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„Opportunities and risks of steel fibres in Grouted Joints“

Motivation

Grouted Joints are typical means of connection the supporting structure with the foundation piles of Offshore Wind Energy Converters (OWEC).Grouted Joints consists of two steel pipes with different diameters are fitted into each other and the resulting gap is filled by a mineral-bound, high strength grout. The grout is generally pumped into the connection below the sea-level. For this purpose a grout system needs a highly flowable consistency with a high stability in the fluid phase for the pumping process, as well as high strength properties. In addition to the extreme fresh and hardened concrete requirements, the acutely challenging offshore conditions place high demands on the Grouted Joint, and consequently on the grout-material itself, in terms of reliability, safety and durability. Furthermore, due to the special construction method, particular attention must be paid to the following aspects:

- The offshore conditions require complex logistics for the filling process and a special pumping technology.
- The possibilities of monitoring the process are limited to rough measurements of global parameters like filling quantity, time for filling, consistency…
- Even a subsequent check referring to contingent discontinuities is not possible.
- In the event of discontinuities in the grout, there are practically no options for correction or reconditioning, so that immense costs are to be expected for repair.

In view of the above mentioned conditions, the homogeneity, reliability and robustness of the material properties as well as the construction method, are of crucial importance.
To meet these requirements, the grout material needs especially high stability in the fluid phase for the pumping process and against segregation.

Grout materials can be used with or without steel fibres, while international experience, predominantly from the oil- and gas industry, is only available with respect to fibre-free Grouted Joints. Because of the brittleness und risk of cracking of high performance grout material discussions have come up in Germany whether to use steel fibres due to their positive and crack-bridging effects. It is therefore necessary to balance the controllability of placing conditions and the behaviour of hardened grout materials with and without fibre reinforcement, as well as grouted joints as a structural element. The basic question is how steel fibres affect in Grouted Joints and if their use is absolutely essential.

State of research

The load-bearing capacity and load-deformation behaviour was be described by extensive experiments on small scaled, axially loaded specimens [1][11][12]. Extensive tests on the effects of the grout properties such as ultra-high strength, fibre reinforcement on the load-bearing capacity and deformation behaviour are reported in [1]. These tests revealed that even for ultra-high strength grout, ductile behaviour is ensured by the confining pressure provided by the steel tubes - regardless of fibre reinforcement. This applies to the static as well as fatigue performance.

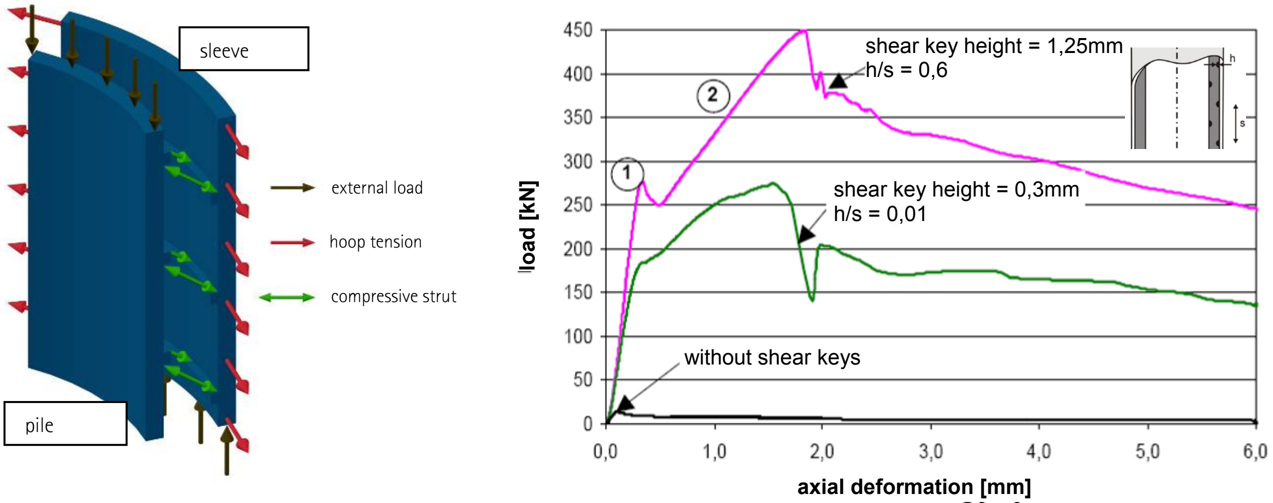

Figure 1: Effect of the shear key height on the load-bearing capacity of Grouted Joints [1]

If shear keys are used in grouted connections strong compressive struts can develop in addition to the low friction and adhesion forces. Only the presence of shear keys allows exploiting the high compressive strength of the grout material. The distinct effect of shear-keys on the load-bearing capacity is displayed in Figure 1. The behaviour of the Grouted Joint is characterized by a first linear-elastic part (1), which is terminated by the first maximum, followed by a second (2) non-linear part (Figure 1 right). Finally the ultimate load is reached. As a result of the compressive struts which developed between the opposite shear keys the outer steel tube (the sleeve) gets hoop tension and provides confining pressure the grout (Figure 1 left). These confining stresses are responsible for the ductile load-bearing behaviour of the connection.

Effects of fibre reinforcement on the fresh concrete properties

The high strength properties will primarily be reached by reducing the water/binder ratio which causes at first a stiffer consistency. This is contrary to the demand of a high flowability. Therefore a large amount of superplasticizer is necessary. In particular the highly effective superplasticizers based on PCE have a low saturation limit, the exceeding of which bears an increased risk of segregation and sedimentation [10]. The option of increasing the water content to reach a better workability stands in opposition to the loss of strength and greater risk of segregation. Considering the targeted combination of high strength and high flowability, the mixture proportioning reaches the limit of technical feasibility.

To a certain degree the requirements of the grout material are comparable to Ultra High Performance Concrete (UHPC) for which some experiences concerning the addition of steel fibres are reported. Because of the very brittle, explosive fracture behaviour of plain UHPC about 2,5 Vol.-% steel fibres are usually added to increase the ductility [9]. However steel fibres degrade the workability by increasing the water demand (Figure 2).

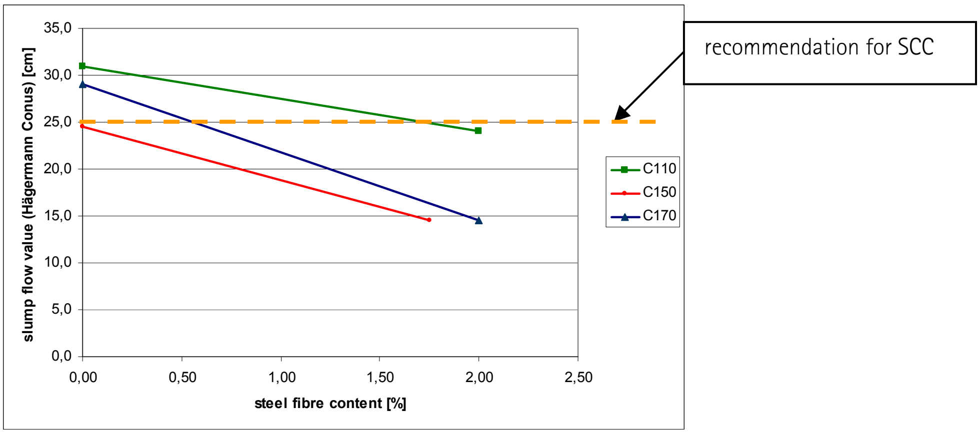

Figure 2: slump flow values of grout materials with different mean strength depending to the steel fibre content

Since highly flowable grout materials require contents of superplastizicers near the saturation limit already without steel fibres, the stability properties of the fresh concrete are severely at risk. In addition there is an increased risk of typical "fibre-balling" which could lead to clogging of pump pipes (Figure 3).

Figure 3: example of typical fibre-balling on site

Effects of fibre reinforcement on the hardened concrete properties

The use of steel fibres increases the first maximum, the area of linear-elastic behaviour as well as the maximal load-bearing capacity. According to Figure 4, increasing the compressive strength of the grout is much more effective to raise the load-bearing capacity than increasing the fibre content would be.

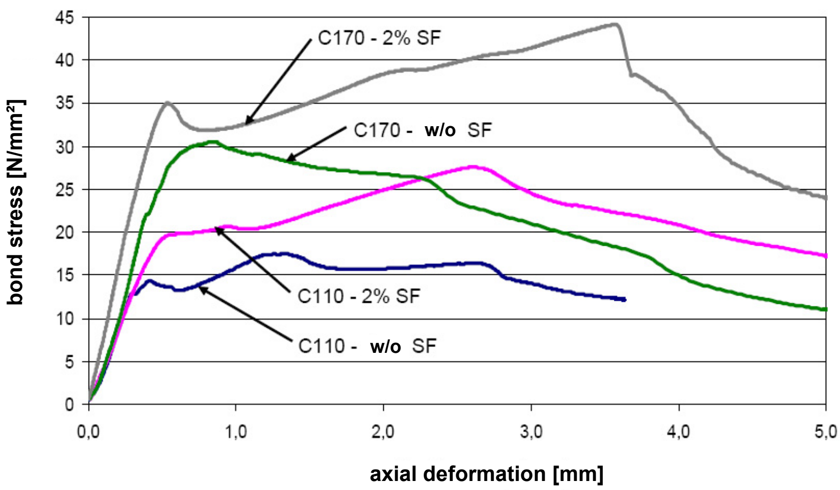

Figure 4: influence of the fibre content on the load-bearing and load-deformation behaviour of Grouted Joints (grout type C110 and C170 with a shear key geometry of h/s = 0,056) [1]

Generally, the experiments showed that an increase in compressive strength, the use of steel fibres and the modification of shear key geometry are three independent means of enhancing the load–bearing capacity. Provided shear-keys are present.

Ultra High Performance Grout filled in hollow tubular columns

Experiences with UHPC filled in tubular columns (hollow profiles) stress the ductility-increasing effect of a confining steel tube. Tests with axial static loading were conducted on two different types of tubes with a diameter of about 150 mm and a height of about 450 mm. The total section thickness was 15 mm. Type one consists of a grouted tube with 2.5 Vol.-% steel fibres and without a confining steel tube. The other specimen was made of fibre-free, plain grout with a confining steel tube (thickness 0.8 mm). The average compressive strength was about 160 N/mm². The containing fibre grout evidently showed problems with the workability during the filling process.

In spite of the high fibre-content the fibre-reinforced concrete specimens show a distinct abrupt failure without any residual load-bearing capacity. Discontinuities resulting from the filling problems could not be detected. In contrast, the specimens confined with a steel tube exhibit a relatively ductile fracture and residual behaviour (Figure 5).

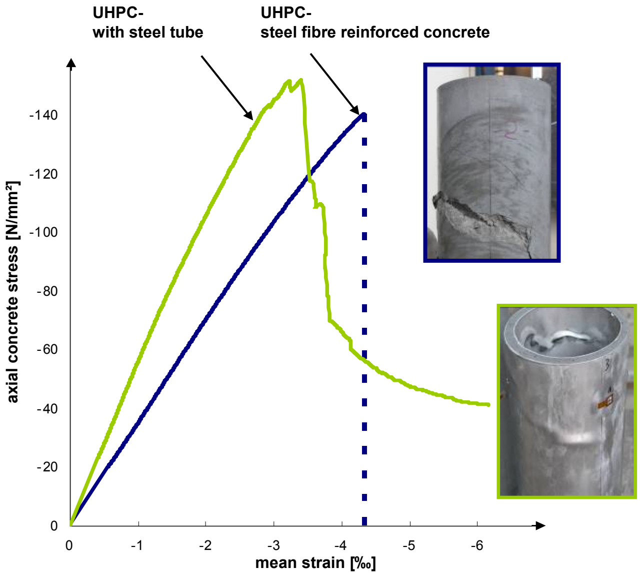

Figure 5: Tests on different axially loaded hollow concrete profiles

Economic efficiency:

Steel fibres must be added at the production plant or on site. Besides the costs of the steel fibres itself the following additional efforts have to be taken into account:

- increased mixing time
- additional equipment (weighing, fibre dispersion, corrosion protecting storage) in case of adding on site
- increased monitoring effort during the filling process

Consequently the use of steel fibres results in a significant cost increase, while the reliability of the execution of the construction work on site decreases.

Conclusion

Generally speaking, the use of steel fibres significant improves the load-bearing capacity of Grouted Joints subjected to static and fatigue loading as well as the load deformation behaviour. The grout's stability can be improved, too. On the other hand, fibres worsen the workability and pumpability. If fibres are used in Grouted Joints, care has to take concerning the properties of the fresh grout.

- A ductile load-bearing behaviour of Grouted Joints subjected to static and fatigue loading is ensured by the confinement of the steel tubes. In case of Grouted Joints steel fibers are not required to provide ductile behavior.
- The use of steel fibres in higher doses increases the load-bearing capacity of Grouted Joints independent from the compressive strength of the grout.
- The use of steel fibres increases the residual load-bearing capacity after reaching the ultimate load, particularly if ultra-high strength grout material is used.
- The increase in load-bearing capacity by increasing compressive strength or modifying the shear keys' geometry is much more economically efficient.
- The stability in the fluid phase against segregation or sedimentation of the grout material is of crucial importance for the load-bearing safety and economic efficiency.

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