Tension and shear performance of anchor channels with channel bolts cast in Fibre Reinforced Concrete (FRC)

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Abstract. The available design rules for anchor channels with channel bolts were developed on the basis of the design rules for fasteners installed in conventional concrete. Recently, also more advanced reinforced concrete types became popular, e.g. fibre reinforced concrete for the production of prefabricated tunnel elements. The existing design rules for fasteners including anchor channels with channel bolts do not cover fibre reinforced concrete. To study the load-displacement behaviour in tension and shear, exploratory tests have been carried out on anchor channel-channel bolt-systems cast in plain and fibre reinforced concrete. The test results demonstrate a superior performance of channel bolts installed in anchor channels which were cast in fibre reinforced concrete if compared with systems cast in plain reinforced concrete.

1. Introduction

Anchor channels with channel bolts (aka T-bolts) allow an easy and reliable connection of any kind of component, e.g. trays, railings, lights, sprinklers and equipment. This connection method is also very suitable for tunnels excavated with tunnel boring machines where prefabricated concrete elements are used for the lining (figure 1). Since the tunnel lining is predominantly loaded in compression, the conventional reinforcement of the concrete segments is increasingly replaced by fibre reinforcement. While fibre reinforced concrete (FRC) makes the post-installation of fasteners difficult, it is an ideal substrate for anchor channels-channel bolt-systems.

Figure 1. Examples for anchor channels cast in a prefabricated element ready to install channel bolts.
2. Background

2.1. Anchoring in concrete using anchor channels with channel bolts

Anchor channels combined with channel bolts allow the reliable connection of steel components to the reinforced concrete structure. To this end, T-shaped channel bolts are locked into C-shaped anchor channels (figure 2a) that have been cast into the reinforced concrete. Conventional anchor channels allow the transfer of tension loads (N) and shear loads perpendicular to the channel (V_\perp). Serrated anchor channels and matching serrated channel bolts have recently been developed to also enable load transfer in the direction of the channel (V_\parallel), thus making load transfer in all directions possible (figure 2b). Simulated seismic load tests showed that the load bearing behaviour of the serrated connection is very robust. This is because adjacent teeth are activated when the teeth in the contact area between the head of the channel bolt and the lips of the anchor channel start to fail. This allows the qualification of the serrated channels according to the highest seismic requirements [1].

![Figure 2. a) Components of anchor channel and channel bolt; b) Serrated systems allow load transfer in all directions.](image)

For installation, the anchor channel is hot glued or nailed to the formwork (figure 3a). Anchor channels are generally furnished with filler material to prevent concrete slurry leaking into the profile during concreting. After the concrete is set and the formwork is stripped off, the filler is removed (figure 3b and c). Channel bolts are then inserted and twisted in the slot of the anchor channel to allow fastening of components at any point along its length (figure 3d).

![Figure 3. Installation sequence a) attaching of anchor channel to formwork, b) pouring of concrete, c) removing of filler, d) twisting-in of channel bolt.](image)
The design of anchor channels with channel bolts is codified in the European standard EN 1992-4 [2] which requires a qualification of the system according to the European assessment guideline EAD 330008-02-0601 [3]. Equivalent counterparts exist in the USA [4, 5].

2.2. Fibre reinforced concrete (FRC)
Even decades after invention, FRC is still largely considered to be new, advanced and innovative – owed to the fact that FRC still has a niche existence despite the compelling advantages if compared with standard reinforced concrete. One reason for this situation is certainly that FRC elements still have to be designed on the basis of project approvals or national guidelines (e.g. [6]). However, the revision of the European standard for the design of reinforced concrete structures EN 1992-1-1 [7] will include FRC in Annex L. By this the use of FRC will gain more popularity.

Currently, FRC is used to replace or to minimize the conventional reinforcement in structural elements which are mostly loaded in compression, such as industrial floors (e.g. [8]) or tunnel linings (e.g. [9]). Further, structural elements loaded in shear are deemed to be suitable for the FRC, such as shear panels (e.g. [10]). Fibre admixtures are also becoming popular to increase the water tightness of perimeter walls and foundation slabs or for the joining of prefabricated elements (e.g. [11]). Structural elements predominantly loaded in tension, however, are rarely designed in FRC.

2.3. Anchoring in FRC
The proliferation of FRC also means that anchoring of structural and non-structural components has to be carried out in this substrate. Not many tests on fasteners used for the anchoring in FRC have been conducted yet.

E Walter and W Ammann [12] studied the behaviour of post-installed undercut fasteners, adhesive fasteners, and wedge fasteners under tension and concluded that a statistically significant increase of the capacities cannot be inferred. Also Y Klug et al. [13] found it difficult to predict the increase in tension capacity of post-installed fasteners and reasoned that this is due to the inhomogeneous distribution and orientation of the fibres. K Coventry et al. [14] recorded a tension capacity increase of adhesive fasteners by about 10% due to steel fibres. C Kurz et al. [15] stated that fasteners post-installed in FRC develop tension capacities which are at least equivalent to the capacity if post-installed in regular concrete. Note that the above studies used typical post-installed fasteners, which may also fail in steel or bond – modes which are not influenced by fibres in the concrete. The only shear tests on post installed fasteners which have ever been carried out and were reported after the test program presented below was accomplished are those of M Tóth et al. [16]. The tests on single adhesive anchors supported a tentative model based on a combination of available design concepts and load increase factors to capture the beneficial effect of steel fibres on the concrete cone and edge breakout capacity. The positive influence of steel fibres in particular with regard to asymmetrically loaded groups of post-installed fasteners was reasoned with an elasto-plastic model according to a performance based approach [17]. Several of the studies mentioned that drilling in FRC with steel fibres is difficult because the steel fibres may cause jamming and increased wear of the drilling tools. This challenge is exacerbated because high performance concrete i.e. high strength concrete is typically used for FRC elements. In these regards, cast-in fasteners are more suitable for the anchoring in FRC, e.g. anchor channels with channel bolts.

R Nilforoush et al. [18] carried out tension tests on cast-in headed fasteners in plain and steel fibre reinforced normal- and high-strength concrete with compressive strengths up to 80 MPa. It was concluded that the concrete capacity (design) method [19] considerably underestimates the tensile breakout capacity of headed fasteners in fibre reinforced concrete and that fibres facilitate a pronounced ductile deformation at ultimate load and prevent a brittle post-peak behaviour potentially associated with high-strength concrete. Some of the first published shear tests on cast-in fasteners have recently been conducted by J-H Lee et al. [20]. The tested cast-in headed fasteners showed a pronounced correlation of ultimate shear capacity and fibre content.

To the knowledge of the authors, neither tension nor shear tests on channel bolts installed in anchor channels which were cast in FRC have been carried out to date. For this reason, an extensive test program...
was launched to investigate the performance of channel bolts-anchor channels-systems in FRC. Because the headed anchors typically fail in concrete related modes and develop a group behaviour due to the joint connection to the channel, fibres should have beneficial effects.

3. Tests

3.1. Specimen
For all tests, a concrete mixture with a tested compressive strength of about 95 N/mm² was used which is representative for applications where FRC is used. The fibres provided from the producer KrampeHarex were made of circular, non-alloy steel wire with end hooks, diameter 0.75 mm, length 60 mm and a nominal steel yield strength of 1900 N/mm². The fibre mass content was 40 kg/m³, equal to about 0.5% by weight. 320 mm long JORDAHL© anchor channels JTA W 53/34 were cast into the concrete members. These anchor channels were made of hot-rolled profiles with two anchors at a distance of \( s = 250 \) mm. For embedment depths smaller than the standard depth of \( h_{cf} = 155 \) mm with round headed anchors riveted to the channel, I-shaped anchors made of cut I-beams were welded to the channel. Shutter and concrete works were carried out in a precast yard of the company Max Bögl. The installation of the JORDAHL© T-bolts JB M16 prior to testing completed the test specimens. The grade 8.8 channel bolts had a nominal steel yield strength of 640 N/mm².

3.2. Program
The 8 shear and 8 tension test series presented in this paper (table 1) are part of a larger test program. The number of test repeats within each series was typically 3 for shear and 5 for tension tests in fibre reinforced concrete and 2 for shear and 3 for tension reference tests in plain concrete. The edge distance \( c_1 \) and the embedment depth \( h_{cf} \) varied for the shear and tension test series, respectively. In addition to the 48 tests on anchor channel-channel bolt-systems, tests to determine the performance class of the fibre reinforced concrete were carried out that are not discussed in this paper.

| Table 1. Test program. |
|---|---|---|---|---|
| Series* | Repeats | Load direction | Concrete type | Concrete strength \( f_{c,test} \) [MPa] | Edge distance \( c_1 \) [°] | Embedment depth \( h_{cf} \) [mm] |
| S-p-50-155 | 2 | Shear | plain | 96.4 | 50 | 155 |
| S-f-50-155 | 3 | Shear | fibre | 98.6 | 50 | 155 |
| S-p-100-155 | 2 | Shear | plain | 96.4 | 100 | 155 |
| S-f-100-155 | 3 | Shear | fibre | 98.6 | 100 | 155 |
| S-p-150-155 | 2 | Shear | plain | 96.4 | 150 | 155 |
| S-f-150-155 | 3 | Shear | fibre | 98.6 | 150 | 155 |
| S-p-200-155 | 2 | Shear | plain | 96.4 | 200 | 155 |
| S-f-200-155 | 3 | Shear | fibre | 98.6 | 200 | 155 |
| T-p-∞-69 | 2 | Tension | plain | 94.1 | ∞ | 69 |
| T-f-∞-69 | 5 | Tension | fibre | 98.2 | ∞ | 69 |
| T-p-∞-95 | 2 | Tension | plain | 94.1 | ∞ | 95 |
| T-f-∞-95 | 5 | Tension | fibre | 98.2 | ∞ | 95 |
| T-p-∞-120 | 1 | Tension | plain | 94.1 | ∞ | 120 |
| T-f-∞-120 | 5 | Tension | fibre | 98.2 | ∞ | 120 |
| T-p-∞-155 | 3 | Tension | plain | 92.5 | ∞ | 155 |
| T-f-∞-155 | 5 | Tension | fibre | 92.8 | ∞ | 155 |

* Code: Shear or Tension-plain or fibre-c_1-h_{cf}. ∞ equals to any distance larger than 2h_{cf}
3.3. Setup
The tests were carried out at the Jordahl Test Laboratory. Two different unconfined test setups were used where the support has sufficient distance to the anchoring in order to allow the development of a full concrete breakout (figure 4). For shear loading, the test specimens were placed on a strong floor and tied down to counteract the vertical uplift forces deriving from eccentricity effects. A support accommodated the actuator for shear loading and provided horizontal bearings at a distance of $5c_1 + s$. A PTFE sheet was placed on top of the anchor channel and surrounding concrete before the loading fixture was connected with a balance beam to ensure equal loading of the two channel bolts installed above the anchors. For tension loading, a support with the mounted actuator for tension loading formed with the test specimen a self-equilibrium system. The contact area had a distance of at least $2h_{ef}$ from the centre of anchoring. The loading fixture was connected to a channel bolt installed above an anchor.

The anchor channel-channel bolt system was monotonically loaded to failure at a constant rate within 2 to 3 minutes. Load cells and displacement transducers recorded load $F_u$ and displacement $\delta$ at a rate of 5 Hz.

![Figure 4. Test setup for shear loading (left) and tension loading (right).](image)

3.4. Results
The coefficients of variation (cv) were reasonable despite the small number of test repeats per series (table 2): The cv of the ultimate load $F_u$ was typically well below 15% which is the threshold commonly accepted for concrete related failure modes in fastener qualification testing. The high cv of one series (S-f-100-155) can be attributed to a test with a bias towards an outlier. The cv of the displacement at 50% of the ultimate load $\delta(0.5F_{u,m})$ was always below 40% which is the maximum accepted in the context of fastener qualification.

Overall, no clear trend of the coefficients of variation with regard to the concrete type (plain or fibre) could be inferred. By trend, the recorded displacements $\delta(0.5F_{u,m})$ and $\delta(F_{u,m})$ confirmed that fibres consistently support a more ductile behaviour also of anchor channels with channel bolts. More prominent, the fibres significantly influenced the ultimate load $F_u$ and the failure modes of the tested anchor channel-channel bolt-systems: Subjected to shear load, only the systems cast in fibre reinforced concrete with the largest tested edge distance $c_1 = 200$ mm failed in steel due to shearing off the bolt, otherwise concrete edge breakout was decisive. Under tension load, only the systems cast in plain concrete with the embedment depth $h_{ef} \leq 95$ mm failed consistently by concrete cone breakout, otherwise steel failure of bolt, lip or anchor occurred (rupture or bending). Clearly, if steel failure is the controlling failure mode, fibres have no effect. If failure occurs due to concrete breakout, the fibres
increased the capacity significantly by the factor of about 1.8 for shear and 1.4 for tension. Moreover, the fibres allow the shift of the transition from concrete breakout to steel failure (figure 5).

Table 2. Test results.

| Series   | $F_{u,m}$ [mm] | $cv(F_u)$ [%] | $\delta(0.5F_{u,m})$ [mm] | $cv(s(0.5F_{u,m}))$ [%] | $\delta(F_{u,m})$ [mm] | Failure mode* |
|----------|----------------|---------------|---------------------------|-------------------------|------------------------|---------------|
| S-p-50-155 | 47.6           | 1.6           | 0.71                      | 13.46                   | 3.00                   | 2 C           |
| S-f-50-155 | 81.0           | 0.8           | 1.23                      | 27.8                    | 4.66                   | 3 C           |
| S-p-100-155 | 71.8          | 11.2          | 1.42                      | 23.3                    | 2.67                   | 3 C           |
| S-f-100-155 | 172.0         | 21.3          | 1.94                      | 15.6                    | 5.43                   | 3 C           |
| S-p-150-155 | 105.0         | 4.1           | 1.58                      | 16.6                    | 3.23                   | 3 C           |
| S-f-150-155 | 212.6         | 3.6           | 1.77                      | 10.7                    | 5.21                   | 3 C           |
| S-p-200-155 | 144.4         | 2.8           | 1.83                      | 17.9                    | 2.84                   | 3 C           |
| S-f-200-155 | 269.4         | 2.0           | 2.71                      | 12.4                    | 7.98                   | 3 S<sub>b</sub> |
| T-p-∞-69    | 89.6           | 8.0           | 0.66                      | 18.4                    | 5.61                   | 2 C           |
| T-f-∞-69    | 110.3          | 2.9           | 1.31                      | 17.8                    | 9.11                   | 1 C, 1 S<sub>l</sub>, 3 S<sub>b</sub> |
| T-p-∞-95    | 99.6           | 15.0          | 0.90                      | 5.5                     | 8.29                   | 2 C           |
| T-f-∞-95    | 106.0          | 3.6           | 1.23                      | 9.4                     | 9.13                   | 1 C, 2 S<sub>l</sub>, 2 S<sub>b</sub> |
| T-p-∞-120   | 105.2          | –             | 1.06                      | –                       | 11.21                  | S<sub>l</sub>  |
| T-f-∞-120   | 109.2          | 2.4           | 1.42                      | 10.2                    | 11.94                  | 4 S<sub>l</sub>, 1 S<sub>b</sub> |
| T-p-∞-155   | 93.5           | 4.3           | 0.95                      | 37.4                    | 20.70                  | 1 S<sub>l</sub>, 2 S<sub>b</sub> |
| T-f-∞-155   | 91.3           | 7.1           | 0.93                      | 37.7                    | 22.44                  | 4 S<sub>l</sub>, 1 S<sub>b</sub> |

* S<sub>b</sub>: steel failure bolt; S<sub>l</sub>: steel failure lip; S<sub>a</sub>: steel failure anchor; C concrete cone or edge breakout

Figure 5. Capacities achieved in plain and fibre reinforced concrete tested in a) shear and b) tension.

To compare the performance of anchor channel-channel bolt-systems cast in plain and fibre reinforced concrete further, the influence of edge distance $c_1$ and embedment depth $h_{ef}$ is illustrated by means of typical curves recorded during the shear and tension tests (figure 6): The fibres cause a substantial increase of the shear capacity where the failure mode remains concrete edge breakout if
tested with an edge distance of $c_1 = 50 \text{ mm}$ (figure 6a) but changes to steel failure if tested with an edge distance of $c_1 = 200 \text{ mm}$ (figure 6b). In this case, the displacement at ultimate load is roughly tripled. The fibres also cause a change from concrete cone breakout to steel failure, accompanied by a distinct increase in tension capacity and displacement, if customized systems with an embedment depth of $h_{ef} = 69 \text{ mm}$ are tested (figure 6c). In contrast, no significant influence of the fibres can be determined if the standard system with an embedment depth of $h_{ef} = 155 \text{ mm}$ is tested since for this configuration steel failure is controlling already in case the anchor channel-channel bolt-system is cast into concrete without fibres (figure 6d). The examples demonstrate that the fibres increase the ductility of concrete breakouts and may allow a change to steel failure modes.

**Figure 6.** Load-displacement curves of anchor channels-channel bolt-systems cast in plain and fibre reinforced concrete tested in shear with a) small and b) large edge distance and tested in tension with c) small and d) large embedment depth.

### 4. Summary and conclusion

Fibre reinforced concrete (FRC) gains importance for the construction of structural members, e.g. tunnel segments. The drilling in FRC for the post-installation of fasteners is challenging, not least because of the high concrete strengths prevalent for FRC. Also due to other reasons, anchor channels with channel bolts are a suitable solution for the connections of components with FRC. However, no study on the performance of anchor channel-channel bolt-systems in FRC has been published to date.

For this reason, a research program was launched to compare the performance of channel bolts installed in anchor channels cast in plain and fibre reinforced concrete. The results of 48 shear and
tension tests presented in this paper demonstrate that anchor channel-channel bolt-systems cast in fibre reinforced concrete sustain higher ultimate loads and develop larger corresponding displacements if compared with identical systems cast in plain concrete. The increase in capacity and ductility may lead to a positive shift from rather brittle concrete breakout to more ductile steel failure modes.

The views expressed in this paper are the views of the authors only and do not necessarily reflect the views of KrampeHarex, Max Bögl, and Jordahl.

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