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Innovative Seismic Fuse Concept using T-Bolts Installed in Cast-in Anchor Channels

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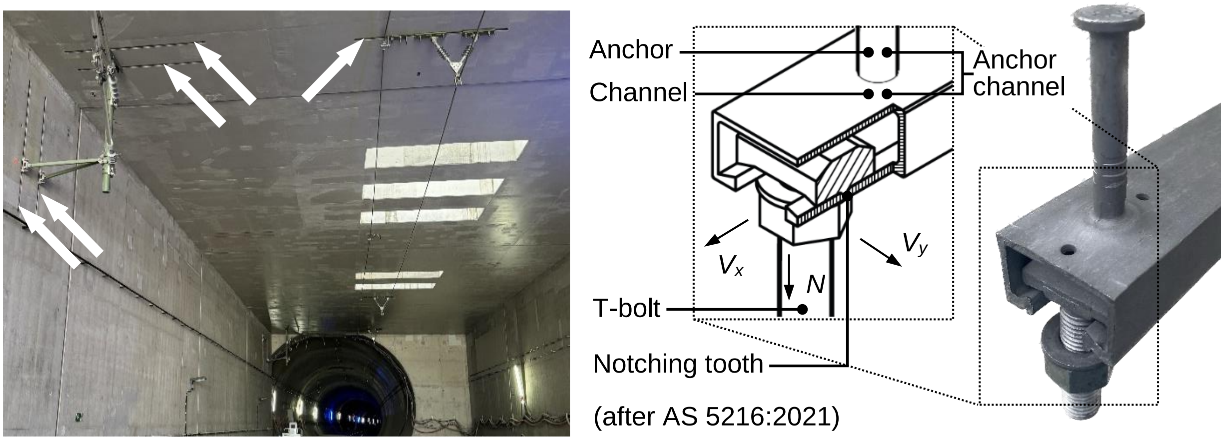
Abstract

Due to their robustness, reliability, and simplicity, cast-in anchor channels with T-bolts are a perfect solution to connect any construction element, e.g. MEP works or platforms, to a reinforced concrete structure. According to the reinforced concrete design codes, the best option to design single-point concrete fasteners for seismic tension load is to use ductile steel and provide sufficient free stretch length. Static and seismic tests were carried out on T-bolts with a code-compliant free stretch length to validate the concept also for anchor channels.

Keywords: anchor channels, T-bolts, seismic fuse, stretch length, value-engineering.

1 Introduction

Since their invention by Jordahl in 1913, anchor channels with T-bolts provide versatile possibilities to connect construction elements, e.g. façade panels, elevator railings, sound barriers, platforms, and MEP works (Figure 1a), to reinforced concrete structures.



a) *b)*

Figure 1. a) Anchor channels used to connect the catenary system at the 20 billion AUD railway project S21 in Germany; b) Anchor channel parts and matching notching T-bolt.

According to recent building design codes, concrete fasteners including anchor channels have to be qualified if used for safety-relevant connections. Because of their high load capacity, anchor channels are typically used to fix heavy loads and therefore always qualification. Besides the careful selection of suitable and certified products by the specifier, a professional engineer is required to design a safe connection with anchor channels.

The design rules for anchor channels are mostly based on the general design rules developed for single-point concrete fasteners, i.e. post-installed concrete anchors and cast-in headed studs. Unique failure modes of anchor channel and T-bolt, however, require additional and quite complex design rules (Mahrenholtz and Sharma 2019). The framework of the design rules is explained below, following the presentation of some background information.

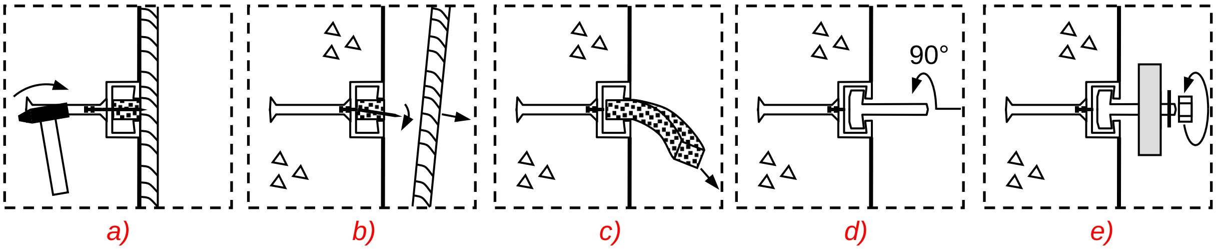
2 Background

The invention of anchor channels with T-bolts more than 100 years ago (German Patent 292751 1913) was driven by the need to connect construction elements, e.g. supports for transmission belts, to the then upcoming reinforced concrete structures. T-bolts are locked into C-channels which are fitted with anchors and cast flush in the reinforced concrete. Conventional smooth anchor channels with smooth T-bolts allow the transfer of tension loads (N) and shear loads perpendicular to the channel (V_y). To enable the load transfer also along the axis of the channel (V_x), serrated T-bolts matching with serrated channels were developed in the 1980s, making the load transfer in all directions possible (Figure 1b). As an alternative, notching T-bolts for gripping in smooth channels have been invented (German Utility Model 202005000146 1980). Note that the code-compliant term for T-bolt is channel bolt which is always part of the system, though the system is often simply called anchor channel.

Anchor channels became a popular method for the connection of construction elements, e.g. components with base plates, to the reinforced concrete structure also because of the following benefits (Mahrenholtz et al. 2022):

- Quick and simple installation of the anchor channel during concreting
- Tolerance compensation by adjusting the position of T-bolt along the anchor channel
- Robust load transfer due to mechanical interlock (bolt-channel, anchor-concrete)
- No on-site welding required, thus no weld quality issues, or fire risks
- No drilling required, thus no cut reinforcing and health risks due to silica dust
- Later positional adjustment, or replacement, is made easy at any time

The installation of anchor channels as well as T-bolts is fail-safe because of the simple installation: First, the channel is nailed to a template (for top-of-slab installation) or to the formwork (for front-face installation) before concreting (Figure 2a). After the concrete has set and the template or formwork is removed (Figure 2b), the pliable filler material, which prevents the concrete from leaking into the profile during placement, is removed from the channel (Figure 2c). T-bolts are then inserted and twisted in the slot of the anchor channel (Figure 2d), allowing the fastening of construction elements at any point along the length of the channel (Figure 2e). Only properly qualified and designed anchor channels should be used. The qualification and design are outlined in the following.



a) b) c) d) e)

Figure 2. Anchor channel installation sequence: a) Nailing of the anchor channel, placing of the concrete, b) stripping of the formwork; c) removing of the filler material; d) inserting of the T-bolt; e) fastening of the construction element, e.g. base plates of any component to be connected.

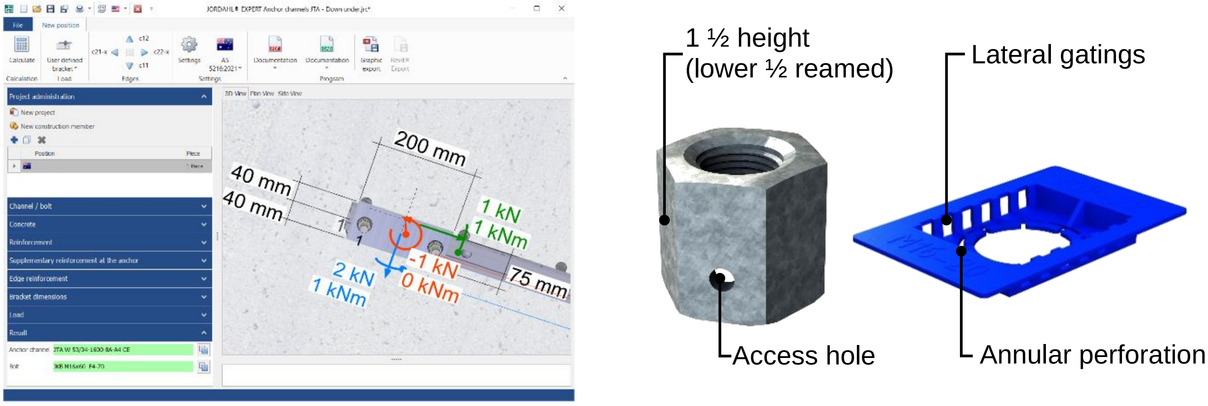
3 Qualification and design

In **Europe**, the design provisions for concrete fasteners including anchor channels are provided in EN 1992-4 (2018). Qualified anchor channels receive European Technical Assessment (ETA) certificates, e.g. ETA-09/0338 (2024), if qualification tests have been successfully carried out according to the relevant European Assessment Document (EAD) which was recently updated as EAD 330008-04-0601 (2024) and now also includes the qualification for seismic applications. Currently, the seismic design is covered in the Technical Report (TR) of the European Organisation of Technical Assessments, EOTA TR 047 (2022).

Since 2018, **Australia**'s engineers carry out the design according to AS 5216 (2021), a separate code specifically addressing concrete fasteners including anchor channels. Previously, the design and qualification regulations enforced in the USA or Europe have been used in Australia (C. Mahrenholtz 2016). The latest revision of AS 5216 also includes shear loads in the axis of the anchor channel. Supporting information for seismic applications can be found in AEFAC TN-10 (2020) which is referenced in AS 5216, however, anchor channels are not within its scope. The qualification document ETA provides the required design data also for Australia.

When it comes to anchor channels, **New Zealand**'s engineers currently rely on the design code for concrete structures in the **USA**, ACI 318 (2019). The design rules for anchor channels are not yet included in ACI 318. For this reason, amendments are provided in AC232 (2021), the Acceptance Criteria (AC) for anchor channels in the USA, defining required qualification tests to attain Evaluation Service Reports (ESR), e.g. ESR-2854 (2024). For New Zealand, ESRs may be specifically validated as NZ Appraisal Reports (ENZ), e.g. ENZ-2854 (2024).

The design and qualification regulations for anchor channels in Australia, Europe, and the USA (and thus indirectly New Zealand) are very similar (Pokharel et al. 2020) and have in common that the design takes into account almost 20 possible failure modes. The lowest resistance corresponding to all possible failure modes determines the capacity of the whole system comprising T-bolt, anchor channel, and concrete in which is anchored. Calculating some resistances requires product-specific parameters which are provided in the qualification documents ESR and ETA. Due to the complexity of the design provisions, structural engineers typically use free software available also for the Australian code framework (Figure 3a).



JORDAHL® EXPERT Anchor channels JTA - Down under.jrc*

Anchor channel: JTA W 53/34-1600-BA-A4 CE

Bolt: JKB M16x60 F4-70

a) b)

Figure 3. a) Screenshot of free software to design qualified anchor channels and T bolts (JORDAHL® EXPERT, 2024); b) JORDAHL® gap filler set JGF comprising a special nut and an insert.

The following discussion is based on EOTA TR 047 which may serve as a reference also in Australia until a revision of AS 5216 or AEFAC TN-10 includes also seismic applications of anchor channels. Seismic applications are associated with low-cycle fatigue (LCF), i.e. a low number of cycles (typically less than 10.000 cycles) at a higher load and displacement level, potentially in the plastic domain. On the contrary, high-cycle fatigue (HCF), i.e. a high number of cycles (typically more than 10.000 cycles) at a lower load and displacement level in the elastic domain, is a matter of what is known in the fastening technology as dynamic applications. Premium anchor channels can cope with fatigue loads. Qualification and design for fatigue loads, however, are discussed elsewhere.

By and large, EOTA TR 047 validates the provisions stipulated in EN 1992-4 for other concrete fasteners also for anchor channels with either serrated or notching T-bolts to allow the load transfer in any direction (Figure 1b). A prominent provision of EN 1992-4 is Clause 9.2 (7) which suggests for non-structural connections and requires for structural connections the filling of the gap between the fastening and base plate. According to Clause C.5 (2), the characteristic resistance against seismic loading, that is the seismic capacity of the fastening, is calculated as:

$$R_{k,eq} = \alpha_{gap} \cdot \alpha_{eq} \cdot R^0_{k,eq} \tag{1}$$

For steel related failure modes of concrete fasteners, the factor α_{eq} equals 1.0, for concrete related failure modes, α_{eq} is reduced up to 0.75 to take into account the adverse effect of large concrete cracks on the basic capacity of the fastening $R^0_{k,eq}$ – for anchor channels, however, α_{eq} is always defined as 1.0 (though not for supplementary reinforcement) because the mechanical interlock guarantees a favourable seismic performance. For tension loaded fastenings, α_{gap} is defined as 1.0. For shear loaded fastenings, α_{gap} is defined as 1.0 only if the gap between base plate and fastening is filled with adhesive developing a compressive strength of at least 40 MPa (EN 1992-4, Clause 6.2.2.2). If the gap between the fastening and base plate remains unfilled, α_{gap} is specified as 0.5. This provision is reasoned by the hammer effect which approximately doubles the seismic **load** when the base plate pounds against the fastener. It is important to note that gap filling is also improving the **resistance**, however, this effect is not taken into account, and therefore, gap filling is not considered in the qualification scheme. For anchor channels with T-bolts, gap filler sets are available (Figure 3b and 4) which essentially double the usable capacity for seismic applications (Mahrenholtz et al. 2023).

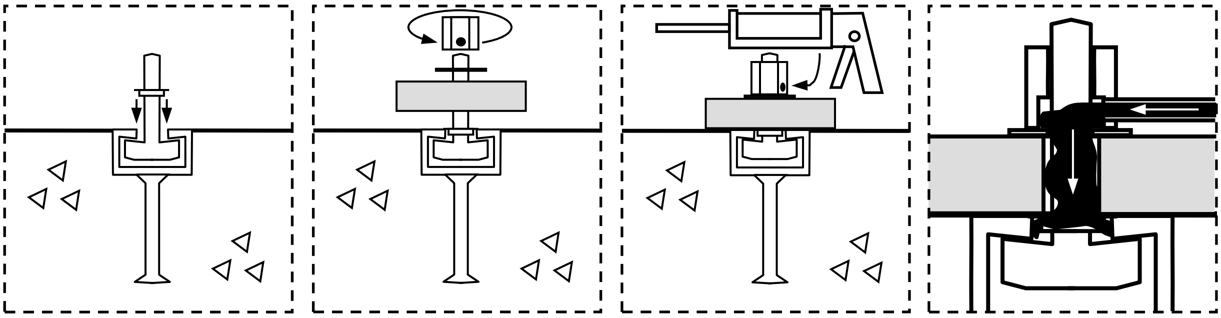


Figure 4. Gap filler installation sequence.

For anchor channels, only the qualification according to the seismic category C1 is specified where concrete test members with a maximum crack width of 0.3 mm are used: According to EAD 330008-04-0601, no seismic category C2 is defined, where crack widths up to 0.8 mm are required. Because the load is transferred by mechanical interlock, high performance anchor channels with premium channel bolts can cope easily also with seismic category C2 testing, resulting in no further reduction of the seismic resistances (Mahrenholtz, Cunningham, and Woods 2023). Therefore, the introduction of a seismic category C2 is deemed to be unnecessary for the qualification of anchor channels (Mahrenholtz and Stollberg 2020). Since the seismic category C1 qualification only is available for anchor channels, these must be designed according to the elasticity design concept. This design concept comes along with calculated loads that are typically doubled due to overstrength factors taken into account in the course of the seismic design (Heausler 2015). On the contrary, other concrete fasteners in tension may be designed according to the ductile design concept, if their qualification covers the seismic category C2. This design concept allows lower calculated loads resulting in a more economical design. Moreover, the ductile design leads to a better seismic performance because it increases the possible displacement capacity – the energy dissipation of fastenings, however, is negligible (Mahrenholtz and Eligehausen 2018) and therefore, to be neglected.

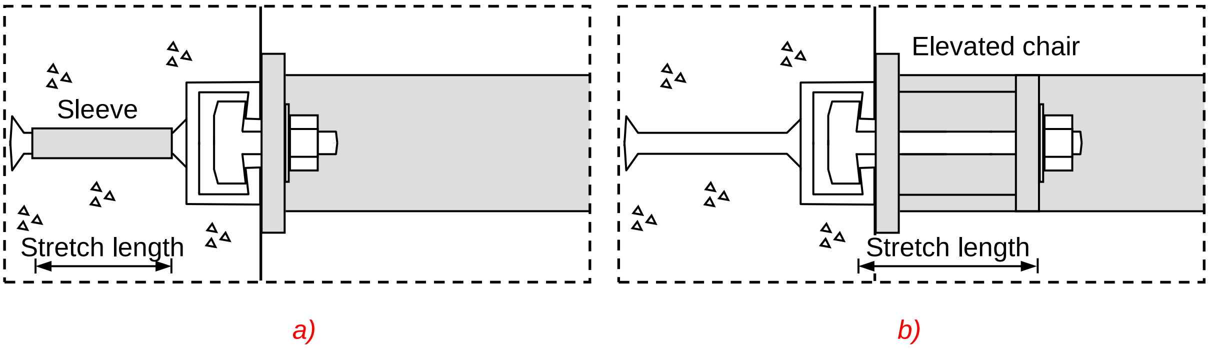


Figure 5. Possible location of free stretch length: anchor with sleeve or bolt resting on an elevated chair.

The ductile design concept requires that the ductile element of the concrete fastener has an ultimate tensile strength $f_u \leq 800$ MPa, its ratio with the yielding strength must be $f_y / f_u \leq 0.8$, and the percentage rupture elongation measured over a length of 5 times the diameter d_0 is at least 12%. Finally, a free stretch length of 8d must be provided. Two parts of anchor channels with T-bolts may fulfil these requirements (Figure 5): Either, the anchors of the channels are furnished with debonding sleeves before concreting. Or, the T-bolts extend up-air and sit on an elevated chair being part of the connected construction element.

The stretch length of 8d to ensure a ductile failure despite all uncertainties (design model, qualification testing, geometry, and material of product), EN 1992-4 and AEFAC TN-10 require a safety margin to a potential brittle failure. For this reason, the minimum characteristic seismic resistance for steel related failures $R_{k,s,eq}$ must not be larger than 70% of the minimum characteristic seismic resistance for all concrete related failures $R_{k,c,eq}$:

$$R_{k,s,eq} \leq 0.7 \cdot R_{k,c,eq} \qquad (2)$$

Because the ductile design leads to a more economical design and a better seismic performance, this design concept would be preferable also for anchor channels. To better understand how the ductile design approach can be realized for cast-in anchor channels with installed T-bolts, the individual failure modes of this system can be represented as links of a chain (Figure 6). The weakest link of the chain determines the decisive failure mode.

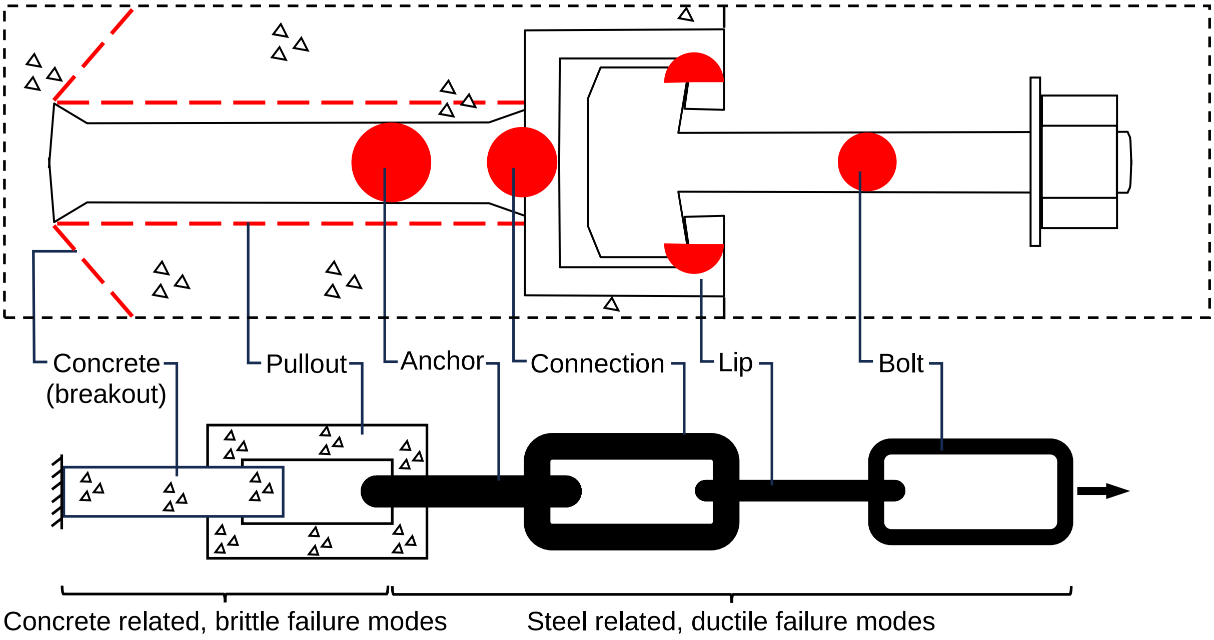


Figure 6. Chain of brittle and ductile links representing the failure concrete related and steel related modes of anchor channel and T-bolt.

In principle, also the anchor of the channel could serve the purpose of providing a free stretch length of 8d, however, the T-bolt being the weakest link of the chain is advantageous: The T-bolt acts as an easily replaceable and very inexpensive seismic fuse sacrificed to protect the concrete, the anchor channel, and the attached construction element, e.g. base plates and connected MEP works, from damage beyond repair in case of overloading during earthquakes. To demonstrate the ductility performance of T-bolts installed in anchor channels, tests on T-bolts installed in anchor channels were carried out as discussed in the following.

4 Tests

4.1 Method and specimens

All tests were carried out on smooth JORDAHL® anchor channels JTA W53/34 with notching T-bolts JKB, qualified for seismic applications as certified by ETA-09/0338 (ETA-09/0338 2024). The diameter of the bolts was M12 and the grade 8.8 (yield strength f_y = 640 MPa, tensile strength f_u = 800 MPa). The channels were 200 mm long and furnished with two anchors. According to the codified design model, the load of the T-bolt is distributed via the channel to the anchors (Mahrenholtz and Sharma 2019). For these centrically loaded specimens, the load on the bolt is therefore equally shared by the two anchors, each carrying half of the load. To determine the hierarchy of failure, the resistances corresponding to failures occurring at the anchor must therefore be doubled, to allow the comparison with the resistances corresponding to failures occurring at the bolt.

As discussed above, for anchor channels and T-bolts in tension, α_{gap} and α_{eq} equal 1.0. Assuming cracked concrete with a nominal compressive cylinder strength of f_c = 25 MPa being typical, the resistances and hierarchy of failures can be determined as follows (Table 1).

Table 1. Hierarchy of failures.

Part of failure1)	***Material of failure***	***Location of failure***	κ5) [-]	**R^0_k6) [kN]**	**$R_k = R^0_k \cdot \kappa$ [kN]**	***Position of hierarchy***
Bolt	Steel related	@Bolt	1	67.4	**67.4**	1
Lip2)				72.0	72.0	2
Connection3)		@Anchor	2	55.0	110.0	4
Anchor				56.0	112.0	5
Pulllout	Concrete related			49.6	**99.2**	3
Concrete				57.1 4)	114.2	6

1) Others deemed not to be decisive; 2) aka connection channel-bolt; 3) connection anchor-channel; 4) $8.7 \cdot 30^{0.5} \cdot 155^{1.5} \cdot 0.68$ (0.68 = $\psi_{ch,s,N}$: influence of neighbouring anchors); 5) distribution factor (denomination not codified); 6) according to ETA 09/0338

For the tested specimens, the evaluation shows that the bolt is the weakest link (hierarchy of failure position: 1, failing first) and that the distance between the governing ductile and the governing brittle failure modes is sufficient: The minimum steel resistance (corresponding to the bolt failure) is smaller than 70% of the minimum concrete resistance (corresponding to the pullout failure), i.e. 67.4 kN < 0.7 · 99.2 kN = 69.4 kN (Equation 2). The specimens are therefore in line with the intended and favoured ductile design concept discussed in the previous chapter.

4.2 Setup and procedure

The tests were carried out according to the seismic tension test series stipulated in the American and European qualification guidelines AC232 (2021) and EAD 330008-04-0601 (2024) which are technically identical. The purpose of the test series is to determine how the anchor channels cope with seismic tension loads. Because the testing was designed in a way that steel failure governs even if cast in concrete and because the concrete capacity of anchor channels is not reduced by seismic loading, the tests were carried out in the air.

In the following, the test setup and test procedure of the static and seismic tension tests are briefly described (Figure 7): The anchors of the channel were gripped by a fixture connected to a fixed support. The T-bolt was connected to a servo-hydraulic actuator using another fixture.

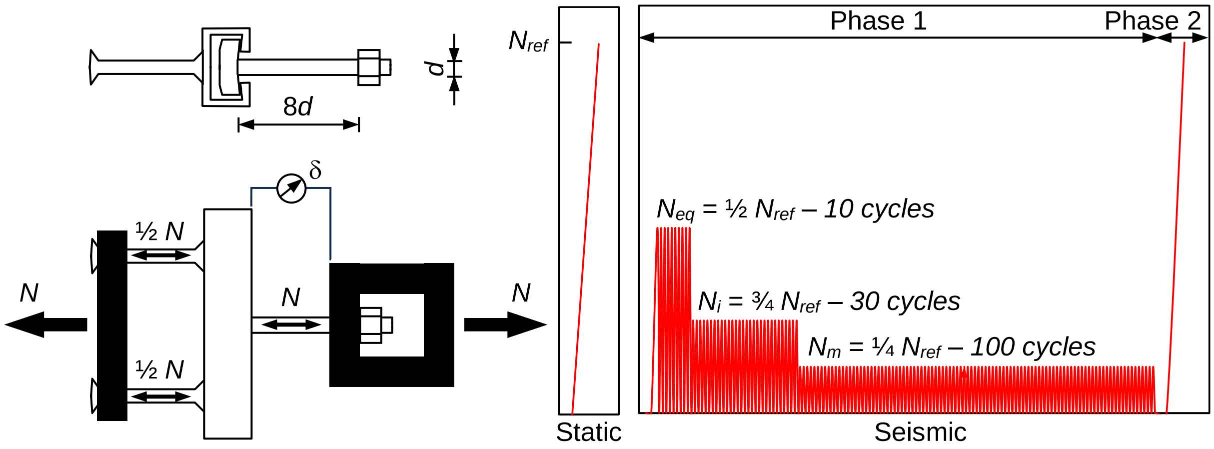


Figure 7. Test specimen and protocols for static/monotonic and seismic/cyclic tests.

The load protocol of the static reference tests is a monotonic ramp to load the fixture until failure of the tested specimen and thus to determine the ultimate load capacity $N_u = N_{ref}$. The load protocol of the simulated seismic tests has two phases. Phase 1 is cyclic triangular comprising 140 cycles of stepwise decreasing alternating tension loads between $\pm N_{eq}$ = ½ N_{ref}, $\pm N_i$ = ⅜ N_{ref}, and $\pm N_m$ = ¼ N_{ref} calculated on the basis of the reference ultimate load capacity (determined as 98.7 kN in the course of the test campaign). Phase 2 is identical to the static reference test in tension to determine the residual ultimate load capacity N_u of the simulated seismic tests. A load cell at the actuator and a displacement transducer are used for continuously recording load N and displacement δ to plot load-displacement diagrams.

4.3 Program and results

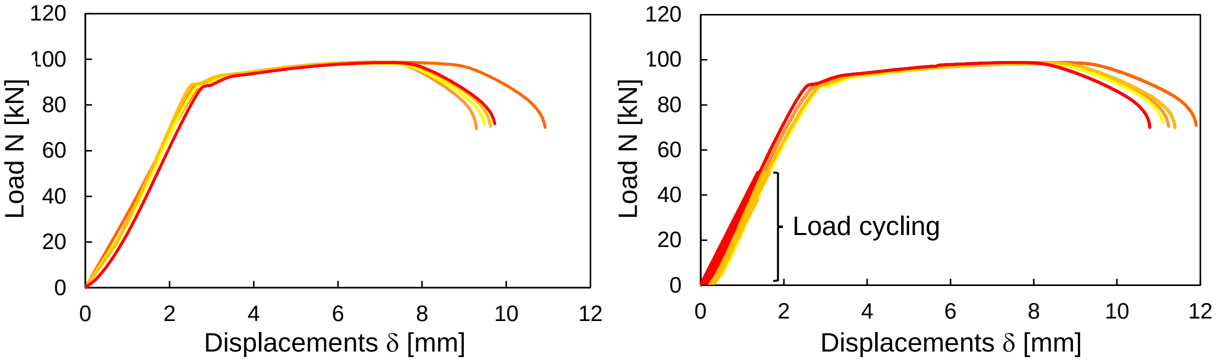
The test program comprised one monotonic (static) and one cyclic (seismic) test series (Table 2). The two test series comprised 5 repeats and were carried out at the Jordahl Lab (Mahrenholtz, Eynghalaei, and Schlünder 2024).

Table 2. Test program and test results.

Series	***Repeats***	***Failure mode***	***Earthquake test load***			***Mean capacity***
			N_{eq} [kN]	***N_i [kN]***	***N_m [kN]***	***$N_{u,m}$ [kN]***
Static	5	S				98.7
Seismic	5	S	½ · 98.7 = 49.4	⅜ · 98.7 = 37.0	¼ · 98.7 = 24.7	98.6

* S: Steel failure of the T-bolt (shank) due to yielding

Both, the static and the seismic test series showed a very responsive and stable performance with an almost ideal elastic behaviour up to a load of about 90 kN, followed by a pronounced plastic behaviour (Figure 8). The maximum load N_u was reached at around 8 mm displacement. The mean capacity $N_{u,m}$ was for both test series the same, approximately 99 kN. The scatter was negligible (COV: 0.2%) because of the well-defined yield failure of the bolt.



a) *b)*

Figure 9. Load-displacement curves of a) static and b) seismic test series.

The pronounced ductility was possible because of the available free stretch length. The observed yielding failure was identical for static and seismic test series: Necking occurred at the end of the T-bolt close to the fixture; the anchor channels remained undamaged (Figure 10). The bolt length was measured after testing to determine the rupture elongation. On average, the free stretch length of $L_0 = 8d = 8 \cdot 12$ mm $= 96$ mm was 9.5 mm larger after testing. This translates to a percentage rupture elongation of $[(96 \text{ mm} + 9.5 \text{ mm}) / 96 \text{ mm} – 1] / 100 = [1.099 – 1] /100 = 9.9\%$.

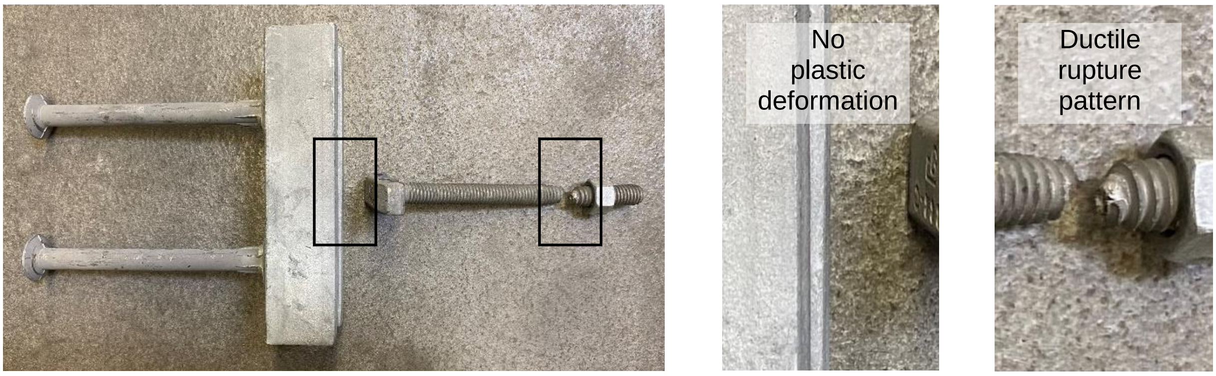


Figure 10. Yielding failure mode of the tested specimen (identical for static and seismic test series).

Evaluating the measured ductility requires the following calculation method: The tested M12 bolts have a stressed area of 84.3 mm^2 (ISO 262 2023), equalling a diameter of $d_0 = (4 \cdot 84.3 \text{ mm}^2 / \pi)^{0.5} = 10.4$ mm. Together with the stretch length L_0 deduced from the nominal diameter d of 12 mm as $L_0 = 8d = 8 \cdot 12$ mm $= 96$ mm, the conversion factor of $2 \cdot [d_0 / L_0 \cdot (\pi / 4)^{0.5}]^{0.4} = 2 \cdot [10.4 \text{ mm} / 96 \text{ mm} \cdot (\pi / 4)^{0.5}]^{0.4} = 0.783$ is calculated to allow the comparison of the tested ductility based on $8d$ with the required ductility based of $5d_0$. The conversion factor of 0.783 multiplied with the required minimum percentage rupture elongation of 12% (refer to chapter 3) yields $12\% \cdot 0.783 = 9.4\%$ which is smaller than the tested 9.9%. Thus, the bolts fulfilled the requirement. This is not surprising as the minimum percentage rupture elongation of 8.8 bolts, related to $5d_0$, is 12% (ISO 898-1 2013).

Because the ductility criterion is met, the proposed method considering the hierarchy of failures (refer to chapter 4.1) allows the application of the ductile design concept (refer to chapter 3). Provided sufficient stretch length and gap filling is carried out, the usable capacity of anchor channels with channel bolts may be doubled if compared to the outcome of the conventional elasticity design concept (Mahrenholtz, Kam, and Baron 2024):

- Tension capacity benefits from the stretch length
- Shear capacity benefits from the gap filling

5 Summary and conclusions

The fastening system consisting of anchor channel and T-bolt for anchoring any component in reinforced concrete structures is introduced. The most relevant design codes and qualification guidelines are outlined and the ductility design is discussed, which requires a free stretch length. Possible locations of the free stretch lengths for anchor channels with T-bolts were shown. The chain comprising brittle and ductile links as a representation of the various concrete and steel related failure modes is presented.

This model serves as a basis for the test concept and the selection of the test specimens to ensure a hierarchy of failures where the bolt fails first and acts as a fuse. The test setup and test procedures were laid out. The test program comprised one static and one seismic series that were carried out either monotonically or cyclically. The test results showed that pronounced yielding failure can be reliably allocated in the T-bolt while the anchor channel remains completely undamaged. Therefore, the ductile design approach known for other concrete fasteners is usable also for anchor channels with T-bolts. Most importantly, the system comprising anchor channel and channel bolt can be used as an innovative seismic fuse to protect fastened components from damages during earthquakes: If the fuses were activated, i.e. the T-bolts yielded, these can be swapped conveniently at low costs while the anchor channels embedded in the concrete remain intact – true value-engineering.

The views expressed in this paper are the views of the authors only and do not necessarily reflect the views of Jordahl (PohlCon), Silva Global, and Baron Consulting.

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