Longitudinal joints of tubbings with newly designed high-strength reinforcement

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Abstract
Continuous tunneling using a tunnel-boring machine is a very popular method when it comes to the construction of large tunnel projects. The use of precast reinforced concrete elements, called tubbings, is a highly economical way to secure the tunnel post excavation. Unfortunately, a loss of the load-bearing capacity has been observed in the past in the joints between the tubbings. Reasons for that are among others the required reduction of the cross section in the longitudinal joint area and, above all, the high normal compressive forces that arise due to soil pressure. This paper describes experimental testing of longitudinal joints of tubbings conducted at TU Wien. The increase of the load-bearing capacity of a newly designed and optimized tubbing with high-strength joint-compressive reinforcement, which was developed and patented by the Institute of Structural Engineering at TU Wien, is presented. The high-strength steel is characterized by its high yield strength of 670 MPa, as well as the very large available bar diameters of up to 75 mm. This new optimized tubbing enables the production of thinner tubbings compared to conventional designs, and can thus achieve a reduction in material, transport and excavation costs.

KEYWORDS
high-strength reinforcement, joint reinforcement, longitudinal joint, precast tunnel segments, tubbing

1 | INTRODUCTION

1.1 | General
The application of precast elements can be a very economic construction method where a high repetition rate of the same or similar components occurs. The advantages of prefabricated elements have not only made them popular in high-rise but also in tunnel constructions. For the latter, prefabricated elements called tubbings, have become popular when using tunnel-boring machines for continuous driving. A tunnel ring is usually formed by 6–10 tubbings and extends over a width in tunnel direction of about 2 m (see Figure 1). With tunnel lengths of several kilometers, this results in a large amount of structurally identical precast reinforced concrete elements. The optimization of the components’ designs and therefore dimension would result
in economic advantages for this area of application. In addition to reducing the weight of a single tubbing, which has economic advantages in terms of tubbing transport and concrete costs, the excavated volume of the tunnel cross section is also significantly reduced.

Tubbings have to withstand large normal compressive forces in combination with small bending moments due to high soil pressure. In order to be able to absorb minimal rotations of two tubbings without any damage, such as the spalling of the concrete edge due to large edge tensile stresses, a geometric cross-sectional reduction in the longitudinal joints is necessary.\(^1\) The design of the longitudinal joint can basically be divided into four different types (see Figure 2). Each of these design variants has slightly different properties with regard to the transfer of bending moments, angle of rotation and tightness of the joint. The simplest and most frequently used design variant is the even longitudinal joint (see Figure 2(a)). This design prevents the rotation of two tubbings due to its geometry and can therefore transfer small bending moments.\(^2\) The following article only refers to even longitudinal joints.

Regardless of the design variant of the longitudinal joint, this area of discontinuity can cause a loss of the load-bearing capacity. The newly developed joint design, patented at TU Wien,\(^3,4\) compensates for the loss of load-bearing capacity while evading the problematic of other existing designs at the same time. In addition to a description of the origin of the idea and a brief insight into the current state of the art of dimensioning of longitudinal tubbing joints, the successfully conducted experimental investigations and their results are presented in this paper.

2 | ORIGIN OF THE IDEA AND STATE OF THE ART

In the following chapter, the development of the idea for an optimized tubbing joint is explained in more detail. The problem, which is being addressed, is that of butt joints, initially only regarding those of prefabricated columns. The authors soon realized that the joints of prefabricated columns were not the only ones that should be investigated resulting in further research in the areas of other prefabricated constructions, tubbings in particular. The developed solution for a design of longitudinal joints of tubbings, will subsequently be presented. This chapter concludes with the current state of the art for dimensioning longitudinal joints of tubbings and a review of the development of the formula apparatus.

2.1 | The column butt joint

Butt connections of two precast elements are often found in high-rise construction. Even though the connections of
two precast columns are often found in buildings, the design still has numerous flaws and problems. Due to the pursuit of slender column cross sections and the use of high-strength building materials, including high-strength reinforcing steel, special attention must be paid to the design of the joints. In Reference 5, two different designs for column butt joints are presented. The main difference between the two is the absorption of the occurring transverse tensile stresses in the joint area, namely by end face reinforcement, or by steel plates at both ends of the columns. Nevertheless, according to Reference 5, a loss of load-bearing capacity can only be completely prevented by using at least 1 cm thick steel plates. When using end face reinforcement, the load-bearing capacity must be reduced to 90%. In addition to the steel plate, a decisive role is played by the length differences of the compressive bars (distance from the end of the bars to the joint) and positioning of the compressive bars.\textsuperscript{5–7} Even small distances between the ends of the compressive reinforcement and the joint area can result in a significant loss of load-bearing capacity. Activating the peak pressure at the ends of the compressive bars and minimizing the unreinforced area in the joint is of great importance for a successful load transfer.

While looking into the design possibilities for the column butt joints a resemblance to those of tubbing longitudinal joints was found. The problems occurring in the joints of both structural components were similar enough to try to find a suitable solution that could be used for both designs or adapt designs from one area to the other. As with precast columns with end face reinforcement, the resulting transverse tensile stresses at the tubbing longitudinal joints are absorbed by splitting tensile reinforcement, but no longitudinal reinforcement or compressive reinforcement is used directly in the contact area of the longitudinal joint. This creates a large unreinforced area measured across the joint, which can lead to a loss of load-bearing capacity. In contrast to precast columns, the connection of tubbings is constructed as a dry joint (without grouting mortar). As a result, the idea of implementing joint-compressive reinforcement in tubbings was developed and patented at the Institute of Structural Engineering at TU Wien\textsuperscript{3,4} in 2020.

2.2 Optimized tubbing design

Numerous suggestions for increasing the load-bearing capacity of longitudinal joints of tubbings have been presented in various publications and patents in the past.\textsuperscript{8,9} In practice, however, the designs were never truly accepted or implemented. The needed built-in parts for the joints were designed to be made of steel or other metallic materials, resulting in high manufacturing costs, low corrosion resistance, as well as a rapid loss of load-bearing capacity in the case of fire. The newly developed design at the Institute of Structural Engineering at TU Wien (patented in AT Patent No. 50433/2019, 2019; PCT Patent No. PCT/AT2020/060030, 2020), is capable of not only compensating the disadvantages of the other designs but also significantly increase the load-bearing capacity of the longitudinal joint when compared to currently used tubbing joints.

By using additional compression bars (see Figure 3), an increase of the load-bearing capacity of the longitudinal joint can be ensured. These compression bars are inserted in the longitudinal joint area and are butted against or are guided as close as possible to the contact surface. The aim of this design is to allow for a reduction of the compressive stresses on the concrete in the joint area by redistributing the forces from the concrete into the additionally arranged compression bars. The force in the compression bars of a tubbing is then passed on via peak pressure into the compression bars of the neighboring tubbing and subsequently redistributed to the standard cross section by bond stresses.

For the greatest possible increase in load-bearing capacity, high strength reinforcing steel is recommended for these compression bars. Investigations on compression members with high-strength reinforcement steel have shown numerous advantages, for example, the increase of the load-bearing capacity compared to conventional reinforcement, in the past\textsuperscript{10–13} and have already been used successfully in high-rise constructions.\textsuperscript{14,15}

![FIGURE 3 Optimized tubbing with joint compressive reinforcement\textsuperscript{3,4}](image-url)
2.3 | High-strength compressive reinforcement in compression members

The use of high-strength reinforcement in compression members is one of the latest developments in high-rise constructions. Due to the large diameter of up to 75 mm, it is possible to build very slim concrete columns with a reinforcement ratio of up to 20%. The higher yield strength of 670 MPa compared to a conventional reinforcement steel (in Austria 550 MPa) cannot be fully exploited when designing according to the regulations of.16 The EC2 limits the maximum reinforcement ration of precast concrete columns to 9% while simultaneously limiting the maximum concrete strain in the ultimate limit state (ULS) to 2‰. In order to efficiently utilize SAS 670/800, a high-strength reinforcement developed by Stahlwerk Annahuette (Germany) initially for geotechnical applications like anchors, soil nails, and micro-piles17 a strain of 2.91‰ would be required. For this reason, numerous tests have been carried out on various columns in the past.10,15 These tests led to the attainment of the European Technical Approval ETA-13/0840.18

By considering creep and shrinkage strains of the concrete during the construction and utilization phase, a force redistribution from the concrete to the reinforcement steel is considered. Due to this force redistribution, it is possible to calculate with the entire yield strength of SAS 670/800 and therefore ensure a resource-efficient implementation. The deformation increase due to creep is depicted in Figure 4 based on two column tests, one with a fast load history (dashed line) and the other with a slow load history with a planned creep phase during testing. In addition, the strain in the naked reinforcing steel and unreinforced concrete are illustrated in Figure 4. The compressive strain gain due to creep redistribution is clearly visible and can be subdivided into the following three sections: (1) $\varepsilon_1$ as a result of the creep and shrinkage of the concrete, (2) $\varepsilon_2$ caused by loading after the creep phase, (3) $\varepsilon_3$ caused by different loading rates.10

2.4 | Partial area loading

The introduction of concentrated loads via partial area loading occurs in reinforced concrete constructions on a regular basis in practice. Investigations of the plane and spatial problems in regard to this problematic go back to the year 1876. The first experiments and the resulting cubic root formula, which considers the area ratios of the contact area and the load propagation area, were first published by Bauschinger.19 The tests were carried out on unreinforced sandstone samples resulting in the fact that the formula could only be used for plane problems. The square root formula for spatial problems, which acts as a base for the current normative approach in Deutsches Institut für Normung [EC2]16 (Equation 1), was first presented in 1959 by Spieth. Spieth20,21 uses this approach for unreinforced and also reinforced bodies, with only the size of the safety factor differing for unreinforced bodies, as they fail suddenly.

$$F_{\text{Rdu}} = A_{c0} \cdot f_{cd} \cdot \sqrt{A_{c1} / A_{c0}} \leq 3.0 \cdot f_{cd} \cdot A_{c0}$$ (1)

In 1977, Wurm and Daschner7 also investigated the influence of various types of reinforcement in regard to the absorption of the transverse stresses in the load propagation area. It was found that the design of the transverse reinforcement (mats or stirrups) also has a significant influence on the increase in load-bearing capacity. In Reference 16, transverse reinforcement is set as mandatory in order to absorb the transverse tensile stresses that arise. The normative additional condition of the geometric similarity of $A_{c1}$ to $A_{c0}$ was determined based on tests carried out by Wichers22 investigating the plane problem of load propagation in disc-shaped construction parts. This geometric similarity is explained in detail in Reference 23.

2.5 | Design basis of the longitudinal joint of tubbings (state of the art)

The German Committee for Underground Construction (DAUB) gives recommendations for the design, manufacture and installation of tubbing rings.1 The design of the longitudinal joint of tubbings is realized by comparing the permissible concrete compressive stresses with partial area pressure with the existing concrete compressive

![FIGURE 4 Load history of a fast loaded (dashed line) and slow loaded column tests based on Reference10](image-url)
stresses in the contact area of two tubbings. As long as no experimental investigations are carried out, the cross-
sectional resistance in the contact joint can be determined using the equation according to EN 1992-1-1, Section 6.7 Partial area load (Equation 1). However, this formula apparatus may only be used in compliance with the specified area ratios and expansion geometries. In addition, sufficient transverse reinforcement must be placed over the height of the load propagation area, which has the effect of preventing transverse strain. With this verification, the design of tubbing longitudinal joints results in an approximation on the safe side. Static and geometric eccentricities reduce the compression transfer area or the contact area and must be considered with twice the value of the total eccentricity (explained in detail in Reference 1).

According to Reference 16, the distribution area $A_{c1}$ must be geometrically similar to $A_{c0}$. In the case of tubbings, this requirement cannot be met due to the required geometries and the design of the contact surface. The admissibility of waiving this geometric condition is justified, among other things, by the results of project-specific experimental investigations, for example, in References 24, 25.

3 | EXPERIMENTAL PROCEDURE

In order to be able to show the advantages of the newly developed tubbing (chapter 2.2) compared to a conventional tubbing (CT), experimental investigations were carried out on the longitudinal joints of tubbings. The following chapter contains a detailed presentation of the investigated test specimens as well as an explanation of the entire test procedure.

3.1 | Test specimens

A total of four large-scale centric compression tests were carried out in a first test series, whereby two different design variants were examined for their normal force load-bearing capacity. The influence of geometric eccentricities, as they are not uncommon in construction, are to be examined in a planned second series of experiments. The investigations concentrated on the tubbing area next to the longitudinal joint. The tubbing length with 635 mm was chosen so that any influence in the area of the longitudinal joint could be excluded. The thickness and the dimensions of the contact surface of the test specimens were chosen based on a tubbing cross section frequently used in Austrian tunnel constructions as well as with the equations and guidelines from Fischer et al. A tunnel with an outer diameter $\Omega_o$ of at least 8 m was assumed, resulting in a tubbing thickness of 400 cm ($\Omega_o/20$). The recommended tubbing width was calculated to be 2 m. Due to the maximum possible force application of 18 MN in the testing rig, the test specimens had to be scaled in their width by a factor of 0.35. The dimensions of the test specimens can be seen in Figure 5 and were chosen to be the same for both design variants. These tubbings were designed with a standard cross-sectional reduction in the area of the longitudinal joint. The reduction in the size of the contact surfaces prevents the edge areas from spalling when two tubbings are rotated relative to one another, and also enables the placement of frequently required sealing strips. In order to guarantee a constant load introduction into the test specimen, a steel plate with a thickness of 30 mm was placed at the ends.

3.1.1 | Conventional tubbing

Two destructive compression tests were carried out on tubbings with a conventional reinforcement layout. In order to avoid a failure caused by splitting tensile forces, ladder reinforcement was installed in three layers (see Figure 6). The reinforcement cage was assembled using an ordinary reinforcement mesh. The bars of the ladder reinforcement (two layers of ladder 1 [L1] and one layer of ladder 2 [L2]) and the bars of the reinforcement mesh were welded together at each crossing joint with a shear factor of at least 50%. The assembled mats were tack welded to the ladder reinforcement. The chosen rebar diameters of the ladder reinforcement are listed in Table 1. The concrete cover was chosen with 40 mm in the direction of thickness and 45.5 mm to the longitudinal joint, corresponding to the concrete cover needed according to the Austrian tubbing standards. The larger distance to the longitudinal joint was calculated based on the assumption of a sealing groove and a guiding rod in...
the longitudinal joint area. The concrete cover in the direction of the width (which was scaled) was chosen based on Reference 28 with a thickness of 15 mm.

### 3.1.2 Optimized Tubbing

In order to demonstrate the advantages of the patented optimized tubbing developed by TU Wien, four specimens for two compression tests according to the new design were manufactured. The installed reinforcement was almost identical to that of the CTs described in Section 2.1.1. The only difference in the reinforcement layout was the integration of 16 high-strength reinforcing bars SAS 670/800 from Annahütte (Germany), which served as compression bars, located in the contact area (see Figure 7). To prevent the joint compressive reinforcement from buckling, stirrups with a diameter of 12 mm were additionally installed. During production, particular attention was paid to the perfect installment of the high-strength reinforcement SAS to ensure the smallest possible distance to the contact surface. This would allow for the highest possible utilization and a particularly high level of efficiency of the bars.

The completed reinforcement cages and the formwork of a conventionally reinforced specimen and a specimen with the new TU Wien design are shown in Figure 8.

### 3.2 Material properties

In addition to the production of the test specimens, further samples were produced in order to determine the material properties of the concrete (maximum aggregate size 16 mm). The determination of the material properties took place before the tests and made it possible to adapt the load history. The tests were carried out 10–12 days after concreting in order to obtain the desired concrete compressive strength of about 50 MPa (cylinder compressive strength), which is typical for prefabricated tubbings (40–60 MPa). The hardening of the concrete was more than 90% completed at the time of the tests. Tensile tests were carried out on three bars of the high-strength reinforcing steel SAS 670/800. The results of the tests are shown in Table 2.

### 3.3 Test setup

The experimental investigations were carried out in the compression test rig at TU Wien, in the laboratory of the...
Institute of Structural Engineering (Figure 9). All test specimens were tested under uniaxial longitudinal pressure without any eccentricity. The horizontal installation resulted in a small but negligible vertical force component in comparison to the applied horizontal force (0.07%-0.1%) due to the dead weight of the test body. The test setup was based on the column butt joint investigations of where the entire joint area was tested using two adjoining column stubs. This setup ensures very realistic conditions, since the force transmission in the reinforcement bars via peak pressure significantly influences the load-bearing capacity of the joint area. As in column stubs, this load transmission via peak pressure is also of great importance for the newly developed

![Figure 7](image1.png) Reinforcement of the optimized tubbing (OT): Top view (a); section a-a (b); section 1-1 (c)

![Figure 8](image2.png) Formwork and reinforcement cage: Conventional tubbing (a); optimized tubbing (b)

| TABLE 2 Material properties |
|-----------------------------|
| Concrete | Compressive strength [MPa] | Young's modulus [GPa] | Tensile strength [MPa] |
| C 50/60 | 51.9 | 33.8 | 3.1 |
| Reinforcement | Yield strength [MPa] | Young's modulus [GPa] | Ultimate strength [MPa] |
| B 550 | 550\(^a\) | 200\(^a\) | |
| SAS 670/800 | 776.3 | 200\(^a\) | 872 |

Note: Mean value of three tests.
\(^a\)Characteristic values according to (EC2,16).
optimized tubing design. The additionally introduced high-strength compression bars in the joint area of a tubing transfer the loads mainly via peak pressure to the high-strength joint compression bars of the adjoining tubing. In order to demonstrate this force transmission in a practical manner, two identically reinforced tubbings were pressed against each other in the large-scale tests.

During the tests, the load was monitored using four load cells and the strain of the test specimen in all four corners using linear variable differential transformers (LVDT’s). In order to better assess the failure process and crack development, a photogrammetric measuring system (Aramis by Gom GmbH) was applied to one side surface. In addition, the crack widths of the remaining surfaces were measured manually using an optical crack magnifier at the various load levels. A total of five load levels (30%, 40%, 50% and 80% of the expected maximum load) were planned, with the last holding phase being held for 1 h. The tests were carried out with a displacement-regulated load control. The applied displacement was set from 80% of the expected maximum load with an increase of <0.005 mm/s.

4 | EXPERIMENTAL RESULTS AND DISCUSSION

The results obtained are shown in a force-strain diagram in Figure 10. Both design variants showed a similar initial stiffness. The circled area (black or gray circle) marks the excess of the serviceability limit state (SLS) load. To determine the SLS the highest requirement class AT1 (mostly dry) for tubbings according to,27 with a maximum permissible crack width of 0.2 mm was chosen (tightness tests were not carried out). By evaluating the photogrammetric and the optical recordings (using a crack magnifier), the SLS load was determined. The comparison of the two design variants clearly shows that the maximum crack widths were reached at an earlier load level during the testing of the CT, with 6850 and 5900 kN. The optimized tubbings OT were loaded with 9400 and 10,400 kN before reaching the SLS. At the time of the SLS load of the CT specimens, no cracks were observed on the test OT specimens. The longitudinal strain, when SLS was reached, was lower in the CT specimens with 2.0 ‰ and 1.7 ‰ (OT specimens 3.0 ‰ each). In both design variants, a crucial crack developed along the edge area in the longitudinal direction of the tubing. This observation shows that a spalling of the concrete cover begins at a load far below the ultimate load of the standard cross section of the tubing.

The failure mechanism of the test specimens was very ductile with the exception of tubbing CT1. After the concrete cover had partially flaked off, a further minimal increase in force was possible. The strain increased disproportionately until an increase in load was no longer possible, after which the test was terminated. The test specimen CT1 failed prematurely, for which no clear reason was found. No difference in the crack patterns, failure type nor test body stiffness was noted in comparison to the CT2 specimen.

When comparing the crack patterns of the two design variants CT and OT in the ultimate load state (ULS) major similarities were identified. The largest cracks occurred along the edge area in the longitudinal direction of the tubing and are ascribed to the splitting of the concrete cover. A higher amount of cracks in the middle area were observed on the newly developed optimized tubing OT compared to the conventional solution (see Figure 11).

The higher load-bearing capacity of the newly developed design for the longitudinal tubing joints with the
high-strength joint compressive reinforcement SAS were clearly demonstrated during the large-scale tests. The test results show that in addition to increasing the SLS load, an increase of the load-bearing capacity of the longitudinal joint by approx. 44% was possible. The achieved fracture strains of 7.6‰ and 8.3‰ indicate a strongly confined core cross section.

The recalculation of the test specimens from the experimental investigations was carried out according to the current state of the art. According to,1 tubbing joints can be dimensioned using the permissible concrete compressive stress by partial area pressure. The normal force load-bearing capacity of the longitudinal joint of tubbings was subsequently determined using the equations according to16 for partial area loads. Table 3 lists the results of the test recalculation. For the CT, the results are overestimated by 6% (CT1) and underestimated by 9% (CT2).

For the newly developed optimized tubbing OT, the calculation of the load-bearing capacity had to be extended by the factor $F_{sj}$, as shown in Equation (2). In addition to the concrete load-bearing capacity with a partial area loading $F_{c}$ (Equation (3)), the force from the joint compressive reinforcement $F_{sj}$ (Equation (4)), is added. This adaptation resulting in Equation (2) made it possible to calculate the ultimate load-bearing capacity in accordance with the test results with compliance factors of 0.97 and 0.99 for the tests OT1 and OT2, respectively.
With the current standard verification according to References 1, 27 the load-bearing capacity of longitudinal joints of both tubbings (CT and OT) can be well simulated.

When comparing mean values of the ultimate compression forces of the CT specimens with those of the OT specimens, it can be seen that the joint compressive reinforcement could not be fully utilized in the component tests. Recalculations show an activation of approximately 90% of the compressive reinforcement. This discrepancy could be explained by the deviations of the positions of the reinforcement at the butt joint from the planned positions. In the case of the test specimen OT2 for example, only about 67% of the total joint compression area of the single reinforcement bar are overlapped (see Figure 12). Therefore, when using joint compression reinforcement, the correct installation and positioning should be of highest importance during the production of the tubbings and should be controlled throughout the process.

\[
F_{cal} = F_c + F_{sj} \quad (2)
\]

\[
F_c = \min \left\{ \frac{A_{c0} \cdot f_{cm} \cdot \sqrt{A_{c1}}}{3.0 \cdot f_{cm} \cdot A_{c0}} \right\} \quad (3)
\]

\[
F_{sj} = f_{sj} \cdot A_{sj} \quad (4)
\]

In order to determine the degradation in the load-bearing capacity of the tubbing due to the presence of a longitudinal joint, the ultimate loads from the experimental investigations are compared with the cross-sectional resistance \(F_{cs}\). The normal force load-bearing capacity of the entire cross section (700–400 mm) of the tubbing \(F_{cs}\) is determined with Equation (5), with the assumption that the compressive reinforcing bars (B 550) will reach the yield stress.

\[
F_{cs} = f_{cm} \cdot A_{c,n} + f_{ym} \cdot A_{sl} \quad (5)
\]

The results of this recalculation show that the load-bearing capacity in the joint area of the CT is far below that of the standard cross section of the tubbing. Calculative, only about 69% of the cross-sectional resistance was achieved in the control range. This proves a significant loss of load-bearing capacity due to the longitudinal joint. When using the newly developed optimized tubbing, this loss of load-bearing capacity can be partially compensated. The use of high-strength joint compressive reinforcement increased the ultimate load of the longitudinal joint to 94% of the cross section in the control range of the tubbing.

### TABLE 3 Test results

| Tubbing | \(F_{max}\) [kN] | \(\varepsilon_{Fmax}\) [%] | \(F_{SLS}\) [kN] | \(\varepsilon_{SLS}\) [%] | \(F_{cal}\) [kN] | \(F_{max}/F_{cal}\) [-] | \(F_{cs}\) [kN] | \(F_{max}/F_{cs}\) [-] |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| CT1     | 9198            | −3.6            | 6850            | −2.0            | 9742            | 0.94            | 15,299          | 0.60            |
| CT2     | 10,626          | −6.3            | 5900            | −1.7            | 9742            | 1.09            | 15,299          | 0.69            |
| OT1     | 14,049          | −7.6            | 9450            | −3.0            | 14,530          | 0.97            | 15,299          | 0.92            |
| OT2     | 14,404          | −8.3            | 10,400          | −3.0            | 14,530          | 0.99            | 15,299          | 0.94            |

Note: Bold values are one of the main results.
Abbreviation: CT, conventional tubbing; OT, optimized tubbing; SLS, serviceability limit state.

**FIGURE 12** Contact surface of the joint compressive reinforcement in the longitudinal joint of CT2. CT, conventional tubbing.
5 CONCLUSION AND OUTLOOK

In this article the experimental investigations of two different types of segments are presented and discussed. In addition to a conventional tubbing design (CT), a newly developed optimized tubbing (OT) with high-strength joint-compressive reinforcement is presented. The aim of the redesign is the enhancement of tubbings in the area of the longitudinal joint in terms of load-bearing capacity and the serviceability limit state. The following conclusions can be drawn from the four tests with 400 mm thick tubbings:

- With the presented test setup based on Reference 29, the longitudinal joint area of the segments could be realistically mapped. Above all, the possible force transmission of the high-strength compressive bars in the optimized tubbing could be examined.
- The experiments proved that a successful installation of the high-strength reinforcement SAS 670/800 is possible and that the yield strength can be reached with this construction.
- The critical load when reaching the maximum permissible crack width could clearly be increased by the tubbing OT. This indicates a greater level of safety in the serviceability state.
- In addition to the SLS-load, the load-bearing capacity was also significantly increased compared to the tubbing CT. As a result, the design variant OT enables the production of thinner tubbings, which has a positive effect on material consumption in tunnel constructions (reduction of the required tubbing concrete and reduction of the excavated volume of the tunnel cross section).
- The loss of load-bearing capacity in the longitudinal joint area of tubbings could be partially compensated by the use of high-strength joint-compressive reinforcement.

In the next step, component tests will be carried out with eccentric loading. In addition, the influence of tolerances of the high-strength compressive reinforcement, such as positional inaccuracy and the distance to the contact surface will also be investigated.

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NOTATIONS

\[
\begin{align*}
A_{c,n} & \quad \text{netto cross section} \\
A_{c0} & \quad \text{loaded area (contact area)} \\
A_{c1} & \quad \text{maximum design distribution area with a similar shape to } A_{c0} \\
A_{sj} & \quad \text{area of joint compressive reinforcement} \\
A_{sl} & \quad \text{area of compressive reinforcement} \\
F_{cal} & \quad \text{calculated ultimate load} \\
F_c & \quad \text{strength in concrete} \\
F_{ca} & \quad \text{load capacity of the tubbing cross section} \\
F_{sj} & \quad \text{strength in joint compressive reinforcement} \\
F_{Rdu} & \quad \text{design ultimate load} \\
f_{cd} & \quad \text{design value of concrete compressive strength} \\
f_{cm} & \quad \text{compressive strength of concrete} \\
f_{sj} & \quad \text{yield strength of joint compressive reinforcement} \\
f_{sym} & \quad \text{yield strength of compressive reinforcement in the tubbing cross section} \\
\end{align*}
\]

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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