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CFGFRPT PILES WITH A CIRCULAR CROSS-SECTION AND THEIR APPLICATION IN OFFSHORE STRUCTURES

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ABSTRACT

The possibilities of using concrete piles in a polymer composite reinforced with glass fibres in offshore facilities were shown. Laboratory tests of CFGFRPT type piles compressed axially and in eccentric compression for the analysis of CFGFRPT piles were used. Methods of analysis of dynamic systems for mathematical modelling of the displacement of the hammer in the pile driving process were applied. The possibilities of combining CFGFRPT piles, including the creation of hybrid piles were also presented. For example, concrete piles can be combined with concrete piles in a polymer composite reinforced with glass fibres with different fibre beam angles. The possibilities of using such hybrid piles in offshore facilities were indicated.

Keywords: concrete-composite piles, composite reinforcement, beam angle, hybrid piles

INTRODUCTION

Using concrete and composite, it is possible to construct piles with a circular cross-section of different lengths and diameters. These are, for example, CFGFRPT piles (Concrete Filled Glass Fibre – Reinforced Polymer Tubes), i.e. piles in the form of a concrete-filled tube made of glass fibre reinforced polymer composite. A pipe made of composite, used to constrain concrete (called "concrete confinement"), shall be called a pile coating.

It is obvious that a pile structure constructed in this way has mechanical and durability features of concrete as well as of the composite and its reinforcements – in this case, of glass fibres. This combination of materials creates new construction and operation possibilities also for piles used in offshore facilities.

The matrix material is one of the basic factors affecting the process of production and exploitation of the composite material. For the production of composite materials, virtually all groups of manufactured polymeric materials are used, as the polymers themselves generally meet the conditions set for the components of composite materials. They are corrosion-resistant and lightweight. Their presence greatly minimizes the disadvantages of high-strength fibres, including glass fibres. This is especially true for the brittleness of these fibres [7].

As stated in [7], [23], the first synthetic resins were polyester resins. They are the most frequently used polymer matrices in composites, mainly in glass fibre reinforced composites [7]. Epoxide resins with great possibilities of modifying their properties are also frequently used [7]. They are resistant to the direct influence of water, including seawater. The material of the matrix is also thermosetting epoxy resins mainly due to high mechanical strength, significant chemical resistance and good electrical insulation properties. Contact with water does not adversely affect the properties of this material. So it is advisable to use piles in a composite or fibre-reinforced composite coating in the design and construction of offshore facilities.

As we shall see further, composite materials produced on the basis of resins with reinforcement in the form of glass fibres (Glass Fibre Reinforced Polymer, GFRP – [1]) are exposed to various damage occurring during their operation. Typical

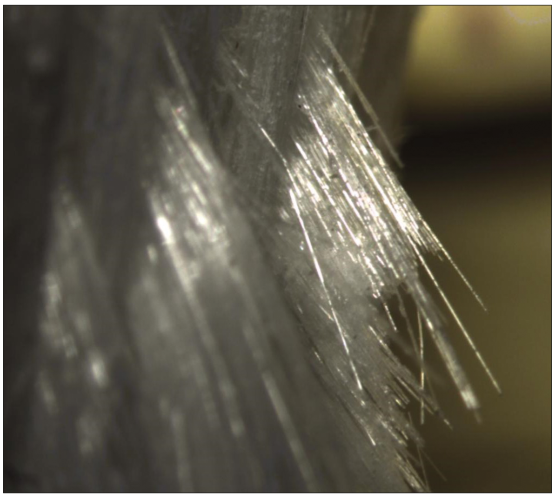

Fig. 1. Stereoscopic view of the fracture of a pipe sample made of glass fibre reinforced composite

Fig. 2. Destruction (debonding) of a pipe made of glass fibre reinforced composite

types of damage that composite materials undergo include: fatigue cracks in the matrix or in the reinforcing fibres, fibre and matrix debonding, and in the case of multilayer materials the damage also include delamination. The crack propagation in the reinforced composite causes the warp crack approaching the fibre and then it develops on the other side of the fibre. At the same time, propagation of the crack occurs along the fibre-warp interface, with the fibre remaining intact. It is only later that the fibre ruptures and is pulled out of the matrix, it disperses the energy of the crack propagation (Fig. 1).

In the case where the composite consists of several fibre layers forming the laminate, the crack propagation process in the material, selecting the path requiring the smallest energy, leads to stratification of the laminate [9], [17], [21]. This is clearly seen in Fig. 2.

If the composite material cracks, its development is important. The correct hypothesis of the development of the crack provides for the determination of the time interval when the crack is subcritical, i.e. the fracture does not develop rapidly, leading to the ultimate fatigue scrap. The methods of fracture mechanics allow estimation of the time of safe work of the structure in conditions where the crack has already occurred. Fatigue hypotheses of linear fracture mechanics can, therefore, be useful in systems monitoring the technical condition of composite structures, where apart from the detection and location of damage it is important to determine the level of risk associated with this fracture. Crack development hypotheses are usually described using ordinary differential equations [13].

As has been mentioned, concrete is introduced into the cylindrical shell (coating) of a reinforced composite. In longitudinally compressed concrete elements with an external coating, the transverse deformation of the concrete due to restraint is limited. As a result, the core concrete of such a construction element operates in a three-axial compression state.

Depending on the type of pile-soil interaction and the manner of transferring loads by the pile to the soil, for the testing of piles, it is possible to use laboratory tests of columns with the same structure as the aforementioned pile. It can be assumed that in such a case there is a certain mathematical isomorphism between the column and the pile. This relationship will be used in this work. The paper does not deal with pile-soil interaction problems.

PILES AND CFGFRPT PILES

The preparation of the foundation of the naval structure includes, among others, strengthening the soil foundation. One method of reinforcing the ground is piling. Prior to the piling process, subsoil recognition must be carried out which can be layered [20]. This can be done with the use of static penetration. In the test, a static push probe uses two

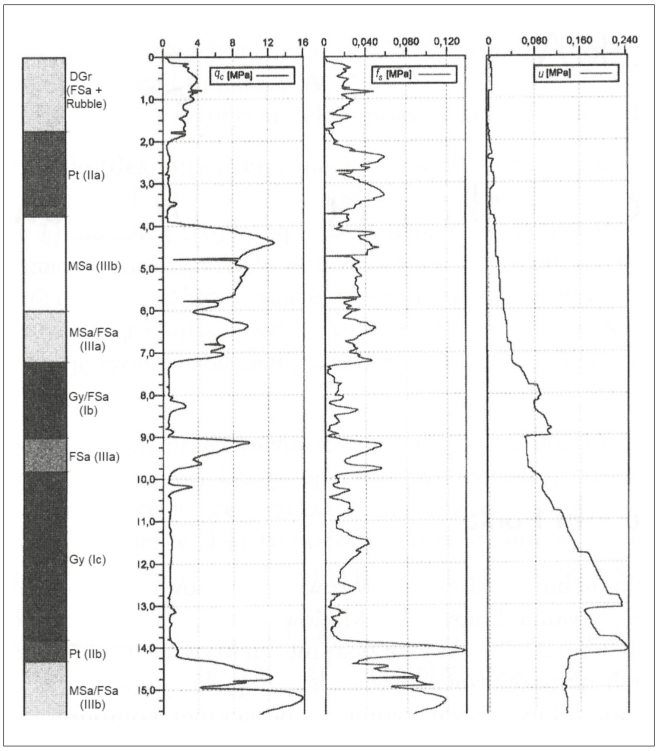

Fig. 3. An example of the CPTU test result at the selected probing point (node) [19]

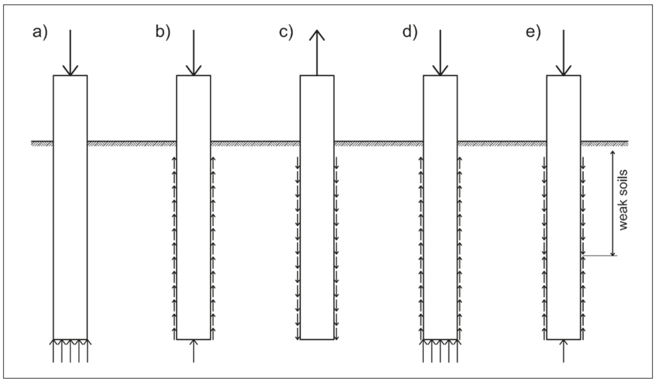

Fig. 4. Scheme of transferring loads through a vertical pile to the soil

Fig. 6. Sea corrosion of piles [10]

methods of penetration. One of them is the CPT method without measurement of water pressure in soil pores and the other – CPTU method with measurement of water pressure in soil pores. The results of such recognition can be presented by means of appropriate graphs (Fig. 3). The diagrams show resistance on the probe cone q_c, friction on the friction sleeve f_s, pressure of water in the pores of the soil u.

The basic task of the pile, as well as the foundation [11], is to transfer loads to the deeper soil layers. That is to more durable layers than the layers through which it passes, e.g. through seabed sediments [8]. Passing loads through a vertical pile to the ground can be done in many ways (Fig. 4): through the base (Fig. 4a), through the pile side, as: push-in (Fig. 4b) or anchor – pulled out (Fig. 4c), through the base and pile side (Fig. 4d) and taking into account negative friction (Fig. 4e), which may occur when the pile is driven through low-bearing soils, non-consolidated e.g. silt, peat, sediments [5].

The pile can be made in the ground or embedded in the ground vertically or diagonally, individually, in groups [4] or rows.

Steel, concrete, reinforced concrete piles (pre-compressed) can be driven into the soil by hammering or pressing. They can be formed with or without a cast pipe (drilled piles). Pallets or impact and vibrating hammers are used to drive in a pile. In the case of offshore works, work is performed using floating floats, special pontoons, work platforms or special vessels. Drilled piles are made using drills. An example of using piles is shown in Fig. 5.

The piles used in offshore facilities are exposed to sea corrosion of concrete and steel (Fig. 6).

Sea corrosion of concrete piles is the destruction of the concrete in seawater. This may be chemical or biological corrosion. The first one includes: corrosion caused by water of low transient hardness (concrete leaching of binder components easily soluble in soft water – leaching corrosion), corrosion resulting from reaction between cement components and aggressive compounds dissolved in seawater (magnesium corrosion), corrosion consisting of on the formation and settling of water-insoluble salt crystals in concrete pores causing concrete disintegration (sulphate corrosion).

Fig. 5. Offshore platforms with connecting bridges [10]

Biological corrosion is caused by the activity of marine pests (pholas dactylus, molluscs, crustaceans). There is also chloride corrosion of reinforced concrete piles, leading to mechanical damage of concrete, occurring when chlorides get to the reinforcement and cause corrosion.

Sea corrosion of steel piles is the destruction of steel piles and steel reinforcement inserts in reinforced concrete piles as a result of seawater.

The piles in the composite or reinforced composite coating, i.e. CFGFRPT piles, are more resistant to the negative impact of seawater on concrete or steel. The mechanical properties of the reinforced coating also cause that such piles are more resistant to lateral forces caused by sea waves. The applied cover limits carbonization of concrete and its cyclical freezing and thawing with penetrating water, thus increasing the lifespan of piles exposed to seawater.

In the case of engineering applications, it is worth bearing in mind that composite-concrete piles, in addition to the features described above, are also characterized by high aesthetic values. For example, directing the laser beam to the GFRP (Glass Fibre Reinforced Polymer) composite gives an interesting effect – Fig. 7.

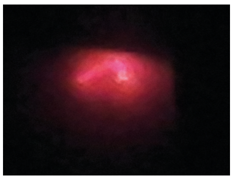

Fig. 7. The effect of directing a laser light beam on the GFRP composite

As stated in [25] piles for offshore structures have been implemented in the USA in CFGFRPT technology for many years. The use of these piles in the US is regulated by the standard [3], published in 2014 by the world-recognized standardization organization ASTM International. For example, in [24], the use of 28.3 m long piles and of 42 cm outside diameter for the construction of a wharf cover is described. The quays of the port are located in the moderate cold climatic zone with cold winters. The coating walls were 7 mm thick and were made of polymer material reinforced with continuous glass fibre (i.e. roving) type E (fibre made of boron-aluminum-silicon glass). The piles were made outside the construction site.

Fig. 8. A sample in a hydraulic press

Fig. 9. Destroyed composite coating

LABORATORY TESTS

Cylindrical tubes with a length of 2 m, outer diameter of 0.2 m and medium wall thickness from 5.8 to 7.1 mm were prepared for the tests. The pipes were made of a composite (polyester resin) reinforced with glass fibres E in the form of roving with different beam angles: 20°, 55°, 85°. The beam angle is the angle between the tangent to the winding curve (roving curve) and the generating line of the cylinder. In the laboratory of the Faculty of Civil and Environmental Engineering of the Gdańsk University of Technology, the composite piles (coating) and piles filled with C30/37 concrete according to the Eurocode were tested. Composite piles and composite piles filled with concrete will also be called samples.

Samples of coating and concrete-filled composite pipes of different beam angles of glass fibres were compressed in a strength hydraulic press manufactured by the Swiss company Walter + Bai AG, model 102/5000-HK4, with a capacity of 5000 kN and with a press piston extension from 0 to 100 mm (Fig. 8). Loading was controlled by a fixed extension of the press piston, or displacement. Due to the assumption (Figure 4a), the samples worked like squeezed poles. A single experiment lasted several dozen minutes until the sample was destroyed – Fig. 9. (See also Fig. 1 and Fig. 2.). Examples of registered test results for compressed samples are shown in Figure 10.

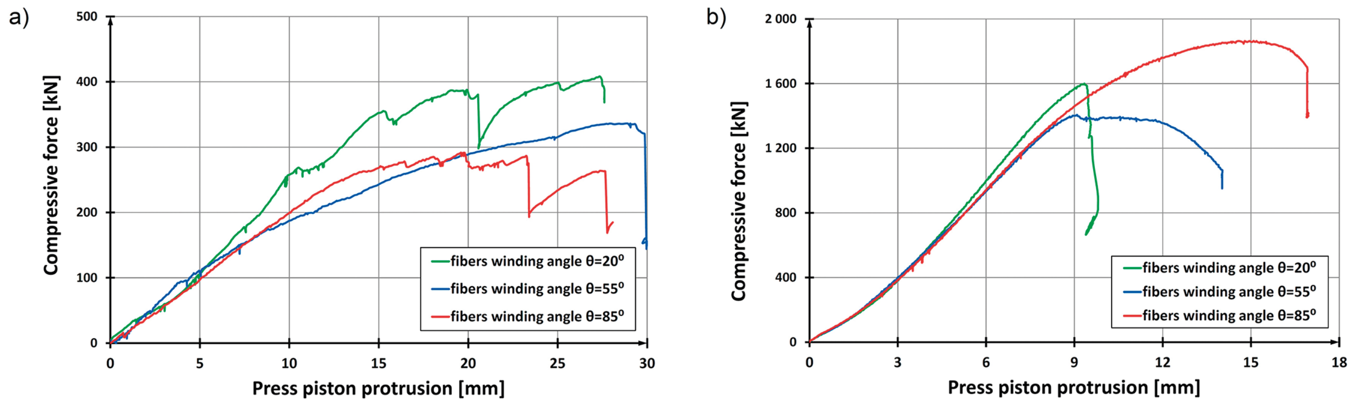

Fig. 10. Relation between force and displacement for: a) coating, b) composite pipe filled with concrete

The experiments carried out show that the load capacity and post-critical behaviour of the samples tested experimentally are determined by the angle of the beam of the glass fibres in the applied coating. Differences in the load capacity of the samples resulting from the different direction of the fibre winding in the coating are up to approximately 30%.

The research shows that the brittle way of destruction (Fig. 1 and Fig. 2) and the low post-load bearing capacity eliminate the piles in the coating with an angle of the beam of fibres close to 20° for offshore applications. This is particularly important where the bearing capacity of offshore structure is important.

Coats with a fibre beam angle close to 20° are characterized by increased longitudinal compression strength (in the described studies by as much as 100%) and a larger modulus of longitudinal elasticity. These advantages, however, are of little relevance to the shortcomings of these composite tubes described earlier.

More details on experiments and laboratory tests can be found in [1], [2].

In offshore structures, piles are exposed to horizontal forces due to the waves of seawater and work simultaneously on compression and bending. This fact was taken into account in the laboratory studies by introducing the replacement piling concept. It is a pile, whose behaviour under the influence of horizontal forces is modelled as the behaviour of an eccentrically compressed pillar supported articulated at both ends.

The columns subjected simultaneously to axial compression and bending are generally designed as eccentrically compressed. The magnitude of the eccentrically compressive axial force e, compressive N is the quotient of the bending moment M and that force N, acting in the considered cross-section of the pile. A commonly used practical method of calculating the load-bearing capacity of eccentrically compressed concrete columns is the use of nomograms representing the so-called curves of interaction of normal force N and bending moment M, simultaneously affecting the cross-section of the column. Such curves can also be made for steel or composite steel-concrete poles, corresponding to the respective piles. Fig. 11 shows an illustrative interaction curve for a CFST (Concrete-Filled Steel Tube) composite column. The area inside the curve is safe for the load capacity of the column section, and outside – it is dangerous. Similarly, for the pile being modelled here.

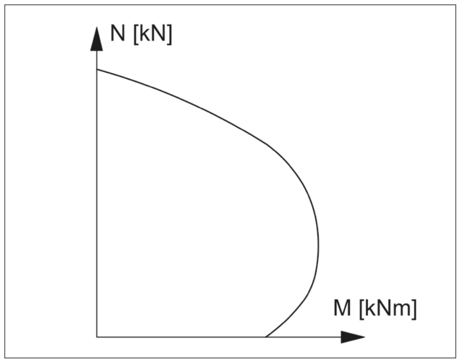

Fig. 11. An interaction curve for a cross-section of an exemplary steel-concrete composite column of the CFST type

Analyzing the impact of horizontal loads on the pile's load capacity, experimental studies of nine eccentrically compressed CFGFRPT columns [1] were used. The samples were made in the same way as the axially compressed samples described earlier. The test conditions of all samples were virtually identical (temperature, humidity, sample preparation, etc. [1], [2]). Among the eccentrically compressed samples, six were compressed on the eccentricity e = 26 mm, and the remaining three – eccentricity e = 52 mm. The first of these values e corresponds to the boundary of the cross-sectional core. This means that the six described samples experienced the kind of eccentric compression that on one of the edges of the cross-section normal stresses were equal to zero (without taking into account the effects of the second-order). The group of the six examined elements was divided into two subgroups: three were tested as standard, and the remaining three were loaded before the actual test with ten load cycles in the force range from 105 kN to 750 kN. This accounted for a maximum of 88% load capacity of previously tested eccentrically compressed e = 26 mm, not loaded cyclically.

As it turned out, the impact of bending on the load capacity was significant (Fig. 12). As expected, the load capacity of the columns decreased with the increase of eccentricity.

The visible effect of the deadweight capacity of the CFGFRPT samples tested were coating cracks along the fibres

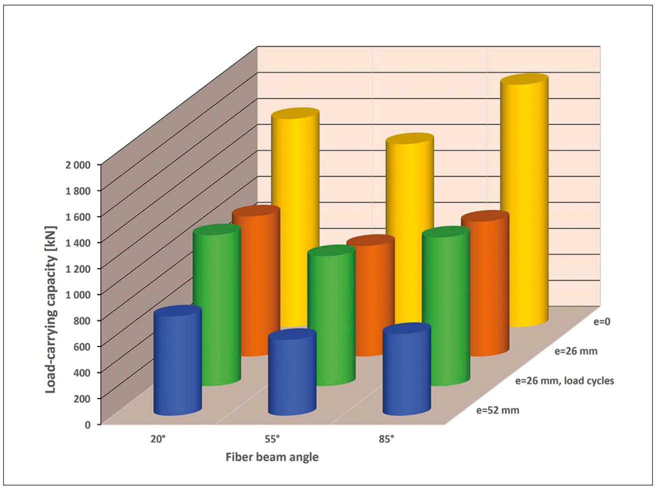

Fig. 12. Load capacity results obtained in experimental studies of CFGFRPT samples

(coat with 20° fibre bundle) or global buckling (coatings with beam angles of 55° and 85°). In the case of the latter, the composite of the coat showed after the test in the central zone (in the zone with the greatest curvature during buckling and at the post-coating step) cracking of the resin matrix, both on the tension side and on the compression side. No damage was observed in the pressure zone of the samples.

CFGFRPT samples with 20° beam were characterized by the most brittle way of destruction. However, they were not the least bearing ones. Certainly, this was due to the high load-bearing capacity of the coating itself, which (without the core) turned out to be twice as large after the test than for the other two types of fibreglass beam.

Attention should also be paid to the fact that in each of the four test series the lowest load capacities were recorded for CFGFRPT samples with a fibre beam angle of 55°. The probable reason for this was the fact that on the one hand they were characterized by low longitudinal strength of the coating, and on the other – the medium ability to excite the triaxial state of compression in the core concrete. However, to confirm this conclusion, a larger number of samples should be tested.

When discussing the results obtained for compressed samples on the eccentricity of e = 26 mm, one should notice a clearly beneficial effect on their bearing capacity of a series of ten cyclic loads carried out prior to the fundamental destructive load. All samples subjected to cyclic loads proved to be more efficient than their counterparts not subjected to these loads. The average percentage difference for the three pairs of samples was 11.4% of the lower load-bearing capacity.

MATHEMATICAL DESCRIPTION OF THE SELECTED PROBLEM

The driving of piles in the composite coating into the ground is also performed by the hammering method [5], i.e. using impact hammers. This method meets the requirement of the American standard [3]. According to it only the tip of the pile with a length of 61 cm can suffer damage when driving a pile. In this process, there is also the propagation of vibrations in the pile and in the ground. The process of propagation of vibrations in the ground can be members/elements using analogue models [14]. The impact of the hammer on the pile head can be treated as collisions of the respective masses and analyzed using methods from [16]. The masses m1, m2 can correspond respectively to the pile weight and hammer mass.

In modelling, all these situations are specific cases of generalized dynamical systems [13] and lead to continuous or discrete dynamic systems [12], [13]. In the first case, the description uses differential equations, and in the second one – difference equations. The results are recorded in the form of continuous u or discrete u_k signals. Due to their large diversity in the analysis of the obtained results and further applications, the signal parameters are used along with probabilistic methods [18]. For example, the average of signals is used to average the signal. This parameter for the continuous signal u in interval $<t_1,t_2>$ is given by the formula

$$\overline{u} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} u\,(t)\,dt \tag{1}$$

This parameter is also used in the analysis of signals registered in the CPTU probing process (Fig. 3).

In pile-soil interaction models, rheological elements of the type springs, slide and piston responsible for the inner stickiness can be used [15].

Pile driving is accompanied by various processes. Among them is the displacement um of the hammer.

Taking the designations as in [12] we get a continuous dynamic system described in [12] by the differential equation

$$S^3 u_m + 2nS^2 u_m + p^2\, S u_m = 0, \tag{2}$$

where

$$2n = \frac{\beta + \gamma\lambda m_m + \frac{\gamma c_p m_m}{EpAp}}{m_m + \lambda\beta m_m + \beta\frac{c_p m_m}{EpAp}} \tag{3}$$

$$p^2 = \frac{\gamma}{m_m + \lambda\beta m_m + \beta\frac{c_p m_m}{EpAp}}, \tag{4}$$

while

$$S = \frac{d}{dt}$$

In the expressions (3) and (4), the following designations were adopted:

- E_p – substitute modulus of elasticity depending on the modulus of elasticity of concrete and steel or composite,
- A_p – the cross-sectional area of the pile,
- m_m – hammer mass,
- c_p – the velocity of stress waves propagation in the pile,
- γ – constant defining the increase in the permanent settlement of pile head,
- λ – constant defining the permanent deformation of the pile head,
- β – constant taking into account the frictional pressure in the pile head.

Dynamic system (2) is a chain connection of an oscillating element and an integrating element – Fig. 13.

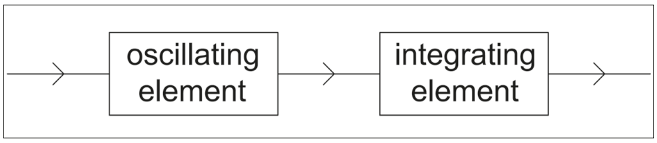

Fig. 13. Chain connection of the oscillating and integrating elements

If so, then the properties of the dynamic system (2) are derived from the connected chains of the oscillating and the integrating elements. The response of the system (2) can be determined using the methods of determining the response of complex dynamic systems [13]. These methods allow formulating patterns for the response of complex dynamic systems. These formulas use formulas for the response of individual members/elements of the system [13]. Directly from these formulas, it follows that the response of the dynamic system (2) with conditions

$$u_m(0) = 0$$

$$\dot{u}_m(0) = \sqrt{2gh} = v_m$$

$$\ddot{u}_m(0) = -\frac{\beta v m}{\gamma}\, p2$$

(g – standard acceleration due to gravity, h – hammer release height) is given by the formula

$$u_m = \frac{v_m}{\sqrt{p^2 - n^2}}\,[(p^2 - 2n^2)\exp(-nt)\, sin\sqrt{p^2 - n^2}\; t +$$
$$+\, 2\sqrt{p^2 - n^2}\; n\,(1 - \exp(-nt)\, cos\sqrt{p^2 - n^2}\; t\,) -$$
$$-\, \frac{\beta v_m}{\lambda\sqrt{p^2 - n^2}}[\,\sqrt{p^2 - n^2}\;(\,1 - \exp(-nt)\, cos\sqrt{p^2 - n^2}\; t\,) -$$
$$-\, nexp(-nt)\, sin\sqrt{p^2 - n^2}\; t\,] \tag{5}$$

when

$$p^2 > n^2.$$

Based on the properties of the components of the system, one can infer the properties of a complex system. The properties of generalized dynamic systems [13] show that the spectral transmittance of the system (2) is the product of the transmittance of the oscillating element and the integrating element, and this facilitates the analysis of such systems in the frequency domain.

In complex systems, for example in the case of work of the piles in groups, as is the case in offshore facilities, the work of piles can be analyzed using numerical methods [4].

COMBINING PILES AND CREATING HYBRID PILES

There are known methods of joining prefabricated concrete piles with a square cross-section. These methods allow for the efficient joining of piles at the construction site using steel joints (Fig. 14).

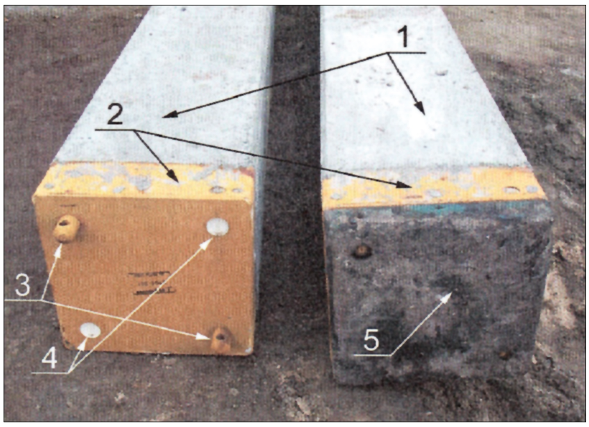

Fig. 14. Prefabricated piles with steel joints [6]: 1 – reinforced concrete piles, 2 – steel joints, 3 – steel bolts with holes for connecting bolts, 4 – steel sleeves for pins with safety plugs, 5 – Teflon washer protecting bolts during pile driving

Using the method of joining piles with 0.4 x 0.4 m cross-section shown in [6], one can propose a method of joining circular piles in a composite coating. On the lower end of the upper pile an "empty roller" without one base (pile shoe) is placed on the pile coating – Fig. 15. The upper end of the lower pile is finished with a full steel cylinder (Fig. 15). The pile shoe and the steel roller together with the pins and sleeves constitute the so-called steel CFGFRPT pile connector.

The steel joint should be anchored in the concrete pile core to a depth of about 1.10 m [6], in the form of spindle extensions with steel bars Ø20 mm. Similarly, as in [6] for piles 0.4 x 0.4 m, it is proposed to use connectors with two pins and two sleeves or with four bolts and four sleeves. The connectors are integrated respectively with four or eight pins φ 18.8 mm, made of stainless steel with a design strength of 400 MPa. In the case of the first, these bolts will carry 515 kN, and in the case of the second 1030 kN [6]. In any case, it is the maximum pulling force acting on the pile, which will be transferred by the connecting pins working as double-sided pins.

Between the steel elements of the pile connector, a Teflon washer or a polyurethane spacer (Fig. 15) should be introduced, modelled on polyurethane pads, for example type PWE6094. Due to its properties, it will ensure good cooperation between the contacting surfaces of the steel joint.

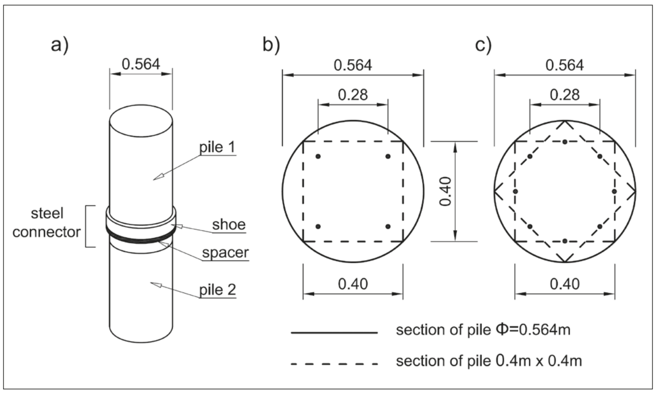

Fig. 15. Steel joint for circular piles in a composite coating: a) diagram for joining piles, arrangement of bolts and sleeves: b) two bolts and two sleeves, c) four bolts and four sleeves (Dimensions in Fig. 15b and 15c are based on a pile with a 0.4 x 0.4 m cross-section)

Additionally, the spacers are resistant to cyclic loads (3 x 10^6 cycles) or temperature changes. They have insulating properties (including electrical). They have a long service life – even after 10 years of use, the physical and strength tests of the spacers give good results. The applied spacer in the steel joint will fulfil a similar beneficial role in the steel connection of the piles, as the spacers in rail connections.

When more than two piles are connected to each other, the initial and final piles have one element of the steel joint (respectively the shoe and the other element of the joint). The remaining piles have complete joints, as in Fig. 15.

As has already been mentioned, piles of offshore facilities are exposed to corrosion of concrete and steel under the influence of the seawater environment. Marine corrosion is primarily limited to zones of varying levels of the seawater surface, especially to splash zones. There its intensity is the greatest. In principle, offshore steel structures are corrosion resistant only when they are permanently submerged in seawater. Mainly at greater depths, where oxygen access is limited. The average increase in corrosion of steel offshore facilities is about 0.10 mm per year. However, the strongest corrosion occurs at a depth of about 0.5 m below the average level of the water surface, because at this level seawater has a higher content of oxygen and salt than on the surface.

From these facts, it appears that at least in the zone directly above and below the surface of the seawater surface, it is worth using CFGFRPT piles that are resistant to seawater. It is enough, therefore, to use hybrid piles. A hybrid pile is a combination of a pile without a coating with a pile in a composite coating (Fig. 16).

In the subsurface zone, it may be a part with a composite coating of a hybrid pile, and below this zone, it may be a part without a composite coating. Both parts of the hybrid pile are connected with each other by a steel joint (Fig. 15).

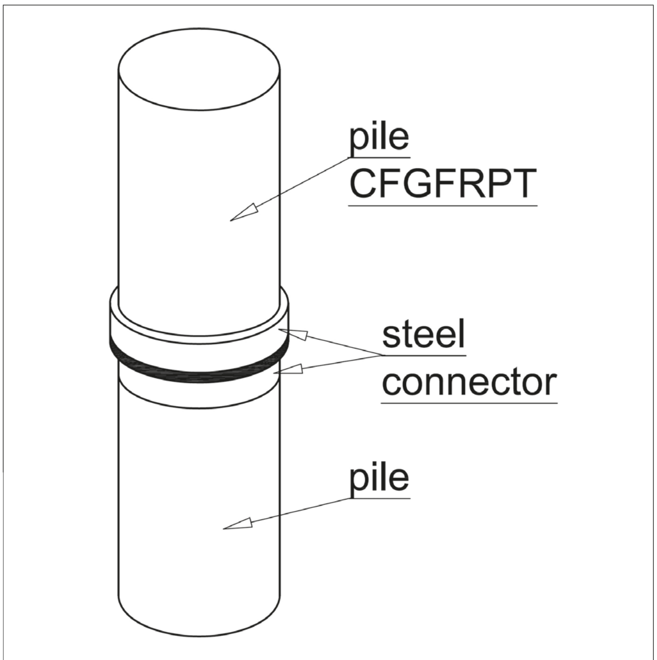

Fig. 16. Hybrid pile scheme (a combination of pile with no coating with pile in composite coating)

CONCLUSION

The use of a composite concrete pile coating prevents physical, chemical and biological degradation of concrete and steel. It limits the carbonization of concrete and its cyclical freezing and thawing with penetrating water, thus increasing the lifetime of piles exposed to seawater in offshore facilities.

CFGFRPT piles are characterized by the simplicity of their technology (i.e. concreting and the possibility of driving them in the ground by classical methods) and high aesthetics.

The introduction of the concept of isomorphism between the pile and the column allowed the use of laboratory tests of piles in the reinforced composite coating to determine the behaviour of a certain type of piles.

Eccentric compression of the samples allowed to assess the impact of simultaneous axial compression and bending of the pile on its life.

The mechanical properties of the glass fibre reinforced coatings also cause that these types of piles are more resistant to lateral forces caused by sea waves.

A significant influence of the beam angle of the glass fibres on the work of piles has been demonstrated.

It is advisable to use combined piles (hybrid piles) in surface water zones.

The use of hybrid piles is an important form of corrosion protection for piles of offshore facilities.

Serial connection of basic elements of dynamic systems is beneficial from the point of view of mathematical modelling of problems related to the functioning of piles.

To increase the load-bearing capacity of the soil substrate other methods can be used to improve its quality [22].

Coatings made of glass fibre reinforced composites are easy to be recycled, for example, using the energy method.

The use of CFGFRPT piles and hybrid piles in offshore infrastructure facilities is fully justified.

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