Strengthening of Historical Masonry Vaults and Pillars with Carbon Fabric

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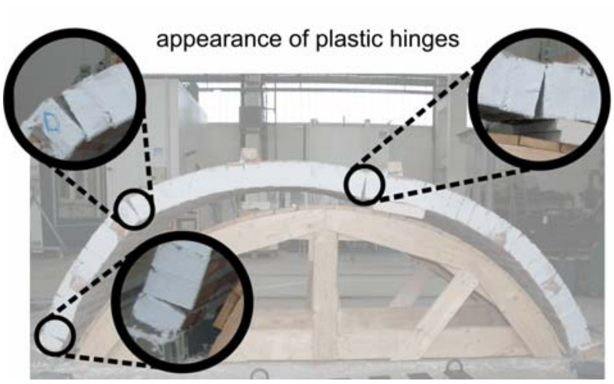
ABSTRACT: Unlike reinforced concrete structures, the strengthening of masonry structures by means of carbon fibres still lacks adequate theoretical and experimental verification (CSN EN 1998-3, Appendix A). The arrangement and execution of the strengthening carbon fabric onto primarily compressed masonry structures (pillars, barrel vaults) has a decisive effect on the ultimate bearing capacity of the strengthened structure and the type of its failure. The reliability and efficiency of the strengthening of masonry pillars and barrel vaults by carbon fabrics significantly depend on the strength of the connecting layer between the carbon fabric and the masonry structure.

1 STRENGHTENING OF MASONRY BARREL VAULTS WITH CARBON-FIBRE FABRICS

The failure mechanism of a masonry vault or a vault segment or structurally acting vault ribs differs from the failure mechanism of masonry pillars (Fig. 1).



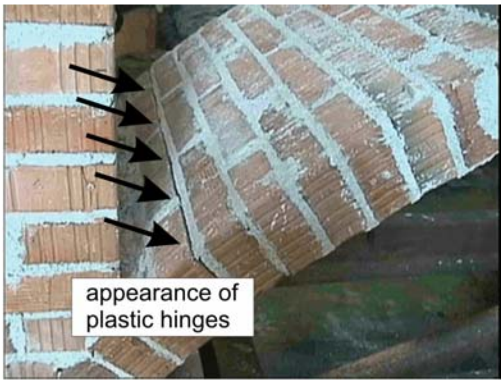


Fig. 1 Characteristic failures of non-strengthened masonry barrel vaults by tensile cracks

The vault failure process is highly complex comprising two significant mechanisms – local and overall vault system changes in shape and the vault masonry failure itself due to the action of tensile and compressive normal stresses reaching - at points of the appearance of tensile cracks - values of ultimate bearing capacity of the vault masonry in compression. For, the complete failure – vault collapse is, as a rule, the result of two related parallel processes. It is characterized by the vault buckling together with local failures followed by the vault disintegration. Both of these two processes are simultaneous and inseparable. The stress state during its loading and failure is aptly described by the course of the pressure line in individual phases of the vault system's action. The failure mechanism and reaching the vault ultimate bearing capacity are dramatically affected by the nature of loading, in particular, by its potential non-symmetry and, further, by shape and geometric discrepancies and imperfections and, last but not least, by the rigidity and stability of the supports.

Experimental research concentrated on the efficiency of rehabilitation of masonry barrel vaults with different vertical rises, reinforced by carbon-fibre fabrics applied in areas of action of tensile stresses – at the crown on the surface and at the vault impost on the extrados. Experimental research manifested a significant growth in the ultimate bearing capacity and ductility of barrel vault structures strengthened by carbon fabric. When vaults are strengthened, the consequences of the increased loadability of the strengthened vault affecting the growth of horizontal forces in the supports must also be considered (Witzany et al, 2008).

Segmental masonry barrel vaults with vertical rises of 750 mm and 1000 mm strengthened by carbon fabric (CFRP) showed, as a result of vault strengthening in the area of critical cross sections and thus prevention of the vault failure due to a loss in stability, on the whole, lower vertical and horizontal deformations (by ca 20-70%) under the same load as compared to the deformations of non-strengthened vaults (Fig. 2). This effect due to strengthening did not manifest so dramatically in segmental compressed vaults with a vertical rise of 375 mm (in vaults with the central angle smaller than 120°, i.e. in vaults that do not contain areas of so-called critical cross sections – with tensile stresses on the extrados at cross sections adjoining the impost).

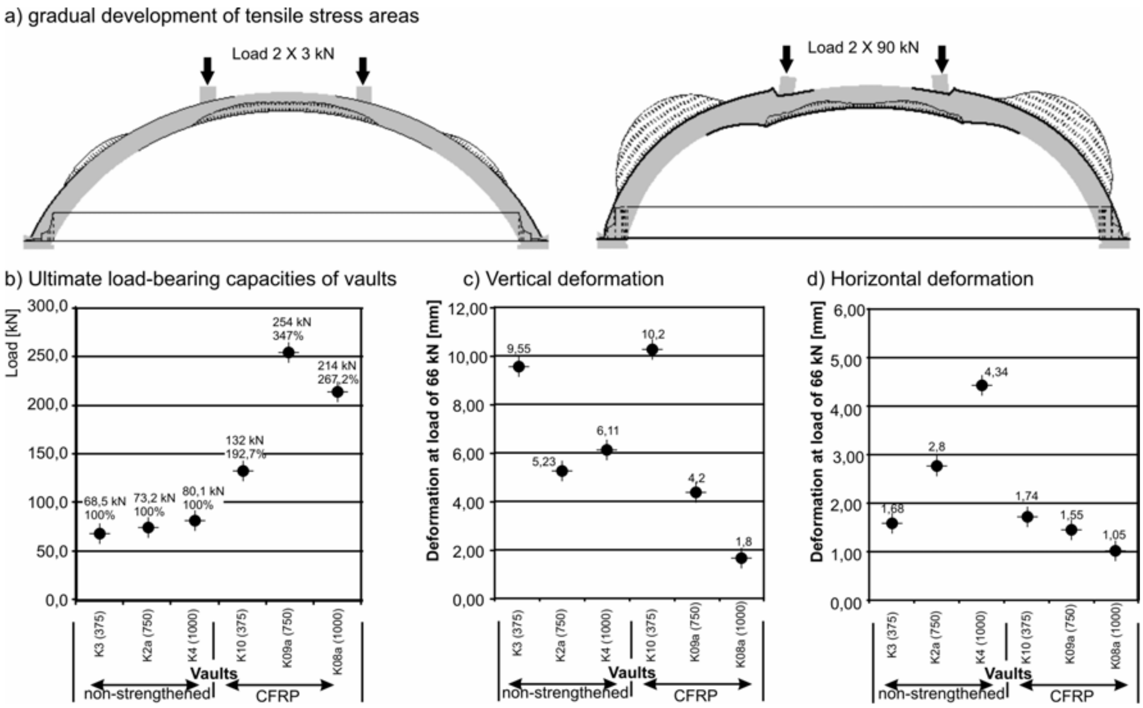


Fig. 2 a) Gradual development of tensile stress areas on the vault extrados and intrados (K08 vault strengthened by carbon fabric), (non-linear analysis, Maršík, V. 2008); b) Comparison of experimentally determined ultimate bearing capacities of non-strengthened and strengthened vaults; Vertical (c) and horizontal (d) deformations of non-strengthened segmental vaults and vaults strengthened by carbon fabric (CFRP)

The ultimate bearing capacity of segmental masonry barrel vaults strengthened by carbon fabric (CFRP) according to Fig. 5, symmetrically loaded by two vertical weights at thirds of the vault span (Fig. 3) reached values of ca 190-350% of the ultimate bearing capacity of non-strengthened masonry vaults (Fig. 2).

The limit deformations of vaults strengthened by carbon fabric with a vertical rise of 375 mm reached ca 150 to 285% values of the limit deformations of non-strengthened masonry barrel vaults, and the ultimate bearing capacity of strengthened vaults with a vertical rise of 375 mm reached values of ca 160-190% of the ultimate bearing capacity of non-strengthened vaults (Fig. 2).

The application of carbon fabric (CFRP) in vaults with higher vertical rises (750 and 1000 mm), in areas where tensile cracks arise (lower surface at the crown in the extent of ca 1/3 of the vault arch length, on the extrados in areas specified by the vault impost and the central angle of ca 120° in the extent of ca 1/3 of the vault length at points of so-called hazardous cross sections), limited the appearance and development of these characteristic tensile cracks enhancing, at the same time, the vault stability (Fig. 3, Witzany et al, 2008). The issue that has not been completely solved yet is the optimum length of the strengthening carbon fabric anchoring in the stressed parts of the vault on the extrados or on the parts on the face immediately adjoining the reinforced vault cross sections where tensile stresses arise on the extrados or on the face. In the contact joint between the vault masonry and the carbon fabric, apart from shear stresses, tensile normal stresses also arise acting perpendicularly to the contact joint and substantially reducing the load-bearing capacity of the contact joint in shear. As a consequence, adhesion between the vault masonry and the fabric is prematurely impaired, this is followed by complete vault failure. This problem will become the subject of special interest in the next phase of theoretical and experimental research.

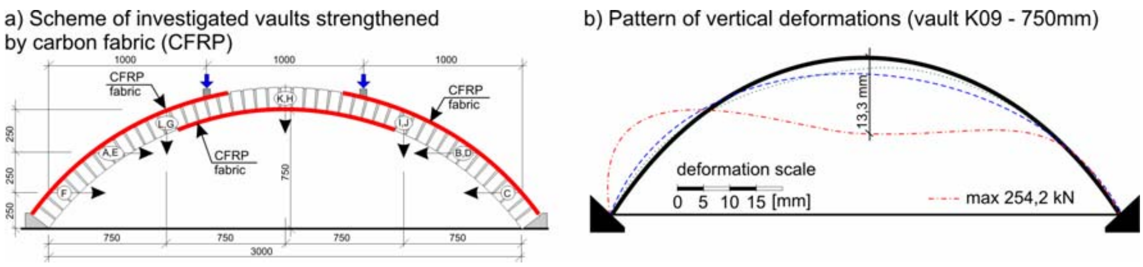


Fig. 3 a) Scheme of investigated vaults strengthened by carbon fabric; b) The pattern of vertical deformations of a vault with a vertical rise of 0.75 m (K09) strengthened by carbon fabric (prominent non-symmetry of the deformation line of a symmetrical vault, symmetrically loaded);

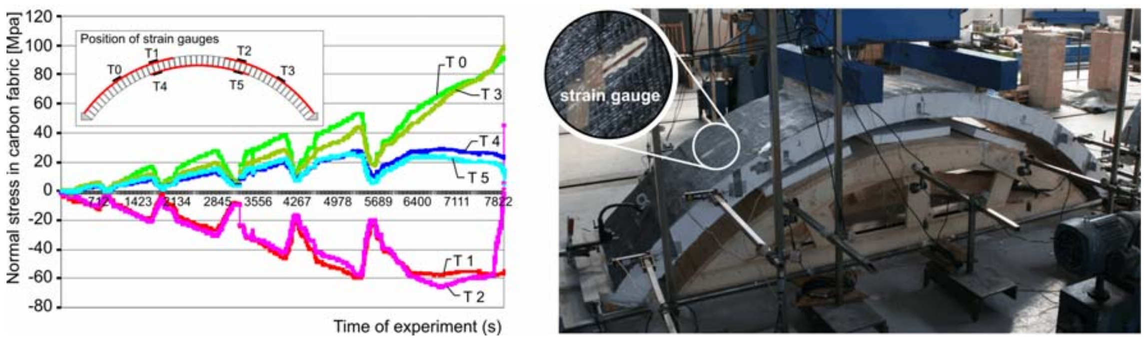


Fig. 4 Normal stresses in carbon fabric

The efficiency of vault strengthening in areas of the tensile stress appearance which precede tensile cracks in non-strengthened vaults is confirmed by the pattern of stresses in the carbon fabric. Fig. 6 shows a gradual growth in stresses in the carbon fabric under vault loading in the phase of vault masonry failure. The nature of failure of the masonry barrel vault reinforced in areas loaded by tension by carbon fabric is affected by the arrangement of strengthening fabrics in the anchoring areas. The incorrect arrangement of carbon fabric anchoring areas on the extrados and the vault face placed one above the other substantially affects the vault disintegration process, its nature impairing the ultimate load-bearing capacity of the vault (lower efficiency of the strengthening structure. This minor but serious problem of strengthening masonry barrel vaults by carbon fabrics, which is presently the subject of model numerical analyses and demanding experimental verification, is related to the overall concept of the application of carbon fabrics onto masonry vaults, i.e. mainly to finding the optimum arrangement and anchoring of strengthening carbon fabrics on the vaults or vault segments.

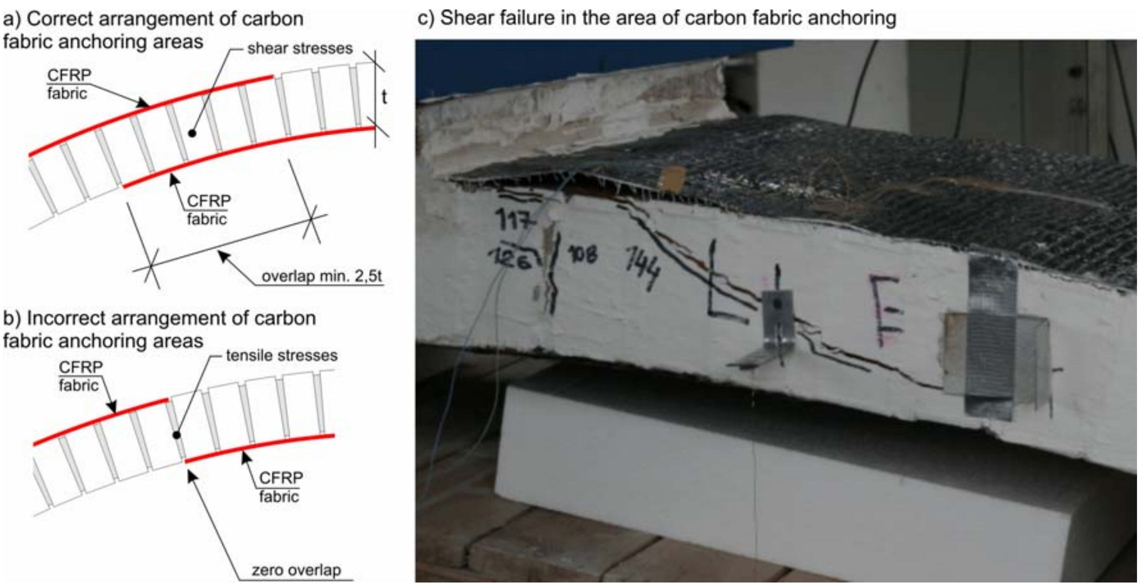


Fig. 5 Anchoring areas of opposite carbon fabrics

2 STRENGTHENING OF MASONRY PILLARS WITH CARBON-FIBRE FABRICS

The failure mechanism of masonry columns is characterized by tensile crack appearance due to the effect of transversal tensile stresses, which results in load bearing capacity lower than the ultimate load bearing capacity of masonry. Experimental research of the strengthening of masonry columns with carbon- or glass-fibre fabric showed a prominent effect of FRP on the reduction of characteristic tensile cracks and thus on a significant increase in the load bearing capacity.

Masonry is a non-homogeneous, non-isotropic, relatively brittle material consisting of two components with different characteristics. In common types of masonry, tensile (vertical) as well as compressive (horizontal) deformations of mortar under masonry loading by the normal force are, as a rule, greater than the corresponding deformations of bricks.

The mechanism of the interaction of both components of masonry and the results of microanalysis of an compressed masonry member for the given ratio of the strength fd, or the modulus of elasticity E respectively, are displayed in Fig. 1. The pattern of the principal stresses σ1 clearly shows the effect of different modulus of elasticity of bricks (Ec) and mortar (Em) and the bed joint thickness. The most frequent cause of failure of a masonry member loaded with vertical compression and exhaustion of its bearing capacity in compression is the appearance and development of vertical, mostly tensile cracks caused by transverse tensile stresses due to the interaction of both masonry components and transverse contraction of compressed masonry. By the division of a masonry pillar by continuous vertical cracks into individual “columns” its ultimate bearing capacity has been reached (Fig. 6).

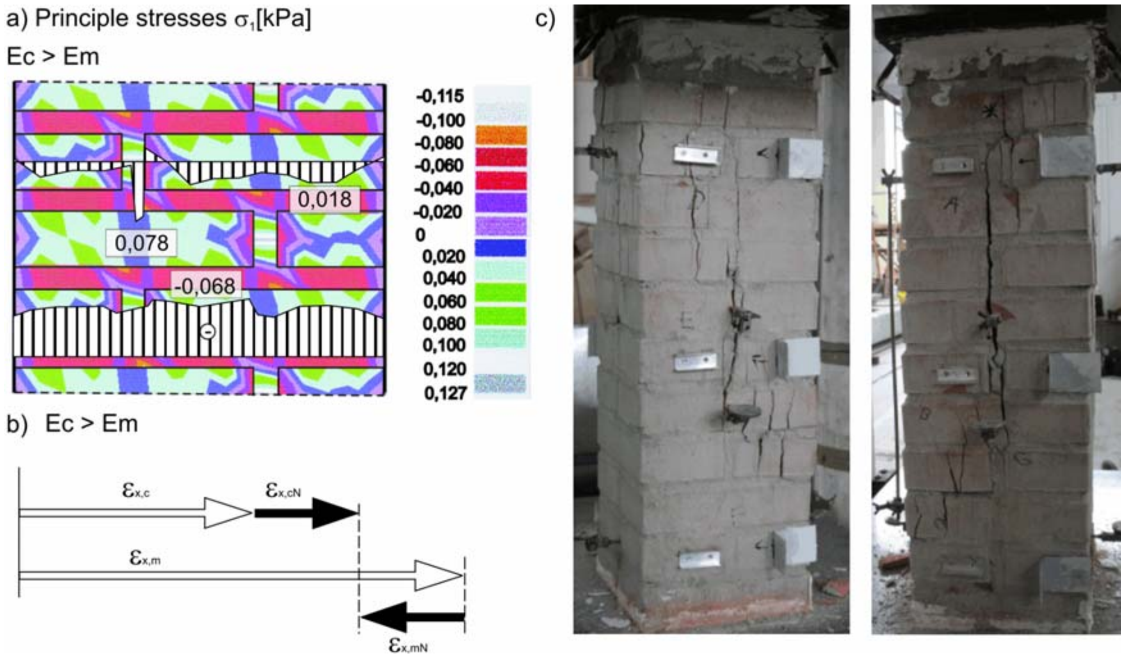


Fig. 6 a) The pattern of principal stresses σ1 in a compressed masonry pillar (450 mm in thickness); b) Mechanism of mutual co-action of masonry units and mortar; c) Characteristic failure of a non-strengthened masonry pillar at the ultimate load

Wrapping masonry in carbon-fibre fabrics avoids premature appearance of tensile cracks in an compressed masonry pillar – the carbon fabric with a high modulus of elasticity (min. 50-times greater than the modulus of elasticity of masonry) prevents transverse deformations of the masonry allowing thus greater (full) use of the bearing capacity of masonry in compression.

Experimental research manifested a significant effect of masonry strengthening by carbon fabrics on the ultimate bearing capacity and rigidity of compressed masonry members. The ultimate bearing capacity of a masonry pillar strengthened by carbon fabric reached the value of over 180 % of the ultimate bearing capacity of a non-strengthened masonry member (Fig. 7).

Special attention must be focused on the strengthening of structures in which there is a threat of further cumulation of failures and on-going degradation (the structure acts in the phase of elastoplastic deformation). This severe structural state must be taken into account during the determination of the bearing capacity of a strengthened masonry member and prior to strengthening, rehabilitation (e.g. grouting) of a degraded original masonry must precede. Progressive failure must be prevented by taking adequate structural measures, e.g. by relieving the original non-strengthened pillar and a subsequent transfer of a greater part of the load onto a strengthened pillar.

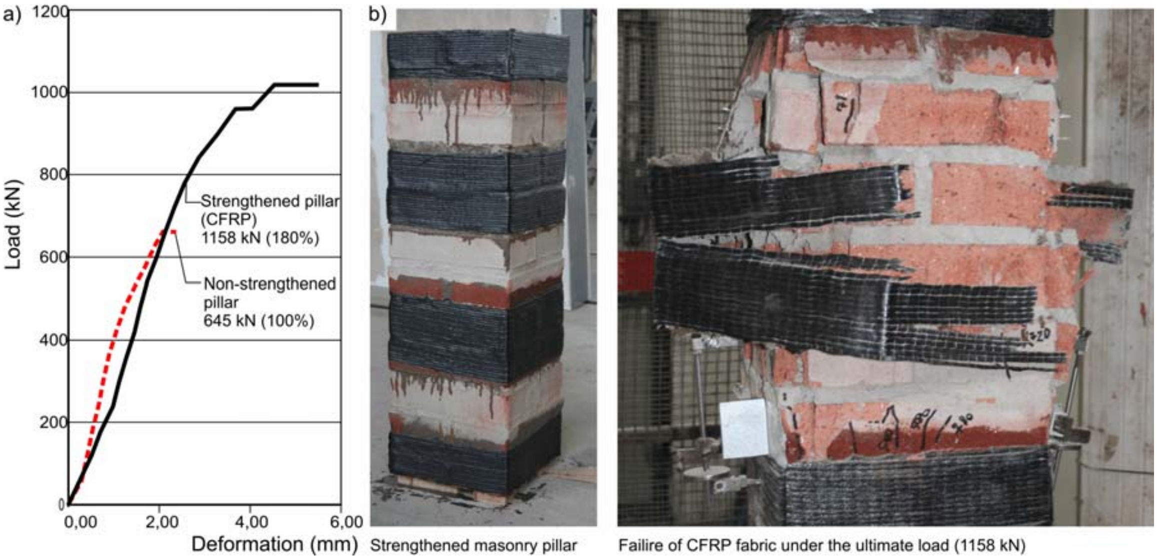


Fig. 7 a) Experimentally determined working diagrams of non-strengthened masonry pillars and pillars strengthened by carbon fabric; b) Strengthening of masonry pillars by wrapping them in carbon fabric and characteristic failure of a strengthened pillar

3 SUMMARY

The original knowledge obtained during experimental research, apart from the limit bearing capacities, characteristic working diagrams and deformation characteristics of strengthened vaults determined, includes the following:

- Strengthening of masonry members by wrapping carbon fabric around them fully exploits the high values of the modulus of elasticity and tensile strength of carbon fibres thus efficiently preventing the appearance of vertical tensile cracks in the pillar masonry, which as a rule precede its failure. The optimum strengthening alternative verified was a solution in which a masonry pillar is strengthened by individual strips of carbon fabric situated in thirds of the pillar height. The effect of tensile normal stresses due to the compressive deformation of vault masonry δ_y on the bearing capacity of the contact joint of "masonry - fabric" is gradually starting to apply with growing heights of the strengthening carbon strips.

- The application of carbon fabrics only on pulled areas of the barrel vault (extending to ca 1/3 of the arch length on the vault face and extrados) exposed to symmetrical vertical load dramatically affects the ultimate bearing capacity of the vault, its deformations and type of vault failure after reaching the ultimate bearing capacity. The failure of a vault discretely reinforced with fabric in its pulled parts, i.e. on the extrados and the vault face, depends, to a certain extent, on the mutual arrangement of the anchoring areas of strengthening carbon fabrics on the extrados and the vault face. The case of mutual overlapping of the carbon fabric anchoring areas as seen in Fig. 5 is characterized by the appearance of a distinct oblique crack at the points of “anchoring“ areas of the carbon fibre fabrics where the principal tensile stress reaches its maximum values. In the case of incorrect arrangement of the “opposite” reinforcing fabrics, the failure process may be accelerated. The failure process – local buckling – of the cohesion of the barrel vault masonry and the carbon fabric in areas exposed to compression is significantly affected by the normal stress in tension acting perpendicularly to the connecting cross joint.

- While strengthening masonry structures by carbon fabrics, we must consistently respect higher deformation and strain characteristics of masonry (with a potential exception of stone masonry of eruptive rock with thin bed joints) as compared to concrete (reinforced concrete). This fact must be taken into account while determining the bearing capacity of masonry strengthened by carbon fabrics respecting simultaneously the admissible relative strain of carbon fibers.

4 ACKNOWLEDGMENTS

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