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Repair of Cracked Historical Masonry Structures by Use of the Flexible Joint Method (FJM) – Laboratory Tests

Arkadiusz Kwiecień and Boguslaw Zając
Cracow University of Technology, Faculty of Civil Engineering, Cracow, Poland

Jan Kubica
Silesian University of Technology, Department of Building Structures, Gliwice, Poland

ABSTRACT: Cracked historical buildings function in a new stress state of static equilibrium that is a consequence of post damage redistribution of the internal forces. This concerns especially unreinforced masonry (URM) buildings damaged by irregular settlements or acting of inertial forces during dynamic excitation. The Flexible Joint Method (FJM) for repairing of cracked historical masonry structures is proposed in this paper. It is based on "softening" of a structure and energy dissipation absorbed by the new joint constructed in place of cracks. In the FJM special polymer fills the cracks of the damaged buildings and thus introduces a new strength. There is given description of the FJM and also results of laboratory tests of polymer and results of tests of bricks joined with investigated polymer are presented. Practical examination of the proposed method was carried out on an unreinforced masonry wall damaged by shear stress, which cracks were filled in with investigated polymer.

1 INTRODUCTION

Damages of historical buildings could be caused by natural or human activity. Most often the natural actions are earthquakes, floods, wind and snowstorms. Direct actions connected with human activity like: inappropriate rebuilding, overloading of a structure and wrong exploitation, and also indirect like: building activity in surrounding of historical structure or paraseismic actions coming from urban traffic vibration and mining exploitation could cause acting of inertial forces and an irregular settlements after additional soil consolidation.

Masonry historical structures are especially very sensitive for such influences because of their brittle characteristic of material properties with low tensile and very often poor shear and compressive strength, and massiveness as well. Failure in masonry takes place when the principal tensile stress exceeds the tensile strength of masonry material. In result, appeared damages are visible on historical structures in form of fissures and cracks.

Damage occurrence develops mechanism of energy absorption that extensively reduces the forces acting upon the structure. When crack divides a member into two parts, they work separately in a new stress equilibrium and static balance being a consequence of stress redistribution. Such cracked buildings are characterised by a decreased resistance to the action of additional loads, to which the building was resistant prior to damage. Even relatively small loads connected, among others, with seismic (after shock e.g.) and paraseismic (urban traffic vibrations e.g.) action, variation of the ground water level, deep excavations, variable temperatures, technology of exploitation and utilisation could cause a further increasing destruction of the damaged building; this can cause loss of static balance heading in consequence to exclusion of the building from use. It should be mentioned that in most cases of retrofitting of cracked masonry historical buildings attention should be focused on avoiding unnecessary interventions and special care should be paid in order to limiting variations of their mechanical behaviour as much as possible (Modena 2004).

2 RETROFITING METHODS OF CRACKED HISTORICAL MASONRY BUILDINGS

2.1 *Short review of strengthening methods of cracks in monument masonry structures*

Generally, in case of cracked masonry heritage structures the repair and strengthening techniques must be chosen with exercise of special care. First of all, during whole repair process at any moment is not permitted to generate any deterioration of the technical state of whole or part of repaired structure. Secondly, the strengthening method should be suitable for the majority of cracks and should be born in mind, dependent upon aesthetic, environmental and real loading conditions.

Usually, the diagonal or similar to vertical cracking are observed. The repair method dependent upon internal stresses and suitable recognition of all factors, which produced them (Freeman *et al*. 1994). In case of cracks connected with increasing of compressive stresses the most typically solution is to fill the crack with appropriate (Lime or Cement-Lime) mortar mix, well rammed in, and repoint the surface. Sometimes is also permitted removing and replacing shaded cracked units with new.

Quite different situation is observed when cracks are produced by appearance tensile and high concentrated stresses in plane of masonry (Parkinson et al. 1996). In such cases is necessary to introduce into existing structure some elements being able to safely transfer the tensile stresses. The most popular is usage of reinforcing stitch bars (made of stainless steel and usually have diameter not exceeds 6 mm) grouted in at appropriate bed joints. Much more effective is putting into bed joints the special stainless steel spiral bars, more flexible, characterised by higher tensile strength and have very good adherence to mortar (Drobiec, Ł. and Jasiński, R.and Kubica, J. 2000). Sometimes, especially in case of stone masonry structures are also in use stiff steel bolts fixed by resin concrete injection across the crack into earlier prepared boreholes. Alternatively, where load the transfer of enhanced structural continuity is required, a stitch stiff lintel or rigid beam could be incorporated into the wall across the crack. This solution is acceptable only in structures with plastering of the masonry surface.

2.2 *Applying of new materials in retrofitting works*

It should be noted that applying of too strong strengthening material to cracked structures (in comparison to the material properties of the wall) could cause additional damages. It is highly preferred to select properly innovative materials to make them work together with the existing materials with better “compatibility” from the mechanical point of view. This is to reduce as much as possible high stress concentration, which could occur using high strength/high stiffness modern bonding materials like resin or high strength mortars in cracked URM masonry (Modena 2004). The main criterion in selection should concern much more deformability than strength, especially in seismic areas.

It is necessary to investigate material properties of masonry before applying a retrofit method based on various materials. The compressive strength and modulus of elasticity define the load-bearing capacity of masonry walls at gravity, whereas the tensile strength and shear modulus define the load-bearing capacity at seismic loads. Additional information regarding the ductility, damping and energy dissipation capacity, as well as strength and stiffness degradation and deterioration is also of relevant importance (Tomaževič 2004).

3 THE FLEXIBLE JOINT METHOD (FJM) IN REPAIR OF CRACKED MASONRY

3.1 *Description of the Flexible Joint Method*

The most of retrofit methods applied up till now tend to restore the primary stiffness of the object and its properties from the pre-damage state. Cracks are usually filled in with rigid inject to assure co-operation of members separated by a crack and receive a new external strengthening. Generally strengthening is typically accompanied by stiffening but in certain cases “softening” can be better than strengthening (Bachmann 2002), particularly in case of cracked historical masonry structures.

The new proposed Flexible Joint Method (FJM) allow to join the disrupted structure elements by means of flexible joints made of deformable elastic-plastic polymers and reinforced polymers filling in the cracks, see Fig. 1. This method is registered in the Polish Patent Department with No. P-368173 and was described in details in papers (Ciesielski and Kwiecień 2004), (Kwiecień and Zając 2004), (Kwiecień et al. 2005).

The new method of protection and retrofit may be regarded as a passive one. Application of this sort of joining structural elements does not involve any additional stress in the damaged object, which could cause new damages in the weakened structure of the building (e.g. in historical buildings). The FJM permits safe work of the retrofitted structure in the new stabilized the state of balance. This is the method particularly conductive to objects, in which a redistribution of stress occurred in consequence of damage (cracks). It permits further safe exploitation of the object under additional static and dynamic loads.

The FJM should be treated as a complement to the existing retrofit methods, which could be applied at determined work conditions of the structure under the protection and retrofit process. It is obvious that reason of damage should be removed before applying of a retrofitted method.

3.2 Cooperation of a flexible joint with a structure element

Details of work of a flexible joint, constructed in a cracked masonry structure, are presented on the basis of an example given in diagrams, see Fig. 2. The strength of the joining material (polymer) is assumed to be lower than the strength of the structure materials ($f_j = 0.67\ f_s$) and the joining material is much more flexible than the structure material ($\varepsilon^u_s = 0.35\%$, $\varepsilon^u_j = 100\%$).

Under an exploitation load, a tension principal stress is much lower than tension strength of the structure and an input energy (area under σ-ε curve) is absorbed by the elastic deformational energy of the structure (Step 1). Under an ultimate load, the tension principal stress is reaching the value of tension strength and the input energy is absorbed by the total deformational energy of the structure. If the input energy grows up, the crack is appearing and the tension principal stress is starting to be equal zero in this place (Step 2). After filling in of crack with polymer the tension principal stress is still equal zero (Step 3).

Under the new exploitation load, the input energy is absorbed simultaneously by both elastic deformational energy of the structure and of the new flexible joint (Step 4). Under the additional load, both absorb the input energy simultaneously: the elastic deformational energy of the structure and also by the elastic and non-linear deformational energy of polymer (Step 5). Under the new ultimate load, the tension principal stress is reaching the value of the polymer tension strength, and polymer undergoes destruction in the joint (Step 6), preserving this way the structure from destruction. Beginning of polymer destruction (visible in form of shear bends) is the signal for a new structural intervention in the cracked structure.

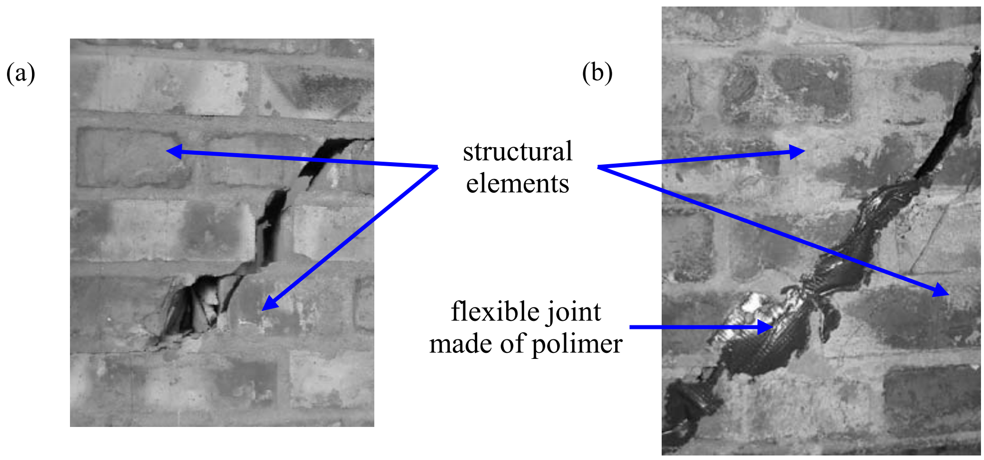

Figure 1 : Application of the Flexible Joint Method: (a) cracked masonry wall, (b) flexible joint made of polymer, filling in crack and joining disrupted structural elements.

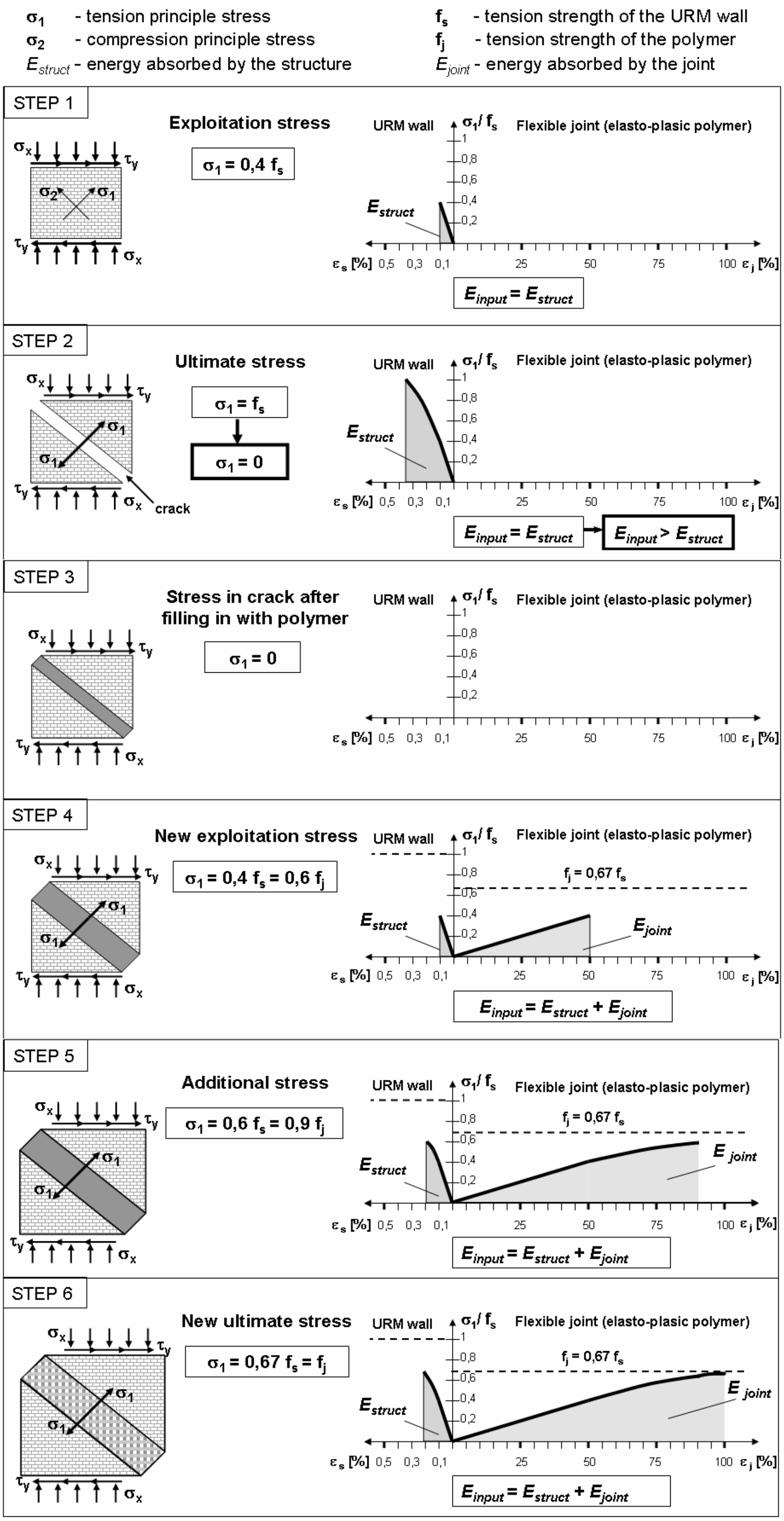

Figure 2 : Diagrams describing cooperation of a flexible joint with a cracked structure after application, working together under an additional load (based on the energy approach)

3.3 Properties of a flexible joint

Cracks filling with specially designed polymer in the previously damaged bearing structure cements the disrupted structural elements. It assures that the damaged building regains tensile, compression and shear resistance in place where bearing capacity was lost. Especially, the tensile resistance, deformability and ductility are greater.

In dynamic aspect, there is an advantageous shift of eigen-frequencies of the structure into lower frequencies and increase in damping and ductility (Kwiecień et al. 2005). There are some advantages of the flexible joint in comparison to a rigid one (Heinzmann et al. 2001):

- deforms when transmitting loads (damps vibrations and equalises deformation);
- assures uniform distribution of stress along the lap joint over the total contact surface, making optimal use of joining material in the constructed connection;
- prevents a sudden unforeseen failure of the joint;

4 LABORATORY TESTS OF FLEXIBLE JOINTS APPLIED TO MASONRY ELEMENTS

4.1 Tests of polymer properties applied in the flexible joints of masonry elements

An investigated polymer 340/45 is a flexible two-component grout based on polyurethane resin, hand and machine applicable. It is reducing vibration shear-resistant and permanently elastic adhesive, insensitive to moisture and also with long life expectance. The polymer is resistant to temperature from -40°C to +80°C (temporary up to +150°C) and UV radiation.

Mechanical properties were investigated during a laboratory test. The results are presented in diagrams given below, see Fig. 3. Modules of deformation are shown near the curves of compression, tension and shearing. Only the shear modulus is almost linear in the tested range of strain. Remaining modules are linear up to strain value of 30% and then start nonlinearly.

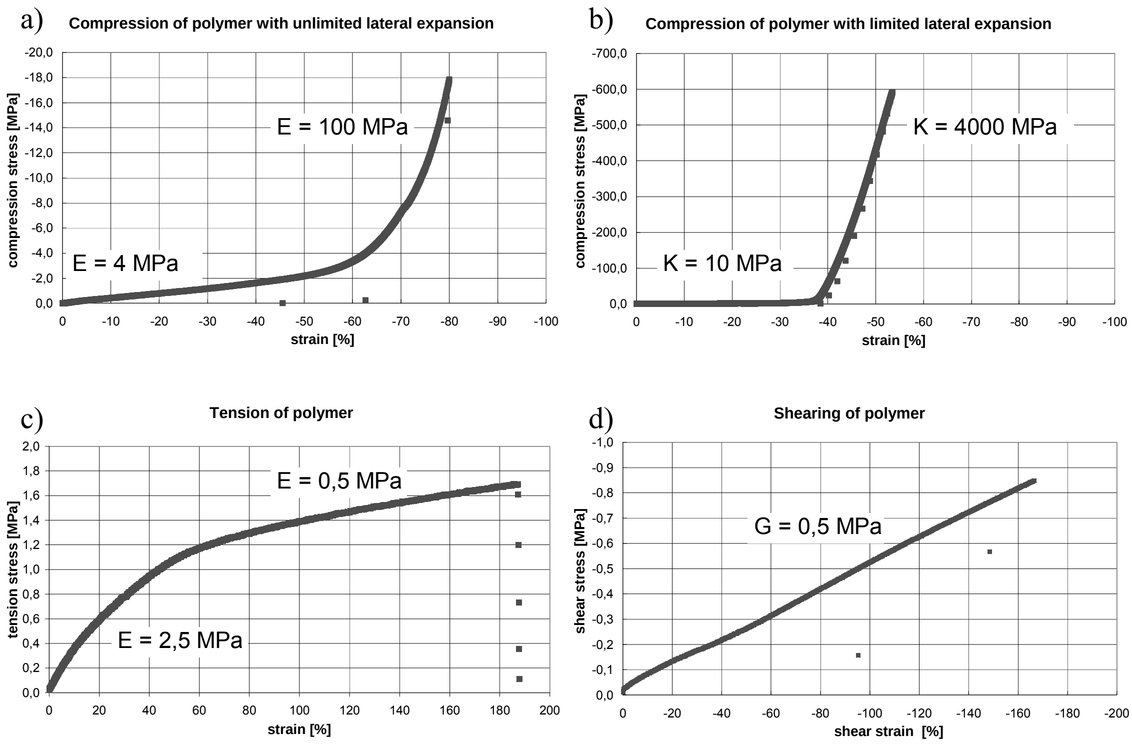

Figure 3 : Results of strength tests of polyurethane polymer 340/45: (a) Unlimited compression test with given Young's modulus E; (b) Limited compression test with given bulk modulus K; (c) Tension test with given Young's modulus E; (d) Shear test with given shear modulus G

From mechanical point of view all strength properties of chosen polymer are "compatible" with historical masonry materials (with wide range), especially are not stronger. Exception is connected with tension strength, which could be stronger in certain cases with strain value beyond 10%. Applying of the chosen polymer in crack allows undergo reciprocal (limited) deformations of disrupted structural elements, loosing in this way the energy of deformation (without introducing any additional unfavorable stress in the structure). Every deformation modules of polymer are lower than masonry ones, even with occurrence of ultimate strain of polymer. It should be pointed that the possible strain range of polymer is much wider than of masonry materials.

4.2 Static behavior of the flexible joint constructed between masonry specimens

Results of static tests with the use of polymer 340/45 joining brick specimens are presented in this chapter. Specimens were joined together with a polymer layer of 10 mm thickness. Dimensions of the joining areas were 12×12.5 cm in case of compression and 12×20 cm in case of shearing and peeling. Diagrams obtained from the tests are presented in Fig. 4. Results of the compression test of brick specimens joined with mortar are shown for comparison in Fig. 4a.

(a)

(b)

(c)

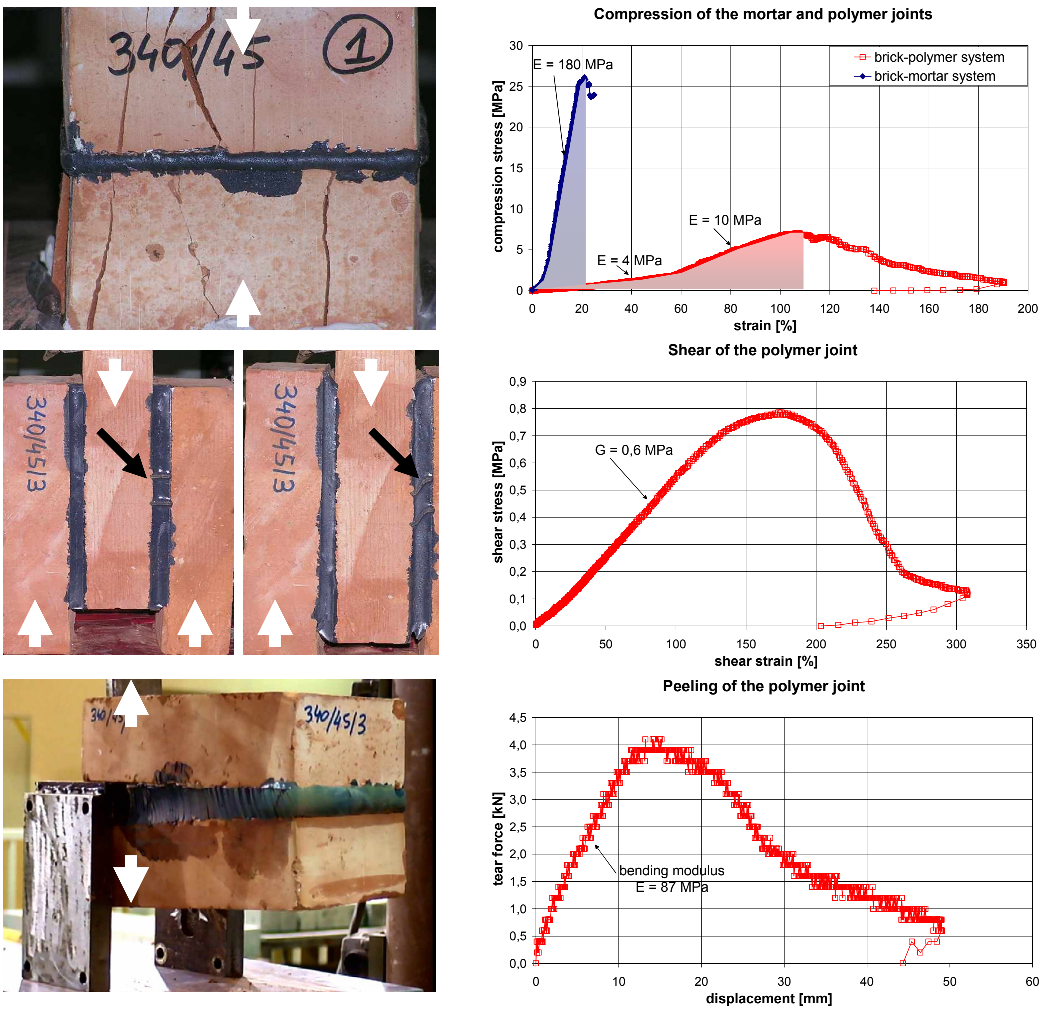

Figure 4 : Tests of brick specimens: (a) Compression of the 340/45 joint and mortar joint with comparison of deformation energy; (b) Shearing of the 340/45 joint; (c) Peeling of the 340/45 joint;

The tests showed good adhesion of the polymer to brick. Compression test of bricks with mortar showed total disintegration of specimen after appearance of ultimate stress. On the other hand, bricks were strong joined together with polymer even after appearance of ultimate stress. Comparison of the area under the curves (Fig. 4a) to the points of maximum deformation prior to failure showed that deformation energy of polymer joint is 30% greater than mortar joint brick specimen. An additional reservoir of deformation energy of polymer, beyond the point where the slop of the force-deformation plot remains negative, is also visible.

Shear and peel tests (Fig. 4b,c) showed too that application of the polymer joint in brick wall introduces new deformation ability. The shear resistance of such joint is “compatible” from the mechanical point of view with masonry materials. The bending resistance of the joint is particularly advantageous property in case of occurrence of large deformation angels and bending moments in cracked walls that act on structures in seismic areas. Important feature of the polymer is its residual carrying capacity after the joint damage, visible in Fig. 4 particularly in form of falling down curves appeared during unloading.

4.3 Preliminary investigation of an unreinforced masonry wall retrofitted with a flexible joint

The masonry wall specimen was made of clay bricks cement-lime mortar joints and had overall dimensions 1.68 × 1.41 × 0.25 m. During investigation two cases of the masonry behaviour were carried out. Firstly, the unreinforced masonry wall (URM), compressed vertically with stress level of 0.6 MPa, was loaded up to failure with a horizontal force pushing the top of the specimen (Fig. 5a). A diagonal crack appeared suddenly with shift of the upper part of the wall but residual force of 25% value of ultimate load (a result of acting friction forces in place of destruction) was remained acting. Next, the polymer 340/45 (the weakest from polymers tested by authors) was applied in place of damage by filling in of 40% of the crack length. This percentage of fulfilment was an initial safe assumption correlated with a possible application in a real structure. Strength of the investigated specimen was much higher than of a typical URM to assure during the test destruction of a new constructed flexible joint, not a structure.

Secondly, 36 hour after polymer application the polymer reinforced masonry structure (PRM) was examined with additional horizontal load up to lost of the joint strength. The failure mode of the new joint is presented in Fig.6. Additionally, the increase in strength of the new constructed joint was about 25% of the URM ultimate strength, even with such poor fulfilment. On the other hand, the PRM obtained over two times higher deformation, carrying additionally at the same time 55% of deformation energy calculated for the ultimate state of the URM specimen (Fig. 5b). Demolition of the specimen showed the residual carrying capacity of the joint.

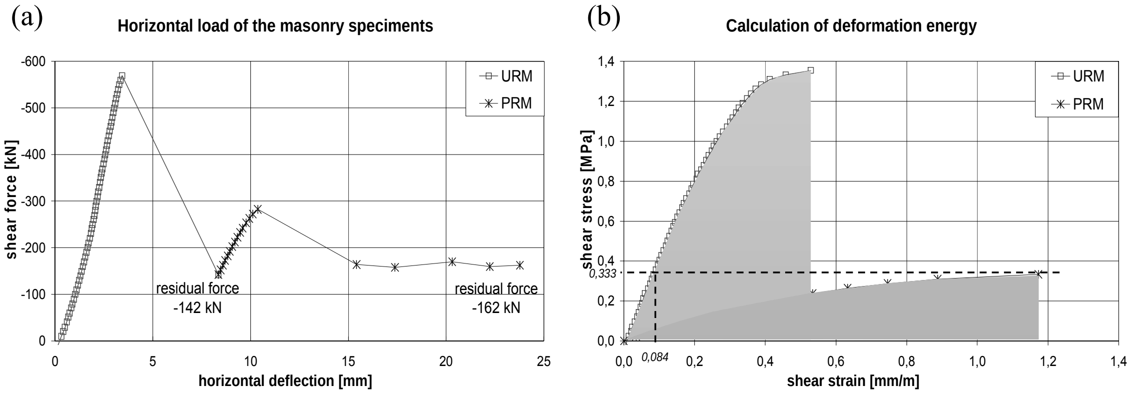

Figure 5 : Comparison of the URM and the PRM specimens: (a) History of loading and observed deflection; (b) Average stress-strain curves with calculation of deformation energy;

Figure 6 : The PRM specimen just after lost of the joint strength and focus on deformation of the joint

Such good relation of values of additional strength and deformation energy, obtained through connection of such strong wall and of poorly applied relatively weak polymer, allows assuming better utilization of properties of the flexible joint in next investigations. It is also good prognosis for application of the proposed method in historical masonry structures, where poor strength of the URM structures occurs.

5 CONCLUSIONS

Presented static laboratory tests of the properties of polymer 340/45 demonstrated much higher deformability than materials typically used in repair of historical structures. Low values of stiffness modules assure safe co-operation of polymer with weak materials and better "compatibility" from mechanical point of view than very stiff epoxy resin or cement, generating high stress concentration. Polymer could be simply apply in cracks of width 3 ÷ 50 mm and then covered with an material acceptable from "conservative" point of view, limiting this way variations of external appearance of historical structures. Good dynamic properties of proposed polymer and ability to dissipation of deformation energy make this material useful to use in damaged buildings in seismic areas (Kwiecień et al. 2005).

Based on this polymer the Flexible Joint Method allows to avoid unnecessary intervention and to ensure acceptable safety condition that was indicated in (Modena 2004). A new flexible joint made of polymer introduces new compression, tensile, shear and peel strength in places of cracks, thus damaged historical structures – like presented in (Jaquin et al. 2004, Agrawal 2004) – can further work safety if would be retrofitted with the FJM. The proposed method is relatively chipped and is not time consuming. It is needed proper fitting of polymer properties and also it is necessary to make a lot of experiments in laboratory and in natural scale to ensure that the new method could safety work in various areas of retrofitting.

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