Application of CFRP laminates as strengthening of cracked brick arches

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ABSTRACT: Many small cracks were investigated in an old historical building from the beginning of XVII century situated in Cracow. The reason of damage caused by inappropriate reconstruction was investigated also by use of measurements and numerical methods. The results of numerical analysis were compared with the results of observations in situ. Seven years measurements of crack width changes showed that the process of destruction of the structure advances. Cracks were caused by differences in the outside and inside temperature, changeable with seasons. Carbon Fibre Reinforced Polymer (CFRP) laminates were adopted as a strengthening of the brick arches in the building. Observations and measurements after repair showed that this kind of strengthening was effective.
2 CAUSES OF INVESTIGATED DAMAGES

Damages of the West Wing in form of cracks and fissures in the vaults, arches, and walls of the building were caused by structural reconstruction in the sixties of the XX century. These consisted in removal of some transverse bearing walls on the ground floor, and first floor (Fig. 4a – state before reconstruction). The large openings that appeared were covered with brick arches (Fig. 4b – state after reconstruction). Arches are flat $f_1=0.14$ and negligibly executed causes of investigated damages

Figure 2. Historical location of the West Wing of the Archaeological Museum in Cracow (Ciesielski & Kwiecień 2003).

Figure 3. The horizontal cross section of the West Wing.

Figure 4. Part cross section of the building before (a) and after (b) reconstruction.

Figure 5. The horizontal cross section of first and second floor of the West Wing with marked cracks and the new arches.

(Ciesielski & Kwiecień 2003). Places where transverse walls were removed and arches formed in their places are shown with a broken line in Figure 5 and denoted with letters A to E.

The introduced changes resulted in decreased transverse stiffness of the building counteracting uneven settlement and introduction of additional horizontal forces causing strutting of the longitudinal bearing walls. Just after the repair works had been finished, cracking of walls and vaults and once uneven settlement of the West Wing was started under the influence of a change in the static system of the building and action of additional strutting forces at the arch base. Cracks in the key occurred also in the newly shaped arches. After stabilization of settlement and redistribution of stresses in the structure (in the sixties of the XX century) the damages were filled with mortar and a new layer of plaster was put on the walls and vaults. This treatment made real damages hidden (no traces in the documentation of the building). The cracks covered with plaster reoccurred in form of fissures whose size has been permanently increasing during the last 40 years. Consecutive reparations of the premises covered the damages but after a time they reappeared; this evidenced permanently proceeding destruction. The fissures and cracks system observed on vaults and
arches is shown in Figure 5. The visible cracks in the building reaching up to 2 mm width proved to be only fissures in the plaster formed in the latest 40 years. They were caused by thermal changes occurring around the building in summer and winter. Real quantities of damages were partly discovered only in 2002 during strengthening works. The uncovered cracks are from 2 mm to 45 mm wide and are found in vaults, arches, and walls (Fig. 6).

3 MONITORING OF SETTLEMENT AND CRACK WIDTH CHANGES

3.1 Results of measurements of crack width changes

Since 1996 measurements of crack width changes have been performed by use of mechanical strain gauges. They showed that fissures in the arches and vaults in the middle part of their span changed in dependence on the acting thermal fields. Temperature changes inside and outside the building were connected with summer and winter season when temperature differences inside and outside the building reached even 40–50°C. These effects caused cyclic closing of fissures in summer time and opening in winter. Changes in fissure width did not oscillate around a certain constant value but increased; this gave evidence of permanent progressing strutting of bearing longitudinal walls. Dynamics of this process threatened with loss of stability of arches and vaults supported by them.

Changes in the width of fissures in chosen arch and vault keys, denoted in Figure 7 with letters E and G on the first floor and C and F on the ground floor were shown in Figure 8. The measured values were presented in form of diagrams for two measured periods. The first one covers the time between November 1996 and July 2002, when the arches and vaults worked without a new strengthening protecting the arches. The second period is between December 2002 and April 2004 when a part of arches in the west part of the West Wing (among other arches E and C in Fig. 7) were already strengthened. Measurement results in both periods for arches E and C show that the applied strengthening method was highly effective.
For comparison measurement results of the arch F and vault G were given; they show a progress destruction of the not strengthened part of the West Wing.

Strengthening works in the east part of the West Wing were given up in consequence of lack of financial means for reconstruction of this object.

3.2 Results of settlement measurements

Since 1992 (with some breaks) measurements of West Wing settlement have been carried out. They proved that the cracked building in which cyclic changes of fissure widths with growing trend, are observed is not subjected to settlement but exclusively to thermal influences. The diagram in Figure 9 of settlement changes of the mark Nr 3 and Nr 11, placed respectively on the west wall (founded on peats, silts and sands) and on the east part of the West Wing (founded on clays and sands) – Figure 7, did not show any settlements in the years 1992–1999. Increase in settlements in the years 1999–2003 is the result of depression sink formed in consequence of building deeply founded hotels in their vicinity. A rapid increase in settlements in the year 2003 is caused by drop of ground water level during the drought and additional consolidation of the ground under the building. In the year 2004 a consecutive stabilization of the West Wing settlement is observed after winter–spring rainfalls.

4 NUMERICAL ANALYSIS OF THE WEST WING OF THE ARCHAEOLOGICAL MUSEUM

4.1 Description of the applied analysis model

The Finite Element Method was used in analysis of the West Wing. Especially MARC (MSC.Marc 2001) system was utilized in this work, as one of the principal systems having mesh adaptation ability.

The part of the West Wing adopted for numerical analysis (Fig. 3) was modelled with surrounding soil as the 2-D plain strain model.

The linear triangle elements in soil and structure models as well as 6-nodes linear plane strain semi-infinitive elements in boundary conditions were applied. Characteristic size h of net of the initial mesh does not exceed $h \leq 0.5 \text{ m}$. The mesh of the used models with transverse walls (Figure 10a) and with removed transverse walls (Figure 10b) is presented.
4.2 Material properties

For simplification of calculation the limestone-brick walls were modelled as brick walls. As previously, the properties of the newly formed arches and brick walls were adopted as identical. As the material of the limestone-brick wall, as well as brick arches and vaults a simple model of linear-elastic isotropic material was applied; its properties in the homogenization process (Urbanski et al. 1995) were determined on the basis of data previously collected (Ciesielski 1999), (Janowski 1998), (Janowski 2000), (Ciesielski 1999), (Polish Standard PN-B-03002). The derived masonry parameters take into consideration the influence of mechanical and environmental degradation on stiffness and strength of the adopted material (Onate et al. 1997). More detailed description of various masonry models can be find in (Molins Borrell 1997), whereas, problems connected with modelling of arches in wall structures were presented more expensively in the paper (Hughes 1997).

In the applied model following material properties were taken: sand E = 90 MPa, \(v = 0.25\); \(\rho = 20\) kN/m\(^3\); clay E = 20 MPa, \(v = 0.32\); \(\rho = 20\) kN/m\(^3\); silt E = 10 MPa, \(v = 0.25\); \(\rho = 18\) kN/m\(^3\); peat E = 7 MPa, \(v = 0.15\); \(\rho = 17\) kN/m\(^3\); limestone masonry E = 1440 MPa, \(v = 0.15\); \(\rho = 27\) kN/m\(^3\); brick masonry E = 520 MPa, \(v = 0.15\); \(\rho = 19\) kN/m\(^3\).

For analysis of the numerical results the upper limit of tensile stresses was assumed \(R = 0.2\) MPa.

4.3 Load cases applied

The applied numerical model was loaded with a vertical load from gravity force, roof weight and filling of the cradle vaults as well as from cloister vaults including filling. Usable load was not considered as negligibly small. Additionally, the structure was loaded with strutting forces deriving from cloister vaults.

Thermal loads connected with temperature changes during the summer and winter period will be taken into consideration in further analysis.

4.4 Principal stresses analysis

Principal stress analysis was applied as a comparative criterion in analysing a model with transverse walls and a model without transverse walls. Distribution of the obtained stress in both cases was presented in Figure 11.

The presented stress fields in the models of the West Wing structure showed that removal of transverse walls and building in flat arches changed in a negative way stress distribution in the ground floor and first floor level. Concentration of stress and their level in the keys of the newly formed arches (Fig. 11) exceeds the material tension strength and shows the places of fissure and crack occurrence. Their location is congruent with location of damages in situ.

4.5 Comment on numerical results

The causes of occurrence of damages of the West Wing given in this paper were confirmed with the results of a simple numerical model of the building in question. The complex character of the problems the authors encountered during modelling the structure did not allow to adopt at the present moment more advanced models (Molins Borrell 1997), (Ofiate et al. 1997) and to consider thermal loads. Works on improvement of this model will be carried further on, so as to be able to take into consideration the mechanism of cracking that was connected with damages of the object. The authors hope that future calculation of a more advanced model

![Figure 11](image-url)
will permit to confirm the changes in the damage sizes associated with field temperature changes (Fig. 8).

5 PRESENTATION OF THE USED METHOD OF ARCH STRENGTHENING

5.1 Idea of the method
The observed distances between longitudinal walls supporting arches, visible in the size of cracks in the middle of arches (Fig. 8) showed a sinusoidal-shape in time changes with growing trend. They were caused by differences in the outside and inside temperature, changeable with seasons. This negative progress of destruction had to be stopped. A “passive method” was assumed as strengthening of the brick arches. The idea of this method was to join the reinforcement in co-operation when the walls were drawing aside. The reinforcement medium was to start working even with a small strain value and had to be simple in use and not expensive. This assumptions was fulfilled by the Carbon Fibre Reinforced Polymer (CFRP) laminates (Meier 1997).

The new arches formed in places where walls were removed on the ground floor and first floor of the west part of the West Wing were subjected to strengthening. The strengthening aimed at binding the longitudinal bearing walls and cracked arches in such a way as to make them carry additional horizontal loads from thermal wall movements and possible loads from damage. The reconstruction method could not introduce additional forces in the structure but was to protect the object against additional factors which could affect the existing, rather stable, state of the structure. It means that after installation of the strengthening the object was to work like so far in a state of balance stabilized in a natural way; in case of occurrence of any additional loads or unwanted displacements a protection was to be put into co-operation in carrying loads.

As the strengthening of the above mentioned arches Carbon Fibre Reinforced Polymer (CFRP) laminates were used; they were stuck by use of glue based on epoxy resins on lateral surfaces on both sides of the arches and additionally anchored in the longitudinal bearing walls using steel glued in anchors (Ciesielski & Kwiecien 2003).

The basic feature supporting for application of CFRP laminates was their low longitudinal deformability required with regard to thermal changes of fissure width in arch keys which increased cyclic during the year by tenths parts of millimeter. High strength of CFRP laminates permitted application of small sections that limited the wall areas subjected to reconstruction works, and enabled (at the designed course of strengthening) to maintain the existing usable area in the workrooms.

As the applied method is concerned limited interference into the object structure and arduousness of reconstruction works was an essential factor. Especially important with regard to a historical character of the object, was lack of necessary interference and changes in the building elevation and erection of high scaffolding that increase costs.

The adopted solution is a very recent one and gives many positives as compared with the traditional strengthening method (e.g. binding walls by use of steel rebars). It should be mentioned, however, that application of this method requires adequate accuracy of reconstruction works, hence they were carried out under the supervision of technologists proper for the used specialistic materials. A relatively high cost per unit of the applied materials affecting the final price of the strengthening was in the general account considerably lower in comparison with cost of traditional strengthening methods.

5.2 Technical scheme of strengthening
For strengthening of arches CFRP laminates S512 of tensile stress 2800 MPa and Young modulus 165 GPa (Meier 1997) were used. They were glued on lateral surfaces on both sides of the cracked arch on the level of the down part of the key. The coupling element transferring the forces from the CFRP laminates on to the anchors was constituted by a specially shaped metal sheet to which CFRP laminates were glued and anchors screwed. A draft of the strengthening, designed in 1998 and achieved in 2002 (Ciesielski & Kwiecien 2003), is shown in Figure 12.

5.3 Description of the strengthening method
In order to execute strengthening plaster was removed on both sides of the width of the CFRP laminates on the whole length of the arch in such a way that the CFRP laminates passed horizontally through the down tail of the arch; subsequently the joints were cleaned at the depth of 1 cm. The so formed furrow in form of a comb assure better co-operation of the joined materials (Fig. 13).

On the extension of the formed furrow on both its ends niches were made in the wall for fixing the metal sheets. Then in the niches at the depth of 30 cm two holes $\phi$14 were drilled at an angle of 30° to the horizontal plane and vertical plane of the arch (Fig. 12); after their through cleaning from dust steel tapped bars $\phi$12 were fixed on glue HIT RE500 (Fig. 14). Anchors were checked in a random way for pulling out with a positive result.

In order to receive smooth surface the cleaned brick was surfaced with a reprofiling mass Sikadur 41 (Fig. 15). Then the downer part of the nodular metal sheet, cleaned to the degree Sa 2½, was fixed and
screwed to the sticking out anchor ends (Fig. 16) in order to receive the initial stress.

The cleaned CFRP laminates were glued to the arches and to the nodular metal sheets with the glue Sikadur 30 (Fig. 16) and the top part of the nodular metal sheets was glued. After the glue was dry the top metal sheets were pressed strongly by them tight to the base.
base (Fig. 17). After the strengthening was mounted on all arches "packers" were fixed in the crack and fissures in keys and arch base, and subsequently injection by use of injection mass Sikadur 52 was performed.

At the end the niche was walled up and the CFRP laminates covered with plaster.

6 CONCLUSIONS

Measurements of changes in the width of fissure in the cracked brick arches carried out with in the recent years showed that the longitudinal bearing walls of the building of the Museum part drawing aside under the influence of strutting forces of the arches and of the acting on them changeable thermal fields. As a protection of the structure the strengthening was performed, based on CFRP laminates anchored in the brick wall by use of glued in steel anchors.

The presented solution permitted a quick, effective, and relatively inexpensive protection of the damaged part of building. However, this kind of strengthening requires great precision of work since even small imperfections in execution may have a negative influence on the work of the strengthening. Application of CFRP laminates permitted to include the strengthening into full co-operation already at very small structure deformations without necessary introduction of pre-stressing (steel rebars) which could influence negatively the damaged object being in a relative state of balance after occurrence of fissures and cracks.

Applied strengthening system is one of the first solutions of this type adopted to a historical brick structure in Poland. Over one year's observations of changes in the width of fissures in keys of repaired arches showed that the strengthening works properly according to the designers' expectations (Fig. 8).

Measurements of fissure width changes in arches and in the other parts of the building of the Museum are continued and will be carried till the whole building is strengthened and for another two years after its completion.

Strengthening of the concrete and reinforced concrete with CFRP laminates has already become a standard in building technique (Meier 1997), (Kendall 1999), (Brosens 2002). Wall strengthening with composites is also now thoroughly considered (Schwegler 1994), (Hamilton 2001), (Tumialan et al. 2002). There is relatively little information on implemented composite applications in reconstruction of historical objects. Problems concerning the way of anchoring, the solution of which may cause some trouble, are specially important.

The described case is one of the first successfully implemented solution of this type and therefore it deserves attention.

A successive, attempt stage of works, will comprise checking how the CFRP laminates strengthening of the cracked arches works. Numerical simulation of the work of the whole West Wing after strengthening by use of other methods is also planned.

REFERENCES


