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Evaluation of Fire Resistance Concerning Bond Failure for Injection Anchors with Variable Embedment Depths

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In the last decades injection anchors became a common fastening system. With the frequent use, the requirements in load capacity and the fields of application expands. Therefore, there is also the demand for assessments in case of fire. At the same time the knowledge about the load-bearing behaviour under fire exposure is small. In this scientific work the impact of high temperature loads on anchors is determined by static calculations and thermal-transient simulations. Furthermore, the load capacity and load-bearing behaviour of bonded anchors concerning bond failure is investigated experimentally for mortar temperatures between 20°C and 400°C. Influencing factors on the bond stress-temperature behaviour of injection mortars like anchor diameter, moisture of concrete, internal and external forces and the type of test execution are examined. The work identifies bond failure and steel failure as the main failure types for injection anchors in case of fire. As a result of the presented research a calculation method for the bond failure on the basis of temperature profiles and the behaviour of the load capacity of bond materials under high temperatures is presented. The assumed temperature profile and the determination method for the BST-Curves were found as the main influencing factors on the fire resistance. In total the research work shows and evaluates the complexity of fire events and the numerous influencing factors on injection anchors. Fire resistances or rather methods for the calculation of fire resistances on the safe side can be given. Nevertheless, the confirmation with experimental tests in real fire tests cannot be completely replaced.

Keywords: *bonded anchors, fire resistance, assessment, experimental investigation, transient thermal simulation*

Introduction

An injection anchor is a fastening system for use in concrete or masonry to ensure the attachment of construction components. It consists of an anchor rod (mostly threaded rod) and the injection mortar. Figure 1 shows the setting procedure beginning with drilling and cleaning of the hole, injection of the mortar and setting of the anchor. The assessment of injection anchors is regulated by European Assessment Documents (EAD) and/or Technical Reports (TR) which are published by the European Organization for Technical Approval (EOTA). The design of anchorages is implemented in part four of Eurocode 2 (DIN EN 1992-4 2019). In case of this study only injection anchors for use in concrete are considered.

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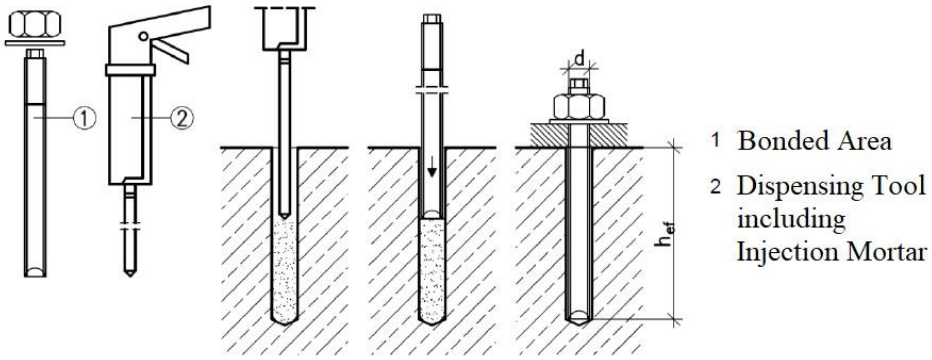
Figure 1. *Setting Procedure for Injection Anchors*



Source: EAD 330499-00-0601 2017.

The evaluation and design of injection anchors for use in constructions with requirements concerning the fire resistance are missing so far. The Technical Report which covers the evaluation of metal anchors in case of fire is TR020 (2004). The technical report defines a simplified design method and an experimental design method. The simplified design method gives design equations based on the load capacity for normal ambient temperature, which are on the safe side. For the experimental design method, the execution of fire tests where the **u**niform **t**ime **t**emperature **c**urve (UTTC) according to DIN EN 1991-1-2 (2013) is applied, is required. Because of the lack of knowledge concerning the load-bearing behavior of injection anchors this type of fastenings is currently excluded of the regulation.

In case of fire generally the same failure types as at normal ambient temperature could possibly occur. The types of failure are concrete cone failure, splitting and concrete edge failure, bond failure and steel failure. Because of the significant decrease of steel strength for temperatures higher than 500 °C, steel failure is one of the main failure modes defining the fire resistance for metal anchors. Besides that, a significant temperature dependence for injection mortars is already known. The existing assessments for post-installed rebars shows that the bond resistance of injection mortars could drop to almost zero for temperatures above 200 °C to 300 °C. The exact load bearing behavior concerning bond resistance of injection anchors is at current state of the art mainly unknown.

Literature Review

In the last decade just a few researches have dealt with the fire resistance of bonded anchors. Fuchs and Silva (2012) and Mallèe et al. (2012) published papers about the topic and the lack in regulation. They specifically pointed out that in a lot of cases steel failure is decisive and that fabricators using the experimental based design method preferably because of its higher loads in comparison to the simplified design method.

In parallel some researchers treated the evaluation and design of post-installed rebar connections in case of fire, for which in many times the same injection

mortars were used for bonded anchors. For example, Pinoteau et al. (2011) investigated the influence of heating type and heating rate on the fire test for determination of bond stress versus temperature curves for a specific product according to EAD 330087-00-0601 (2015). He could find an influence on the evaporation effects which did not lead to significantly different test results. In the last years several additional research work was published which deals with post-installed rebars or bonded anchors in case of fire, testing methods and the influencing factors, e.g., Lahouar et al. (2018) and Al-Mansouri et al. (2020).

Subsequently the idea of a simplified method for the calculation of the fire resistance concerning bond failure on the basis of the **b**ond-**s**tress-**t**emperature-curve (BST-Curve) rose. The research idea and first results were published by Patil and Thiele (2015), Lakhani and Hofmann (2017) as well as Reichert and Thiele (2017).

Methodology

First a clarification of the influences on injection anchors in case of fire should give a basis for calculations and experimental tests. Two main influences were outlined, the temperature itself and the stress distribution in concrete slabs which represents the anchorage ground. The temperature distribution along the anchorage depth was determined by transient thermal simulations with the finite element tool ANSYS. With the help of temperature distributions caused by uniform temperature-time curves (UTTCs) in concrete slabs and the thermal and mechanical properties of concrete under increased temperatures the stress distribution in concrete slabs could be calculated. A sequential calculation by using an Excel sheet was used.

Furthermore, temperature tests for the determination of BST-Curves were conducted which could replace real fire tests as far as possible. Two test setups were used. Firstly, temperature tests using a heating ring (HR-Test) according to EAD 330087-00-0601 (2015) were executed. Secondly, a new designed test setup using a heating device (cartridge) (HC-Test) in the inner of the anchor rod and with a shortened embedment depth was established. Several influencing factors like type of test execution, duration of temperature load, geometry and type of anchor rods, compression stresses in test members and moisture were examined.

Impact on Injection Anchors in Case of Fire

The main impact on anchors in case of fire is the extreme temperature load, with temperatures above 1000°C. As a consequence, restrained forces in the concrete occur and possibly also influence the sustainability of injection anchors under fire exposure. As a first step in the investigation of the load bearing capacity of injection anchors the impacts on them are described.

For the determination of temperature profiles along the embedment depth for an arbitrary anchor a transient thermal simulation was used. An anchor with

specified anchor diameter and embedment depth, as well as a concrete cylinder, were modeled. The data output was taken at the interface between anchor and concrete, see Figure 2 (right). The mortar layer was neglected in the simulations. For confirmation of the simulation results temperature measurements on anchors with the same length and diameter in a real fire test were carried out. The temperatures were measured at three points with thermocouples. The thermocouples were positioned with a distance of 10 mm from the surface, at half of the embedment depth and at a distance of 10 mm from the end of the embedment depth. For the example shown in Figure 2 and Figure 3 with an embedment depth of 80 mm, it leads to a measurement at 10 mm, 40 mm and 70 mm distance from the heated surface. In both simulation and real fire test the UTTC was applied. The comparison between the measured and simulated temperatures shown in Figure 2 and Figure 3 confirm each other. That means the simulation of temperatures along the embedment depth with transient thermal simulations is possible with a good comparison to the test results. Further investigations with simulated and measured temperatures showed the following influencing factors on the temperature distribution of anchors:

- **Anchor diameter**: Bigger anchor diameters lead to higher temperatures at the same point of embedment depth (Thiele et al. 2017).
- **Anchorage depth**: Anchors with bigger embedment depth can emit more heat to the concrete. A bigger embedment depth therefore leads to smaller temperatures at the same point of embedment depth (Thiele et al. 2017).
- **Moisture**: With rising temperatures the combined water in concrete evaporates. This phenomenon leads to a cooling effect. Location, time and amount of released water are unknown and it is not possible to replicate this effect with simulations (Reichert 2020).
- **Fixture**: Presence and size of a fixture has a high influence on the measured temperatures in fire tests. This shielding effect can just be simulated in parts, because it is also influenced by moisture and air streams (Reichert 2020).

Figure 2. *Comparison of the Measured and Simulated Temperatures over Time (left), Model of the Anchor (right)*

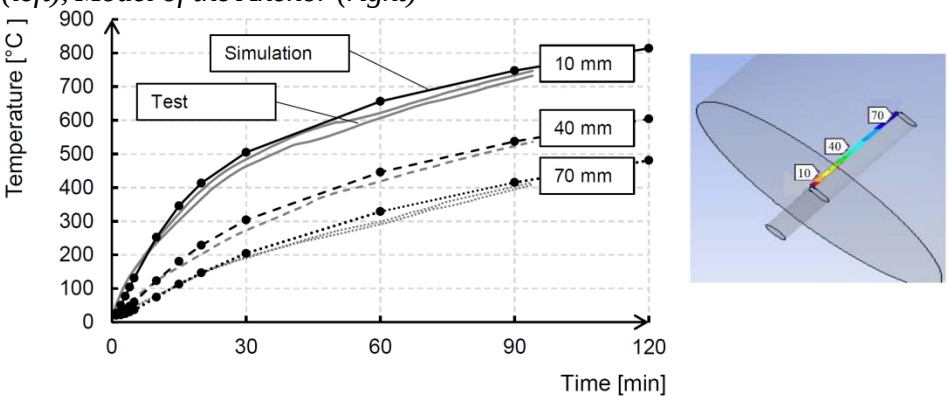
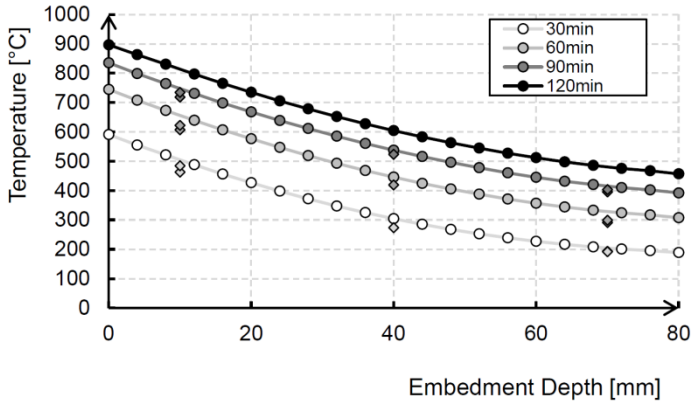


Figure 3. *Comparison of Measured and Simulated Temperatures over Embedment Depth*



Besides temperature profiles for anchors the transient thermal simulation allows the determination of temperature distributions in the concrete. Due to the relatively small thermal conductivity of concrete (1.3-2.0 W/mK at 20 °C) and the very high temperatures during a case of fire (>1000 °C) there is a high difference in temperature between the fire side and cold side results. This leads to a bending of concrete slabs when they are exposed to fire from one side only. Figure 4 (left) shows the free thermal strain ε_{th} of concrete concerning the actual temperature in a concrete slab (dotted line) and the total strain ε_{res} of the slab regarding Bernoulli hypothesis (see Equation (1) line 1). In the following, the difference between these strains is called the stress-generating strains $\varepsilon_{\sigma,}$ see Equation (1) line 2 and 3, see Hosser and Richter (2013). They depend on time in the UTTC, thickness of the slab and percentage of reinforcement. A typical qualitative distribution is shown in

where: ε_{res} Total strain
ε_0 Diameter of anchorage
k Curvature
z Height of the section
ε_σ Stress-generated strain
ε_{th} Free thermal strain

Figure 4 (right). It shows positive strains on the edge areas and negative strains in the middle of the slab.

$$\begin{aligned} \varepsilon_{res} &= \varepsilon_0 + k \cdot z \\ \varepsilon_{res} &= \varepsilon_\sigma + \varepsilon_{th} \\ \varepsilon_\sigma &= \varepsilon_{res} - \varepsilon_{th} = \varepsilon_0 + k \cdot z - \varepsilon_{th} \end{aligned} \tag{1}$$

where: ε_{res} Total strain
ε_0 Diameter of anchorage
k Curvature
z Height of the section

ε_σ Stress-generated strain
ε_{th} Free thermal strain

Figure 4. *Total and Free Thermal Strains in Concrete Slab (left), Stress Generating Strains in Concrete Slab (right)*

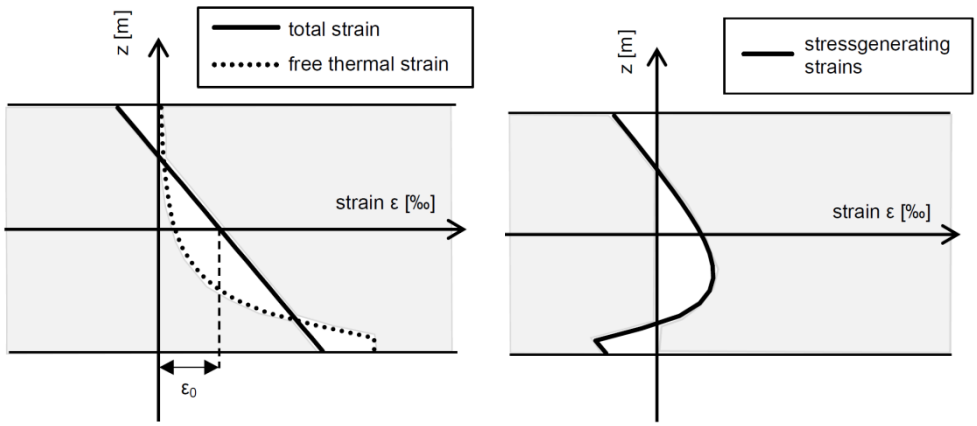
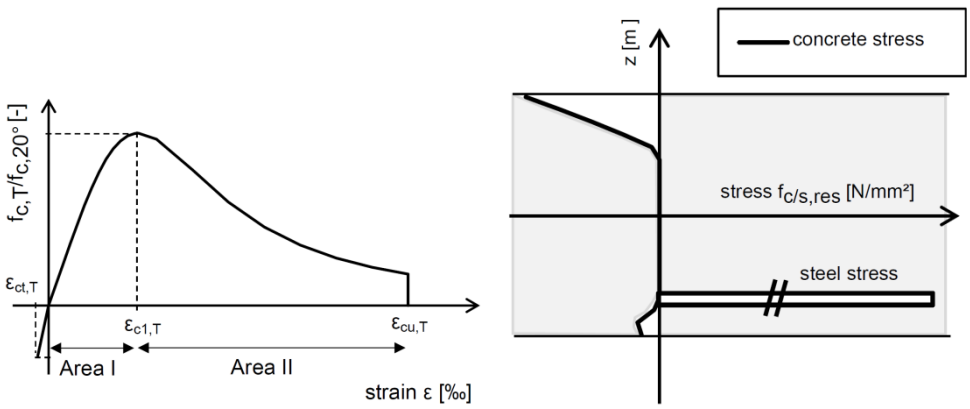


Figure 5. *Reduction Factor of Concrete Strength over Strain (left), Obtained Stresses in Concrete Slab (right)*



In consideration of the load-bearing behavior of concrete at a particular temperature (Figure 5, left) the calculation of the concrete stresses in the cross section of the concrete slab is possible. The procedure is also described by Reick (2001). Figure 5 (right) shows a typical distribution, which indicates high concrete compression stresses on the "cold side" of the slab, small compression stresses (due to the very high temperatures) on the fire exposed side of the concrete slab and a cracked area in the middle of the cross section. The influence of the compression stresses and the inner cracks on the fire resistance of injection anchors is unknown and requires further research.

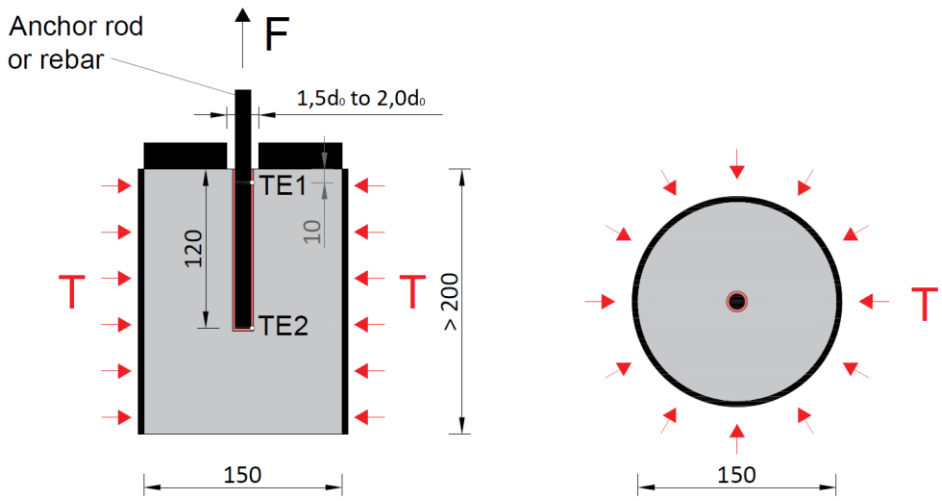
The presented calculation of the restrained forces caused by the temperature distribution in concrete slabs under fire exposure neglects the influence of anchors on the temperature distribution. Due to the high thermal conductivity of steel (54 W/mK at 20 °C) the temperature of the anchor itself and the surrounding concrete is higher than the temperature of the remaining concrete cross section. It

could be followed that in the surrounding area of an anchor due to the higher temperatures bigger thermal strains occur and lead to a reduction of tension stresses, as well as an increase of compression stresses.

Experimental Investigation of Bond Failure

As described in Introduction, the fire resistance of post-installed rebar connections can be evaluated according to EAD 330087-00-0601 (2015). The test setup used to determine the BST-Curve for an injection mortar is shown in Figure 6. The test setup consists of a rebar installed in a steel coated concrete member according to the fabricator's manual. The shell surface of the concrete member can be heated by a heating device. In the test executed in the framework of this research an electrical heating ring with a maximum temperature of 600 °C was used. The heating ring leads to a temperature distribution similar to the reality, which indicates that the temperature increase is initialized through the concrete and a constant temperature distribution along the embedment depth follows. In the HR-Tests according to EAD 330087-00-0601 (2015) a transient test execution is scheduled, that indicates that the anchor is loaded by a constant load while the concrete member is heated, see Figure 8 (left). The test ends by failure of the anchor. The mortar temperature at the time of failure (measured with two thermocouples at position TE1 and TE2) can be related to the bond stress with which the anchor was loaded. With a minimum number of 20 tests the BST-Curve can be defined.

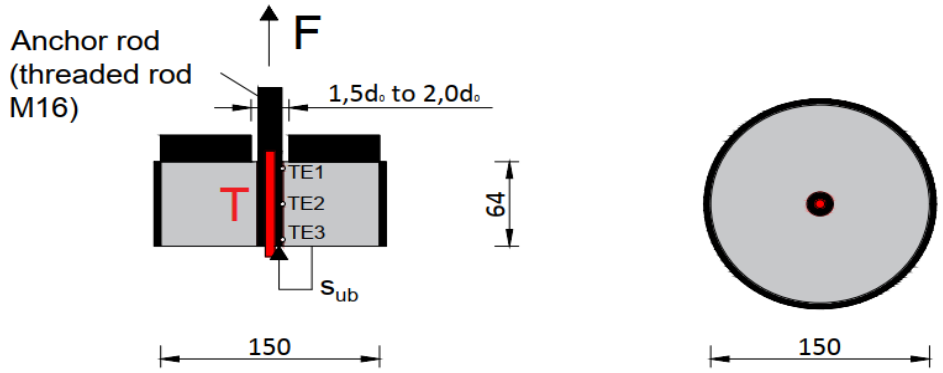
Figure 6. *HR-Test Setup according to EAD 330087-00-0601 2015*



Besides that a new test setup was developed to study the load bearing behavior of injection anchors under increased temperatures, see Figure 7. The test setup enables a direct heating of the anchor rod due to a heating cartridge inside the concrete. This follows the curcumstances in reality where the temperature increase in the mortar is also initialzed through the anchor rod. Furthermore the new test

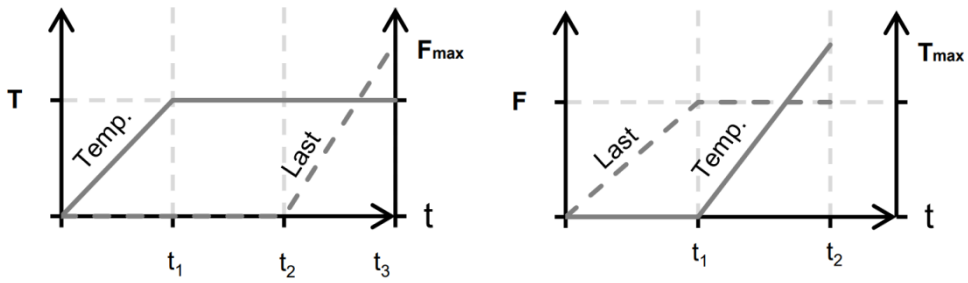
setup allows a measurement of the anchor displacement s_{ub} on the unloaded side of the anchor, which shows the slippage of the anchor.

Figure 7. *HP-Test Setup*



Due to the direct heating different types of test procedures are possible. Beside transient tests, like in the HR-test setup, also pullout tests at constant temperature (see Figure 8 right) or creep tests at constent load and temperature can be executed.

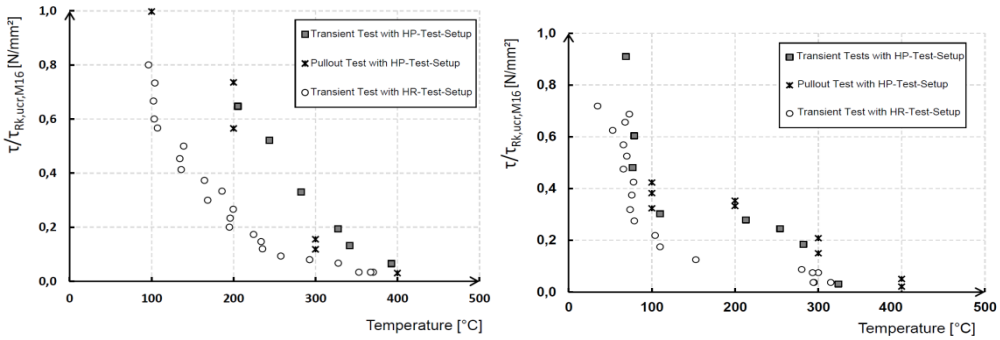
Figure 8. *Test Procedure for Pull-Out Tests (left) and Transient Tests (right)*



Influence of Test Setup

In Figure 9 test results from the transient tests and pullout tests executed in both types of test setup with two mortar types are shown. It can be seen that the type of test setup can have a significant influence on the BST-Curves. In the HP-Test setup higher failure temperatures occurred for same loading than in HR-Tests.

Figure 8. *Comparison of BST-Curves Determined with Different Types of Test Setup on Two Mortar Systems, left: Polymer Resin, right: Epoxy Resin*

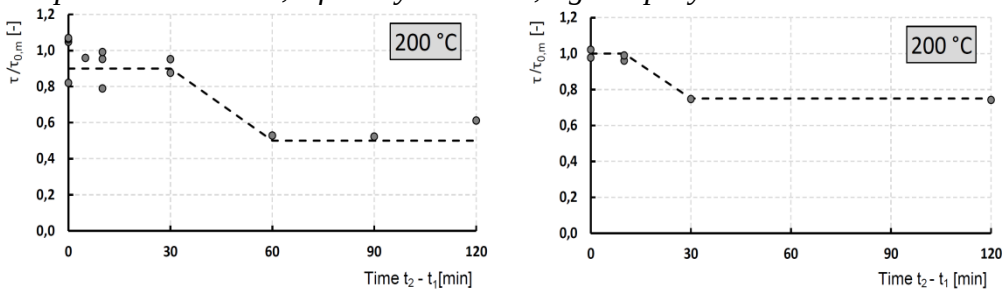


In the authors' opinion one main reason for the differences is the restrained forces caused by the temperature distribution in the concrete member. Due to the direct heating on the anchor the mortar temperature can be increased fast while the temperature in the surrounding concrete increases slowly. This leads to a temperature profil with high temperatures in the inner part of the concrete member (up to 400°C) and low temperatures at the shell surface (ambient temperature, about 20°C) and prevents deformations. According to the considerations made above compression stresses inside the concrete member occur. This could have a positive effect on the load capacity of the injection anchor and could be the reason for the differences in the obtained BST-Curves in the HP-Test and HR-Test. Besides this explanation the heating rate, the heating direction including insulating properties of the mortar and moisture streams as well as gemoetry and size of the anchor could be a reason for the differences in the obtained BST-Curve.

Influence of Duration of the Temperature Load

The HP-Test setup allows a direct and instant temperature load on the anchor, as well as the option of holding the temperature at a specified level. On the two types of resin introduced before the influence of a duration of the temperature load was investigated. Therefore, pullout tests in the HP-Test setup were conducted at 200°C. In the executed tests the times after reaching the specified temperature of 200°C t_1 and beginning of the pullout test t_2 (see Figure 8, left) differ between 0 min and 120 min. As the reference value the average value of the test results for t_2-t_1 equal to 0 min was used. The relationship between the bond stresses and the temperature duration is shown in Figure 10.

Figure 9. *Relation of Bond Stress and the Bond Stress in Reference Test over Temperature Duration, left: Polymer Resin, right: Epoxy Resin*



It can be seen that the obtained bond stress in the presented pullout tests decreases with the increase of temperature duration t_2-t_1. For the polymer resin the obtained bond stresses are constant up to a duration of 30 min and drops subsequently at 50% of the bond stress in the reference tests. In the tests with epoxy resin a drop to 75% can already be seen after a 30 min duration of temperature before the start of test execution.

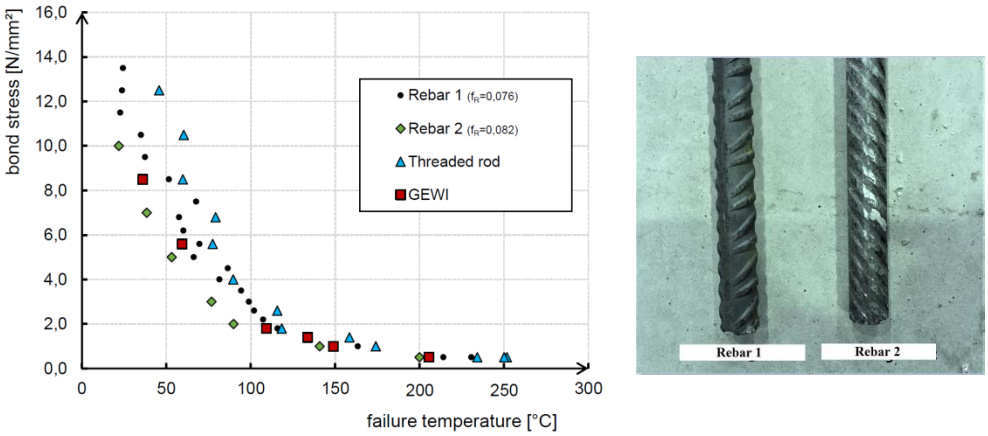
As a reason for the phenomenon shown in Figure 10, two main explanations can be given. Firstly, during the heating on the anchor, the temperature distribution in the concrete member changes. With an increase of temperature duration, the temperatures in the concrete member are getting uniform. This reduces the restrained forces caused by the temperature profile. Secondly, time dependent chemical effects in the mortar could change the load bearing behavior with the increase of time.

Influence of Geometry of Anchor Rod

The HR-Test discribed in EAD 330087-00-0601 (2015) was developed to determine the fire resistance of post-installed rebar connections. Therefore, reinforcement bars were used in the test setup. If the BST-Curves determined with this test method are to be used and transferred onto the injection anchors the influencing factor of geometry and diameter of the anchor rod has to be excluded.

To investigate the influence of anchor type, which means the difference in using a threaded rod and reinforcement bars, HR-Tests with different anchor types were executed. Two different types of rebars with differences in the related rib area f_R were used. All values are normalized by $(f_R/0.08)^{0.4}$. Also a threaded rod and a prestressing steel by the company GEWI were used. All anchor rods had an anchor diameter of 12 mm. The obtained BST-Curves are shown in Figure 11.

Figure 10. *Comparison of the BST-Curves Obtained on Different Types of Anchor Rods in the HR-Tests*



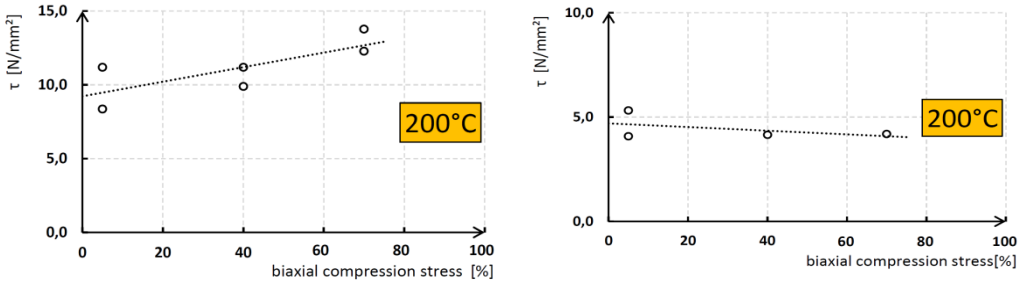
It can be seen that the type of anchor rod does not influence the main bond stress – temperature behaviour. For temperatures near to normal ambient temperatures the transient tests with threaded rods lasted longer with the same bond stress while with rebar type 2 lower failure temperatures can be detected. With the increase of temperature the BST-Curves converge. For temperatures above 100 °C no difference in the BST-Curves can be seen.

In the frame work of Thiele et al. (2017) and Reichert (2020) further investigations on the influence of anchor type and anchor diameter were done. The result is that the influences which can be determined at ambient temperature decrease with the rise in temperature. In the authors' opinion this influence can therefore be neglected for the definition of the fire resistance.

Influence of Compression Stresses on Concrete Members

Due to the findings concerning the restrained forces caused by temperature profiles the hypothesis assumes that compressive loading could have a positive influence on the sustainability of injection anchors. To investigate this assumption, pull-out tests in the HP-Test setup were conducted under compression stress on the concrete member. Therefore, cubic concrete members instead of cylinders were used. A biaxial compression stress of 5%, 40% and 70% was applied on the shell surfaces whiles the pull-out test was executed. Figure 12 shows the test results at a temperature of 200°C. Again, in the left figure a polymer resin and in the right figure an epoxy resin were used.

Figure 11. *Maximum Bond Stress in Pull-Out Tests with Biaxial Compression Stress, left: Polymer Resin, right: Epoxy Resin*

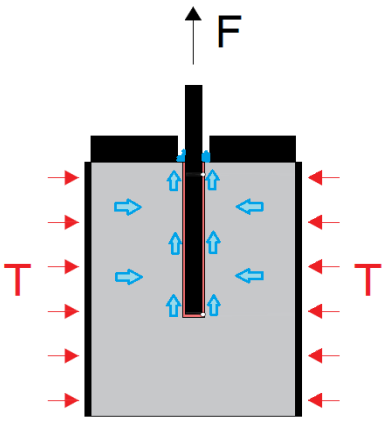


The results are showing a different behaviour for the two mortar types tested. While the tests conducted with the polymer resin show an increase of about 20% in the compressive strength, while from 5% to 70% of the tests conducted with the epoxy resin show no influence. In the frame work of the research by Reichert (2020) this type of test was executed also at 20°C, 100°C, 300°C and 400°C. The behaviour detected at 200°C can be confirmed from the further tests. This shows that that the influence of compression stresses depends on the mortar type used in the tests.

Influence of Moisture

The investigation of the impacts on anchors in case of fire showed that the moisture in concrete influences the temperature profiles in a relevant way. When the differences in the test results between the test execution in the HR-Test setup and HP-Test setup were found, the question rises up that moisture could be an influencing factor also in this case. The reason for this hypothesis is that in the HR-Tests water evaporizations can be observated during the tests, which indicates the existance of moisture streams. Evaporated water is moving from hot to cold concrete areas until it reaches the concrete surface and is condensing there. The assumed moisture stream flows first in radial direction to the core of the cylinder and subsequently longitudinal through the mortar layer, see Figure 13 the left part. For investigation of the influence of moisture streams through the mortar layer a test series with injection anchors installed in steel members instead of the use of concrete were conducted, see Figure 13. To recreate a bond surface, an internal thread was generated. The anchors were set in the internal thread, so that the contact surfaces with interal thread-mortar and mortar-external thread occur. The tests were carried out as the transient tests at the same heating rate.

Figure 12. *Left: Assumption of Moisture Stream in the HR-Test, Right: Rebar Installed in Steel Test Member*



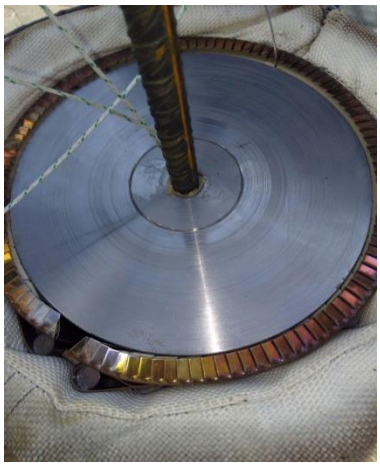
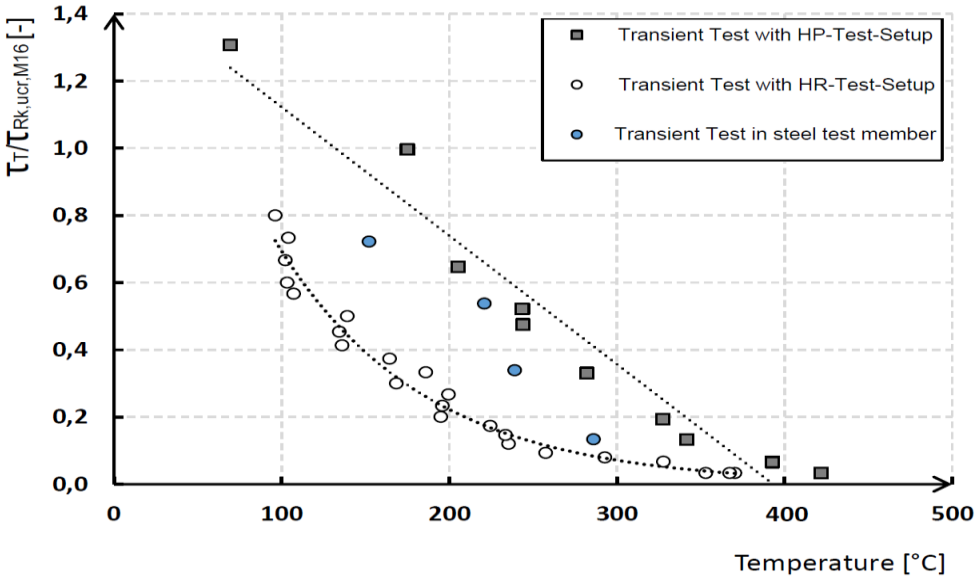


Figure 14 shows the test results compared to the test results conducted in the HP-Test-Setup and HR-Test-Setup with the polymer resin. It can be seen that the transient tests executed on the steel members to exclude the influence of concrete moisture show the inhanced test results compared to the tests executed on concrete members in the HR-Test. Nevertheless the comparison to the HP-Test shows lower failure temperatures for the same load level. Despite the small number of tests, the test resutls indicate that the moisture of the concrete has a negative influence on the test results in the HR-Tests.

Figure 13. *Test Results in Steel Test Members Compared to Transient Tests with the HP-Test-Setup and HR-Test-Setup*



In addition to these tests by Reichert (2020) also the transient tests in the HR-test setup with different moisture contents were executed and compared. Therefore, different forms of storage were used. Tests in dried concrete at 80°C and 110°C as well as concrete members with storage in water bath or at normal ambient

temperature were done. The different types of storage lead the moisture contents to vary between 0.3% and 3.0%. The results showed no significant influence of moisture content on the BST-Curve.

Summary of Influences on the BST-Curve

This paper resulted in the framework of the research described in by Reichert (2020). The work includes several more tests to describe the influences on the BST-Curve for injection anchors. Table 1 summarizes all influencing factors and findings.

Table 1. *Influences on the BSC-Curve*

Influence	**Test setup**	**Execution**	**Result**
Test Setup	HP/HR	Transient	Type of test setup can have significant influence on the BST-Curve Up to 100% higher bond stress with the same failure time *Statement: Reason can be due to the restrained forces caused by temperature distribution or the effects caused by moisture stream.*
Duration of temperature load	HP	Pull-out	The increase of load duration leads to the decrease of bond stress by up to 50%. *Statement: increase of duration leads to decrease of restrained forces in the concrete member or time dependent chemical effects in the mortar.*
Geometry of anchor rod	HR	Transient	Type of anchor rod (rebar/threaded rod or diameter) can have an influence on the BSC-Curves but the overall behavior stays the same. *Statement: Influence of anchor type can be classified as small. It occurs mostly for temperatures < 100°C and is product-specific.*
Compression stress on concrete member	HP	Pull-out	The increase of the compressive stress on concrete member leads to an increase of bond stress by up to 20%. *Statement: The effect is product specific and differs with temperature.*
Moisture	HR	Transient	Tests with the concrete moisture between 0.3 to 3.0% show no significant influence. Tests on the steel member (0% moisture) lead to higher BSC-Curves up to the level of the HP-Test *Statement: Concrete members always have a residual moisture (also dried), and the moisture streams could have an influence on the BST-Curve*

Calculation of Bond Failure in Case of Fire

The information about temperature profiles of an anchor and the BST-Curves of the used mortar can be used to calculate the fire resistance for an injection anchor. Therefore, the time in the UTTC for which the fire resistance should be

calculated, has to be chosen. In the example explained later the fire resistance for an anchor with an M16 threaded rod and 80 mm embedment depth after a30 min of fire is calculated. The first step of the calculation is to read out the temperatures 2 for each embedment depth 1, see Figure 15 (left figure). Subsequently, the temperature information 2 can be related to a bond stress 3 (or reduction factor of bond stress) with the help of the BST-Curve, see Figure 15. The two pieces of information can be used to link every step of the embedment depth 1 to a bond stress 3. This is done in Figure 16. It shows that for the first 35 mm of embedment depth the temperature is higher than the limit temperature T_{max}, which means no loads can be transferred. In the rear part of the embedment depth stresses up to 2 N/mm² can be transferred according to the BST-Curve. The integral of the bond stress over the embedment depth results in the fire resistance N_p 4 for the chosen time in the UTTC, see Equation (2).

Figure 14. *Temperature Profiles for M18-80 (left), BST-Curve for the Used Mortar (right)*

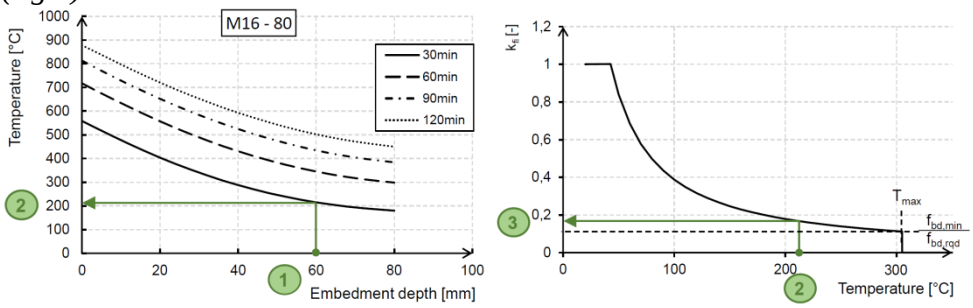
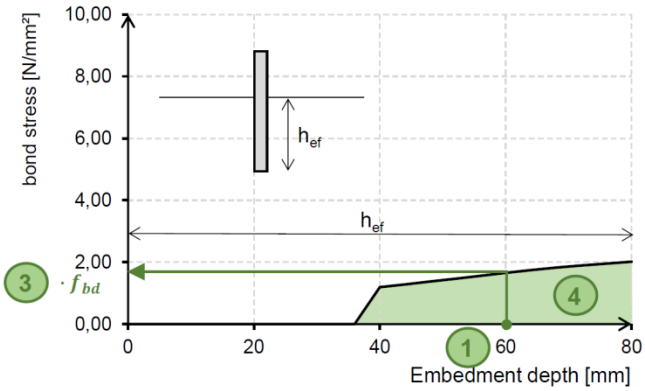


Figure 15. *Bond Stress Distribution along Embedment Depth*

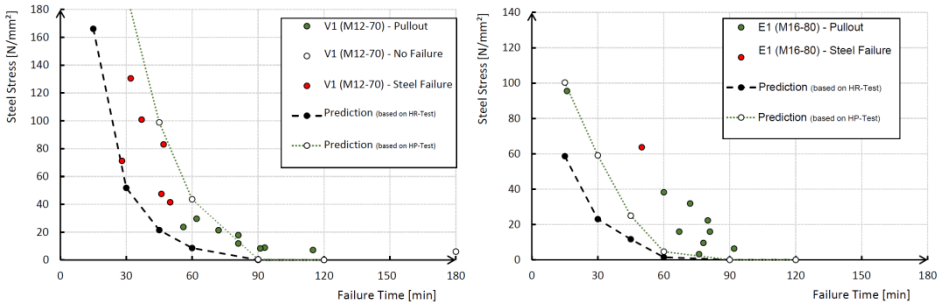


$$N_p = \pi \cdot d \cdot \int_0^{h_{ef}} f_{b,T}(h_{ef})\, \partial h_{ef} \qquad (2)$$

where: N_p Fire resistance concerning pull-out failure
d Diameter of anchorage
h_{ef} Embedment depth
$f_{b,T}$ Mortar specific bond stress in dependence of temperature

To confirm the calculation method the predicted fire resistances are compared with the results from the real fire tests. Figure 17 shows comparisons of two different mortar types: on the left side a polymer system, and on the right side an epoxy system. The prediction where the BST-Curve determined on the transient tests in the HR-test setup was used is presented with the black dashed line. The prediction where the BST-Curve determined on transient tests in the HP-test setup was used is presented with the green dashed line. It can be seen that the prediction is in any case on the safe side. Meanwhile the quality of accordance differs greatly. Especially for durations of fire longer than 60 minutes the predicted resistance drops to values of almost or even zero while the anchors are able to carry small loads for much longer. The results also show that the prediction based on the BST-Curves determined in the HP-Tests sometimes overestimates the fire resistance.

Figure 16. *Comparison of the Prediction of the Fire Resistance and Test Results*



Within the scope of this research influencing factors on this prediction method were investigated. Four main aspects were considered as follows.

- **Temperature Profiles:** This example is presented before the temperature profiles determined without considering shielding influences of a fixture. Having regard to this and vaporization of water lower temperatures can be anticipated. This could be one reason for the results on the safe side. An overall implementation of these effects in the temperature profiles is in the authors' opinion neither feasible nor advisable.
- **The BST-Curve for the temperatures higher than T_{max}:** Caused by the test procedure for determination of the BSC-Curves the information about the bond resistance of mortars above the temperature T_{max} is missing. Nevertheless, fire durations up to 180 min can be monitored by fire tests with small loads ($f_b < 0.5$ N/mm²). A "grain-to-grain-support" could be a reason for that. The determination of a minimum bond strength $f_{b,min}$ related to the grain diameter could be a solution. This needs further research.
- **Determination of the BST-Curve**: The previously shown studies on determination of the BSC-Curves indicated many influences on the resulting curve. Especially the type of test execution shows a great impact. The restrained forces caused by temperature distribution in the test slabs of the real fire tests could be a reason for predictions on the safe side. For an explicit statement to the influence further research to this topic is necessary.

- **Anchor displacements:** The prediction method shown above does not consider the displacement and deformation of the anchor during loading. In the research work this paper refers to Reichert (2020) an exemplary calculation is presented, which considers stress induced strains and thermal strains of the anchor and uses load-displacement curves determined by the pullout tests in the HP-Tests. In conclusion of the calculated example no significant reduction of the predicted fire resistance is necessary.

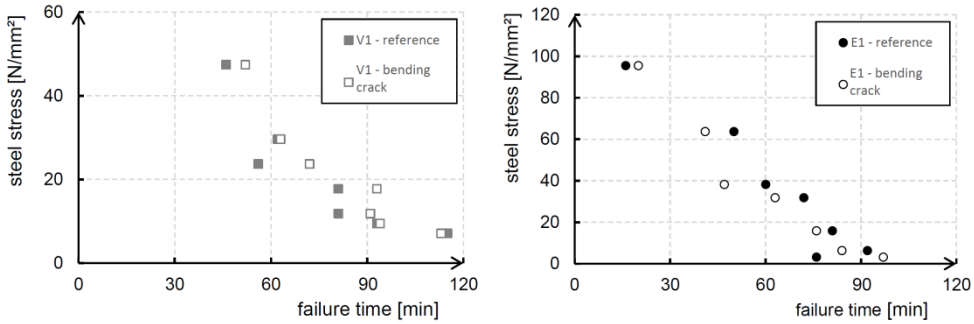
Influence of Cracks on Bond Failure

The investigations on stress distribution in concrete slabs during fire showed that for common dimensions of slabs inner cracks occur. The influence of cracks for injection anchors are described by two hypotheses:

- Cooling effect: One explanation is that the cracks yield space for evaporated water and lead to a cooling effect and therefore higher fire resistances.
- Bigger displacements: On the other hand, the cracks should consequently lead to lower fire resistances like at room temperature, because of bigger displacements and the interruption of the adhesive bond.

For the assessment of the influence of cracks real fire tests on the cracked and uncracked concrete were conducted. The condition (cracked or uncracked) of the concrete is estimated before the start of the test. For the tests on the cracked concrete, bending cracks were caused and the anchors are installed in the cracks. Also, during fire exposure the slabs are loaded with a dead weight which causes a steel stress of 270 N/mm². For the test on the uncracked concrete no preloading is done and also during the test the slab is not loaded. Nevertheless, the occurrence of inner cracks is not prevented. The tests were conducted for two mortar types. The results are shown in Figure 18. It can be seen that for mortar type V1 (left) no influence of cracks developed, and the anchors installed in the cracks lasted even longer (average +6 min). For mortar type E1 a negative influence of cracks could be interpreted. The anchors failed on average 7 min earlier.

Figure 17. *Steel Stress versus Failure Time for Anchors in the Cracked and Uncracked Concrete*



Overall the tests are showing failure times with a typical scatter for fire tests (± 10 min) so that no significant influence of precracked concrete for the described type of test execution can be concluded. It can be recorded that a classification in cracked and non-cracked concrete, as it is done for normal ambient temperatures, is not useful for tests under fire load. Instead, the definition of the dimensions and supporting conditions for real fire tests should be clearly defined. Bigger span widths should be preferred in contrast to smaller ones. Furthermore, hinged and horizontal sliding supports should be used.

Discussion

In case of fire a complex combination of temperature distribution and stresses are influencing the sustainability of injection anchors. The research work identifies bond failure and steel failure as the main failure types for injection anchors in case of fire.

The determination of temperature profiles with use of transient thermal finite element simulations is possible. This study finds anchor diameter and anchorage depth as well as moisture and presence of a fixture as the main influencing factors. The anchor geometry can be implemented easily into the simulation, while the presence of moisture and/or fixture leads to lower temperatures and can therefore be neglected as an assumption on the safe side.

Also, the usage of the BSC-Curves determined for post-installed rebar connections seems to be an assumption on the safe side. The study showed that the BSC-Curve can be influenced by many influencing factors. Especially the determination of the type of test execution and the influence of the restrained forces caused by the temperature profile in the concrete members require further research.

The presented prediction method gives a simple opportunity to calculate the fire resistances on the safe side. However the safety level can differ largely by different mortar types. Therefore, further research is recommendable for a better understanding of the load bearing capacity and its influencing factors. The presented HP-Test could be a good opportunity to get a better understanding of the load-bearing behaviour because of its ability to measure displacement and regulate temperature specifically.

The considerations due to the restrained forces caused by the temperature profile in concrete slabs show that a concrete member in case of fire has a cracked cross section in most cases. A definition of cracked and non-cracked concrete at it is handled at normal ambient temperature is not possible or useful for real fire tests. Tests with anchors installed in bending cracks could not prove a clear influence.

Conclusions

The research gives an overview to the load-bearing behaviour of injection anchors in case of fire and the main influencing factors. It deals mainly with the

bond failure mode. An opportunity for the calculation of bond failure is given. Further research is recommended to clarify the influence of fixture, moisture and test execution for determination of stress-temperature curves.

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