Influence of the Steel Fibres on the Tension and Shear Resistance of Anchoring with Anchor Channels and Channel Bolts Cast in Concrete

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Abstract. The current design method for anchor channels with channel bolts is based on test results for fasteners installed in conventional concrete. The field of application for steel fibre concrete have been growth over the last years and recently steel fibre reinforced concrete became popular e.g. for the production of prefabricated tunnel elements. The existing design rules for fasteners including anchor channels with channel bolts do not cover steel 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 steel fibre reinforced concrete. The test results demonstrate a superior performance of channel bolts installed in anchor channels which were cast-in steel fibre reinforced concrete if compared with systems cast in plain reinforced concrete. The results of the experimental investigations will be explained und discussed in this article.

Keywords: Anchor channel · Channel bolt · Anchorage · Steel fibre reinforced concrete (SFRC) · Concrete · Capacity · Ductility

1 Introduction

The addition of steel fibres to the concrete mix increases the tensile strain capacity and ductility as well as improves the structural properties of concrete in its hardened state such as the tensile strength, impact strength, toughness, fatigue strength and the ability to resist cracking and spalling. Due to better mechanical and physical properties became the usage of steel fibre reinforced concrete (SFRC) over the last decades a better alternative to the conventional reinforcing concrete and being widely used as a construction material. Due to addition of steel fibres, the overbridging of cracks (Fig. 1) is ensured and so the cracking resistance of concrete increases [1]. This beneficial effect leads to an increase in the concrete resistance under quasi-static, cyclic and impact loading and furthermore, to the increase of the spalling resistance [1–3].

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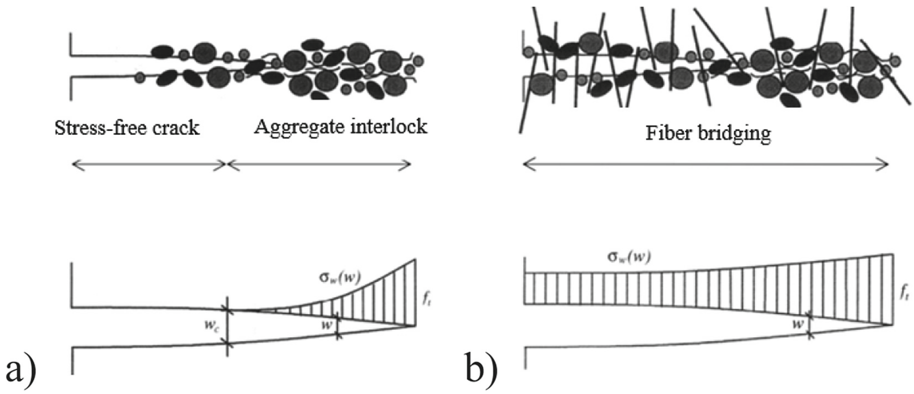

Fig. 1. Crack-bridging mechanism, a) in normal concrete and b) in SFRC from [2, 3].

Various factors and mechanisms influence the tensile behaviour of SFRC, including the pullout behaviour of individual fibres, the random distribution of fibres, and the effects of finite member dimensions [4]. Especially in members with end-hooked fibres, the tensile behaviour of mechanical anchorage is essential in addition to the frictional bond behaviour between fibres and concrete matrix [4]. The use of medium-high steel fibres contents significantly improves the post-peak behaviour in tensile for flexure, by extending the softening branch and reducing the negative slope. Steel fibres give to the concrete a sizable post-peak residual strength. This lead to an improved fracture energy and toughness of SFRC materials with high fibre content compared to ordinary concrete [4].

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 (Fig. 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 $(V_{||})$, thus making load transfer in all directions possible (Fig. 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 [5, 6].

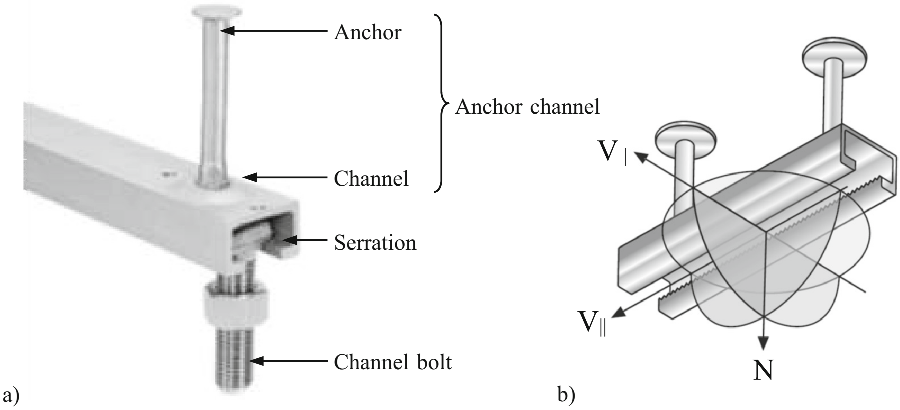

Fig. 2. a) Components of anchor channel and channel bolt; b) Serrated systems allow load transfer in all directions.

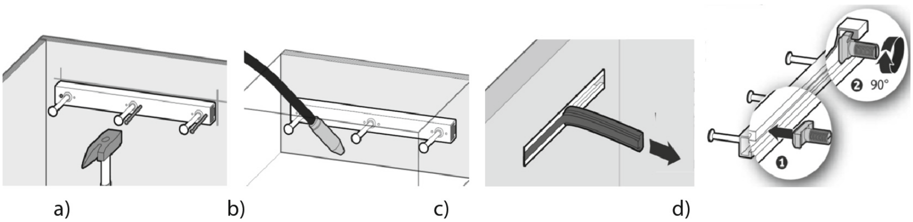

Fig. 3. Installation sequence a) attaching of anchor channel to formwork, b) pouring of concrete, c) removing of filler, d) twisting-in of channel bolt.

For installation, the anchor channel is hot glued or nailed to the formwork (Fig. 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 (Fig. 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 (Fig. 3d).

Connections using anchor channels with channel bolts have several advantages, making anchor channels with channel bolts suitable for the connection of any kind of component in concrete, e.g. elevator guide rails, curtain wall brackets, and particularly technical equipment in tunnels [7–9]:

- Quick and easy installation of the anchor channel during concreting
- Compensation of building tolerances by adjusting the position of channel bolt along the length of the anchor channel
- Robust load transfer due to mechanical interlock (bolt-channel, anchor-concrete)

– Unlike for anchor plates no on-site welding is required, thus no weld quality issues, or fire risks
– Unlike for post-installed fasteners no on-site drilling required thus no hassle with positioning or cutting of reinforcing bars, and no exposition of the workforce to harmful silica dust
– Later positional adjustment, or replacement of attached components is made easy at any time

The design of anchor channels with channel bolts was just recently codified as the European standard EN 1992–4 (2018) [10] which requires a qualification of the system according to the European assessment guideline EAD 330008-02-0601 (2016) [11].

SFRC in Precast Segment for Tunnel Lining
Due to the advantages of SFRC in performance, durability and in terms of cost reductions compare to traditionally reinforced concrete the application and the use of SFRC in precast tunnel lining design is a growing trend [12, 13] (s. Figure 4). Anchor channels with channel bolts (aka T-bolts) allow an easy and reliable connection of any kind of component for such structures, e.g. trays, railings, lights, sprinklers and equipment. While SFRC makes the post-installation of fasteners difficult, it is an ideal substrate for anchor channels-channel bolt-systems.

Fig. 4. Construction of the tunnel lining segments, from [14].

Anchoring in SFRC
The proliferation of SFRC 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 SFRC have been conducted yet.

Walter, E. and Ammann, W. [15] 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 Klug, Y., Holschemacher, K. et al. [16] 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. Kurz, C., Thiele, C. et al. [17] reported that fasteners post-installed in SFRC develop tension capacities which are at least equivalent to the capacity if post-installed in regular concrete. To the knowledge of the authors, no shear tests on post-installed fasteners have ever been carried out yet. All studies mentioned that drilling in SFRC 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 SFRC elements. In these regards, cast-in fasteners are more suitable for the anchoring in SFRC, e.g. anchor channels with channel bolts. Nilforoush, R., Nilsson, M. 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 (Fuchs, W., Eligehausen, R. et al. [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 Lee, J.-H., Cho, B.-S. et al. [20]. The tested cast-in headed fasteners showed a pronounced correlation of ultimate shear capacity and fibre content. However, neither tension nor shear tests on channel bolts installed in anchor channels which were cast in SFRC have been carried out to date. To investigate the performance of channel bolts-anchor channels-systems in SFRC, an extensive test program was launched.

2 Experimental Investigations

2.1 Materials

For all tests, the same concrete mixture with a tested compressive strength of about 95 N/mm^2 was used which is representative for applications where SFRC is used. No reinforcing bars were installed since anchor channel-channel bolt-systems are generally cast in unreinforced concrete members to study their load-displacement behaviour, e.g. for product qualification. The steel 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/mm^2. The fibre mass content was 40 kg/m^3, equal to about 0.5% by weight. 320 mm long anchor channels JTA W 53/34 from the producer Jordahl 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_{ef} = 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 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/mm^2.

2.2 Test 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_{ef} 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.

2.3 Test Setup

The tests were carried out at the Jordahl Test Laboratory (three point bending tests were carried out at the Frankfurt University of Applied Sciences and concrete tests were carried out at the Max Bögl 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 (Fig. 5 and 6). 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 min. Load cells and displacement transducers recorded load F_u and displacement δ at a rate of 5 Hz.

Table 1. Test Program, [6]

Series*	Repeats	Load direction	Concrete type	Concrete strength $f_{c,test}$ [MPa]	Edge distance c_1° [mm]	Embedment depth h_{ef} [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: **S**hear or **T**ension-**p**lain or **f**ibre-c_1-h_{ef}; ° ∞ equals to any distance larger than $2h_{ef}$

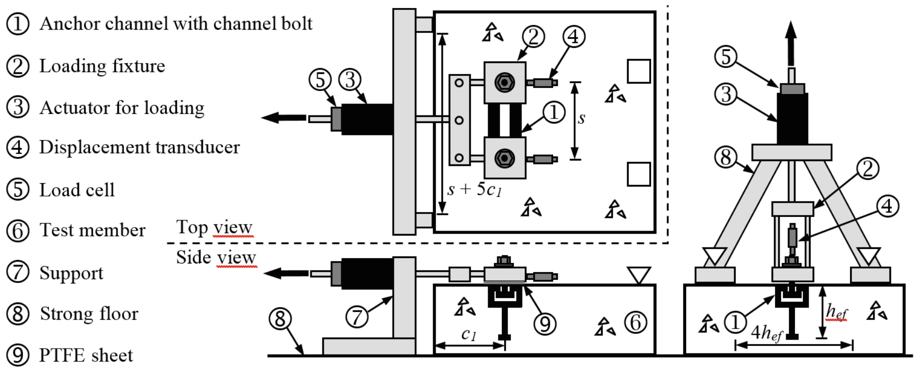

Fig. 5. Test setup for shear loading (left) and tension loading (right), [6].

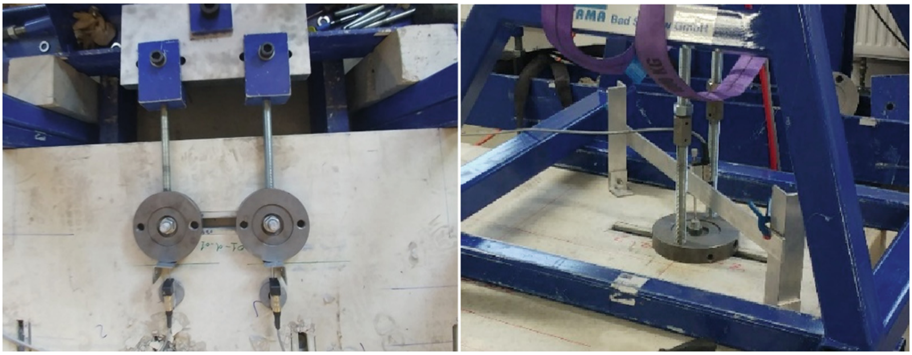

Fig. 6. Pictures of the test setup for shear loading (left) and tension loading (right).

2.4 Test 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.

Table 2. Test results, [6].

Series	Ultimate load $F_{u,m}$ [mm]	Coeff. of var. cv(F_u) [%]	Displacement $\delta(0.5F_{u,m})_m$ [mm]	Coeff. of var. cv(s(0.5$F_{u,m}$)) [%]	Displacement $\delta(F_{u,m})_m$ [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_b
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_l, 3 S_b
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_a, 2 S_l
T-p-∞-120	105.2	–	1.06	–	11.21	S_l
T-f-∞-120	109.2	2.4	1.42	10.2	11.94	4 S_l, 1 S_b
T-p-∞-155	93.5	4.3	0.95	37.4	20.70	1 S_l, 2 S_b
T-f-∞-155	91.3	7.1	0.93	37.7	22.44	4 S_l, 1 S_b

* S_b: steel failure bolt; S_l: steel failure lip; S_a: steel failure anchor; C concrete cone or edge breakout

Overall, no clear trend of the coefficients of variation with regard to the concrete type (plain or fibre) could be inferred (s. last paragraph). 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 (s. Fig. 7, 8 and 9). The dashed lines (Fig. 9a and 9b) represent the mentioned transmission to steel failure depending on the test results (s. Table 2, failure mode).

Fig. 7. Pictures of the failure under tension loading.

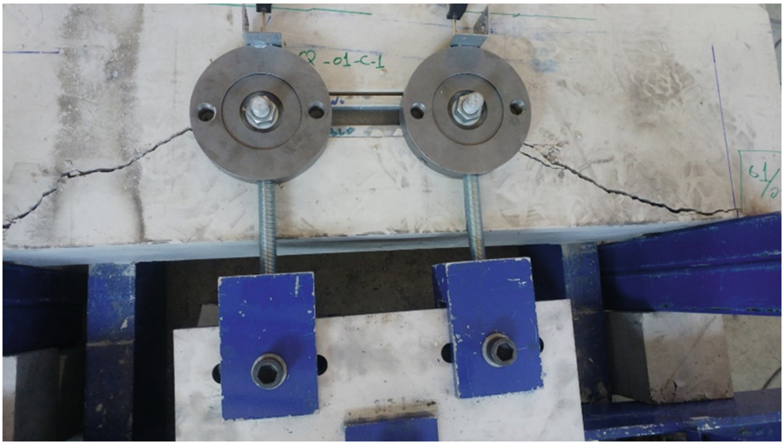

Fig. 8. Pictures of the failure under shear loading.

To compare the performance of anchor channel-channel bolt-systems cast in plain and fibre reinforced concrete further, the influence of the edge distance c_1 and embedment depth h_{ef} is illustrated by means of typical curves recorded during the shear and tension tests (Fig. 10): The fibres cause a substantial increase of the shear capacity where the failure mode remains concrete edge breakout if tested with an edge distance

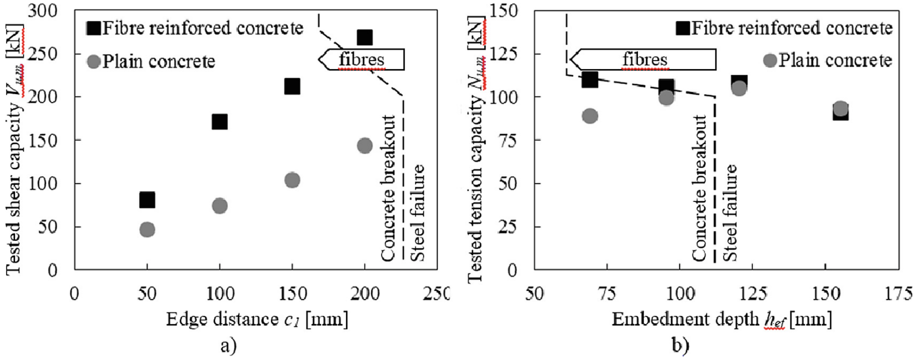

Fig. 9. Capacities of anchor channels-channel bolt-systems cast in plain and fibre reinforced concrete tested a) in shear and b) in tension for different edge distances and embedment depths, respectively, [6].

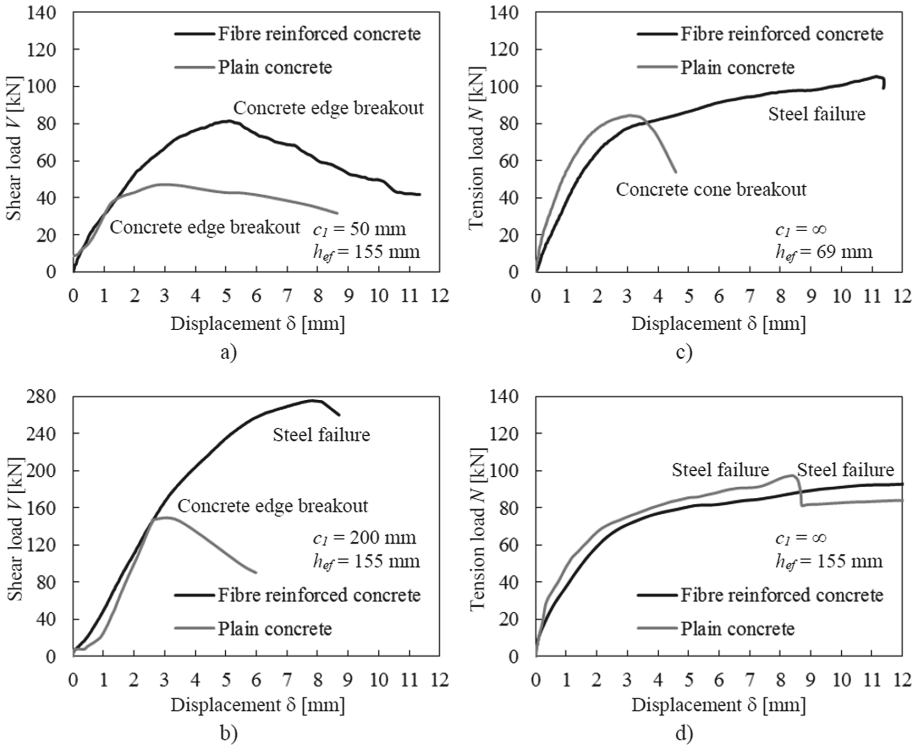

Fig. 10. Load-displacement curves of anchor channels-channel bolt-systems cast in plain and fibre reinforced concrete tested in shear with a) small and b) large edge distance and tested in tension with c) small and d) large embedment depth, [6].

of c_1 = 50 mm (Fig. 10a) but changes to steel failure if tested with an edge distance of c_1 = 200 mm (Fig. 10b). 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 mm are tested (Fig. 10c). In contrast, no significant influence of the fibres can be determined if the standard system with an embedment depth of h_{ef} = 155 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 (Fig. 10d). The examples demonstrate that the fibres increase the ductility of concrete breakouts and may change it to steel failure modes.

3 Summary and Conclusion

Steel Fibre reinforced concrete (SFRC) gains importance for the construction of structural members, e.g. tunnel segments. The drilling in SFRC for the post-installation of fasteners is challenging, not least because of the high concrete strengths prevalent for SFRC. For this and other reasons, anchor channels with channel bolts are often a favourable solution to connect any component to structural elements made of SFRC. However, no study on the performance of anchor channel-channel bolt-systems has been published to date.

To this end, 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 Jordahl, Max Bögl and KrampeHarex.

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