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Project Cityringen Branch off to Sydhavnen

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Example of application for segments

Das Gesamtprojekt Cityringen bedeutet für die Stadt Kopenhagen einen immensen Fortschritt im Ausbau des öffentlichen Verkehrs. Die Abzweigung nach Sydhavnen ist dabei ein wichtiger Bestandteil des U-Bahn-Konzepts. Mit dieser Erweiterung wird der südliche Bezirk mit dem bestehenden U-Bahn-System von Kopenhagen verbunden und wird dadurch auch ein Schlüsselelement für die weitere städtebauliche Entwicklung. Der Tunnel für den Abzweig Sydhavnen besteht aus zwei ca. 4 500 m langen Röhren mit einem Innendurchmesser von jeweils 4,90 m, mit einem Querschlag. Zusätzlich sind fünf Bahnhöfe und zwei Schächte entstanden. Aufgefahren wurde die Strecke mit zwei EPB TBM. Für die Herstellung der Tübbings im System 5+1 mit 30 cm Dicke wurde bereits in der Planung die Verwendung von Stahlfasern (Anteil der Stahlfaser-Tübbings ca. 85 %) als Bewehrung vorgesehen. Die Bemessung für den Stahlfaserbeton erfolgte nach DBV-Merkblatt.

Stichworte Tübbinge; Betonfertigteile; Segmente; Stahlfaserbeton; Stahlfasern; Tunnel

Project Cityringen Branch off to Sydhavnen – practical example for tunnel lining segments
The overall Cityringen project means enormous progress in public transport for the city of Copenhagen. The extension towards Sydhavnen is an important part of the underground concept. With this expansion, the southern harbour district will be connected to the already existing metro network of Copenhagen and will therefore also become a key element for further urban development. The tunnel for the Sydhavnen extension consists of two approx. 4,500 m long tubes with an inner diameter of 4.90 m, with one cross passage. In addition, five train stations and two shafts have been created. The route is driven with two EPB TBMs.
For the production of the tunnel segments in 5+1 system with a thickness of 30 cm, the use of steel fibres as reinforcement (approx. 85 % of the overall production is foreseen with SFRC) was already foreseen in the planning. The design of the steel fibre reinforced concrete was carried out according to DBV data sheet.

Keywords TLS; tunnel segments; precast; steel fibre reinforced concrete; steel fibres; tunneling

1 Project overview

1.1 General

The client Metroselskabet (owned by the municipalities of Copenhagen and Frederiksberg as well as the Danish Ministry of Transport) has awarded the project to TUNN3L JV I/S, a joint venture between the globally leading construction companies HOCHTIEF Infrastructure GmbH and VINCI Construction Grand Projets. Metroselskabet implements the project in collaboration with the municipalities of Copenhagen and Frederiksberg. The project is planned to be executed over the period from 2018 to the opening of the route and the stations in 2024. The extension is designed to meet the transport needs of the city's growing population. The new line is expected to move roughly 43,000 passengers a day, while the annual passenger volume is estimated at 15.5 million.

1.2 Details of the Sydhavn metro line

The Sydhavn metro line was approved by the Danish Parliament in February 2015 as part of the Copenhagen municipality's strategy for the development of the Sydhavn area. The line will be integrated into in the already existing Cityringen (City Circle Line) and will have five new stations around the former port of Copenhagen and the neighbourhood of Sydhavnen (Image 1). It is an extension of the Copenhagen metro line 4 (M4). In February 2018, the joint venture between Vinci Construction Grands Projets and HOCHTIEF Infrastructure GmbH was awarded the design and construction contract for the Sydhavn metro line project worth EUR 460 million. HOCHTIEF acts as the joint venture's technical lead. Gottlieb Paludan Architects designed the five new metro stations of the Sydhavn line. The architectural firm worked together with COWI, Systra and Arkitema Architects in preparing the design.

The project comprises the construction of 4.5-km-long twin- tube tunnels with an inner diameter of 4.90 m and an outer diameter of 5.50 m. The tunnels are driven with two earth pressure balance tunnel boring machines (TBMs). The TBMs are scheduled to work from Q1/2020 to Q2/2021, including a total of twelve launches and twelve retrievals as well as four times two tunnelling operations in the stations to be constructed. In addition, both tunnel boring machines are disassembled after driving a tunnel section of about 3.5 km, transported back to the initial starting shaft (Image 2), reassembled, and the re-

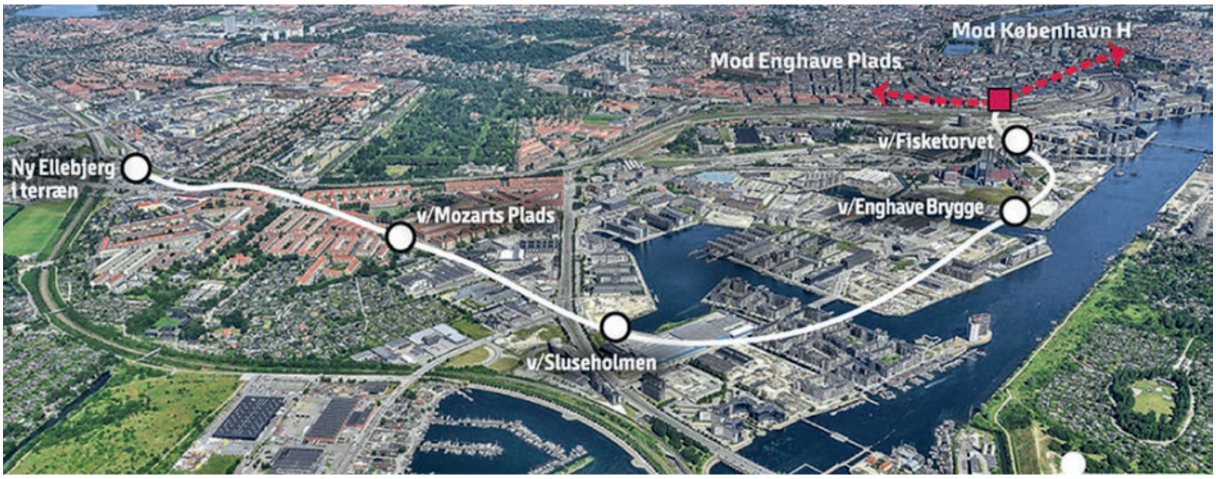


Bild 1 Verlauf der U-Bahn-Linie und Lage der Stationen
Course of the line and location of the stations

Bild 2 TBM „Inge" und „Olivia" im Startschacht Enghave Brygge (EBR)
TBM „Inge" and „Olivia" in the starting shaft Enghave Brygge (EBR)

maining tunnel section of about 1 km is then driven in the opposite direction. The tunnel lining segments are planned to be manufactured from mid-2019 to early 2021. The machines achieve advance rates of up to 45.4 m per day.

2 Tunnel lining segments with steel fibre reinforced concrete

2.1 General

The positive effect of steel fibres on various properties of concrete is well known and has been sufficiently studied and documented. Some examples of these positive aspects include excellent durability, less damage during handling, storage and transport (avoidance of edge breaks), lower manufacturing costs than conventional reinforced concrete, saving of cost and space for storing the reinforcement cages, less waste, fewer rejects and reduced CO_2 footprint. A very important and crucial aspect is the huge economic advantage arising from manufacturing the prefabricated parts of steel fibre reinforced concrete. The segments can be manufactured much more easily, faster and with less effort. Numerous tunnel projects throughout the globe have already been successfully completed using tunnel lining segments of steel fibre reinforced concrete, including the related project "Metro Cityringen Copenhagen – Branch off to Nordhavn" [1].

2.2 Requirements for steel fibre reinforced concrete

For this project, the following requirements were specified for the steel fibre reinforced concrete:

- Fibre concrete class F1.6/1.0 according to the DBV Guide to Good Practice, cf. [2]
- Fibre dosage: to be determined by the manufacturer to reach the required fibre concrete class of F1.6/1.0
- Consistency: S2
- Minimum compressive strength class: C50/60
- Water to effective binder ratio: no more than 0.4
- Characteristic value of flexural tensile strength: $f_{fctk,fl} \geq$ 4.7 N/mm^2
- Characteristic equivalent tensile strength in the deformation area I $f_{eq,ctk,I}$: 1.6 N/mm^2 (L1)

– Characteristic equivalent tensile strength in the deformation area II $f_{eq,ctk,II}$: 1.0 N/mm^2 (L2)

Selecting the appropriate type of steel fibres or at least defining some key parameters to reach the defined properties is just as important during the planning.

2.3 Requirements for steel fibres

For this project, steel fibres with the following requirements were sought:

- Made of low-carbon and cold-drawn wire
- According to DS/EN 14889-1: Group 1, cf. [3]
- Shape: round cross-section and hooked ends
- Tensile strength of the wire: $f_{ft} \geq 1{,}100$ N/mm^2
- Nominal length $l_f \leq 60$ mm
- Slenderness $\lambda = l_f/d_f$ (length-to-diameter ratio of the fibre): between 50 and 75

Furthermore, there were specifications for the type of fibre addition and dosing. This had to be done using an automatic dosing and weighing system to rule out any inaccuracies and fluctuations of dosing in the continuous process. The steel fibres were supplied in safety big bags of 500 kg each for filling the automatic dosing system.

2.4 Manufacture of the tunnel lining segments

The KrampeHarex wire fibre DE 60/0.8 M was selected to manufacture the tunnel lining segments of steel fibre reinforced concrete [4]. This is a cold-drawn steel wire fibre with a length of 60 mm, a diameter of 0.8 mm, a slenderness of 67 and a tensile strength of 1,550 N/mm^2. Experience from other projects and research in the KrampeHarex concrete laboratory clearly indicate that this is the most suitable fibre for the planned class C50/60 F1.6/1.0 steel fibre reinforced concrete. The high performance, quality and tensile strength combined with an excellent length-to- diameter ratio perfectly match the required fibre concrete class F1.6/1.0 and guarantee consistently good test results throughout the entire production period. The required dosing quantity was determined in preliminary tests. Another important aspect is the outstanding workability. Despite the addition of individual fibres instead of adding fibre bundles that are glued together, there is no “balling” effect (clumps of fibres that may form during manufacturing as a result of insufficient fibre separation). This makes it possible to avoid adverse effects of the adhesive on the concrete properties. An automatic dosing system allows for directly feeding the fibres into the concrete mixer in the specified quantity. The loose fibres are added separately and distributed evenly in the concrete, forming a homogeneous and isotropic reinforcement.

Compared to conventional reinforcement (only steel bars), the use of steel fibres in prefabricated segments offers many advantages, such as increased durability, faster and easier production processes, fewer cracks and less damage on the segments, longer service life due to reduced maintenance requirements and overall saving of time and cost.

Quelle: KrampeHarex GmbH & Co. KG

Bild 3 Big bag mit 500 kg Stahlfasern zum einfachen Nachfüllen der Dosiereinheit
Big bag with 500 kg steel fibres for easy refill of dosing unit

The tunnel lining segments are manufactured in Germany and then transported to an interim storage facility in Denmark by rail. From this interim storage facility, the segments are transported to the construction site in pairs of two rings per lorry (Image 4). This has already proved to be a problem-free and economical solution during the construction of the Nordhavnen line. A total of about 5,700 rings are produced for the Sydhavnen tunnel, which is equivalent to 34,200 individual tunnel lining segments. Since the segments were transported to Denmark by train, more than 6 million kilometres of road travel were saved. Despite the logistic challenge and partly simultaneous operation of the tunnel boring machines, there were no delays in the construction process caused by any problem in the supply chain.

Quelle: Marc Steinfeld, HOCHTIEF

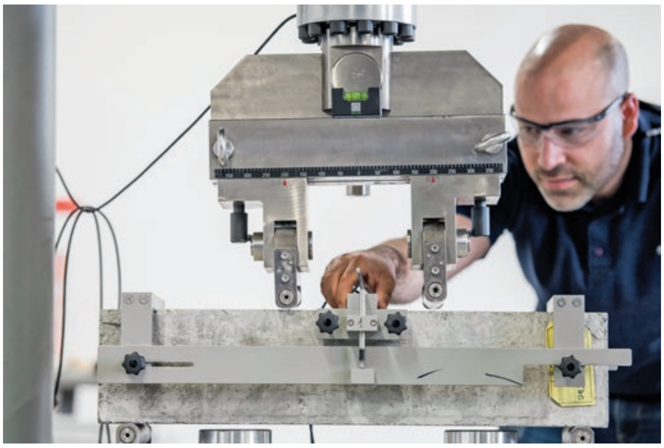
Bild 4 Transport von zwei Ringen zur Baustelle
Transport of two rings to the construction site

3 Concrete tests

Besides the usual concrete tests according to EN 206 [5] and DS 2426 [6], additional tests are required for steel fibre reinforced concrete. The steel fibre content needs to be determined according to EN 14721 (method B) [7]. The steel fibre content of an individual specimen must exceed 80% of the specified minimum value and the average steel fibre content of three concrete specimens must reach at least 85% of the minimum value. To measure the steel fibre content in fresh concrete and for the purpose of constant monitoring, three specimens are taken, compressed accordingly and weighed. The cement paste is then washed out until the fibres can be collected using a magnet. After cleaning and drying, the fibres are weighed (cf. [6]).

The characteristic flexural tensile strength ($f_{fctk,fl}$) of the steel fibre concrete tunnel lining segments is tested using the 4-point flexural test (cf. [1]) and must be ≥ 4.7 N/mm^2. The characteristic equivalent tensile strength $f_{eq,ctk,I}$ is ≥ 1.6 N/mm^2 in the deformation area I (directly behind the crack) and the residual tensile strength $f_{eq,ctk,II}$ is ≥ 1.0 N/mm^2 in the deformation area II (at a strain of $\varepsilon^f_{ct} = 100‰$).

The tests to determine the tensile strengths are performed as 4-point flexural tests on beams with the dimensions w x h x l = 150 mm x 150 mm x 700 mm (bearing spacing = 600 mm), as shown in Image 5. In this process, a stress-strain diagram is recorded up to a deflection of 3.5 mm. Thereafter, the equivalent flexural tensile strengths can be calculated based on the DBV Guide to Good Practice.



Quelle: KrampeHarex GmbH & Co. KG

Bild 5 Interne Qualitätskontrolle, Balkentest zur Ermittlung der Faserbetonklasse
Internal quality control, beam test for SFRC performance

4 Summary

The use of steel fibres (including in combination with steel bars) for the reinforcement of tunnel lining segments has turned out to offer many advantages. This has been repeatedly confirmed in numerous projects all over the world. In the "Cityringen Branch off to Sydhavnen" project, the use of steel fibres was considered early on in the planning phase, adopting a design approach that has already proved its worth in the Nordhavnen project.

Alongside the technical benefits and the significant positive effects on the durability of the tunnel lining segments, economic advantages are among the top priorities in large- scale infrastructure projects. The faster and safer production process makes it possible to substantially accelerate the manufacture of tunnel lining segments with steel fibre reinforcement. Moreover, there is less damage and fewer rejects of prefabricated parts on average, because the steel fibre reinforcement extends up to the edges, reducing the occurrence of edge breaks (especially with early stripping, storage and transport).

The innovative and pragmatic approach of the parties involved in this project also serves as another positive example that can be used as a blueprint and inspiration for future projects. The demand for tunnels will continue to grow in the course of urbanisation. Reliable, long-term and economical concepts are needed to cover this increasing demand. The early planning of the concept and the integration of steel fibres as reinforcement for tunnel lining segments is an economical solution that offers substantial advantages for all involved.

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Fibres: 1,000 t
Fibretype: DE 60/0.8 M

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