Additional Horizontal Stiffening of Historical Masonry Structures with FRP Strips

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ABSTRACT: A frequent case that may occur during the reconstruction of historic masonry buildings is the absence or insufficient efficiency of the stiffening structures. By preventing the appearance and development of tensile cracks in the bearing masonry caused by the effects of induced deformations, the effects of horizontal loads as well as the effects of technical or natural seismicity, enhanced safety and reliability of the masonry system may be achieved.

1 INTRODUCTION

A stiffening structure composed of wall ties and transverse (e.g. so-called beam) ties takes up, in particular, the tensile stresses in masonry, thus increasing the masonry shearing strength and preventing the appearance and development of cracks. Stiffening structures are of crucial importance in preserving the resistance of the load-bearing masonry system to the effects of vibrations and seismic loads (Kos, 1984).

The activation of loose tie rods requires serious interventions in the load-bearing masonry and, in particular, strengthening in the area of anchoring elements of beam ties, or even an intervention in the suspended floor structure.

Insufficient stiffening of the masonry of historic buildings produces very severe negative consequences manifested mainly by tensile cracks impairing the integrity of masonry, or by masonry deformations. These cases may frequently reach such an intensity that poses hazards to the building’s stability (Witzany et al., 2010).

2 PRESTRESSING OF MASONRY

A complex stress state arises in the area where local prestress is applied characterised by extreme values of tensile and compressive normal and shear stresses (Fig. 1). This differs from the stress state arising due to a gradual, “linear” stress application (by e.g. a CFRP strip glued by its overall surface onto the masonry surface or into a groove in masonry) which is characterised by a uniform distribution of vertical compressive stresses and by a continuously (into the centre of a reinforced structure) growing horizontal compressive normal stress. In both cases of the application of prestress onto a load-bearing wall, a favourable elimination of local stress concentrations occurs. The drawback of the continual application of prestress is the concentration of horizontal stress states into the centre of a prestressed structure which requires more detailed structural analysis in this area.

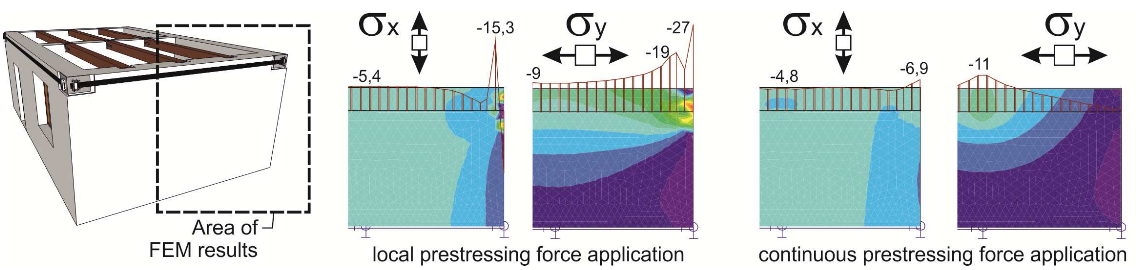

Fig. 1 Stress state in the area of application of prestressing

Horizontal tensile stresses that may be the cause of the appearance of vertical tensile cracks arise in places of openings in the heads of load-bearing masonry walls due to the effect of the deflection of the principal stress trajectories from vertical loading. In the case that the tensile strength of masonry is exceeded, cracks develop and the head cross section is gradually degraded. Horizontal prestress of a structure efficiently eliminates these tensile stresses preventing the appearance or development of tensile cracks (Fig. 2).

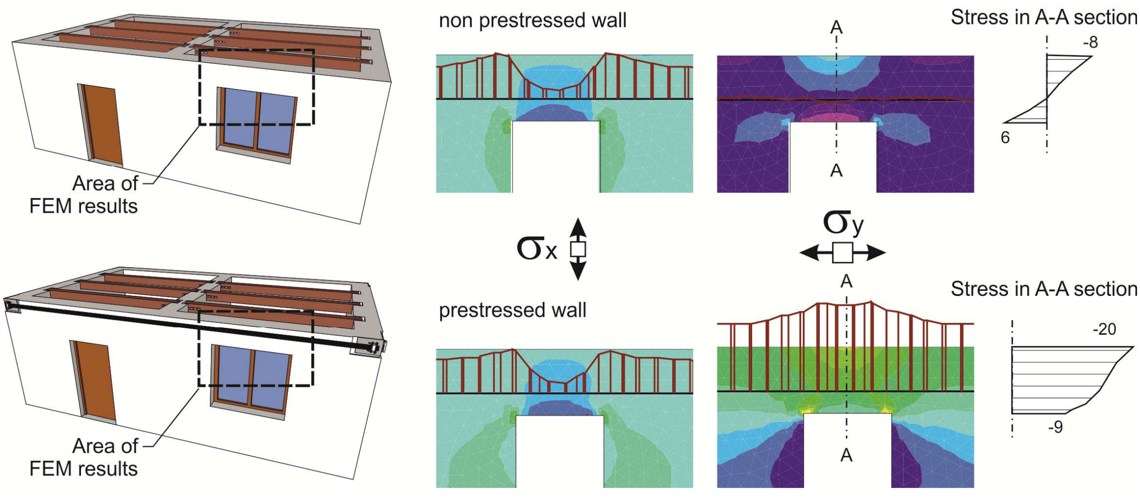

Fig. 2 Elimination of tensile stresses above openings in masonry walls due to the prestressing

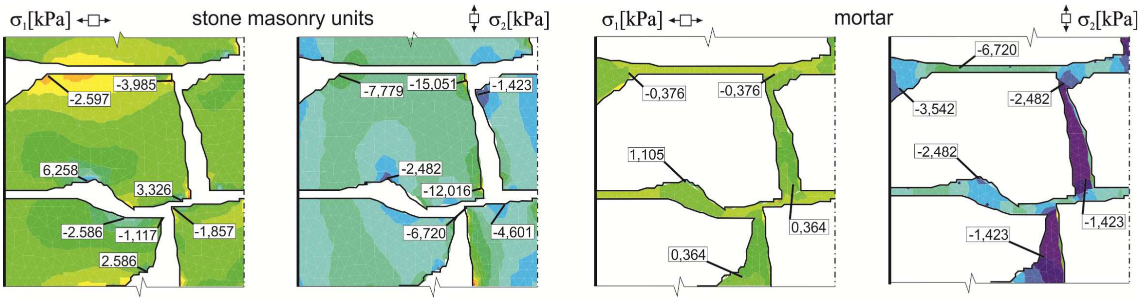

Fig. 3 Complex stress state in the vicinity of irregular masonry units

A complex stress state in the vicinity of irregular masonry units in load-bearing masonry, in particular around sharp edges of masonry units, is characterised by the appearance of local, often extreme values of normal and shear stresses which precede the subsequent appearance and development of cracks in the masonry (Fig. 3). The prestress of the structure accompanied by the elimination of mainly local peaks of tensile normal stresses significantly contributes to enhancing the usable strength of masonry.

Figure 4 displays the strength curve of masonry under biaxial stress state (a simplified case of triaxial stress state) which shows a significant increment in the masonry strength in connection with a change in the stress state from the “compression-tension” quadrant to the “compression-compression” quadrant due to prestress. The reserve in the masonry strength thus obtained may expediently be used in rehabilitations and reconstructions of existing buildings whose residual load-bearing capacity is insufficient.

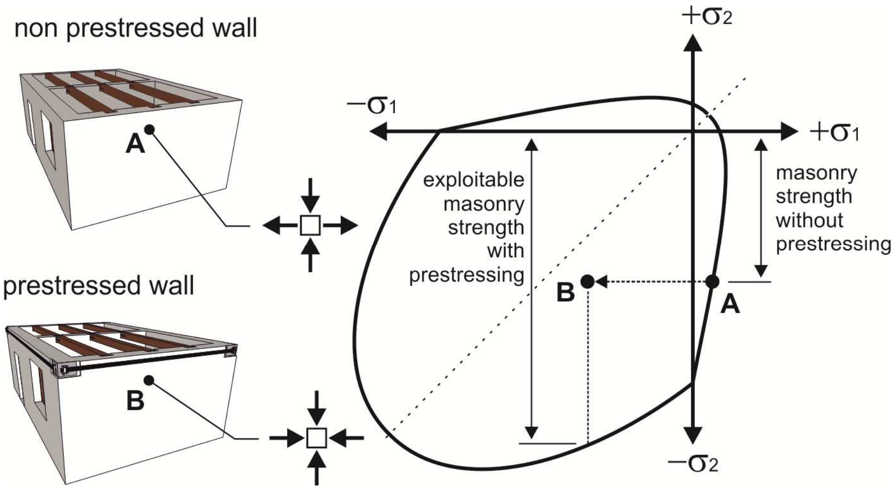

Fig. 4 Strength curve of masonry under biaxial stress state

3 HORIZONTAL STIFFENING OF MASONRY STRUCTURES WITH CFRP STRIPS

Additional stiffening of the masonry of historic buildings is presently performed using mainly steel tie rods or prestressing cables which are mounted in deep grooves in the face of load-bearing walls at the floor structure level. Some of the disadvantages of these existing methods of additional execution of “beam ties” are eliminated by the solution consisting in the application of strips based on carbon fibres fitted with special metal anchoring elements and load-distribution steel plates in their end parts; the carbon strips used may be designed as non-prestressed, or they may be prestressed to the required force by means of special anchoring elements (Witzany et. al, 2012). The carbon strips may be placed immediately on the treated masonry surface, on a levelling layer of cement or in a shallow grove or they may be applied in masonry bed joints. This solution results in a significant elimination of the degradation of historic structures. Figure 5 shows stress patterns before and after prestressing the load bearing (outer) walls of small church with prominent tensile crack caused by foundation subsidence.

Reinforcing strips based on carbon fibres are special strips produced by so-called pultrusion, 60 – 160 mm in width composed of carbon fibres 0.25 – 0.32 mm in thickness possessing the tensile strength of 3000 – 4000 MPa, the modulus of elasticity of 200 – 250 GPa, the maximum tensile strain of 1.5 – 1.9 %, the density of 1.5 – 2 g/cm^3 and the areal weight of 600 – 700 g/m^2.

Prior to their installation, special carbon-fibre-based reinforcing strips are on both ends fitted with enclosed-shaped metal sleeve anchors with a wedge-shaped hole for passing through the strip, after the strip is passed through it allows its anchoring by means of wedge-shaped metal plates provided with special surface treatment on both sides consisting of roughened surface at the contact point with the strip and grooves at the contact point with the enclosed sleeve fitted with analogical grooves allowing reliable fastening of the strip and preventing its slacking off. Prior to adjustment, contact surfaces of the strip and the anchoring metal plates are fitted with epoxy resin.

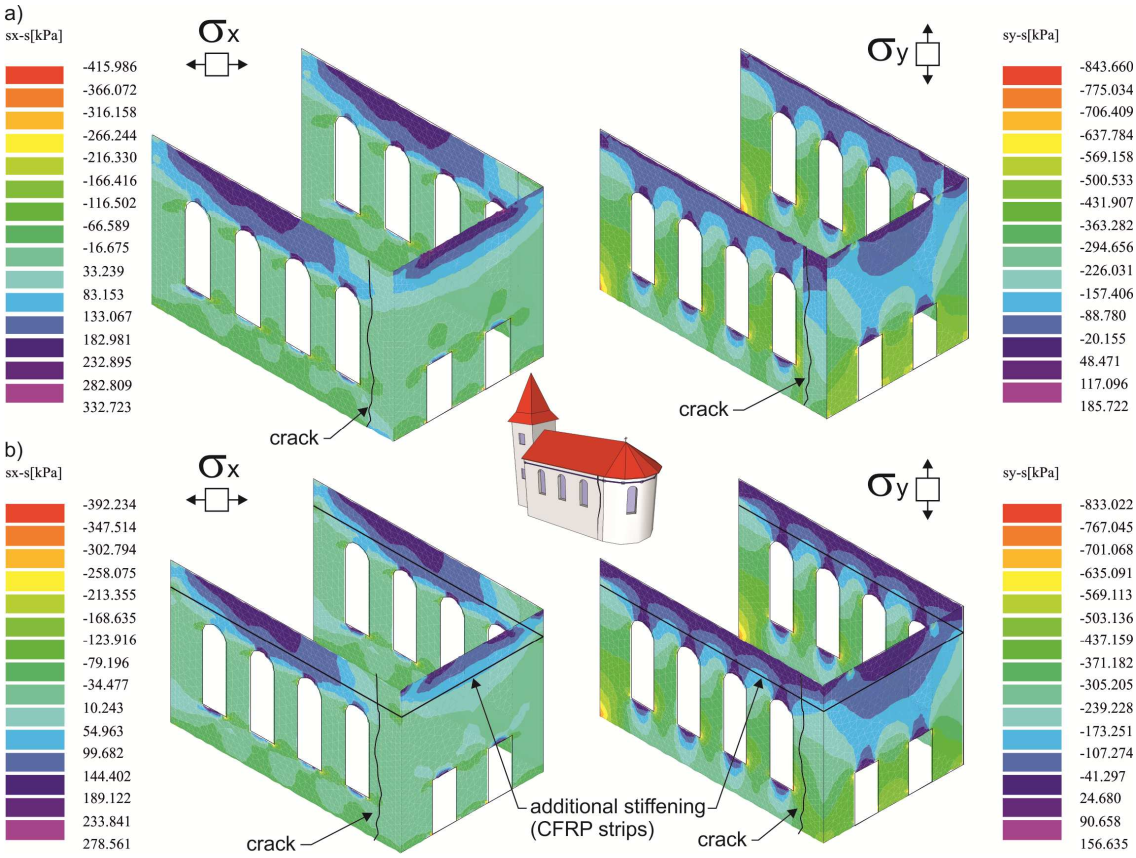

Fig. 5 Example of a sacral building stiffened by carbon strips along its perimeter

L-shaped load-distribution corner metal plates are mounted in semi-flush corner pockets in masonry and are fitted with dowels 18 – 20 mm in diameter with a periodic surface and 200 mm in length inserted in purpose-made holes 24 – 28 mm in diameter and filled up by polymer cement mortar.

Special carbon-fibre-based reinforcing strips are mounted only after the required strength of the contact joint between the L-shaped load-distribution corner metal plates and the masonry has been reached.

The L-shaped load-distribution corner plate is modified to allow the mounting of metal anchoring elements at the ends of reinforcing strips oriented in a mutually perpendicular direction. The mounting element in the load-distribution corner metal plate allows the embedding of sleeve anchors fitted with two screws for the strip activation in their central part. The prestressing of the strips to the required force may be achieved by means of prestressing screws (distance bolts) fixed on the sleeves and by using so-called “torque” wrenches (Fig. 6).

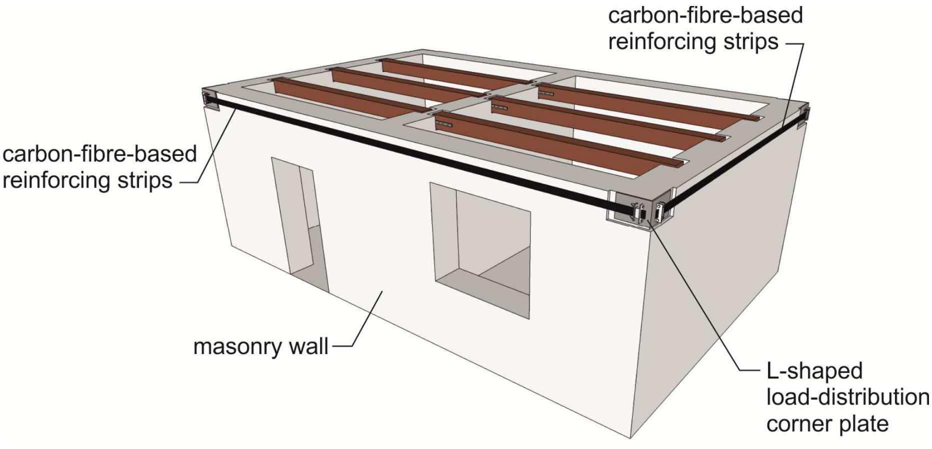

Fig. 6 Carbon fibres based reinforcing strips along the building perimeter (Witzany el al., 2011)

Depending on specific conditions and in keeping with the requirements for fire resistance or the requirements for the protection from mechanical damage, carbon-fibre-based strips may be protected by special purpose-made cover fillets fitted with fire resistant spray-coating or with external plaster.

In the case of historic buildings with e.g. timber floor structures, it is expedient to execute transversally oriented tie rods tying opposite load-bearing masonry walls which are situated in the place of timber beams or steel girders, in the place of transverse walls and partitions, or at the heel of transversally arranged masonry barrel vaults (Fig. 7).

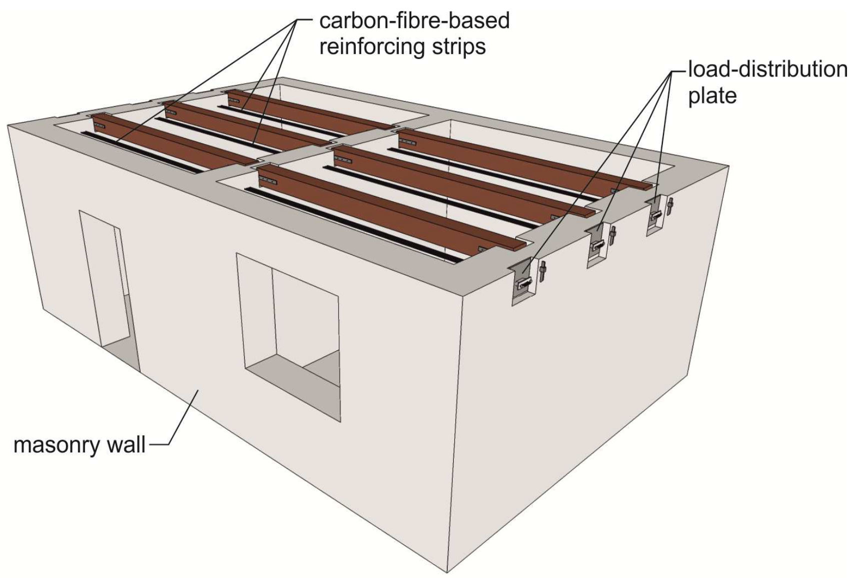

Fig. 7 Carbon fibres based reinforcing strips situated in the place of timber beams (Witzany el al., 2011)

According to the suggested design solution the carbon-fibre-based strip is fixed in a special enclosed-shaped metal sleeve anchor with a wedge-shaped hole for passing through the strip which allows the anchoring of the strip after it is passed through it. The contact surfaces of the strip and the metal anchoring plates are fitted with epoxy resin before adjustment. At the points of the anchoring of additionally executed strip beam ties, partially flush-mounted load-distribution metal plates are mounted in the masonry. Analogically to the previous case, the specially designed metal sleeve allows the prestressing of the strips (Fig. 8).

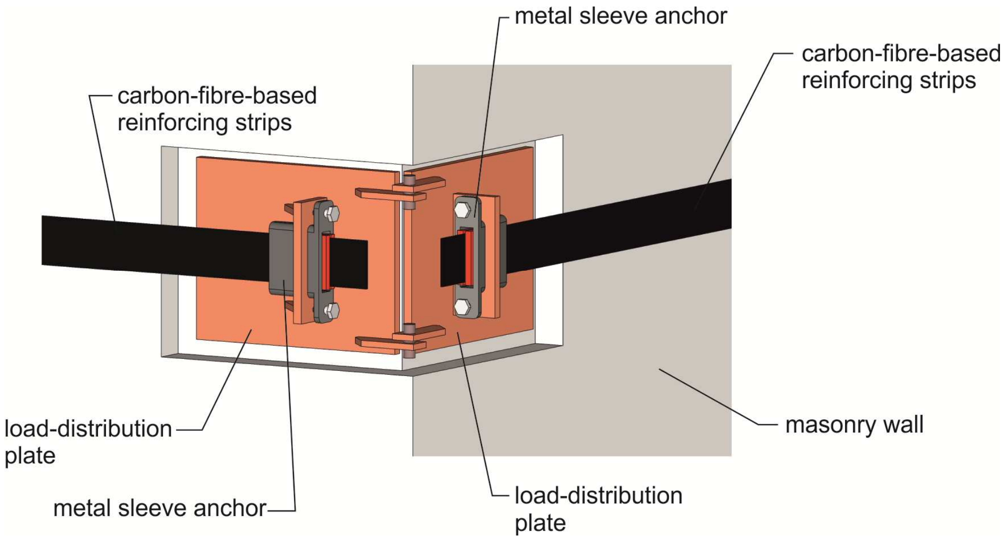

Fig. 8 The scheme of the anchoring zone of prestressed strips (Witzany el al., 2011)

4 SUMMARY

Horizontal stiffening at the floor structure level fulfils a significant function in terms of securing spatial rigidity, stability and resistance to the effects of induced deformations, to the effects of horizontal loads and the effects of technical or natural seismicity.

The advantage of the utilisation of horizontal prestress, e.g. by means of CFRP strips fixed in steel anchoring elements, is the efficient elimination of the appearance and development of vertical local tensile or shear cracks in masonry or changes in the shape of the footing bottom, around openings, etc.

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