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BOND STRENGTH OF INJECTION ANCHORS AS SUPPLEMENTARY REINFORCEMENT INSIDE HISTORIC MASONRY

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Abstract

Supplementary injection anchors are used as a repairing-system inside historic masonry. They basically consist of a tensile element - usually steel - inserted into the slightly larger borehole and the annulus is grouted with cement. Assuming successful grouting, considerable tensile forces can be transferred at short bond lengths.

More then 500 pull-out tests in laboratory and in-situ have been performed to obtain the loadbearing characteristics of such anchors. As a result, design recommendations have been developed. The paper summarises the state of the design recommodations from the point of structural failure and reflects on the interaction between fresh grout and surrounding masonry. Latest results about the influence of restraint to free transverse deformations are provided.

Key Words

Historic Masonry, Repair, Injection Anchors, Bond Strength

1 Introduction

Supplementary injection anchors (figure 1) are used as a repair-system for old and historic masonry to cover tensile forces that can not be sustained by the masonry alone. In Germany, such anchors are utilised since the 1920s. They perform as untensioned steel reinforcement or as prestressed tendon. Forces are transmitted by bond between the anchor and the surrounding masonry in axial direction.

Required borehole diameters are about 56 mm for untensioned anchors and 76 mm for prestressed tendons to realise a sufficient cement-coating for corrosion protection. Stainless steels are used increasingly for the repair of historic masonry and therefore, borehole diameters might be reduced under consideration of grouting technology and safe force transmission. Borings for untensioned anchors are usually less than 4,0 m, whereas for prestressed tendons they may go up to 35 m in length. The drilling method will be selected on the basis of cost effectiveness and sympathetic treatment of the historic structure.

Anchor materials are standard reinforcing steel, threaded rods or special prestressing bars with roll-formed sections. After clearing and pre-wetting the drill hole, the anchor element is inserted, centred with spacers and grouted. The admissible grouting pressure has to be adjusted according to the state of the masonry and may vary between 1 to 6 bar.

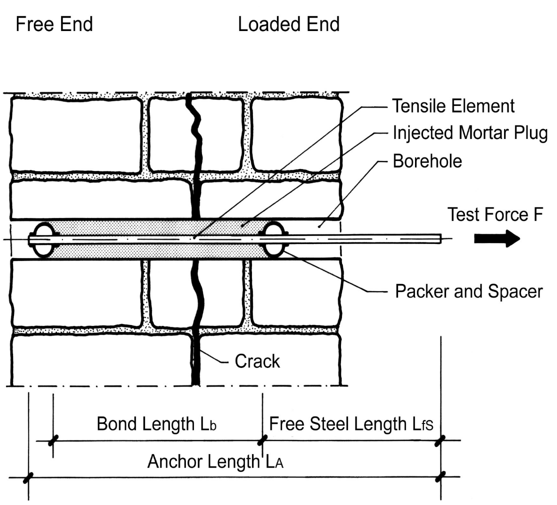

Figure 1: Diagram of a supplementary injection anchor (left), picture of injection anchors inside monolithic sandstone after pull-out testing (right)

Injection anchors are particularly suited to the repair of historic monuments considering aspects of „minimum intervention", because the function and appearance of the masonry will not be affected and the new element will be discernible. The original substance is only replaced within the boring hole with a physical and mechanically similar material, if cement or cement-lime suspensions are grouted. The precedent for use of metal based materials in masonry structures is centuries old (Wenzel et al 2000). Figure 2 gives examples for the utilisation of injection anchors in masonry. The examples show the repair of small elements like stone corbels and reinforcing of walls and foundations that might require prestressed tendons. Sometimes, e.g. to connect two shells of masonry, extremely short bond lengths have to be used.

Recommendations for the design of injection anchors have been given by Gigla (1999) and Gigla/Wenzel (2000), based on a research project at Sonderforschungsbereich 315 (Collaborative Research Centre 315: „Care and maintenance of historic buildings", University of Karlsruhe 1985 - 2003). Certain aspects of force transmission are part of ongoing research at University of Applied Sciences, Lübeck. This paper is focussing on a detailed approach of the interaction between fresh grout and surrounding masonry and latest results about the influence of restraint to free transverse deformations.

2 Mechanism of failure

Force-transmission between the surrounding masonry and the tensile element includes two intersections: the outer intersection between borehole surface and injected mortar plug and the inner intersection between injected mortar plug and tensile element. Basically, five different types of failure might be described (compare figure 3):

2.1 Poor shear strength of injected mortar plug and cavity (figure 3 a)

This kind of failure is usually due to grout that does not suit the particular requirements or to flawn injection works. Especially when grouting water absorptive stone material, it has to be ensured that required grouting-time and -pressure are observed. Inadequate grouting operations are frequently causing significant cavity. Cavity tends to occur deep inside the borehole and usually can not be detected visually from the mouth of the bore (see overcored injection anchor in figure 4). In this case the resistance against tensile forces is very poor. Therefore, the quality of grouting works has to be controlled by a

consultant. If anchors relate to structural safety, field pull out tests, e.g. up to 125% of estimated working load, have to be performed.

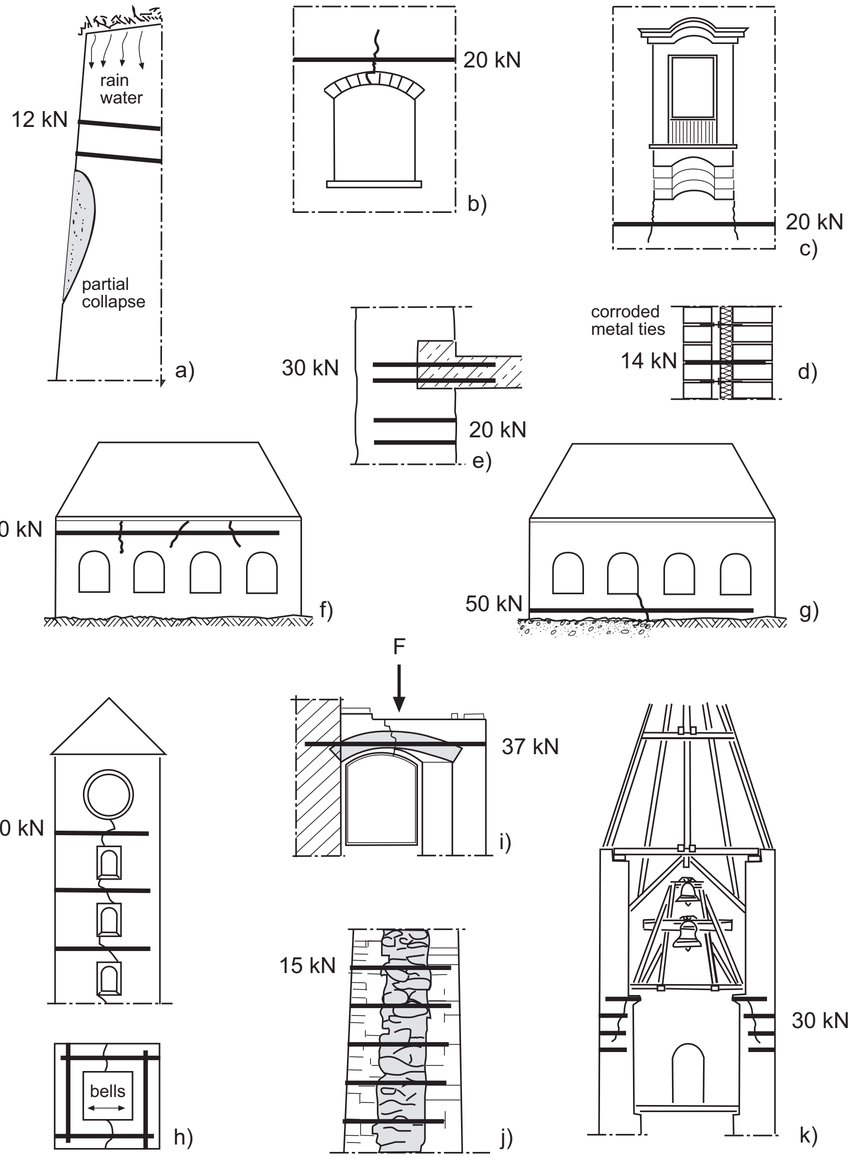

Figure 2: Utilisation of injection anchors

a), d), j) Anchors stabilising cracked or deformed masonry leaves
b), c), f) Anchors fixing cracked structures
h), k) Strengthening against dynamic loads
e, i) Joints or keys between old and new work
g) Reinforcing of walls or foundations against uneven settlement

2.2 Exceeded tensile strength of surrounding stone or masonry (fig.3 b)

Force transfer between borehole and tensile element causes transverse tensile stresses around the borehole. This stresses might effect cracking of the surrounding stone or bed joints respectively. Therefore, the maximum anchor tensile force has to be limited in accordance with the properties of the surrounding material. Figure 5 shows the stress distribution in theory, compared with the cracking of an overloaded anchor in laboratory. Tensile element on the picture (figure 6, right) is a 26,5 mm diameter prestressing tendon with roll formed section. Borehole diameter is 76 mm.

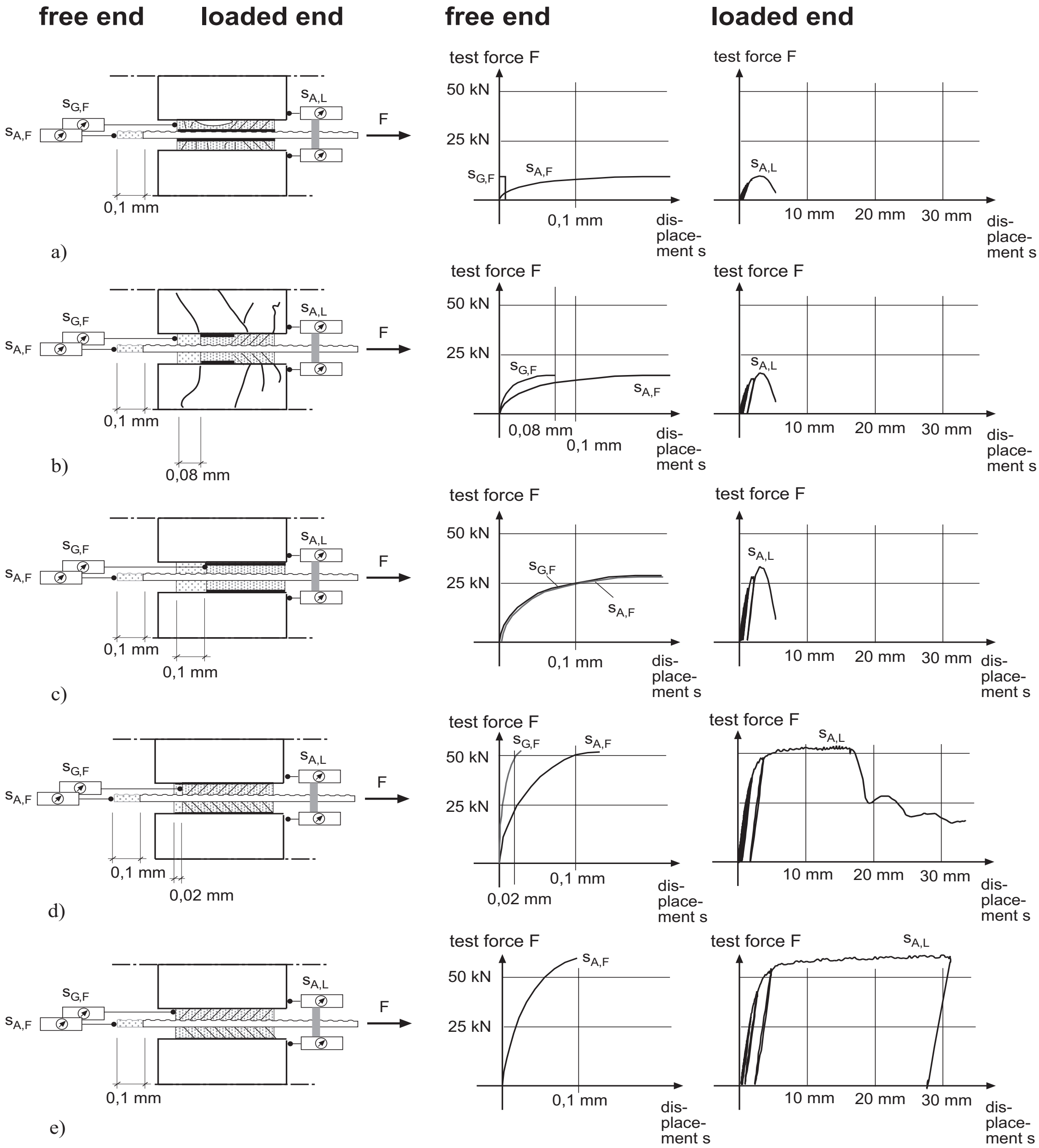

Figure 3: Analysis of structural failure

a) Poor shear strength of injected mortar plug and cavity (usually flawn injection works)
b) Exceeded tensile strength of surrounding stone or masonry
c) Failure of the intersection between injected mortar plug and borehole surface
d) Combined failure of injected mortar plug and c)
e) Failure of injected mortar plug, anchor steel is loaded until tensile strength

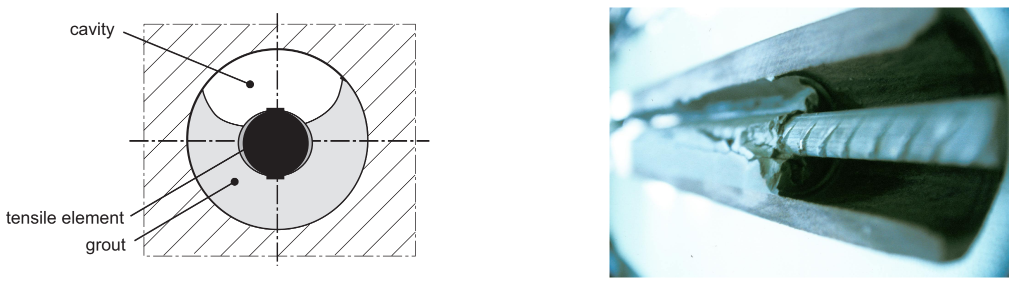

Figure 4: Diagram and picture of an overcored injection anchor from inadequate grouting works. The upper half of the borehole has not been filled with grout

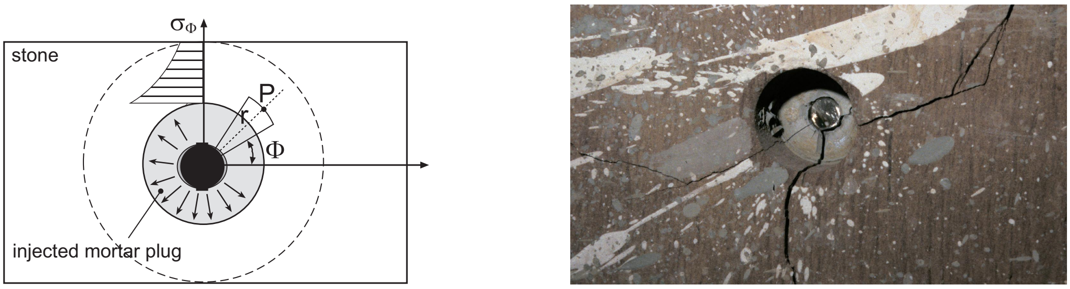

Figure 5: Diagram of transversal tensile stresses referring to theory of elasticity. Injection anchor with resulting cracks caused by high anchor load in sandstone

2.3 Failure of the intersection between injected mortar plug and borehole surface (figure 3 c)

This kind of failure is expected with injection anchors in non water absorptive surroundings, especially in very tight and smooth stone material like limestone or granite. The relation between force and displacement can be described with a model based on the Coulomb-Mohr-expression. Higher anchor loads require long bond lengths or greater borehole diameters, if possible. If bond lengths are too short, the whole injected mortar plug will be drawn out, together with the tensile element. One important factor to consider this kind of failure is the porosity of the surrounding stone, described by its water absorptive capacity (Gigla,1999).

Figure 6 shows thin layer microscopic views of an 3,62 x 3,62 mm section of the interface between sandstone (variety Posta) and injected mortar plug on the left and granite (variety Raumünzach) and injected mortar plug in the middle. The macroporosity of the sandstone results into an interlocking between borehole surface and injected mortar plug. This mechanism prevents relative displacements of the outer intersection. In contrary, the surface of the borehole inside the granite is absolutely smooth with no interlocking. The picture on the right shows a pulled out injection anchor in granite in laboratory. At the beginning of the pull-out-test both anchors at the picture had the same starting position. During pull-out testing, the anchor on the left has been moved forward to the mouth of the borehole.

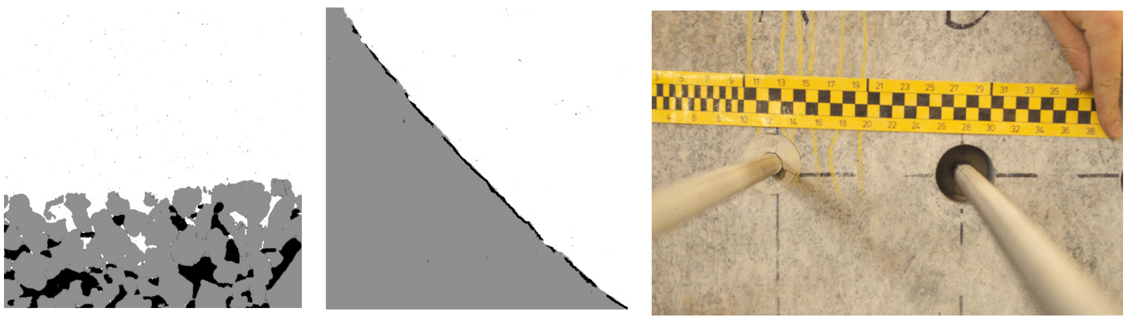

Figure 6: Thin layer microscopic views of an 3,62 x 3,62 mm section of the outer intersection between sandstone and injected mortar plug (left) and granite and injected mortar plug (middle), picture of drawn out injection anchor inside granite (right)

2.4 Combined failure of injected mortar plug and the intersection between injected mortar plug and borehole surface (figure 3 d)

With better interlocking between surrounding material and injected mortar plug, the developing displacements between both surfaces will be smaller and higher anchor loads are applicable. In relation to the angle of skin friction, the anchor resistance against

tensile forces now depends on the compressive and tensile strength of the injected mortar plug.

The surface of the tensile element is a parameter of less relevance for ribbed or roll formed sections, though the research program evaluated, that reinforcing steel performs better then threaded rods. Supplementary anchorage at the end of the tensile element like nuts with washers will not improve anchor tensile strength. Test series showed that the compressive strength of the injected mortar locally will be exceeded, so that there is no advantage against pure bond.

2.5 Failure of injected mortar plug (figure 3 e)

Without displacements in the outer intersection, the maximum anchor tensile strength will be developed, assuming good grouting work. The forces are transferred between borehole surface and tensile element by inclined cone-shaped segments that are developed inside the injected mortar plug during loading. The observed angles of such segments, which are separated by hair cracks are about 45° to 55° to the anchor axis, while their dimensions depend on rib spacing (figure 7). If rib spacing is adequate and the resulting shear forces parallel to the tensile element are covered by the segments, then failure occurs due to to local exceeding of injected mortar compressive strength.

Figure 7: Diagram of model of force transfer between tensile element and borehole surface [3]. Picture of resulting cone-shaped segments developed by force transmission of an tested anchor inside sandstone

3 Design-Recommendation

3.1 Design value of bond strength, $X_{A,d}$

The design-recommendation is based on the results of more then 500 pull-out tests in laboratory and in situ (Gigla/Wenzel 2000). They are referring to characteristic values of bond strength (5%-fractiles), nominally defined at free-end steel displacements of 0,1 mm. The recommendations are based on trass cement grouts (w/c-ratio: $0{,}5 < \omega < 1{,}0$) and anchor-steels with a surface similar to reinforcing bars, e.g. like defined in standard DIN 488-2 (1986). The steel diameter should be chosen to one third of borehole-diameter, if stainless steel-bars are used. The required cement coating for corrosion protection is 20 mm of thickness in minimum for ordinary steel, e.g.: resulting in a 56 mm borehole diameter for 16 mm ordinary steel. Further advice for corrosion protection of injection anchors are given by Wenzel et al (2000). Aspects of corrosion protection have to be especially obeyed during work at historic monuments.

The established basic design-function (1) is empirically based on the compressive strength of grout $f_{G,c}$, determined in accordance with German standard DIN 18555-3 (1982): Three Prisms of 16 · 16 · 4 cm (2 days in mould, 5 days outside mould at 95% humidity, 20°C, 21 days at 65% humidity, 20°C) are divided into halves during testing of bending tensile strength. The compressive strength is then obtained at each of the six halves. Size of proof stamp is 40 · 62,5 mm.

$$X_{A,d} = \frac{\Phi_J}{\gamma_M} \cdot \left(\frac{f_{G,c}^{\,2}}{500} + X_{B,W} \right) \tag{1}$$

$X_{A,d}$: Design value of bond strength, independent of bond length. Required minimum bond length: L_b = 150 mm inside monolithic stone, L_b = 190 mm in bed or head joints of brick and L_b = 430 mm in bed and head joints of blockwork

$f_{G,c}$: Compressive strength of grout, standard DIN 18555-3 (1982). Minimum value: $f_{G,c}$ = 16,6 N/mm². Maximum value covered: $f_{G,c}$ = 38,7 N/mm². A minimum bending tensile strength of $f_{G,ct} = f_{G,c} / 8$ = 2,0 N/mm² is required.

$f_{G,ct}$: Bending tensile strength of grout referring to standard DIN 18555-3 (1982)

Φ_J: Reduction factor for bond in bed or head joints, Φ_J = 0,5.

$X_{B,W}$: Term to describe the increase of bond strength inside water absorptive stone material, see figure 8, left. $X_{B,W}$ = 0 ... 15 N/mm²

γ_M: Partial factor for property, recommended: γ_M = 1,35

The function $f_{G,c}^2$ / 500 has been found adequate to describe the relation between anchor bond strength and grout compressive strength in non water absorptive stone material. It covers the lowest 5%-fractiles, observed at limestone (variety Kelheim) with Failure of the intersection between injected mortar plug and borehole surface (figure 3 c). Therefore, it lies on the safe side. The reduction factor Φ_J has to be considered for anchors located in bed or head joints, estimated from the location of the bore mouth. The effect of water absorptive surrounding stone material is important. Grouting works in non absorptive material are establishing a grout plug with constant w/c-distribution, analogous with the initial suspension. When grouting high absorptive stone material, significant amounts of water are extracted from the grouting suspension through the borehole surface. As a result, the w/c-ratio ω will be decreased, giving a stronger compressive strength of the injected mortar plug compared to the initial suspension. Hereby, good grouting work is assumed (adequate grout composition and grouting pressure, grouting continued until the full capacity is filled). Proper cleaning and pre-wetting of the borehole does not measurable reduce this effect.

The influence of absorptive stone material is taken into account with the term $X_{B,W}$. This term may be applied, if the water absorptive capacity W has been tested in accordance with German standard DIN 52617 (1987). If W is not known, then expression (1) might be applied on the safe side without $X_{B,W}$. The diagram in figure 8 gives an idea of the effect.

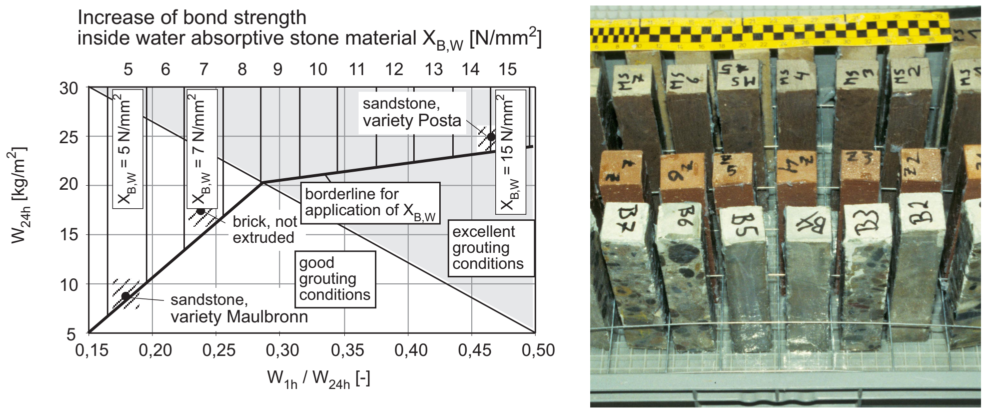

Figure 8: Diagram of the influence of water absorptive surrounding stone material. Picture of testing water absorptive capacity, referring to standard DIN 52617 (1987)

The highest bond strengths during laboratory and in-situ testing have been found in sandstone, variety Posta. In this material, bond strength is a constant, independent of the initial w/c ratio. Trass-cement suspensions between ω = 0,5 and 1,0 are giving the same, excellent bond strength (Gigla, 1999). An empirical term was found adequate to describe this parameter in the range of the tested materials.

The diagram in figure 8 describes two aspects: basically the greater the amount of water absorbed during 24 hours, the higher bond strength will be. Excellent grouting conditions are found, if a high percentage of the 24 hours amount of water is absorbed in a short time during the grouting process. If suction continues at completed grouting works, there is a certain risk of cavity. This aspect is taken into account with the ratio W_{1h} to W_{24h} on the abscissa and the borderline of the diagram.

3.2 Design resistance of the injection anchor, $R_{A,d}$

The design resistance of the injection anchor is calculated following expression (2). $R_{A,d}$ refers to the intersection of steel-bar and grout, $A_{A,d}$ (lateral area of steel bar), calculated with nominal bar diameter and bond length. The factor A_B / $A_{G,d}$ considers the ratio of bed and head joints of the borehole surface across bond length and limites $R_{A,d}$ to bond inside stone sections. Compare figure 9 for geometrical properties.

$$R_{A,d} = X_{A,d} \cdot \frac{A_B}{A_{G,d}} \cdot A_{A,d} \tag{2}$$

$R_{A,d}$: Design resistance of the injection anchor

A_B: Surface of injected mortar plug (lateral area) inside stone section

$A_{G,d}$: Surface of injected mortar plug (lateral area of grout).

$A_{A,d}$: Intersection of tensile element and injected mortar plug (lateral area of steel bar), calculated with nominal bar diameter and bond length.

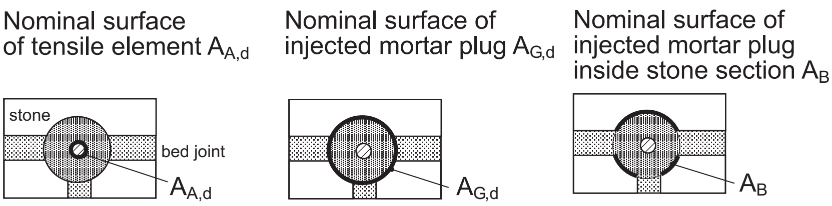

Figure 9: Geometrical values of expression (2)

3.3 Limitation of anchor force to avoid cracking of surrounding material

Based on theory of elasticity the following expression describes the maximum anchor tensile force that might be sustained by surrounding stone sections (Gigla, 1999).

$$F \leq \frac{1{,}9 \cdot f_{B,t} \cdot L_b \cdot \pi \cdot d_B \cdot (h_S^2 - d_B^2)}{\gamma_M \cdot \tan(\varphi) \cdot (d_B^2 + h_S^2)} \tag{3}$$

F: Anchor tensile force

$f_{B,t}$: Tensile strength of surrounding stone

d_B: Borehole diameter

h_S: Minimal height resp. width of surrounding stone

L_b: Bond length

$\tan(\varphi)$: Angle of force transmission between anchor and borehole, about 50° in water-absorptive material and about 60° in non waterabsorptive material

γ_M: Partial factor of safety for stone tensile strength, recommendation: 1,5

4 Influence of vertical stresses on injecton anchors located in bed joints

Focussing on anchors with bond in bed joints, the design-recommendation does not cover the parameter of vertical stresses of a certain wall section. Injecton anchors located near the ground section of a wall are supposed to take higher tensile forces then anchors located near the top. To analyse this parameter, additional pull-out tests have been performed in laboratory. The specimen was made of brickwork with non extruded brick arranged in 13 rows of heading courses (see figure 10). Mortar was based on a trass lime binder with average compressive strength of 2,4 N/mm² referring to standard DIN 18555-3 (1982). Three different series with five injection anchors each have been tested under different levels of vertical load applied to the specimen. Anchor material was stainless reinforcing steel with 10 mm diameter grouted in 30 mm boreholes. The specimen was built on a bearing steel beam. Vertical load could be applied by prestressing threaded rods between the bearing beam and a top steel beam. During pull-out testing, applied vertical load, anchor test force, free-end displacements of tensile element and injected mortar plug and two loaded-end displacements of tensile element have been monitored in 1 Hz intervals. Anchor test force was applied cyclic (figure 10). Figure 11 gives an overview about specifications and results.

The obtained average and 5%-fractile-bond strengths, based on 0,1 mm free end displacements of tensile element, are not confirming a significant influence between vertical load and anchor loadbearing capacity. This has to be explained by the variation of bond-strength during pull-out testing. Additional tests with higher vertical load will be performed to obtain significant values for a detailed discussion of the parameter. Considered

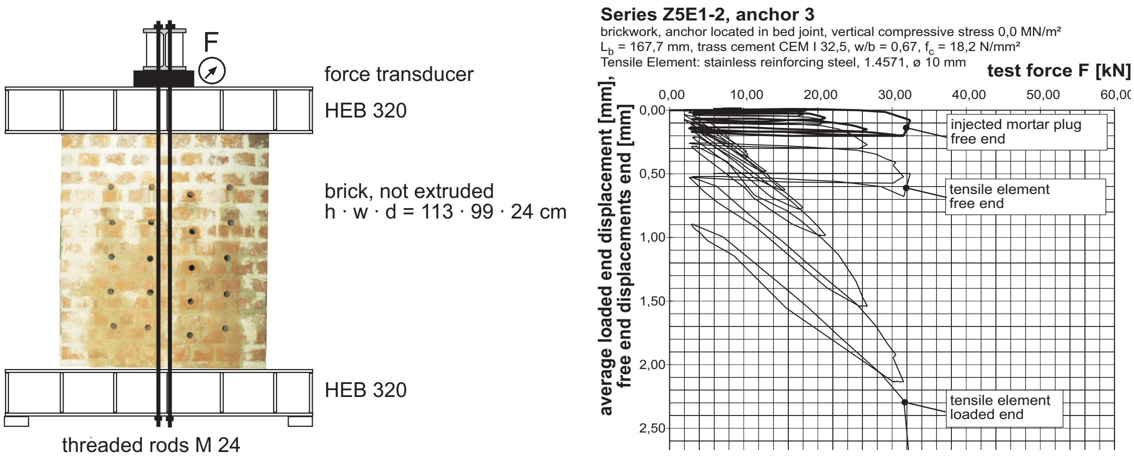

Figure 10: test arrangement for the application of vertical load (left), anchor test force versus free and loaded end displacements under cyclic loading (right)

series	number of anchors	type of grout	grout compressive strength [N/mm²]	average bond length [mm]	average compressive stress [N/mm²]	bond strength at 0,1 mm free end anchor displacement average [N/mm²]	5%-fractile [N/mm²]
Z5E1-1	5	trass-cement CEM I 32,5 R ω = 0,67	18,2	172	0,4	6,6	4,2
Z5E1-2	5	trass-cement CEM I 32,5 R ω = 0,67	18,2	172	0,0	5,4	4,5
Z5E1-4	5	trass-cement CEM I 32,5 R ω = 0,67	18,2	171	0,3	5,5	2,0

Figure 11: Overview of specifications and test results

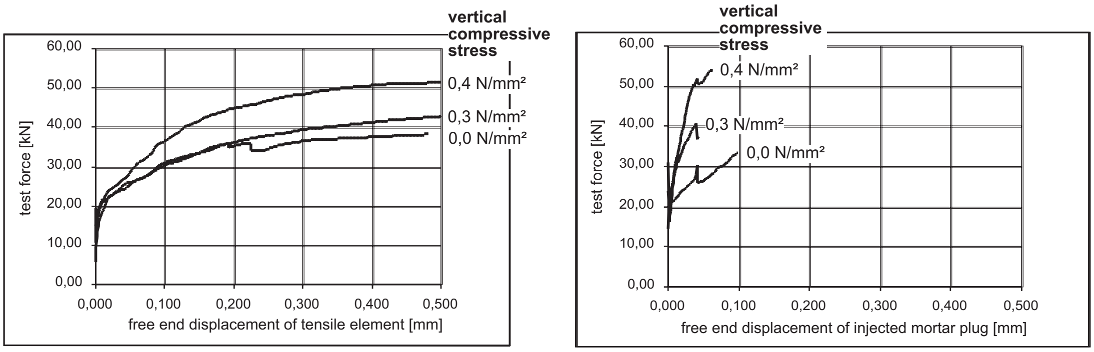

Figure 12: Diagrams of structural failure: test force versus free-end tensile element displacement (left) and versus free-end injected mortar plug displacement (right). Each graph is the average of five tested anchors

from the point of structural failure (figure 12), the influence is underlined. Each of the graphs in figure 12 is the average of five tested anchors. Both, free-end displacements of tensile element (left) and free-end displacements of injected mortar plug (right) clearly show, that even small vertical loads in the range up to 0,4 N/mm² provide a restraint to free transverse deformations between bed joint and injected mortar plug with an improve of bond strength.

4 Conclusions

Proceeding from five different types of structural failure, basic aspects of the design of supplementary injection anchors have been summarised, based on the results of more then 500 tested anchors. The obtained values refer to 5% fractiles of 0,1 mm free end displacements of the tensile element. It has been pointed out, that the water absorptive capacity of the surrounding stone material has to be considered well during anchor design and grouting works. The interaction between fresh grout and the surrounding masonry has been reflected. Another important factor of bond strength is the local bond condition, particularly the ratio of head and bed joints, the restraint to free transverse deformations of the surrounding material and working vertical compressive stresses. Latest results about the influence of restraint to free transverse deformations for anchors located in bed joints have been given referring to test series with applied vertical compressive stresses. Though the paper provides a detailed approach for the design of supplementary injection anchors, additional pull out tests should be performed, if the anchors relate to structural safety.

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