Anchoring of a retaining structure with glass fibre strand anchors

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Abstract. In Copenhagen, Denmark, a large construction pit has been designed to facilitate the excavation for the basement of a new district in the city called "Postgrunden". The retaining wall is constructed by sheet piles installed into the Copenhagen Limestone with the use of pre-drilling and with ground anchors in two levels. The construction pit as well as the anchors are temporary, however, both parts are left in the ground after construction of the basement has been concluded. Most of the anchors were constructed as normal steel strand anchors, however, at one location glass fibre anchors were found to be the best solution due to restrictions concerning installation under third party property. Therefore 82 ground anchors with glass fibre strands were installed. These anchors were the first of their type used in production in Denmark. However, in Denmark there is no Eurocode or National Annex on composite materials at the time of the design and therefore the designers had no direct standard to design by. The design of the glass fibre anchors was therefore based on the index of safety method from Eurocode 0 along with a set of fracture tests made in a laboratory. The tests were used for a statistical analysis that along with a required index of safety gave the characteristic ultimate resistance of the strands and the elastic modulus. During installation the contractor had to consider the different material behaviour of the glass fibre strands compared to the traditional steel strands, e.g. the brittle shear tolerance, that dictates the assembly of the glass fibre strands to steel strand couplers to allow for testing and prestressing of the anchors. Further, the glass fibre anchors are not as heavy and stiff as the traditional steel anchors, which added an extra challenge during installation below the ground water table. Anchor testing was performed using traditional anchor testing equipment. The hollow plunger jacks were chosen in respect to the long piston stroke required for the extra elongation of glass fibre strands due to a low modulus of elasticity. All anchors were tested with either suitability or acceptance test to a factor of 1.43 or 1.30 above the design load, respectively.

1. Introduction
The centrally located former Postal Service Centre in Copenhagen, Denmark, was transformed into a new district in the city, see Figure 1.

The location is adjacent to the railway tracks leading into the Copenhagen Central Station. Further, the location consists of both older preservation worthy constructions busy roads and new constructions as neighbours, see Figure 2.
Figure 1. Left: Mark of Copenhagen with a black circle in Denmark. Right: Mark of the project location with a black circle in Copenhagen.

The mixed-use development project consisted of three parts: a new domicile for a Danish bank, a property for mixed activities, and five high rise towers for both commercial and residential use. Underground a parking basement for 1000 cars was constructed. Therefore, a large construction pit was established with up to 8.5 m excavation depth. The construction pit was established as a sheet pile wall with drilled ground anchors in two levels. The ground anchors were in majority established as strand anchors of steel with 5-8 strands.

Figure 2. View of the construction area in central Copenhagen with all its neighbours.

One of the adjacent properties was registered to the Danish Rail Service (DSB), see Figure 2. The property was at the time of construction of the new district in the city not in use, although DSB wanted to be able to establish a construction pit for future development of the site. Therefore, it was decided to use ground anchors of glass fibre strands for the construction pit in the old Postal Service Centre. Glass fibre has a high ultimate strength; however, the material is brittle perpendicular to the fibres. In case of a new construction pit on the adjacent property, the glass fibre ground anchors can therefore easily be cut by driving a sheet pile wall or by drilling a secant pile wall through them.

1.1. Normative basis

The design of the construction pit was based on the common European Code System along with the Danish national annexes. However, Europe and Denmark did not have a code for composite materials at the time for the design of the construction pit and therefore the design had to be based on Eurocode 1990:2007, ref. [1].
Anchors made with glass fibre strands had at the time of the design of the construction pit not been used in production in Denmark. The contractor on the construction pit, Aarsleff, had the strands in mind for a former project. For that project Aarsleff did four investigation tests on ground anchors made of glass fibre strands. Together with information achieved from the supplier of the glass fibre strands this formed the statistical basis for the determination of the strength of the glass fibre strands.

2. Ground conditions
Prior to the design of the construction pit a geotechnical investigation was carried out.

The ground conditions on the location for the construction pit was relatively uniform. The upper layers on the location consisted of fill in various forms; mould, sand and clay. The fill layers were found to level -0.1 to -6.3 m DVR90. Some drillings showed layers of gyttja fill (soft soils with a high content of organic material), postglacial sand and gyttja and late glacial to glacial sand.

Beneath the fill, postglacial and late glacial deposits different deposits of glacial meltwater sand, silt, clay and clay till, gravel till and sand till to level -7.2 to -10.2 m DVR90 were found.

Under the glacial deposits a 2.5-5 m thick layer of "grønsands” deposits (Green Sand Deposits) from the Selandia period was found. Below this the Danian Limestone was found. Due to the overlaying "grønsands” deposits the limestone was not remoulded from the till and is therefore found hard from the top. The limestone deposits were found from level -10.2 to -14.2 m DVR90. The limestone was not glacially disturbed due to the protecting "grønsand” deposits. The limestone was found to be of induration H2-H3 according to the Danish induration scale (corresponding to R1-R2 on the ISRM rock grade scale) from the top of the limestone deposits. Overall most H2 (corresponding to R2) limestone were found, however 18 % of the limestone was also found with hardness H5 (corresponding to R5-R6). The strength of the limestone was tested with 20 UCS (Unconfined Compression Strength) test. The tests were generally made on the weaker layers in the limestone. A plot of the measured strength as a function of depth and hardness is seen in Figure 3.

3. Glass fibre strands
The glass fibre strands were provided by the German supplier Spantec. The supplier had described the handling of the glass fibre strands to be similar to normal strand anchors. This will be discussed later in this paper.
Furthermore, the glass fibre strands do not corrode, which is an advantage for long-term use. The glass fibre anchors were left in the ground yet can easily be removed simply by cutting them mechanically at a later stage if necessary, which was the reason for choosing glass fibre anchors for this project.

However, the glass fibre strands were more expensive than conventional steel strands.

3.1. Standard specifications
The standard specifications from the supplier are listed in Table 1.

| Item                              | Unit   | Standard specification |
|-----------------------------------|--------|------------------------|
| Breaking load, Cablex-S System    | kN     | > 250                  |
| Tensile Strength single strand    | N/mm²  | > 1000                 |
| Tensile E-Modulus single strand   | GPa    | > 60                   |
| Shear                             | N/mm²  | 480                    |
| Area                              | mm²    | 269,39                 |

The load-displacement curve of a single glass fibre wire is shown in Figure 4. The lack of ductility is evident as the curve is practically linear until wire failure. No yield strength can be observed.

![Figure 4. Measured load-displacement curve for single glass fibre wire, from ref. [2].](image)

4. Design parameters
As mentioned in section 1.1 there was at the time for designing the construction pit not a European nor a Danish code for composite materials. The design was therefore based on DS/EN 1990:2007, ref [1], which allows the designer to evaluate the safety of the design parameters by the $\beta$-index method. In the current project this was calculated by a statistical evaluation of measured values of the ultimate load for the glass fibre strands.

The statistical basis for the estimation of the ultimate strength consisted of four investigation tests on glass fibre strands installed in the ground as well as six tension tests on single glass fibre lines made in the laboratory. The strands are 7-wire strands.
4.1. Characteristic value of tension strength

All the tension tests were used to assess whether the ultimate load of 250 kN informed by the supplier can be used as a characteristic value for the anchor design. As one strand consists of seven wires the weaker wire in the strand was assumed to fail at 1/7 of the ultimate load of the entire strand. The values of the failure load by the tests are listed in Table 2.

| Test no. | Failure load, per strand (kN) | Failure value, one wire (kN) |
|----------|-------------------------------|-----------------------------|
| 1        | 39.0                          | 39.0                        |
| 2        | 38.5                          | 38.5                        |
| 3        | 39.6                          | 39.6                        |
| 4        | 38.2                          | 38.2                        |
| 5        | 39.7                          | 39.7                        |
| 6        | 40.1                          | 40.1                        |
| 7        | 282.5                         | 40.4                        |
| 8        | 270.6                         | 38.7                        |
| 9        | 264.6                         | 37.8                        |
| 10       | 279.2                         | 39.9                        |

At the time for the design of the construction pit there was no practice for testing anchors with glass fibre strands. The anchors were therefore tested based on DS 1537:2014, ref. [3] with the same restrictions for the failure strength of the strands. The proof load was limited to:

\[ P_p \leq 0.8 \cdot f_{uk} \cdot A_s \]  (1)

Here, \( P_p \) is the proof load, \( f_{uk} \) is the ultimate failure strength and \( A_s \) is the cross sectional area.

As the material is a brittle material, see Figure 4, the criterion for the yield strength was not applied. The test situation was the design criterion for the strands, and therefore the mean value for the load applied on the strands were therefore set to 0.8 \( \cdot 250 \) kN = 200 kN. The standard deviation was set as the standard deviation of the test unit used for testing the anchors when installed. This was found to 0.5 %. The characteristic value is according to DS/EN 1990:2007 paragraph 4.2 normally defined as the 5 % fractile value when a low value of the material property is unfavourable. It is assumed that the failure strength of the strands and single lines were normally distributed, and the mean value, standard deviation and 95 % confidence interval value were calculated. The results appear from Table 3.

The supplier informed that the failure value is 250 kN according to Table 1. Both tests on single wires, on strands (7 wires) and on all failure tests showed that the 5 % fractile value was above this level. It was therefore chosen to use a characteristic failure value of \( R_{uk} = 250 \) kN in the design. The test setup for the failure tests on single wires and strands respectively was different, e.g. use of couplers and steel wedges for strands, which is assumed to describe the difference in the calculated standard deviation.
Table 3. Statistical process of failure tests.

|                           | Failure tests on single wires | Failure tests on strands | All failure tests * |
|---------------------------|-------------------------------|--------------------------|---------------------|
| Number of tests (-)       | 6                             | 4                        | 10                  |
| Mean value (kN)           | 39.2                          | 274.2                    | 39.2                |
| Standard deviation (kN)   | 0.74                          | 8.14                     | 0.87                |
| 95 % confidence interval  | 38.6                          | 264.6                    | 38.7                |

* When calculating with "all failure tests" the failure value for the strands are converted into a corresponding failure value for the weakest wire of the strand as 1/7 of the failure value of the strand.

4.2. Index of safety

At the time for the design of the construction pit there was no European code for composite materials. Proper safety of the construction pit was therefore documented by use of the $\beta$-index method in DS/EN 1990:2007, ref. [1].

The safety index is calculated by:

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{\mu_s - \mu_l}{\sqrt{\sigma_s^2 + \sigma_l^2}}$$  (2)

Here $\mu$ is the mean value of the failure function $g$, the statistical data $s$, and the load $l$, respectively. And $\sigma$ is the standard deviation of the failure function $g$, the statistical data $s$, and the load $l$, respectively. The mean value and the standard deviation for the statistical data appear from Table 3. The test situation was the critical situation for the load on the strands. The mean value $\mu_l$ was found by formula (2) to 200 kN for one strand, while the standard deviation $\sigma_l$ for the load was found to 0.5 %, corresponding to 1 kN for one strand.

The index of safety was then calculated based on the above for the tests on the strands, single wires, and all failure tests. The results are presented in Table 4.

Table 4. Results from the calculated index of safety in the test situation.

|                           | Failure tests on single wires | Failure tests on strands | All failure tests * |
|---------------------------|-------------------------------|--------------------------|---------------------|
| Index of safety, $\beta$ [-] | 14.1                          | 9.0                      | 12.0                |

* When calculating with "all failure tests" the failure value for the strands are converted into a corresponding failure value for the weakest wire of the strand as 1/7 of the failure value of the strand.

The index of safety should be compared to the recommended index of safety in DS/EN 1990 DK NA:2019 table B.2 DK NA, ref. [4]. The construction pit was designed in normal consequence class (CC2). The index of safety should then be above 4.3, which was found to be the case for both failure tests on single lines, failure tests on strands and all failure tests.

The statistical basis for the evaluation of the characteristic value of the failure strength and the index of safety was small. However, both the failure strength and the index of safety were found much larger than what was necessary to fulfil the Eurocode and Danish national annex. Therefore, the safety of the design was found sufficient.
4.3. Modulus of elasticity
To analyse the serviceability limit state, information about the modulus of elasticity was needed. The supplier had given information about the modulus of elasticity in their standard specifications for the anchors, see Table 1.

4.4. Design of the construction pit
The design of the construction pit was modelled using the finite element software PLAXIS 2D. The considerations of the finite element model are not within the scope of this paper and will not be discussed further.

5. Installation of ground anchors
The installation of the chosen glass fibre anchors was not that different from installation of traditional steel strand anchors. The drilling process and drilling equipment was the same as used for the steel strand anchors provided for the majority of “Postgrunden”.

This was an advantage for the production staff, who only had to adapt to the special material behaviour of the glass fibre product e.g. low density and limited tolerance to shear impact during handling.

In total 82 pcs. glass fibre anchors were installed at “Postgrunden”. Anchor lengths varied between 21 m and 33 m and they were all bonded in the Danien Limestone.

5.1. Handling of glass fibre strands
Several anchor systems based on glass fibre or carbon fibre are available for geotechnical applications. Many of these systems were evaluated prior to settling for the Spantec GFRP cable anchor© system.

The main reason for choosing this system was the easy handling and that the anchor heads, and thereby the test equipment, was standard.

![Figure 5. Coiled up GFRP anchor (Spantec, 2019).](image)

The cable system allowed for the anchors to be coiled up like conventional steel strand anchors. Thereby anchors could be delivered in full-length sections and on-site assembly was avoided. All other investigated glass fibre anchors were based on a bar type system where on-site assembly in 6 m to 9 m sections were required.

The weight of the glass fibre anchors was approximately half of the equivalent steel strand anchor. This offers obvious advantages in transport and storage although it requires special attention during installation.
The low density and low stiffness of the strands provided very little resistance to uplift within the borehole. Inserting the anchor into a borehole stabilised/prefilled with grout was not possible and all anchors were equipped with grout tubes in order to grout the boreholes after anchor installation.

When retracting the casings care had to be taken not to pull the anchors out of the borehole as the grout density of $\sim 1850 \text{ kg/m}^3$ was only slightly lower than the glass fibre density of $\sim 2190 \text{ kg/m}^3$. Friction between casing and the anchor couplers or spacers was sometimes enough to lift the anchor slightly. When this happened, the anchor had to be pushed gently back in.

All glass fibre anchors were installed with a 40 degrees inclination to horizontal. Less inclination could have offered a more challenging installation.

The glass fibre strands were not as robust as steel strands and care must be taken during handling that no abrasive action or cuts damages the material. UV resistance was limited, and unprotected storage of more than two months was not recommended by the supplier.

The material was easy to cut with hacksaw or grinder but frays and splinters when pliers, bolt cutters or blows are used.

No guarantee could be obtained for permanent anchors, as the product was quite new in the market, and the supplier had no long-term data on material behaviour at the time.

5.2. Special coupler

In order to transfer the load from the anchor strands to the retaining wall, an anchor head was required. This anchor head was with conventional steel strands made with a locking mechanism where each strand was held in friction with an annular jagged wedge system. Given the limited resistance to transversal loads, the use of such wedge locking mechanism was not suitable for the glass fibre strands.

Instead the glass fibre strands were equipped with a special steel coupler that allows the strands to be connected to a 15.7 mm steel strand. This way the anchor head could be made with conventional steel materials and tension load could be applied with traditional jacking equipment.

The coupler consists of a male section in which the glass fibre strands were glued in with a special glue. In the opposing end of the male section a thread allows connection to the female section where the steel strand was fixed with a conventional wedge locking system. All couplers are glued and pre-assembled by the manufacturer.

The length of the individual sections of glass fibre and steel can be adopted to client specification. At “Postgrunden” the length of the steel sections was limited to $\sim 2$ m to keep the couplers as close behind the retaining wall as possible.

![Figure 6. Coupler, longitudinal section (Spantec 2020).](image)

![Figure 7. Assembled coupler (Spantec, 2020).](image)
As the couplers have an external diameter of 45 mm, they were grouped in layers of no more than 4-5 pcs. The layers are offset by ~500 mm in the anchor axis as seen in Figure 8. Otherwise the bore diameter would have to be excessively large. In general, the large couplers require a large borehole diameter to anchor diameter ratio. The anchors with up to 8 pcs strand anchor were installed in OD 152 mm and OD 177 mm bores.

Figure 8. 8 strand anchor with two layers of couplers offset by ~500 mm (Spantec, 2020).

6. Test of production anchors
All anchors were tested according to DS 1537:2014, ref. [3].

6.1. Test procedure on site
The glass fibre anchors were tested in the same way and with similar test equipment as the steel strand anchors. As the elongation of a glass fibre anchor is approximately 175% of the comparable steel strand anchor, the jacking system and measuring gauges were chosen in respect to the worst-case proof load elongation of about 300 mm.

Spantec technicians performed the first tests and afterwards instructed the Aarsleff test-crew for the remaining tests.

6.2. Suitability test
There were two suitability tests conducted on the anchors. According to DS 1537:2014 Annex G.3.4 ref. [3], group testing should be performed if the characteristic anchor load exceeds 700 kN and the distance between the centres of the grout bodies (fixed lengths) of the anchors (including execution tolerances) are less than 1.5 m, or if the characteristic anchor load is below 700 kN and the distance between the centres of the grout bodies of the anchors (including execution tolerances) are less than 1.0 m.

In the current project the anchor forces were up to 1100 kN. Anchors were placed in every other sheet pile wall, corresponding to a c-c distance between anchors of 2.8 m in the construction pit. However, the anchors were drilled with very long free length to allow the anchor bond length in the Copenhagen Limestone. At the bond zone of the anchors the distance between the centres of the grout bodies were therefore reduced to less than 1.5 m, and therefore group tests needed to be performed on three neighbouring anchors.

The suitability tests were conducted to a proof load of maximum 1573 kN corresponding to 1.43 times the design value of the maximum anchor load.

All the suitability tests (two suitability tests involving six anchors in total) showed the expected behaviour with deformations within the expected range and acceptable creep rates.
6.3. Acceptance test
All other anchors were subjected to an acceptance test. The tests were performed on all anchors with a proof load of 1.3 times the design load of the anchors. This meant proof loads up to 1430 kN.

76 acceptance tests were performed, and all anchors passed the test. For 33 of the anchors the observation period had to be prolonged by the acceptance test as the deformations was larger than 0.2 mm from the second to the fifth minute, as described for anchors installed in rock deposits in DS 1537:2014, ref [3]. They showed deformations up to 0.6 mm from the second to the fifth observation minute, corresponding of a creep rate up to 1.51 mm, and a creep rate up to 0.63 mm from the fifth to the tenth minute.

The remaining 43 acceptance tests all passed the test without extra observation time. The deformations from the second to the fifth minute in the last load step varied from 0.03 to 0.19 mm, with an average of 0.1 mm, corresponding to a creep rate of 0.25 mm.

7. Conclusions
A large construction pit was designed and constructed in the city centre of Copenhagen, Denmark. The construction pit was constructed with an excavation depth of 8-9 m below ground surface. The excavation was designed with a sheet pile wall with anchors in two levels. One of the neighbours wanted to be able to establish a sheet pile wall on their own in the future, and as it was impossible to remove the traditional steel anchors it was chosen to use special anchors with glass fibre strands. These anchors are very strong in the tension direction; however, they are very brittle in the perpendicular direction, regarding shear. The anchors can therefore easily be cut by driving a sheet pile profile through them when installed by the neighbour.

No European nor Danish code existed for composite materials at the time for designing the construction pit. The construction pit was therefore designed by use of the $\beta$-index method in DS/EN 1990:2007, where the safety of the construction pit is found based on a statistical evaluation on 10 failure tests on the glass fibre strands. The failure tests consisted of both investigation tests on vertical glass fibre strands and laboratory tests on single wires. The statistical evaluation showed that a characteristic failure load of 250 kN could be applied in the project.

The anchors were installed with normal drilling equipment in the construction pit. Due to the low weight of the glass fibre strands compared to normal steel strands it was necessary to equip all anchors with grout tubes in order to grout the boreholes after anchor installation.

To be able to test and lock the anchors at the sheet pile wall a special coupler was used on all anchors. This allowed the glass fibre strands to be connected to a 15.7 mm steel strand, and thereafter normal testing equipment and a normal anchor head could be introduced.

All 82 anchors were tested at either a suitability test or an acceptance test, and all anchors showed the expected behaviour and were approved.

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References
[1] Dansk Standard 2007 DS/EN 1990. Eurocode 0: Basis of structural design (Copenhagen, Dansk Standard)
[2] FiReP International AG 2017 GFRP Cable Anchor, CABLEX-S, Technical Documentation (Switzerland, FiReP)
[3] Dansk Standard 2014 DS 1537. Execution of special geotechnical works – Ground anchors - Testing (Copenhagen, Dansk Standard)
[4] Dansk Standard 2019 DS/EN 1990 DK NA. Eurocode 0: Projekteringsgrundlag for bærende konstruktioner (Copenhagen, Dansk Standard)