is N_{core} = 1194.7 kN. Dividing the experimentally obtained load-bearing capacity N_u of the column (Table 6) by its theoretically calculated load capacity N_{theor}, the coefficient of confinement effectiveness of the core concrete may be obtained (Table 7). As can be seen, the fibre orientation closed to the circumferential results in a higher concrete effectiveness. The coefficients of confinement effectiveness of the core concrete are higher for cylinders than for columns. This is due to the buckling phenomenon. The buckling usually occurs much earlier before reaching the load-bearing capacity of the core concrete subjected to the spatial state of compressive stress.

Table 7. Confinement effectiveness of the core concrete for the CFFT specimens

No.	N_{FRP} [kN]	N_{theor} [kN]	Coefficient of confinement effectiveness of the core concrete
1	656.5	1851.2	0.869
2	332.6	1527.3	1.404
3	324.4	1519.1	2.723
4	656.5	1851.2	0.865
5	332.6	1527.3	0.921
6	324.4	1519.1	1.227

6. CONCLUSIONS

CFFT structures are not widely known in modern civil engineering. Their use is particularly justified and desirable in hydrotechnical construction. This is confirmed by successful applications of this technique in other countries.

As shown, CFFT columns reach significant load capacities when axially compressed. In columns of this type, the confinement effect may be achieved in concrete core if the circumferential stiffness and strength of the FRP coat are high enough. The angle of the glass fibre winding, measured with respect to the longitudinal axis of the tube, has an influence on this effect

The relationship between the angle of fibre winding and the bearing capacity of the column depends on too many factors to be accurately described at the present stage of research. The circumferential arrangement of the fibres in the tube was the most advantageous in the presented research.

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