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Investigation of the Performance of Lattice Girders in Tunnelling

By

Th. Baumann and M. Betzle

Philipp Holzmann AG, Munich, Federal Republic of Germany

Summary

In order to investigate the structural and technological aspects of this relatively new constructional element a series of laboratory and field tests were carried out and the results compared with theoretical values. This article is concerned with a description of the lattice girder elements together with the results of the investigations and their practical application in the Munich Underground.

1. Introduction

In tunnelling lattice girders have basically the same function as steel arch supports. They serve as elements of the temporary lining and in some cases also as part of the permanent lining. Since the use of lattice girders is closely connected with that of the shotcrete lining technique here its behaviour will be discussed only in relation to this method of construction. In addition, problems arising in underground railway construction will be considered, as the investigations carried out were initiated by their use in the Munich Underground.

Lattice girders have the following functions:

- Immediate support in the area of the working face over the length of the leading excavated section (Fig. 1).
- Template when applying the shotcrete and excavating the next section.
- Part of the reinforcement of the shotcrete lining.
- Supports for rods and plates, which provide advance support for the next excavated section.

In contrast to full face excavation, with partial excavation lattice girders can be limited either to the roof section of the tunnel or they can be extended into the region of the benches. The main advantages of lattice girders over conventional steel arch supports are, on the one hand, a low weight per metre length of girder and, on the other, a more efficient bond with the shotcrete. Especially when water tightness is required the latter is of great importance. This is the case in the application of shotcrete in subway construction below ground water level using compressed air (Weber, 1983). The inner lining is actually installed under atmospheric conditions, so that the shotcrete lining has to withstand the full ground water pressure. Thus leaks in the shotcrete must be reduced to a minimum. Experience shows that shotcreted steel arches, no matter what form of profile they possess, tend to favour the formation of voids and paths through which seepage occurs. Lattice girders perform better in this respect.

Fig. 1. Tunnel excavation with lattice girders

2. Structural Aspects

In the past lattice girders were used almost exclusively as three chord type girders, though four chord type forms have also been reported (Braun, 1983). The girder type investigated by the authors (System Pantex) is shown in Fig. 2. The connection of the diagonals to the chords is achieved by means of inert gas welding. Smooth steel bars of the type 500/550 GK are used. The junction points of members and footplates consist of steel type St 37.

The radius of curvature of the diagonal bar amounts to three times the bar diameter. This does not fulfil the minimum requirements of DIN 1045. In addition the welds are located immediately after the bend in the bar (a closeup photo of a weld node is shown in Fig. 8). Therefore the strength of this connection had to be investigated in detail at the testing station for reinforcing steel (Rehm, 1983). In addition the strength properties of diagonal bars in bending under various bending block diameters were investigated. The bars were bent to an angle of up to 90^0, then artificially aged and after cooling to room temperature straightened out again. The bars were then tested in tension in order to find the tensile strengths and strains corresponding to the range of the previous bending action. It was shown that the small bending block diameters did not result in any loss of strength for the steel type 500/550 GK used. In order to check the influence of welding, bending tests were carried out during the periodic quality controls. No brittle behaviour due to the welding process was observed in the area of the welds.

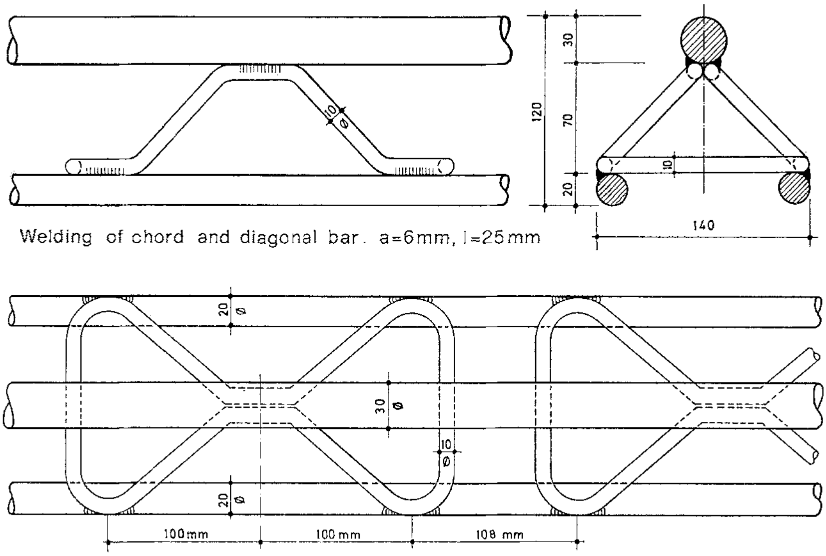

Fig. 2. Typical details of a girder with 3 chords (System Pantex)

The support reaction at the foot of the lattice girder is transmitted by means of a welded-on plate to the ground. In longitudinal direction of the tunnel the lattice girders are braced by means of round steel bars, which are fitted into nuts welded to the girders (Fig. 1).

The joints of the lattice girder must be strengthened to resist the full sectional bending moments, normal and shear forces and they must enable simple mounting at the face. Solutions with

— a welded angle connector and screws (Fig. 3) as well as
— strengthened screw collars (Fig. 4)

have proved to be effective. In addition, complete covering of the joints with shotcrete should be possible so that no shaded areas behind the joints are created.

For tunnels with large cross sections side drifts are first excavated as shown in Fig. 13. For this type the joints shown in Fig. 5 were developed. First of all the two arch segments *L* and *M* of the side drifts are connected together. In the subsequent enlarging of the roof heading the top arch segment *R* is connected to the bottom one *L*, while the temporary segment *M* is later removed.

The girder *L* has a bolt at its top end, which is welded to a steel plate to the two inside chords. At the top end of the temporary girder *M* a plate with a hole is welded to it. This connecting plate is placed over the bolt of the girder *L* so that a hinged connection between the two girders *L* and *M* is obtained. With this form of connection after the heading has been excavated the temporary girder *M* can be removed without damaging the outside girder *L*. The roof girder *R* is also connected by means of a bolt to the lower girder *L*. This bolt is put into a sleeve welded to the lower girder (Fig. 5). The bolt has a thread with a nut screwed onto it. To facilitate easier installation the roof girder *R* is divided into two parts. Once the

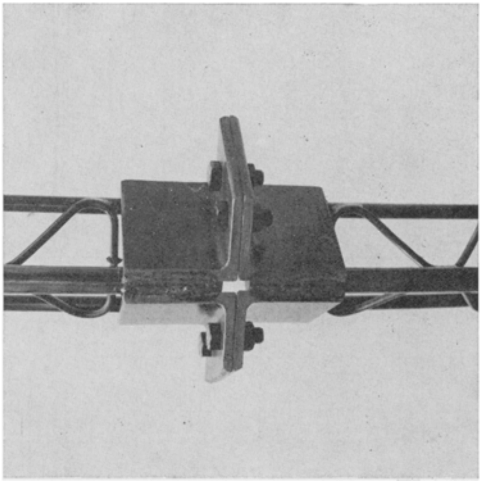

Fig. 3. Joint with angle connector

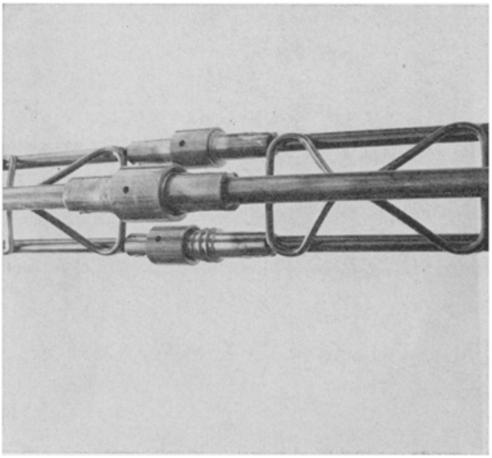

Fig. 4. Joint with strengthened screw collars

two parts of the roof girder *R* have been installed they are connected using an angle connection or a screw collar connection (Fig. 3 and 4). The nut on the bolt mentioned above is then unscrewed until it is tightened firmly to the top plate of the lower girder *L* (Fig. 5). This type of joint has performed well in practice. It permits simple and rapid mounting while fulfilling the statical and constructional requirements.

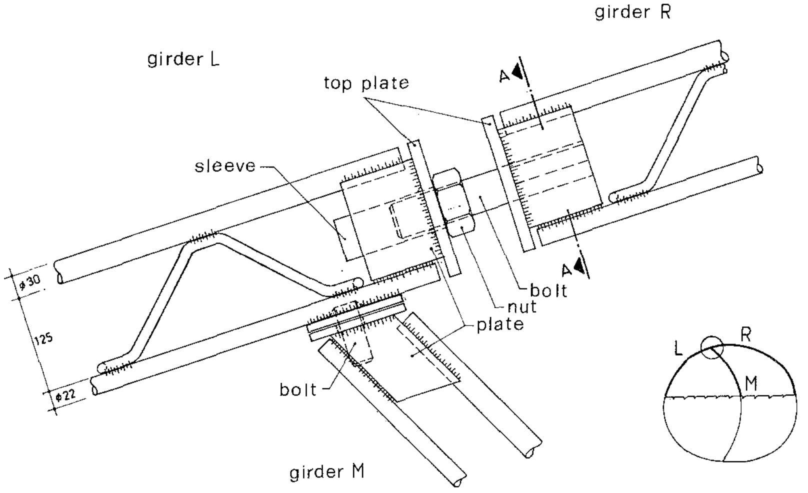

Fig. 5. Construction of the joint in the roof for a two track underground tube with partial face excavation

In order to provide a template for grading the concrete lining the lattice girders have to be bent to the exact shape. With an adequate three-dimensional stiffness the experience gained in this present work shows that they possess an accuracy of profile satisfying completely the requirements of tunnel construction.

3. Design

Based on an assumed loading and a suitable statical system the global sectional quantities (bending moment *M*, shear force *Q* and normal force *N*) in the lattice girder are calculated. From these the local moments and forces in the individual bars of the lattice girder can be found according to Fig. 6. The following relations result from simple equilibrium considerations:

Axial forces in the chords

$$N_o = N \cdot A_o/(A_o + A_u) - M/z \tag{1a}$$

$$N_u = N \cdot A_u/(A_o + A_u) + M/z \tag{1b}$$

(tensile forces positive)

A_o: area of the upper chord (consisting of 1 bar);

A_u: area of the lower chord (consisting of 2 bars).

Shear forces in the chords

$$Q_1 = Q/(1 - l_4/l_2) \qquad (2a)$$

$$Q_2 = Q/(l_3/l_1 - 1) \qquad (2b)$$

$$Q_3 = Q/(l_2/l_4 - 1) \qquad (2c)$$

$$Q_4 = Q/(1 - l_1/l_3) \qquad (2d)$$

Bending moments in the chords

$$M_0 = Q_4 \cdot l_4 \qquad (3a)$$

$$M_u = Q_1 \cdot l_1 \qquad (3b)$$

Compressive and tensile forces in the diagonal bars.

$$D = Z = \frac{l_1 + l_2}{l_3 - l_1} \cdot Q/\sin\alpha \qquad (4a)$$

$$\bar{D} = \bar{Z} = \frac{l_1 + l_2}{l_3 - l_1} \cdot Q/2 \sin\alpha \cos\beta \qquad (4b)$$

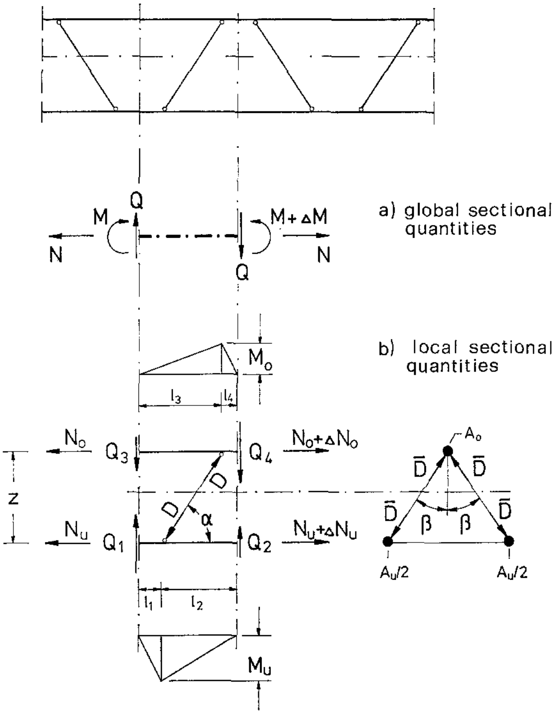

Fig. 6. Global and local sectional quantities (bending moment and forces) for a lattice girder

The steel stresses in the chords can be found from the sectional quantities N_0, M_0 and N_u, M_u respectively. The diagonal bars have to be designed for compressive and tensile forces $\bar{D}$ and $\bar{Z}$. The deviation β of the diagonal bar forces from the plane of the arch have already been taken into account in Eq. (4b).

The influence of second order effects on the complete system can be accounted for by increasing the global normal force by the Omega method (DIN 4114). The buckling length of the arch is found by Pflüger's (1975) method. Embedding of the arch in the ground is not taken into account.

In addition, local buckling of both the chords and the diagonal bar has to be checked. The buckling length is taken approximately as the distance between the welded junctions. To determine the slenderness ratio only the cross-sectional values of the individual bars under consideration have to be considered in the calculation. With the resulting Omega values the compressive forces N_0, N_u in the chords and $\bar{D}$ in the diagonal bar have to be increased.

It does not appear to be necessary to superimpose global and local buckling because neglecting the bedding of the whole system as well as the fixing of chords and diagonal bars in the junctions lead to results by far on the safe side for local buckling.

The maximum loading of the diagonal bars is given at the position of maximum shear force. In general, this is at the foot of the lattice girder. In the case of the chords the most unfavourable loading condition is obtained by superimposing the axial forces due to N and M and the local bending moments due to Q.

4. Investigations in the Laboratory and in the Field

The investigations comprise the deformability and loading capacity of the lattice girder without shotcrete (acting as an arch) as well as the bond behaviour of lattice girder and shotcrete.

4.1 Loading Capacity of Lattice Girders

In order to test the loading capacity of the lattice girders an investigation was carried out at the University of Munich (1983) in which a lattice girder was loaded to failure. Fig. 7 shows the test arrangement and the geometry of the test girder. The load P was applied on steel plates at the end of the arch. For own weight the arch was supported by two rollers. Thus rotations and dilatations of the arch ends were possible without restraint. The span of the test girder corresponded approximately to the distance between the points of zero bending moment of the girders used in the tunnels.

In order to plot continuously the load-deformation curve from the start of the test up to the peak load P_u an inductive displacement transducer was placed at the crown of the upper chord (Fig. 8). In addition, to measure the strains in the three chord bars, each bar was supplied with four crosswise arranged strain gauges. The load was also measured directly and printed out with the other test data using a multi-station system.

The girders failed at a load of 38.2 kN by buckling of a lower chord shortly before the yield limit was reached.

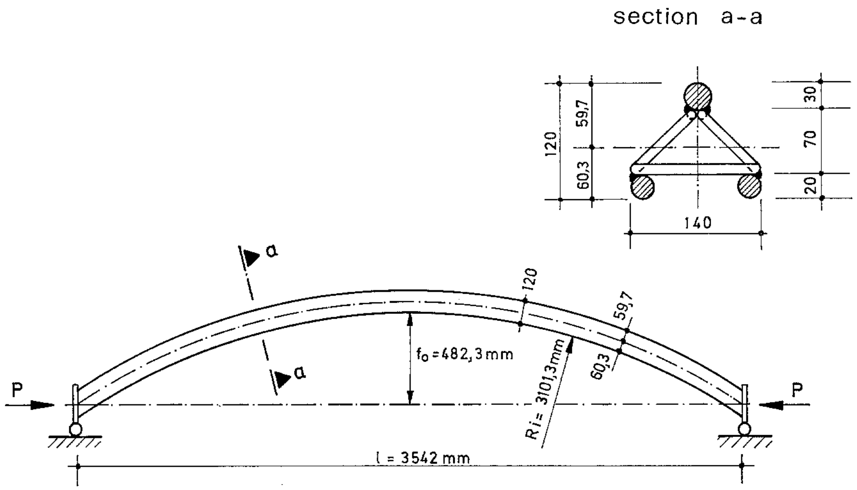

Fig. 7. Loading test on lattice girder

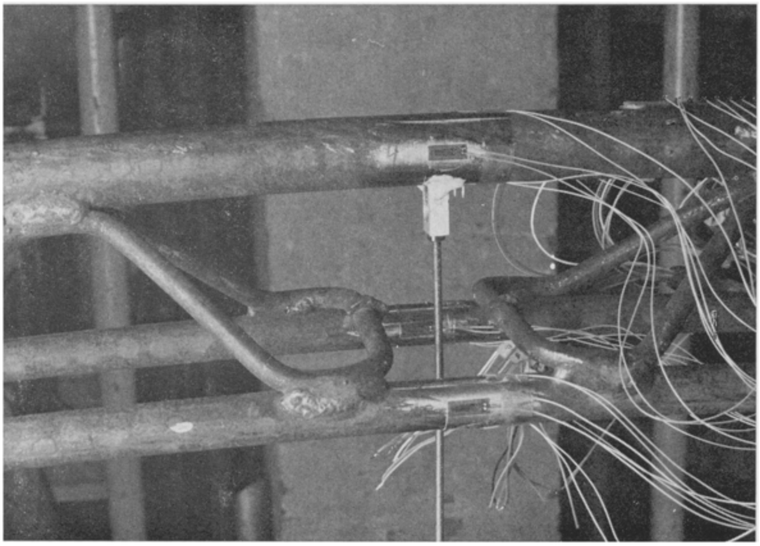

Fig. 8. Strain gauges and inductive displacement transducers at the crown of the arch for the test girder

The measured load-deformation curve is compared with the calculated one in Fig. 9. The loads P at which the lower chords begin to yield was determined by the theory presented in section 3. Thus the yield load at point B was calculated to be 24.6 kN and at point A (centre of girder) 38.0 kN. In addition, the lattice girder was modelled as a space frame and calculated with a computer program. Assuming that the material behaviour remained elastic, the deformation curves shown in Fig. 9 were obtained.

The comparison with the test result shows that after reaching the yield load at point B based on the equations given in section 3, the deformations increase more than proportionally. Thus plastic deformations must have taken place in the girder. Nevertheless, it was possible to increase the load by a factor of 1.5. This reserve in load capacity with respect to the start of yielding at point B is due to the fact that the bending moments in the chords could still be substantially increased by plastification, because the predominant type of the chord loading at point B was of the bending type. Altogether, a maximum deformation of 83 mm was obtained as the girder reached failure. This high value permits a direct contact between lattice girder and ground when used in tunnelling. In this way bedding forces are developed which act in a stabilizing manner on the lattice girders.

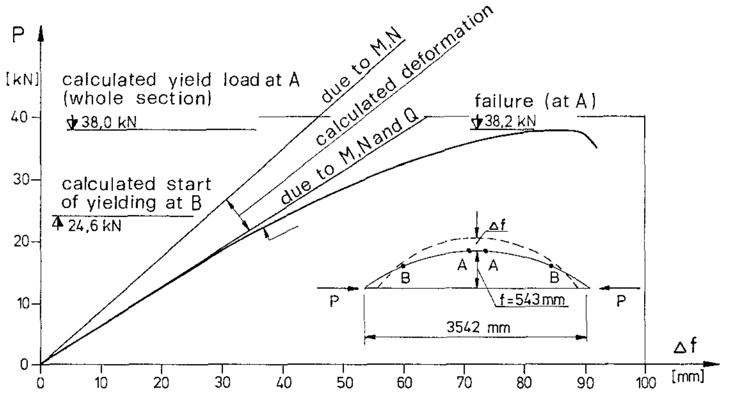

Fig. 9. Measured and computed load-deformation diagram for the test girder

In conclusion, the results of the loading test confirm that the initiation of yield in a lattice girder can be accurately predicted using the equations presented in section 3.

The peak load carried by the girder for the type of girder investigated here gives a margin of safety of 1.5 with respect to the load at which yielding first occurs. At the same time the girder exhibits a high ductility.

Thus it seems justified to assume as working load the load at which the lattice girder starts to yield.

4.2 Bond Between Lattice Girder and Shotcrete

The quality and especially the watertightness of the shotcrete lining is dependent upon the quality of the bond between the tunnel arch and the shotcrete. Plain girders more or less cause a separation in the shotcrete lining since it is practically unavoidable not to get fairly substantial shaded areas behind the arch which are not sprayed with shotcrete.

In the case of lattice girders a decisive improvement can be expected due to their special form of construction. In order to clear up any questions in this connection several test series were carried out. These concern in particular:

- shotcreting tests to determine if any shaded areas are obtained with lattice girders;
- water penetration tests;
- pull-out resistance tests to determine the bond strength of lattice girders embedded in shotcrete.

The tests were carried out on lattice girders of the type described in the previous sections (Fig. 1).

Shotcreting Tests

Three chord type girders were fixed to prefabricated shotcrete slabs simulating the excavation surface and covered with shotcrete. The chords consisted of 30 and 20 mm thick bars. The single bar ($d_s = 30$ mm) was fixed to the slab, i. e. it was on the side facing the ground. Both smooth and deformed bars were investigated. In addition, joints with steel angle connectors and with strengthened screw collars have been tested.

In order to simulate the existing site conditions in the roof and springlines one plate was shotcreted in an overhead manner, the other one in a vertical position. The slabs (with a thickness of 15 cm) with the shotcreted lattice girder were then sawn through in the axial direction and in a cross-section, photographed and tested for water penetration at the material testing division of the Department of Civil Engineering at the University of Munich (Eber, 1983).

Fig. 10 shows a characteristic cross-section of the lattice girder which was shotcreted with a vertically positioned plate (springline area).

The cross-section exhibits an almost completely closed concrete structure inside the bars forming the chords. Areas left uncovered by shotcrete were only observed between the outside chords and the prefabricated concrete slab modelling the excavation surface. The inside chords (i. e. towards the opening) were, however, completely surrounded by shotcrete.

In contrast to the above behaviour, a section through the angle connector showed distinct shaded areas lacking shotcrete (Fig. 11). While the shotcrete structure was free of voids on the side towards the tunnel opening, substantial disturbance to the structure was found on the outside part between the angle connector and the simulated ground. Similar effects can be expected with tunnel arches consisting of plain girders. The screw collar connector, on the other hand, gave a good shotcrete cover to the steel parts.

The following conclusions can be drawn from the evaluation of altogether about 40 sectional surfaces, as reported by Eber (1983).

The bonding of shotcrete on lattice girders is accompanied as a rule by an unavoidable area of voids between the outside chord and the excavation surface. In the case of ground water this area will be the cause of leakage (drainage). However, inward of the outside chord an intact shotcrete layer is constructed in which the diagonal bars, the inside chords and finally the steel reinforcing mesh are embedded.

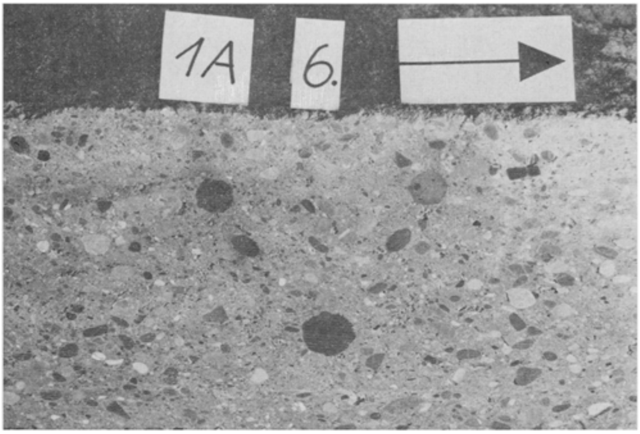

Fig. 10. Section through shotcreted lattice girder with smooth bars

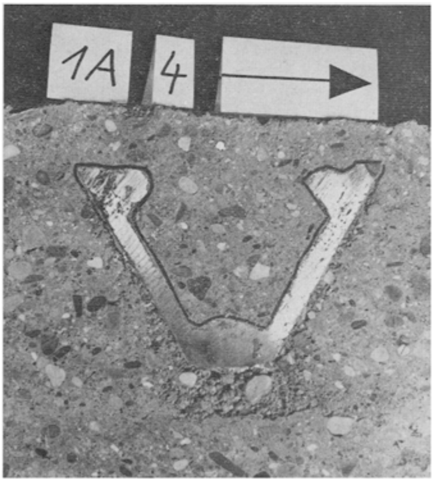

Fig. 11. Section through shotcreted angle connector

This concrete layer is connected without a joint to the shotcrete lining between the lattice girders. Thus the watertightness of the shotcrete lining increases towards the tunnel opening. The shaded areas deficient in shotcrete behind the outer chord could probably be reduced by having a greater distance between them and the excavation surface. However, this would contradict the requirements, which are given by the need of an immediate supporting action of the lattice girders before placement of the shotcrete lining.

Watertightness of the Shotcrete Lining in the Neighbourhood of the Lattice Girders

The sections of test specimen shown in Fig. 10 were subjected to water penetration tests according to DIN 1048. The water pressure was made to act in the opposite direction to that of the shotcrete application, thereby simulating flow out of the ground into the tunnel.

The shotcrete specimens were tested for 48 hours at a pressure of 1 bar, 24 hours at 3 bars and 24 hours at 7 bars. In the case of smooth bars a maximum penetration of 82 mm was observed, whereas deformed bars performed less well with water flowing out, at a pressure of 1 bar after 27 hours, along both inside (20 mm thick) chords.

This result indicates that the concrete structure around the chords is more impervious in the case of smooth bars than in the case of deformed bars.

Experiences at the construction site at section U 5/9-7 (Munich) showed that the imperviousness of the shotcrete lining is not impaired by the lattice girder. Water inflow does not occur in the area of the lattice girders, but primarily where the surface of the shotcrete lining is damaged due to mechanical causes or if it is not continuous, e. g. due to reinforcing bars normal to the surface. This is in agreement with the results of shotcreting tests described here:

The watertightness is mainly provided by the shotcrete layer inward of the outside chord. The inside chords have hardly any influence on the watertightness of this shotcrete layer.

Pull-out Tests with Smooth and Deformed Bars of Lattice Girders

The shotcrete lining of a tunnel carries loads basically as vault by normal forces. On this state of membrane stresses bending moments are superimposed. They are caused by the curvature of the lining due to the deformation following the excavation. These moments, which are of the restraint type, induce bond stresses between the chords of the girder and the surrounding shotcrete in the order of 0.5 MN/m^2.

Thus bonding strengths are necessary for the loading capacity of lattice girders combined with shotcrete to become fully effective. Of main importance here is the bond displacement diagram of the chord bars surrounded by shotcrete. The bonding strengths comprise an adhesive bond component and a frictional component. The deformed bars exhibit an increase of bond strength depending on the form of the profile. This increase becomes effective after the start of deformation. Smooth round bars, on the other hand, slip immediately after the start of deformation exhibiting no increase of bond strength even at high deformations.

In order to test the bonding behaviour of reinforcing bars embedded in shotcrete under site construction conditions, test specimens were shotcreted in the area of the springline of a shotcrete lining of section U 5/9-7 in Munich. After hardening the specimens were tested at the material testing division of the Department of Civil Engineering at the University of Munich.

Fig. 12 shows the corresponding test results compared with specimens of ordinary concrete. These may be summarized as follows:

— the bond strength with deformed and smooth bars for a concrete of quality B 25 is about 1.2 MN/m^2, whereby in this range the smooth bar exhibits somewhat higher values;

— based on the bond strengths given in DIN 1045 one can admit for shotcrete of quality B 25 under working load values of $\tau_0 = 0.6$ MN/m^2.

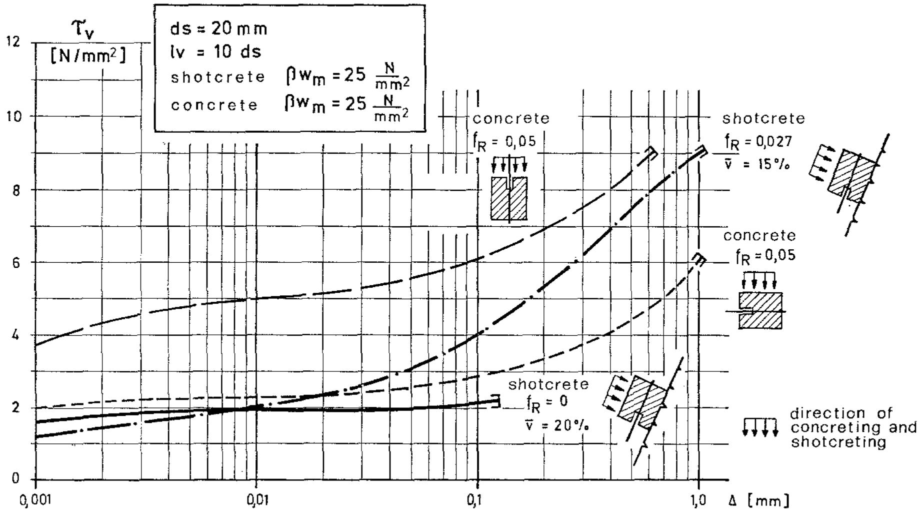

Fig. 12. Relationship between average bond strength τ_v and displacement Δ for various pull-out tests

f_R = area of the ribs related to area of the bar
$\bar{V}$ = coefficient of variation.

This strength is usually sufficient to provide a good bond between the lattice girder and the shotcrete lining. The welded junctions between the diagonal bars and the chords do not, therefore, need to be introduced into the static calculations to verify the system of bonding. However, at large deformations they provide an additional component of safety.

5. Application in the Construction of Underground Transport Systems

The regional capital of Bavaria, Munich, is involved at the present time in the construction of the underground section U 5/9-7. The civil engineering work is being carried out by a consortium of contractors, a leading part of which is the firm Philipp Holzmann AG. The section has two tunnel tubes of approximately 1350 m length, which are excavated using traditional (mining) techniques. The roof cover consisting of alternating layers of tertiary sand and clay is between 12 and 22 m thick. Artesian groundwater conditions are present in the sand layers, necessitating compressed air working.

Supporting elements comprise shotcrete with steel reinforcing meshes and steel plate arch supports (Weber, 1983).

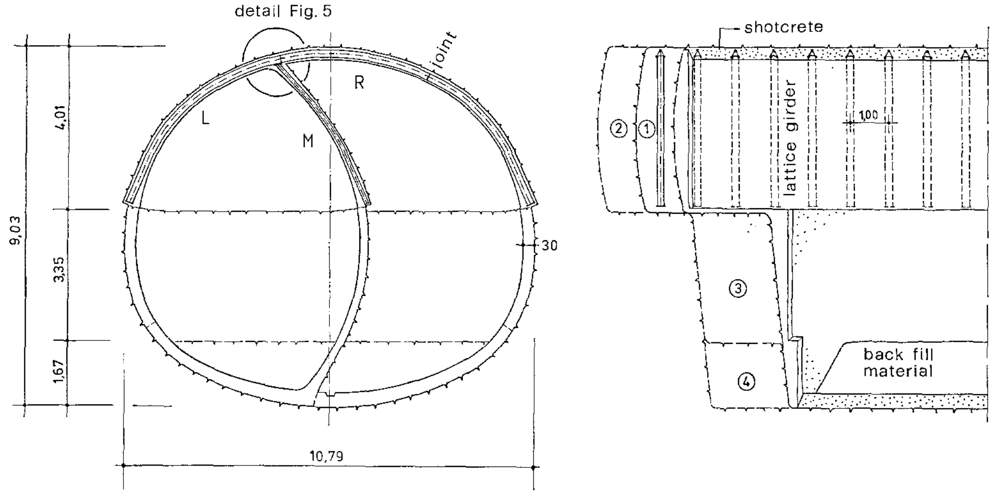

Fig. 13. Constructional method used for the cross-section at a station of the line U 5/9 of the Munich Underground

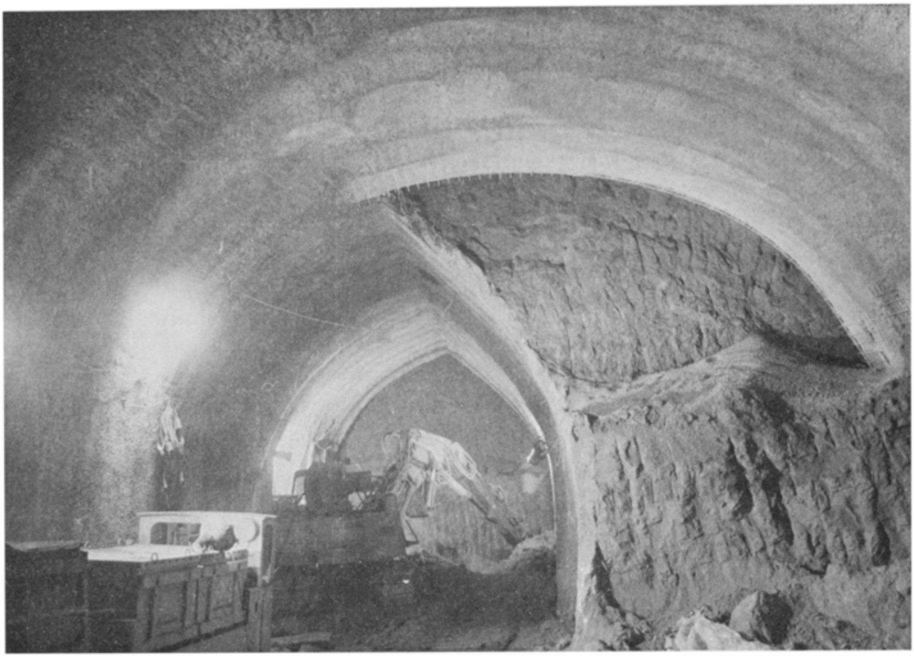

Fig. 14. Construction of a station of the line U 5/9 of the Munich Underground

After completion of the excavation work the compressed air is taken away to permit construction of the inner lining under atmospheric pressure conditions. At this stage the shotcrete lining must be capable of withstanding the full ground water pressure. Thus it must have an adequate statical load capacity and be practically watertight.

These requirements and the considerations outlined in sections 1 and 2 of the paper led to the use of lattice girders (System Pantex).

Tunnel cross-sections of more than 50 m^2 were excavated by the partial excavation method (Krischke and Weber, 1981). Figs. 13 and 14 illustrate this in the case of the station platform section ($A = 80\ m^2$). In the side drifts excavated first the lattice girders for the inside arch were of the same constructional type as in the single track stretch of tunnel. For the outside lattice girders, which are embedded in a 30 cm thick layer of shotcrete, the height of the girder construction was increased to 180 mm.

The diagonal bars of the girder were thickened to $d_s = 12$ mm. These girders were also designed according to the rules described in section 3.

After excavating a total of 900 m single track tunnel tube and 140 m platform cross-section in this constructional section (progress to end of 1983) the results of our investigations have proved beyond doubt the favourable properties of lattice girders even under site conditions. It may be assumed, therefore, that, in the future, lattice girders will have an increasingly wide application in tunnel engineering practice.

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