Static and dynamic properties of a flexible joint working in cracked historical masonries

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ABSTRACT: In the paper, the static and dynamic properties of proposed flexible polymer joints are discussed. The discussion is based on investigations on special polymer, describing its properties obtained during laboratory and field tests. The research has allowed us to point potential advantages of the polymer application in cracked historical masonries. In addition, the rules of the polymer application and the possible conservative mask method of the constructed joint are presented.

1 STRESS CONCENTRATION AROUND STRUCTURAL FAULTS

1.1 Adaptation in masonry
Masonry can be defined as an association of two different materials: brick and mortar, with complementary mechanical properties. Bricks are elastic but brittle elements while mortars are plastic and ductile continuous binding materials. The elastic modulus of brick is always higher than that of mortar. In the case of masonry, there are geometric imperfections and structural faults like the vertical joints between bricks, where stress concentrations occur around the corners of bricks under the action of compressive forces. For long lasting actions like the gravitational ones the ductility of lime mortars protects the brick against failure by the phenomenon known as adaptation. In the case of short time actions of certain level the induced energy is stored by elastic brick as potential energy. Then, by a slow relaxation it is gradually dissipated by the plastic deformation of mortar. When forces of short time are huge, like those developed during an earthquake, the material strength is exceeded and a fault or a crack appears. This behavior is due to lack of time for plastic deformations to redistribute the concentrated stress. (Sofronie 2004, Sofronie et al. 2005).

1.2 Influence of micro-cracks
Damage occurrence develops mechanism of energy absorption that extensively reduces the forces acting upon the structure. It is connected with material defects localized in area where the principal tensile stress (stress concentration) exceeds the tensile strength of masonry material. Micro-cracking in masonry takes place at low load levels and progresses following non homogenous path which combines the two mechanisms with growth and linking between micro-cracks. It causes the reduction of the effective resisting area, leads to an increase of damage until rupture and can be described by the damage variable \( d \). Micro-cracking causes the decrease of elastic modulus and the increase of stress in the masonry material (“effective stress”), having to resist the external loading (Oñate et al. 1996) – Figure 1. When the damage variable \( d \) reaches the critical value the micro-cracks start linking and the rupture comes into being.

When the 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 masonry is characterized by a decreased resistance to the action of additional loads, to which the building was resistant prior to damage. Separated parts of the cracked structure can bring into contact at small areas in some places of the crack. In these points new stress concentrations are formed increasing damage. This process is especially intensive.
under movement caused by settlements, temperature changes and structural vibrations.

It is important that after rupture the surrounding of the crack remains a weak zone with the micro-cracks occurring. In this zone the strength of the masonry material is lower than of the original one what influences the repair strength in the case of the crack bonding.

2 CONCEPTION OF STRUCTURAL INTERVENTION IN CRACKED MASONRY

2.1 Discussion on applying of only original materials

The requirements of safety and use are almost permanently in conflict with the respect of the iconic, historical and material integrity of the monuments and treatment where only using of traditional methodologies is acceptable. In most countries the conservation is controlled by officials having an influence on any action to be undertaken imposing constraints and limitations that sometimes appear unreasonable to the engineer. On the contrary, the engineer tends to achieve safety by means of solutions or procedures which appear unacceptable to the officials in charge of conservation. It is evident that some consensus has to be found. On one side, conservation requires the safeguard of the formal, material and historical integrity of the monument, but also its survival and safe exploitation (Viggiani 2006). It is important to answer the question: do we want to have the heritage object with only original intervention materials with the threat of being destroyed by an earthquake or do we want to have the safe working historical structure for the next generations, protected with small amount of non-original intervention materials that are in compatibility with a monument and invisible for visitors. It is believed that the second option is suitable.

As an example of non traditional methodologies is the steel structure inside the spires of Burgos Cathedral (Ortega et al. 1996), that represents very massive intervention technique and the installation of shape memory alloy devices in the Basilica of San Francisco in Assisi (Castellano & Infanti 2004), representing the group of innovative techniques.

2.2 Rules of intervention in heritage structures

Nowadays, the use of innovative techniques or particular solutions, which efficiency must however be demonstrated, should not be in any case forbidden. On the contrary, the possibilities and limitations of each innovative technique should be briefly explained and also estimated and justified by calculating their effect in terms of variations in the global behavior of the structure. In the first place it is necessary to allow the structure to manifest a satisfactory global behavior, by improving the connections between the masonry walls and between the walls and the floors. Interventions aimed at increasing the masonry strength may be used to re-establish the original mechanical properties lost because of material decay or, alternatively, to upgrade the masonry performance. Techniques used must employ materials with mechanical and chemical-physical properties similar to the original materials (Modena et al. 2006) and neutral from the interaction point of view.

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 concentrations, which occur using high stiffness modern bonding materials like high strength resin or high strength mortars. It should be noted that applying too strong strengthening material in cracked structures (in comparison to the masonry properties) could cause additional damages. As an example, the new crack passing around the mortar injection, too stiff in comparison to masonry material, is presented in Figure 2. The crack is localized at the repaired cloister vault of the Archeological Museum in Cracow (Ciesielski et al. 2004). The cracks appeared after the mistaken intervention in foundation of the structure. The criterion in selection should concern
The Flexible Joint Method (FJM) is the method of bonding disrupted structural elements in places suffering from seismic areas (Modena 2004).

3 THE FLEXIBLE JOINT METHOD (FJM)

3.1 Description of the method

The Flexible Joint Method (FJM) is the method of repair using deformable elastic-plastic polymers and reinforced polymers for bonding of damaged structures. It is dedicated to cracked masonries (of poor quality too), especially to historical structures where minimum intervention is required. The cracks are filling in with the special binary mixed polyurethane mass injection, forming the flexible joints bonding the disrupted structure elements (Fig. 3). This method is registered in the Polish Patent Department with No. P-368173 and was described in papers (Kwiecień et al. 2006a, b). The FJM permits safe work of the retrofitted structure in the new stabilized 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.

Cracks' filling in the previously damaged bearing structure with specially designed polymer strengthens 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 of big importance. The deformation of the flexible joint under load assures uniform distribution of stress along the lap joint over the total contact surface, equalises deformation and damps vibrations. The polymer mass bonds structural faults in places of cracks and limits development of the new stress concentrators.

3.2 Properties of the polymers

Grouting constitutes one of the most common techniques applied to historic masonries. Although grouting is a non-reversible technique, it is well accepted even for monuments of high historical and architectural value, since the materials added to masonry may be of the same nature as the in situ ones and because of the positive effect of grouting on the mechanical properties of masonry (Vintzileou 2006).

The polymers used in the FJM are flexible two-component grouts based on polyurethane resin, hand and machine applicable. They introduce also the positive effect on the mechanical properties of masonry, thus should be accepted as innovative inject technique for application in historical structures. They fulfill requirements of the proper applicability into cracks and the adequate rheological, physical, chemical and mechanical properties.

Rheologically, they are injectable, have sufficient fluidity and stability. Physically, they do not produce high temperatures and shrinkage and also have adequate hardening time and hygroscopic properties. They are resistant to temperature from \(-40^\circ\) C to \(+80^\circ\) C (temporary up to \(+150^\circ\) C) and UV radiation. The polymers are insensitive to moisture and also have long life expectancy. Chemically, the polymers are neutral to the masonry materials (no chemical reactions between them, related to both durability and mechanical properties). Mechanically, the polymers are reducing vibration shear-resistant and permanently elastic adhesives and also have adequate strength and deformability characteristics. Giving an example, for the soft flexible polymer (of the Young modulus \(E = 4\) MPa) described by (Kwiecień et al. 2006a, b) the tear strength is 1.7 MPa and adhesion to the concrete surface is 1.2 MPa with elongation of 60%.

The flexible polyurethane mass shows no significant changes of mechanical parameters after 3 million cycles in the fatigue test (producer data) with elongation of 10%, frequency 5 Hz and maximum stress of 1.0 MPa. Cyclic tension-compression tests under harmonic excitation were also conducted (by the authors of the present paper) for the soft flexible polymer, with frequencies of 0.1, 0.5, 1, 2, and 5 Hz. The set deformations of specimens (of 28 mm diameter and 28 mm height) were of \(+/-\ 10, 20, 30\) and \(40\ \%\) with the corresponding stresses of \(+/-\ 0.16, 0.35, 0.62\) and \(0.97\) MPa. The example results for 2 Hz frequency are presented in Figure 4. The average damping ratio (Jankowski 2003) has been calculated as equal to \(D = 0.06\) for all obtained data.

In addition, the field test (producer data) confirmed that a direct fixation of rail base-plates using flexible polyurethane mass presented only marginal changes in flexibility (6%) after exposure to weathering and frequent dynamic loading over 28 years. The differences obtained during long-term dynamic behaviour in situ were so minimal that the flexible joint can be expected to last for many more years.

The polymers reach the full strength in 24 hours after application. Depending on the actual state of masonry the proper polymer with required properties can be chosen. The application rules of the polymers...
in masonry are the same as for grouts, described in details by (Vintzileou 2006).

3.3 Adhesive aspect of the flexible joint

Adhesiveness of polymers to masonry materials is very important matter. It is necessary to investigate material properties of damaged masonry by the use of diagnostic methods, e.g. micro-drilling (Skłodowski 2006), before preliminary selection of possible structural intervention methods. In the case of the use of the FJM, the description of these properties is needed for proper selection of polymer.

The adhesiveness between original structure materials and polymer is especially important. Investigations made by the authors, using the pull-off test (Bonaldo et al. 2005), showed that the polymers have good adhesion to masonry materials. The ultimate separate strength was equal 0.7–2.5 MPa, measured in laboratory condition on brick specimens with clear and undusted surfaces (over the stress of 2.5 MPa the damage in brick was observed). In cracked masonries such conditions are reachable only with the use of special primers. It is believed, that kind of the primer proper for the polymer should be matched according to the masonry material properties and its condition. This task is not fully recognized jet and has to be investigated in co-operation with chemical engineers having experience with materials of different kinds of heritage masonries.

4 BEHAVIOR OF THE POLYMER JOINT WORKING IN CRACKED MASONRIES

4.1 Reduction of the stress concentration

The stress distribution observed in micro-scale is not regular. The stress concentrations occur at the grain surfaces of brittle materials what was observed during the photo-elastic research on a concrete specimen (Dantu 1957). The peak concentrations are responsible for the micro-cracks appearance when they exceed strength of a masonry material even when the average stress is low (Fig. 5).

In the case of the use of flexible polymers as the adhesive layer the peaks of stress concentration are reduced and the uniform distribution of stress assures the increase of material strength. It is caused by lower amount of micro-cracks appearing in brittle material and thus higher the elastic modulus and the material strength (comp. Fig. 1). This phenomenon was confirmed by a pull-off test made on the same piece of brick with two kinds of adhesives. In the case 2A, the aluminum disk was bonded to the brick surface using the hard flexible polymer ($E = 600$ MPa) and in the case 2B, the stiff epoxy resin ($E = 3300$ MPa) was used as adhesive. Damages were observed in brick (Fig. 6), because of higher strength of adhesives than of the brick.

When the aluminum disk was bonded to the brick surface using flexible adhesive the ultimate force and the potential energy were about two times higher than with the stiff bond (Fig. 7). The use of the soft flexible polymer (with $E < 10$ MPa) will assure much uniform distribution of stress and reduction of peak stress concentrations.
4.2 Damage and repair processes of the tested masonry building

Properties of polymer flexible joints were examined on the real masonry building presented in Figure 8. The original structure was damaged by a caterpillar exciting dynamic forces in the corner of the building at the roof level.

Properties of the damaged structure were obtained indirectly. Modes of damage showed that cracks were caused by maximum principal stress and were passed diagonally through bricks and mortars. The pull-off test made on pieces of bricks, extracted from the inner part of the damaged wall (Fig. 6), showed that the tension strength of the bricks is relatively high. The ultimate stress obtained on four specimens was 0.5–2.3 MPa in case of the stiff adhesive and 1.1–3.3 MPa for the flexible adhesive (compare with section 4.1).

The structure was about to collapse after the action and had to be rectified (Fig. 9) what caused appearance of new cracks. The cracked building was repaired using the Flexible Joint Method. Cracks were cleaned from dust and protected with special primer and then filled in by the soft flexible polymer using injection technique (Fig. 10). The structure was statically and dynamically tested. At the end the destructive test was performed on the masonry in order to examine the ultimate work of the polymer flexible joint (Fig. 11).
Figure 12. Diagnostic dynamic exciters: the Vibrosejs of 20T mass and the modal hammer of 5 kg mass.

4.3 Work of the flexible joint under thermal influences (season changes)

The cracks width (Fig. 10) and the temperature in the opened air have been measured. Measurements were carried on for the period of one year in the temperature range from $-5^\circ C$ to $+28^\circ C$. The polymer joint elastically changed its width in the horizontal direction ($11/H$) up to 0.75 mm without the permanent displacement. It has been observed that the flexible joint allows the cracked structure for limited elastic deformation in places of new erected dilatations, protecting it against permanent unfavorable movement. Additionally, the polymer counteracts formation of stress concentrations when cracks close under influence of temperature changes.

4.4 Loading of the structure with static forces

The building was loaded statically with the horizontal force imposed in place where structure was excited dynamically by caterpillar. The maximum generated force was of 32 kN and caused permanent opening (0.4 mm) of the non bonded small crack ($9/H$), after overcoming friction forces acting in the non bonded crack. Under the same load the bonded cracks showed no reaction ($10/H$ and $11/H$) what gives evidence of the polymer joint strength, keeping the structure elements together and protecting against destruction.

4.5 Diagnostic dynamic excitation of the structure

The tested masonry structure was dynamically diagnosed before damage, just after damage and after repair using the polymer flexible joints. As dynamic exciters the Vibrosejs of 20T mass and the modal hammer of 5 kg mass were used (Fig. 12).

The 16-channels system collected data from the accelerometer system installed on the structure. There was no test with the Vibrosejs on the damaged structure because of the real possibility of collapse. The Vibrosejs excited vertical vibrations at the soil surface at the distance of 15 m in front of the masonry.

The impact of the Vibrosejs plate at the soil surface and the harmonic excitations with frequency range of 6–30 Hz were conducted. The analysis of the building response (presented for horizontal vibrations measured on the sensor localized at the top corner – Fig. 12) showed dynamic characteristics of the structure. Analysis of the impulse excitation pointed that the flexible bonded masonry damps better vibrations than the undamaged stiff structure (Fig. 13). The response of the building repaired using the FJM is almost 40% lower in resonance than for the undamaged building and favourable frequency shift is observed. It should be noticed, that such damaged building, bonded using the flexible polymer joint, survived the horizontal harmonic resonance vibration measured at the top of the building, of the 60 second duration and of the 30 cm/s² acceleration amplitude (Fig. 14). There were no additional damages on the repaired masonry after the vibration test what confirm efficiency of the repair using the FJM.

The excitation using the modal hammer allowed us to determine the inertertacy given by formula (1)

$$|I(\omega)| = \frac{\bar{X}(\omega)}{F(\omega)}$$  \hspace{1cm} (1)
where $\ddot{X}(\omega) = \text{acceleration frequency characteristic; }$ $\ddot{F}(\omega) = \text{force frequency characteristic.}$

The diagram presented in Figure 15 shows that after damage the frequency shift of resonances to lower frequencies is observed (stiffness degradation) and after repair using the polymer joints a significant back shift is visible (stiffness increase). The calculation of the inertial forces (assuming the same level of excitation acceleration) shows that the flexibility increase of the masonry after damage decreases the values of inertial forces over 3 times but they still can be too high for the weakened structure. After the application of the soft flexible polymer in cracks the inertial forces grow up 1.5 times in comparison to the forces acting on the damaged structure but the strength of the repaired masonry is significantly upraised. More details have been presented by Kwiecień & Zając (2008).

4.6 Destructive test on the masonry building
The destruction made on the tested building showed that the strength of the polymer joint is higher than the original masonry. The destructive process went through 3 steps. One crack, partially bonded with polymer (11/H) and partially not strengthened (9/H), was considered for observations. In the first step (after the huge hit), a new crack appeared in the middle of the side wall (Fig. 11) between polymer bonded cracks and was similar to that which came into being after the damage (Fig. 9). The new crack was localized at a certain distance from the bonded one, surrounded by the zone where peak stress concentrations were reduced. The observed crack opened in the non-bonded part (9/H) of 1.54 mm and the bonded one (11/H) opened only 0.25 mm. In the second step, (after the next huge hit), a new crack opened more. The additional increase of the observed crack width was of 2.80 mm in the non bonded part (9/H) and was of 1.20 mm in the bonded part (11/H). In the third step, the masonry structure collapsed and opened crack in the non-bonded part (9/H) was totally opened, when in the bonded part (11/H) the polymer kept fast together pieces of wall (Fig. 16). The test showed that the polymer reduces stress concentrations and protects cracks again damage propagation.

4.7 Repair of the old family building
The polymer flexible joint was tested on a masonry family building localized in the small village in Poland. The building was constructed from spider-web rubble walls of poor quality in 1930. The walls consisted from sand-stones joined with weak lime mortar. Investigated mortar crumbled away under a fingernail. Damages in the building appeared in form of cracked wall and were caused by settlement after a flood (Fig. 17).

The building was repaired using the FJM. The cracks were filled in with the soft flexible polymer after cleaning and priming of crack spaces. Effectiveness of the polymer joint was examined during the window exchange. The triangle wall fragment, visible in Figure 17, was hanging only on the new constructed flexible joint for the period of several hours. There were no notices of any fissures on a wall plaster and on gypsum markers placed on the joint. No cracks or fissures on structure for two years of the exploitation have appeared. This case confirms that a flexible joint equalizes stresses in brittle materials and protects cracked masonries of the weakened structure against appearing of new damages during micro-movements of the separated building parts.
5 THE USE OF A POLYMER JOINT FROM THE CONSERVATION POINT OF VIEW

5.1 Advantages of polymer joints opposite to traditional methodologies

It is obvious that the possibilities and limitations of each innovative technique should be briefly explained. The Flexible Joint Method is the new approach in retrofiting of masonry and 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 cases of monuments repair. It needs proper fitting of polymer properties and various kinds of primers for cooperation with structural materials. The usage of polymer joints in historical masonry have to be weigh out individually and also estimated and justified by calculating their effect in terms of variations in the global behavior of the structure.

The application of the innovative polymer material can assure survival and safe exploitation of monuments. Good dynamic properties of proposed polymer and ability to dissipation of deformation energy make this material useful to use in damaged masonries in seismic areas. It can assure also the safeguard of the formal, material and historical integrity. It is possible, because bonding of cracks with polymer allows us to avoid unnecessary intervention and to ensure acceptable safety condition. The polymer can be simply applied in cracks of width $3 \div 50$ mm and then covered with a material acceptable from “conservative” point of view, limiting in this way variations of external appearance of historical structures.

The proposed method is relatively cheap and is not time consuming. Low values of stiffness modules assure safe co-operation of the polymer with weak materials and better “compatibility” from mechanical point of view comparing to stiff epoxy resin or brittle cement mortars, generating high stress concentration.

5.2 Critical discussion of using the polyurethane mass in repair of historic buildings

The polyurethane mass proposed for application in historical buildings as repair (bonding) mass should be taken individually into consideration in each case. Presented polymer can be subjected in certain range to requirements proposed for repair mortars by Van Balen et al. (2005).

It is obvious that polyurethane as the relatively new bonding material does not respect the traditional practice of the joining of historic materials and therefore the criticism could be provide in regard to its use. It is also known that polyurethanes have hermetic properties and are a barrier for vapor transport, thus detrimental effect on the modification of hygric properties of masonry can take place, if it is using unconsciously. It is especially important in case of hermetic vertical membranes stopping the horizontal evaporation of the moisture from inside of a structure and causing the negative side-effect in the long-term period. In such situation the drainage of the barrier has to be done. On the other hand, the polyurethane repair joint prevent water penetration through a cracked wall. These advantageous properties of polyurethane mass were exploited in renovation of joints in the stone Monument in Latvia (Sidraba 2002). Additionally, polyurethane durability and long-term experience was evaluated in the climatic conditions of the Scandinavia for 15 years, performing good properties in comparison to traditional materials (Sidraba 2002).

6 CONCLUSIONS

The Flexible Joint Method based on polymer flexible joints is proposed as the new approach in retrofiting of cracked historical masonries. The presented properties of the flexible polymer joints, examined in laboratories and on real cracked structures, showed their effectiveness and advantages in the use of it as the repair method of damaged masonries. The innovative polymer material, bonding cracked historical structures, can assure survival and safe exploitation of monuments and also the safeguard of the formal, material and historical integrity. Authors hope that the use of flexible polymer joints can be accepted by conservation authorities and can be widely used as the repair methodologies in historical constructions.

REFERENCES


