INVESTIGATION INTO THE SUITABILITY OF INDUSTRIAL FIXING SYSTEMS FOR THE REPAIR OF HISTORIC MASONRY

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SUMMARY

The core philosophy of minimum intervention is a fundamental principle of conservation engineering in Europe since the 1980ties. Wherever possible, the conservation of monuments should be achieved through approaches that require the least amount of modification, alteration, or removal of the original material. If masonry has to be repaired, its function and appearance should not be affected and new elements should be discernible. If original substance has to be replaced, physically and mechanically suitable material must be applied, to avoid further damage.

However, in some recent cases the track of minimum intervention has been partially forsaken. One reason is the local economy: if a certain monument has become a popular tourist attraction, the city-authorities are demanding a fast building progress, granting less time for research of the original structure. Another factor is an underfinanced public sector: the repair of a monument might require private donors. Therefore, conservation work faces a greater disposition for "quick and easy" industrial solutions. One example is Germany's National Monument "Holstentor" in the historic city of Lübeck (UNESCO world heritage). The Holstentor (town gate, built between 1464 and 1478) has recently been repaired with an industrial fixing system that was developed for repairing separated masonry.

The applied fixing system consists of stainless steel, grouted with synthetic resins by specially designed and patented cartridges. The load transfer mechanism of the applied fixing system and its effectiveness for the repair of historic masonry was investigated during pullout tests in the laboratory. In order to test the fixing system, specimens made of historic clay bricks were built and exposed to simulated frost action. The paper discusses the results of the testing in comparison with the results of 500 pullout-tests that have been performed by the first author in a research project within the SFB 315 at the University of Karlsruhe. The investigations were carried out independently, without support from the manufacturer, to analyse the quality of the repair of the "Holstentor".

Keywords: Historic Masonry; Repair; Reconnecting Walls; Minimum Intervention; Injection Anchor; Holstentor Lübeck

INTRODUCTION

Supplementary injection anchors (fig. 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 have been utilised since the 1920s. They perform as untensioned steel reinforcement or as a prestressed tendon. Forces are transmitted by bond between the anchor and the surrounding masonry in axial directions. Required core hole diameters are about 56 mm for untensioned anchors and 76 mm for prestressed tendons, in order to attain a sufficient cement-cover 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. Bore holes for untensioned anchors are usually less than 4.0 m long, 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 bars.

CASE STUDY: THE HOLSTENTOR (TOWN GATE) IN LÜBECK, GERMANY

HISTORY

Germany's national monument Holstentor (town gate) in Lübeck was built in brick masonry between the years of 1464 and 1478, as a part of the city's fortification. It consists of two round towers with a diameter of 12 m and a wall thickness of up to 4.00 m. The towers are 40 m high and are connected with a gate-house (fig. 2). On account of the weak ground, progressive and uneven settlement appeared affecting the whole building and reached a final value of about 4.00 m in the year 1934. Beginning in the 19th century, the Holstentor was no longer essential for the city's defence. Furthermore, the forthcoming railway system demanded new areas and a demolition of the building was discussed. After years of discussions, the city council decided in the year 1863 to preserve and restore the Holstentor as a historic site. Thereafter, it became one of the first officially protected monuments in Germany. In the meantime, it is one of the most popular national monuments. It is depicted on a banknote, on a new 2€ coin, and is used as a symbol for the conference of German municipal authorities (*Deutscher Städtetag*).

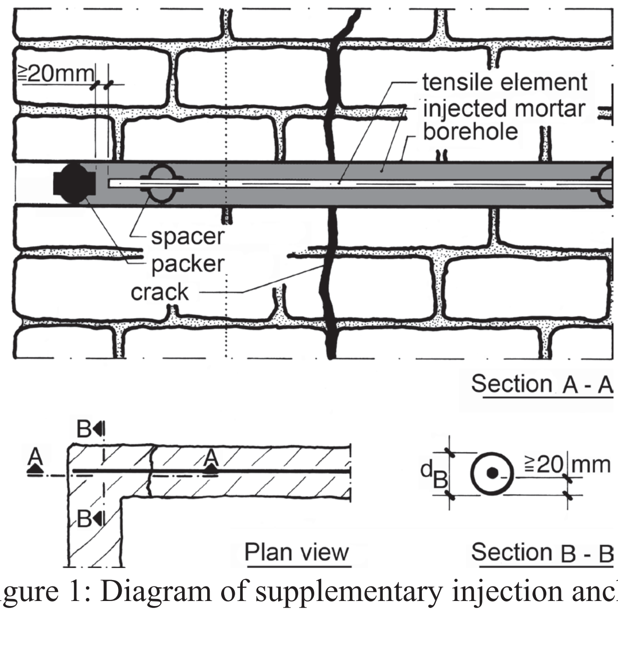


Figure 1: Diagram of supplementary injection anchor

Figure 2: Holstentor Lübeck, Aug. 2007 (town gate, built between 1464 and 1478)

DAMAGE AND BUILDING MAINTENANCE

Until 1840, only periodical standard maintenance work was carried out: mainly bricks of the outer shell have been periodically replaced, when necessary. Compared with this, the restoration works between 1863 and 1871, on the newly designated monument were on a much greater scale: alterations of the façade together with extensive replacement of brickwork. A drawing from a building survey dated from 1854 shows vertical cracking and a partially collapsed outer shell. In 1934 the last extensive maintenance was performed under the supervision of Prof. Rüth from the Technical University Dresden, one of Germany's pioneers in conservation engineering. He integrated a stabilising ring beam of reinforced concrete on the foundation level and succeeded in balancing the building and the surrounding terrain (Pieper, 1983 and 1986).

Since 1934 the structure has not changed, but in 2006 maintenance work at the façade became necessary. The occasional falling pieces of brick was a risk for pedestrians. On behalf of the city of Lübeck, a restoration team repaired mortar joints and bricks. The main terracotta frieze and the plain tile roof cladding of the towers was replaced. During the repairs, structural cracking was observed and the first author was consulted to develop conservation approaches to ensure safety and avoid further cracking. The engineering has been carried out in association with Cornelius Back, Lübeck (Gigla and Back, 2006). The vertical cracking was, in part, caused by historic corroded massive iron hooks that were intended to carry sandbags as a protection against enemy shooting.

Due to a lack of constructional or surveying plans, the first step of the investigation was complete optical plumbing with a laser plumb by Stefan Lorenz, Lübeck. A grid of 1 m range was chosen to provide sufficient data. The analysis of this data generated an overview of the buckling of the outer shell. The rate and amount of buckling were higher than estimated. Several surrounding arrays, of mainly horizontally extended bulges, were located. Typical buckling-areas were around 5 m in width and 2 m in height. In the second, step detachments of the outer shell was mechanically investigated with a rubber mallet. The buckling and detached zones were classified as to having the highest repairing-priority (fig. 3). In the third step, six points in these

zones were selected for structural investigation with a rigid endoscope. The detached outer shell is 12.5 cm thick, and the gap between the inner and the outer shell at the peak of the buckling was found to be 10 cm.

For structural repair the following alternatives were proposed, listed in the order of priority defined by the consulting engineers (table 1). Additionally, it was proposed to establish a survey-drawing with true deformations. The surveying was to be done manually, supported by a laser-scanning system (HDS) from the IfAB of the University of Applied Sciences Lübeck and a total station (TPS).

The recommended alternatives were dated 31st of May. In the view of the need to avoid unwanted scaffoldings during the Christmas time and because of a poor budget, city authorities decided to follow the second alternative of “Conservation Engineering”. But instead of injection anchors, an industrial fixing system was choosen. The selected fixing system is an effective wall-tie designed to cover wind loads on the outer leaf of cavity walls or facework. It is approved to be applied in concrete better than C12/15 and masonry constructions following German standard DIN 1053-1. The anchor bar is made of stainless steel with a diameter of 4 mm, intended for loads up to 1.0 kN. In the case of the Holstentor and after consideration of the wall tie’s limited transferable force and the unknown performance and durability of the historic materials, the consulting engineers refused to take the responsibility for this solution and resigned from their contract.

Alternative/ priority	**alternative**	**plus**	**minus**
1	“Reconstruction” Replacing the buckling and detached zones with compatible new masonry	- traditional approach - only damaged zones are treated - construction work can be done by local bricklayers - highest obtainable safety - high durability - moderate costs - additional information about the buckling process	- loss of historic façade material - addition of new material - auxiliary injection anchors are required to support the upper edge of the bulge during construction
2	“Conservation Engineering” Grouting of the detached zones with compatible lime/cements and repair with injection anchors	- preservation of historic façade material - good win of security - high durability	- extensive work - higher costs - flow and spreading of grout are difficult to control - special contractor has to be engaged for the work
3	“Preservation of the buckling” Repair of the cracks and additional investigation of the detached zones with a geotechnical radar, to establish a structural load-bearing model of the buckled façade	- most minimised intervention - lowest costs	- temporary approach - additional engineering investigation - regular monitoring of the façade is required

Table 1: Alternatives for the structural repair of the Holstentor Lübeck

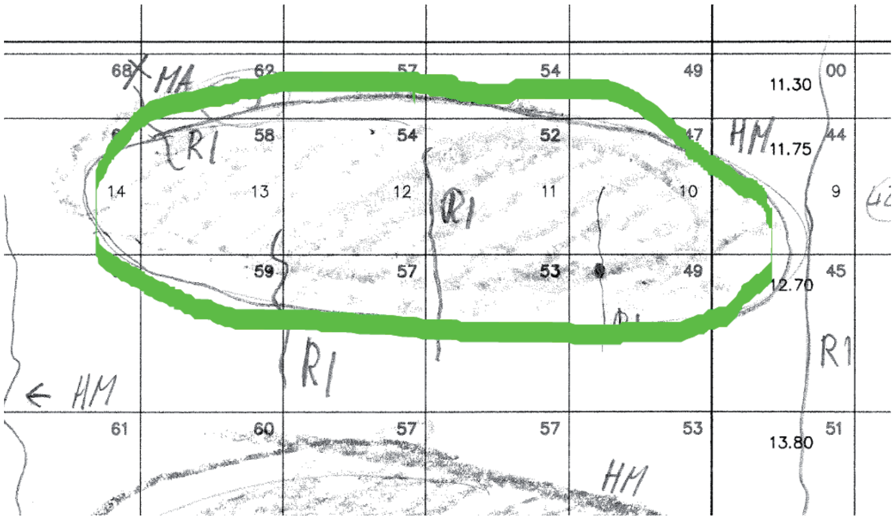
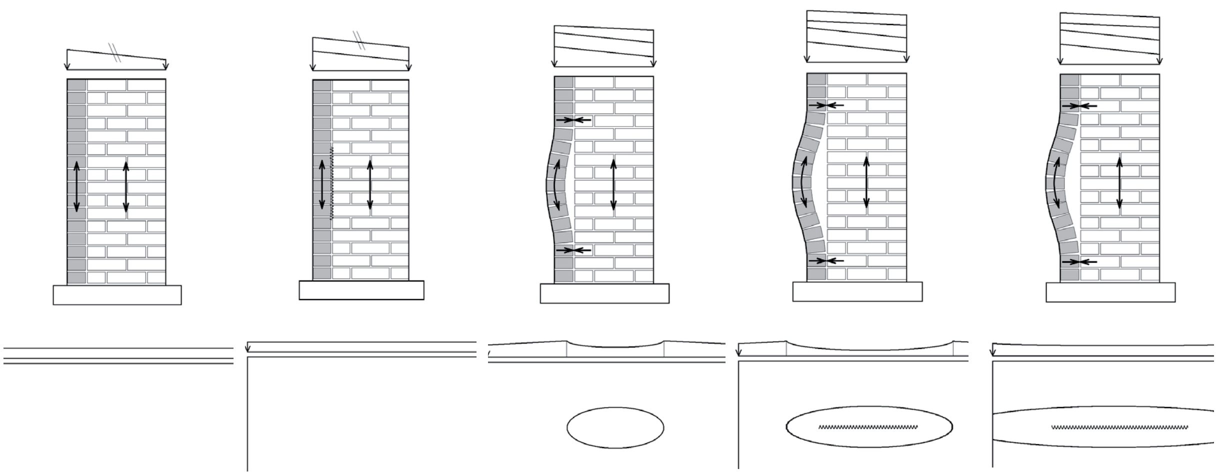


Figure 3:
Detail or the complete surveying plan with 1.00 m grid: detached bulge

BUCKLING OF MASONRY LEAFS

Buckling of masonry is a complex mechanism. The buckling zones tend not to carry vertical loads, causing force redistribution to the surrounding masonry. Abrupt collapse occurs in combination with frost, lateral load, dynamic loads or traffic-vibrations. Nevertheless, the experiments of Egermann (Egermann, 1995) on multi-leaf masonry indicate high load capacity of buckling outer leafs. The diagram in fig. 4 distinguishes idealised states of buckling. First, eccentric load causes a force concentration in the face of the wall. Second, partial detachments initiate a new leaf. Third, buckling starts with vertical deformation on both edges while the bulge still carries the load. Fourth and fifth, with load redistribution lateral deformations increase and the bulge tends to horizontal expansion.

The required horizontal tensile force to limit the horizontal deformations and to ensure safety is usually calculated from the load-eccentricity of the buckling leaf. Assuming a masonry compressive strength of 4 N/mm², for the geometrical conditions found at the Holstentor, a tensile force of 31 kN/m has to be carried.



1. 2. 3. 4. 5.

Figure 4: Idealised states of masonry buckling

UTILISATION OF INJECTION ANCHORS

Injection anchors are particularly suited to the repair of historic monuments while considering the aspects of „minimum intervention“, because the function and appearance of the masonry will not be affected and the new element can be distinguished from the original fabric in the future. The original material is only replaced within the bore hole with a physically similar material, if cement or cement-lime grouts are used. The precedent for use of metal based materials in masonry structures is centuries old (Wenzel et al 2000).

Recommendations for the design of injection anchors have been given by Gigla (2004), based on a research project at Sonderforschungsbereich 315 (Collaborative Research Centre 315: „Care and maintenance of historic buildings“, University of Karlsruhe 1985 - 2003, chairman: Prof. Dr.-Ing. Dr.-Ing. E.H. Fritz Wenzel). In the same paper, examples for the utilisation of injection anchors in masonry are discussed. Certain aspects of force transmission are part of ongoing research at the University of Applied Sciences, Lübeck.

SUITABILITY OF AN INDUSTRIAL FIXING SYSTEM FOR THE REPAIR OF HISTORIC MASONRY

DESCRIPTION OF THE SYSTEM

The remedial wall-tie VBS 8 from Fischerwerke, Artur Fischer GmbH & Co. KG, Waldachtal, Germany is designed for post construction fixing of facing masonry with or without an air gap. The system allows invisible ties to be retrofitted between two leafs of a cavity wall, as per German standard DIN 1053-1. The anchor consists of a perforated plastic sleeve and a 4 mm, 1.4401 or 1.4571 stainless-steel profiled tie. In accordance with the approval of the wall-tie, the chemical mortar FIS V from the Fischerwerke AG has to be used for anchoring. FIS V is a reaction resin injection mortar (two methacrylates and dibenzoylperoxid as hardening compound). The mortar is filled with Portland cement and silica sand as an aggregate.

For construction, the anchor is placed in the bed joint of the outer leaf and inserted into an 8 mm hole. It is suitable for bridging air gaps and insulation layers up to 150 mm with a required minimum bond length in the outer leaf of 90 mm. The whole system comes in one unit (fig. 5).

Figure 5:
Grouting of an industrial fixing system (wall tie Fischerwerke VBS 8) on Holstentor Lübeck

Grouting is done with a system of specially perforated capsules, joined by a static mixer and an injector nozzle. The system ensures, that no grout is applied inside the gap between both leafs. Mixing is done automatically during grouting. After grouting, the tie is manually inserted into the fresh grout. Polymerisation time is specified by the manufacturer to be 35 minutes at 20°C.

APPLICATION AT THE HOLSTENTOR

The application of the VBS 8 wall tie at the Holstentor took place, after the consultants resigned from the contract. The wall ties were placed around the complete façade in a grid of 60 cm into the bed joints. Fig. 5 shows a picture of the grouting works on the Holstentor. During the grouting works, FIS HB mortar was used instead of FIS V. Chemical mortar FIS HB from Fischerwerke AG is similar to FIS V, but consists of only one methacrylate and does not contain Portland cement. The FIS V-mortar is not approved for anchoring the VBS 8 wall-tie.

LABORATORY TESTING

To investigate the suitability of the fixing system for the repair of historic masonry, laboratory pull out tests have been carried out. Tests have been arranged into series of five identical anchors, this is assumed to be the minimum to be able to statistically analyse the results. Samples were made with two historic clay bricks each. The bricks were obtained by a local building company during rebuilding works on historic buildings. Average size (L/W/H) was about 28.7 to 13.9 to 8.8 cm and average density 1.7 kg/m³. Unit compressive strength was obtained to be 19 N/mm² (mean on 50 mm cylinders with 50 mm of height). Laboratory mortar was mixed in accordance with German standard DIN 1053-1, mortar group I. Mortar compressive strength was 3,9 N/mm² and tested on prisms 40 to 62.5 to 40 mm, following German standard DIN 18555-3.

The wall-ties were applied to the specimen after 28 days setting time. They were inserted into 8 mm holes located in bed joints, and grouted following the application rules. Both chemical mortars, FIS V and FIS HB had been considered within the test programme. Prescribed bond length was 40 mm. Compressive strength of the grouted mortars was tested on cylindrical specimens of 36 mm diameter and 36 mm height. The results are a compressive strength of 80.4 N/mm² for the FIS V and a compressive strength of 114.0 N/mm² for the FIS HB mortar. During testing it was observed that the FIS HB, which is not approved for the anchorage of the wall-ties, tends to shrink. The FIS V mortar showed no visual contraction. Furthermore, the FIS HB reached a temperature of about 40°C during hardening. With regard to the durability of the fixing system inside historic masonry, the temperature expansion was investigated on prisms 40 mm to 40 mm to 160 mm. The coefficient of thermal expansion was found to be $30 \cdot 10^{-6}$ 1/K for the FIS V and $46 \cdot 10^{-6}$ 1/K for the FIS HB in the range between 15 and -9°C.

The pull-out tests were performed with the measurement set-up as shown in the diagram in Fig. 6. The test parameters were the type of mortar, vertical load on sample and the influence of temperature on the bond strength. During pull-out testing the loaded and free anchor end have to be distinguished. Usually, the free end is not accessible in field tests and therefore, free end displacements are only to be explored in the laboratory. Anchor displacements at both ends are checked from an independent datum point. The picture in fig. 7 gives an impression of laboratory testing. For a more comprehensive description of laboratory pull-out testing see Gigla 2004.

The pull-out test load was applied cyclically with a hydraulic cylinder (fig. 8). Pre-load during pull-out testing was 600 N. Force and displacement were measured with inductive displacement

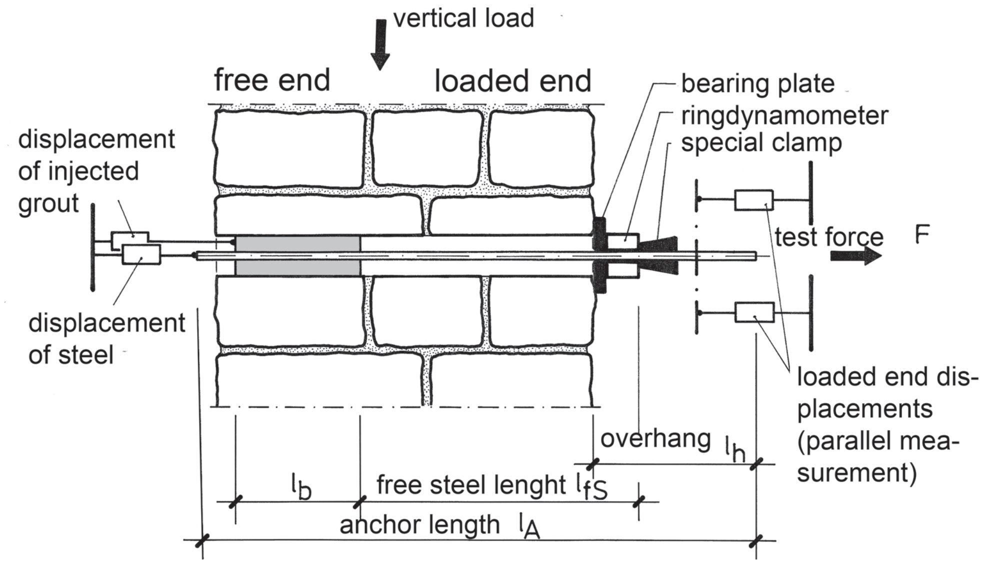


Figure 6: measurement set-up

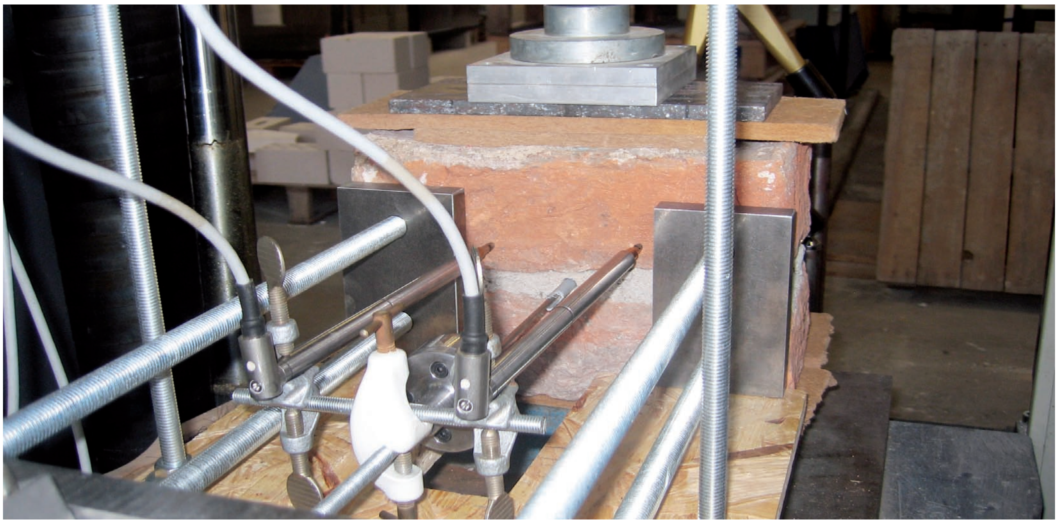


Figure 7: laboratory testing

transducers and a ring-dynamometer at 1 Hz frequency. Vertical stress on selected samples was applied by a compression test machine. For temperature effects, selected samples were exposed to a climatic simulation with 55 cycles from -15°C to + 20°C before pull-out testing. Frost time was 230 minutes and defrosting time 150 minutes. No visual damage was observed due to the changes in temperature.

LABORATORY RESULTS

Test parameters and the determined test forces at free end displacements of 0.1 mm are shown in table 2. Each series included 5 pull-out tests. The values are 95%-quantiles. The following types of failure occurred during testing:

a) bond-failure in grout-borehole interface
b) bond-failure in steel-grout interface
c) failure of steel bar, tensile strength of steel bar exceeded
d) weak grout, steel bar was pulled out of grout plug
e) failure of masonry-mortar
f) shear failure of grout plug according to mechanical damage during grouting works

Series	number of tests/ Type of wall-tie	Type of grout	vertical load [MN/m²]	Temperature effect before pull-out testing	maximum test force (95%-quantile) [kN]	test force at 0.1 mm free end displacement (95%-quantile) [kN]
1	5/VBS 6	FIS V	0,063	none	6.1	4.4
2	5/VBS 6	FIS V	0,083	none	7.8	5.2
3	5/VBS 6	FIS V	0,083	55 cycles -15 to +20 °C	8.4	6.1
4	5/VBS 6	FIS HB	0,083	none	8.5	4.5
5	5/VBS 6	FIS HB	0,083	55 cycles -15 to +20 °C	6.7	3.7

Table 2: Results of laboratory testing

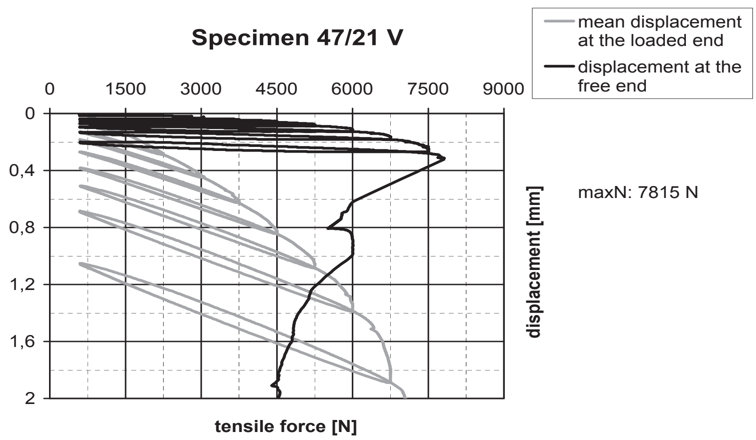


Figure 8: Sample of load versus displacement, during cyclic loading to failure

EVALUATION OF TEST RESULTS

Single test pull-out values deviate between those with short bond lengths and complex test set-up. For discussion, 95%-quantiles of the obtained test forces have been evaluated. The 95%-quantiles of the test forces of 5 pull-out tests show indicatively, that the anchorage with the approved chemical mortar FIS V is more effective, than with FIS HB. Furthermore, the values indicate a better anchorage with higher vertical load and a higher sensitivity of the FIS HB mortar with temperature effects. This would be an indication for less durability. All ties exposed to temperature effects suffered a bond-failure between steel bar and grout (type of failure b). This observation would be in accordance with the different coefficients of thermal expansion of steel and grout. Different expansion of both components would cause debonding in the interface between steel and mortar plug. The FIS V mortar benefits from the addition of Portland cement. The ties without temperature effects tend to fail in the interface between grout and borehole, frequently in combination with failure of the masonry mortar joint. However, the assessment of the durability of grouts made from chemical mortars for bond connections and anchoring in historic masonry requires more test series with longer temperature effect. The approved load of 1 kN per anchor has been covered in all series with a maximum free end displacement of 0.1 mm. Traditional injection anchors made of stainless reinforcing steel and cement-grout as discussed in Gigla (2004) cover higher loads and therefore are more suitable for the repair of buckling masonry. Wall ties with stronger bars, e. g. 8 or 10 mm of diameter could be an opportunity for adequate fields of application if the durability of the chemical mortar inside old masonry is ensured.

CONCLUSIONS

The usage of an industrial fixing system as an alternative to traditional injection anchors for the repair of historic masonry has been discussed on the basis of laboratory testing. Using the example of Germany's national monument Holstentor Lübeck the way in which minimum intervention as a core philosophy of monument protection has been partially forsaken was illustrated. The reasons are the demands of the tourist industry and a poor city budget.

The fixing system utilised was a stainless steel wall tie for the subsequent fixing of facing masonry with or without an air gap. On the Holstentor, approved and more suitable chemical mortar with added Portland cement was not used for grouting. However, laboratory tests indicated, that wfith the applied chemical mortar, tensile forces of minimum 3.7 kN per wall tie at 0.1 mm free end displacements are covered in samples, similar to the historic material. The 1 kN design load is intended to cover wind loads and appears to be rather small to fix buckling masonry. Traditional injection anchors made of stainless reinforcing steel and grout from mineral binders would cover much higher loads, if necessary.

To assess the durability of chemical mortars for bond connections and anchoring in historic masonry, two test series with 5 anchors each have been carried out. The samples were exposed to a climatic simulation of 55 cycles from -15°C to + 20°C before pull-out testing. Depending on the composition of the chemical mortar, lower tensile forces were measured after application of the temperature changes. After temperature changes, the wall ties were more susceptible to failure between the tensile element and grout. The values obtained within the described research programme are still indicative. Therefore, investigations into the durability of anchorages with chemical resins for the repair of historic masonry have to be part of ongoing research.

For applications in the field of minimum intervention, traditional injection anchors seem to be more suitable, because the original material is replaced with a physical and mechanically similar material, if cement or cement-lime grouts are used. Furthermore, the durability of traditional injection anchors is proofed since the 1920s.

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