Highly Deformable Polymers for Repair and Strengthening of Cracked Masonry Structures

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Abstract—Damages existing in masonry engineering structures are caused by various loads and has to be repair because of structural and architectural requirements. Repair of cracked masonry using materials of high stiffness and low deformability, like lime and cement mortars or epoxy resins, does not increase significantly the tensile strength of the repair joint. This is because of the stress concentration occurrence. The use of highly deformable bonding materials allows reducing peaks of stress concentration, causing (after repair) increase of strength of cracked masonry elements. Proposed repair materials of high deformability can be easily covered with original masonry material to ensure protection of architectural value.

In the paper, there were tested masonry units (bricks), investigated in two kinds of loading. One of them was the four point bending test on Polish Bonarka bricks and the second one was the Single Lap Shear Test on Italian Rosso Vivo - A6R55W bricks, strengthened using CFRP and SRP strips bonded on epoxy resin. In both cases, the primary failure appeared in form of cracks (or detachment) going through the brick materials. The failure surfaces of both tests were repaired using materials of low and high deformability. More significant strength increase of the tested masonry elements (after repair) was obtained in the case of the use of highly deformable interface materials than of barely deformable bonding materials.

Efficiency of highly deformable repair materials was also examined as repair on cracked masonry walls in laboratory using polymer injection and externally bonded composite mats made of glass fibers bonded on highly deformable polymer. Additionally, the highly deformable polymer joints were tested dynamically in situ on a masonry building, up to failure also.

Keywords – repair of masonries, masonry units, reduction of stress concentration, high deformability, polymer flexible joints, dynamic test

I. INTRODUCTION

Majority of civil engineering structures are masonries with their brittle properties of structural materials. Structural defects and mismatches between adjacent grains appear in the brittle materials like bricks and mortars, and are the source of stress heterogeneities. Stress concentration at the contact points between adjacent grains causes fracturing.

A conventional assumption in the natural scale analysis is that the tensile stress distribution under loads in the analyzed cross-section of masonry specimen is uniform (nominal stress). In the reality, the stress distribution observed in micro-scale is not regular because of the stress concentration appearance in places of discontinuities [1], [2]. Under the peak of stress concentration brittle materials reach easily their limit of elasticity at the end of crack. Further, the material of a structural member is either in the state of cracking or plastically deforming [3].

This is a problem in the case of traditional repair and strengthening of masonry structures [4], [5], [6], where stiff and brittle bonding materials of low deformability are typically used. In this case, the principal tension stress is responsible for structural damage, appearing in a loaded repair joint in a complex stress state. Its value depends on the bonding material stiffness - the higher material stiffness is the higher peak of stress concentration. This phenomenon influencing brittle substrate was discussed in many publications [7], [8], [9], [10].

Repair of cracked masonries (also historical structures) is connected in many cases with conservation of frescos made on walls and vaults. They require from support that it allows for safe exploitation from aesthetical and mechanical point of view. Unfortunately, damages in masonry structures devastate works of art (Fig. 1) because of cracks appearance, caused most often by settlement, dynamic action, structural material deterioration or inappropriate retrofitting techniques [4].

When the crack divides a masonry member into two parts, they work separately in the new stress equilibrium and static balance being the consequence of stress redistribution. Such cracked masonry is characterized by decreased resistance to the action of additional loads, to which the building was resistant prior to damage. Separated parts of the cracked structure can draw apart e.g. under cyclic repeated settlements caused by fluctuations of a water level (like in Venice – Fig. 2), temperature changes [11] and vibrations (seismic or ambient), of even not very high intensity.

Undertaking repair of a cracked masonry, it is necessary to allow the structure to manifest a satisfactory global stability, by improving the connections between the disrupted masonry elements, without changing of static schemes. Traditionally, stiffening repair methods (metal braces, externally bonded FRP composites) are used in retrofitting of masonries but they are not allowed in the case of historical objects covered with

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frescos (Fig. 1), because of destruction of finishing plasters.

The only method in such case is injection. Typically, cracks are filled using of mineral or epoxy grouts [4], which do not improve significantly the masonry capacity (damage energy) because of: brittleness behavior [12], generation of stress concentration [2] and low deformability (disadvantageous in seismic areas, where materials of high ductility are required).

If masonry structures with possibility of plaster removing are taken into consideration, many methods of strengthening...
are available. Externally bonded strengthening elements (FRP composites, steel flat bars) can be applied because they can be hidden under plaster. Examples of such applications are presented in Fig. 3 and 4. Anyway, typically using bonding adhesives (epoxy resin, lime and cement mortars) are stiff and of low deformability and of brittle behavior. Because of these properties these kinds of adhesives do not improve significantly of masonry capacity [13].

II. Innovative Repair Intervention using of Highly Deformable Polymer Flexible Joints

An innovative repair method by the use of highly deformable polymer flexible joints made of polyurethane mass was proposed, to solve problems mentioned above. This kind of material was applied as a bonding injection filling cracks and as an adhesive for external bonding of FRP composites to masonry substrates.

A. Highly Deformable Injection

The Flexible Joint Method (FJM), as the innovative repair method using of the polyurethane injection (this method is registered in the Patent Department with No. PL368173 (A1) and PL207028 (B1)), were tested in laboratory and in situ tests for last years [12], [14], [15]. Efficiency of the method results from introducing of the polyurethane inject into a repaired joint, which introduces in the repaired masonry greater tensile and shear resistance, deformability and ductility and thus greater bearing capacity (damage energy). Deformations of the flexible joint assure the uniform distribution of stress along the total contact surface, reducing stress concentrations. Polyurethane mass used in polymer flexible joints (selected properly) works together with the masonry materials with proper compatibility from the mechanical point of view and fulfils requirements set for injecting grouts and presented in [16]. An example of polymer flexible joint, constructed in the cracked masonry wall after application of the highly deformable polymer PM, is presented in Fig. 5.

Fig. 5. Polymer flexible joint constructed in the cracked masonry building

B. Highly Deformable Adhesive Bonding FRP Composite

The highly deformable polyurethanes are also applied as adhesive layers in bonding of FRP composites to masonry substrates (this method is registered in the Patent Department with No. PL377570 (A1)). Application of flexible polymer adhesives in strengthening of masonries using of externally bonded FRP composites allows reducing stress concentration, typical for the use of stiff epoxy adhesives layers. Highly deformable adhesives reduce and more evenly distribute shear stress protecting the brittle substrate against the locally acting peak stress, which is responsible for activation of the rapid detachment process and lower exploitation of the FRP composite [13]. More even stress distribution [17] increases significantly the ultimate load of the strengthening system. In the case of highly deformable adhesives (polymer PS), the FRP slip is many times higher than in the case of the barely deformed ones (epoxy resin). High value of the slip generates the significantly higher value of fracture energy [17], which is especially required in seismic areas.

C. Protection of Architectural Value in Repair Joint

The use of the highly deformed joints is dedicated to structures working under conditions of cyclically changing deformations. Such conditions occur among others in cracked masonries in seismic areas where risk of aftershock occur and in cities like Venice, where fluctuations of water level cause changes in the cracks width. Repair methods needed in such cases require deformation capacity allowing withstanding influences of destructive movements caused by dynamic loads or settlements (Fig. 2). Large deformations generate in stiff bonding materials (epoxy resin, lime and cement mortars) high level of stress, destructing masonry substrate at relatively low load level. On the other hand, highly deformable materials carry loads allowing for local deformations, damp vibrations and protect masonry substrate against destructive stress.

From the architectural and conservation point of view, it is required to cover repaired flexible joint with special materials or paintings, which mask the place of damage and restore the primary view of the object (of the condition prior to repair). In the case of flexible polymer application, it is possible to strew the fresh surface of flexible joint with sand, to assure adherence of conservation materials. It is also possible to cover the non-cured polymer with other original materials like gains of old bricks or stones or mortars, to assure the same surface quality and visualization (Fig 6).

Fig. 6. Covering of the flexible polymer with sand, old mortar gains and old brick gains, for preparation of the conservative masking surface quality
Such restored surface of polymer allows the repaired joint to deform, even in large scale. In this case, the particles of the covering material move proportionally to the polymer deformation and the generated small fissures (instead of one main crack) are uniformly distributed at the whole joint surface. It makes the joint deformation invisible (cracks do not appear).

III. FOUR POINT BENDING TEST OF MASONRY UNITS

Comparison of bonding efficiency in the aspect of ultimate loads, carried by repair joints made of various materials of low and high deformability, is presented using specimens made of brick units. The tested units were first broken in a bending test, and next repaired by bonding in the place of crack.

A. Test of Original Bricks up to Failure

The four point bending test was realized (according to the scheme presented in Fig. 7) on the Polish Bonarka bricks of dimension 250×120×65 mm³ (the mean compression strength of 23.3 MPa with the coefficient of variation C.o.V. equal to 16.7 %). The test setup data were as follows: \( L = 220 \) mm, \( L_1 = 44 \) mm, \( L_F = 88 \) mm, \( b = 120 \) mm. Each brick was cut in the middle at the bottom to fix localization of the initial crack. The measured initial (original) heights \( h_O \) of the critical cross-section and maximum forces \( F_O \) (of the original non-failure specimens) are given in Tables I ÷ V for 30 tested bricks. The bending tensile strength of each original brick \( \sigma_O \) was calculated according to (1), but the specimens S330-1 and PST-2 were excluded from analysis because of inadequate data. The calculated mean strength value of the original bricks \( \sigma_O \) was equal to 1.89 MPa (C.o.V. of 24.0 %), and the mean Young’s modulus obtained during bending test \( E = 476 \) MPa (C.o.V. of 22.4 %) as well as the mean ultimate strain \( \varepsilon_u = 0.40 \% \).

\[
\sigma = \frac{3}{2} \frac{F(L-L_1)}{bh^2}
\]

(1)

B. Test of Repaired Bricks up to Failure

All disrupted bricks were bonded together with the joint of 10 mm thickness, made of five kinds bonding materials and were tested again (Fig. 9a). Two of them were of brittle behavior: cement mortar Izolbet - ZA (Young’s modulus \( E = 2570 \) MPa and ultimate strain \( \varepsilon_u = 0.05 \% \) - own

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**TABLE I.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( F_O ) (N)</th>
<th>( F_R ) (N)</th>
<th>( h_O ) (mm)</th>
<th>( h_R ) (mm)</th>
<th>( \sigma_O ) (MPa)</th>
<th>( \sigma_R ) (MPa)</th>
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Mean value (MPa) 1.74 1.18 67.80
C.o.V. (%) 17.39 29.00 -

**TABLE II.**

<table>
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<th>( F_R ) (N)</th>
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<th>( h_R ) (mm)</th>
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Mean value (MPa) 2.72 2.92 107.22
C.o.V. (%) 7.04 5.84 -
research) and epoxy resin Sikadur 330 - S330 \( (E = 4\,500\) MPa and \( \varepsilon_u = 0.22\% \) - producer data). Three of them were of flexible behavior made of polyurethane mass: polymer PT \( (E = 800\) MPa and \( \varepsilon_u = 110\% \) - own research) and polymer PST \( (E = 4\) MPa and \( \varepsilon_u = 140\% \) - own research). Comparison of the bonding materials properties is presented in Fig. 10 and 11.

### TABLE III.
FOUR POINT BENDING OF THE BONARKA BRICK: ORIGINAL (O) AND REPAIRED BY POLYMER PT (R)

<table>
<thead>
<tr>
<th>Specimen</th>
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<th>( F_R ) (N)</th>
<th>( h_O ) (mm)</th>
<th>( h_R ) (mm)</th>
<th>( \sigma_O ) (MPa)</th>
<th>( \sigma_R ) (MPa)</th>
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<td>151.12</td>
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Mean value (MPa) 1.94 3.10 159.89
C.o.V. (%) 7.81 21.94 -

### TABLE IV.
FOUR POINT BENDING OF THE BONARKA BRICK: ORIGINAL (O) AND REPAIRED BY POLYMER PST (R)

<table>
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<tr>
<th>Specimen</th>
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<th>( F_R ) (N)</th>
<th>( h_O ) (mm)</th>
<th>( h_R ) (mm)</th>
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Mean value (MPa) 1.69 2.34 138.84
C.o.V. (%) 2.85 13.42 -

### TABLE V.
FOUR POINT BENDING OF THE BONARKA BRICK: ORIGINAL (O) AND REPAIRED BY POLYMER PM (R)

<table>
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<th>Specimen</th>
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<th>( h_O ) (mm)</th>
<th>( h_R ) (mm)</th>
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Mean value (MPa) 1.49 2.85 191.30
C.o.V. (%) 6.42 15.25 -

The important value in comparison of obtained results is the tensile strength of joined materials. The bending tensile strength of the Bonarka brick is \( f_t = 1.89\) MPa and of the cement mortar Izolbet (ZA) is \( f_t = 3.16\) MPa (after [18], according to EN 998-2). The uniaxial tensile strength of polymers (according to ISO 527-1) is: for PT \( f_t = 20\) MPa, for PST \( f_t = 4.50\) MPa, for PM \( f_t = 1.40\) MPa. The tensile strength of the epoxy resin Sikadur 330 (S330) is \( f_t = 30\) MPa (producer data). The tensile strength of all bonding materials are compared in Fig. 12 and show that only tensile strength of the polymer PM is lower than the strength of the tested brick.
The measured heights $h_R$ of the repaired critical cross-section and maximum forces $F_R$ of the repaired specimens are given in Tables I ÷ V for 30 tested bricks. The bending tensile strength of each repaired brick $\sigma_R$ were calculated according to equation (1), but specimens S330-1 and PST-2 were excluded from analysis because of inadequate data of the original specimens. Failure modes of the repaired specimens were cohesive in brick in the cases of S330, PT and PST (Fig. 9c, 9d, 9e) and cohesive (joint) – adhesive in the cases of ZA and PM (Fig. 9b, 9f). The calculated values of $\sigma_R$ with the mean values and the C.o.V. are presented in Tables I ÷ V and the normalized values $\sigma_R/\sigma_O$ are compared graphically in Fig. 13.
C. Discussion of Obtained Results

In the case of repair using the cement mortar ZA, there was observed decrease of the specimen strength after repair (Fig. 13a), despite the tensile strength of the cement mortar is higher than the repaired brick (Fig. 12). During the bonding process, the mortar is unable to fill fully porous surface of the failure cross-section, thus the developed working surface is lower than the original one (of the brick). Moreover, the repair mortar is brittle, of high stiffness and of low deformability (Fig. 10 and 11), therefore did not reduce the peaks of stress concentration (Fig. 14) overcoming the material strength (cohesive failure of mortar – Fig. 9b). The micro-cracks caused by the peaks of stress concentration initiated the joint failure at the relatively low value of the average tensile stress (Fig. 13a), significantly under the brick strength.

On the other hand, the epoxy resin S330 of the very high strength (Fig. 12) is able to fill fully porous surface of the failure cross-section, but it is also brittle, of high stiffness and of low deformability (Fig. 10 and 11), therefore did not reduce the peaks of stress concentration (Fig. 14) overcoming the material strength (cohesion of brick – Fig. 9c) at the relatively low value of the average tensile stress (Fig. 13b). The micro-cracks caused by them initiated the brick failure barely over the brick strength. The new failure surface is located close to the repair joint (Fig. 9c), in the brick zone weakened by the micro-cracks (caused by the peaks of stress concentration).

Application of the flexible polymer PT, of the high strength similar to the epoxy resin (Fig. 12) but of almost six time lower stiffness and ten times higher deformability (Fig. 10 and 11) caused significant increase of the brick strength after repair (Fig. 13c).

This phenomenon results from proper covering of the failure surface by the polymer and from the reduction of the stress concentration peaks by the flexible polymer, thus the average tensile stress obtains higher value when the reduced peaks of stress concentrations reach the material strength (Fig. 14). Similar rules were observed in the case of the repair using the polymer PST (Fig. 13d), of much lower strength (Fig. 12), stiffness (Fig. 10) and many times higher deformability (Fig. 11).

In the case of repair using the polymer PM, there was observed relatively huge increase of the specimen strength after repair (Fig. 13e), despite the tensile strength of the polymer PM joint is lower than the repaired brick (Fig. 12). This phenomenon results from the reduction of the stress concentrations peaks by the polymer of high deformability (Fig. 11) and by the stress redistribution in the critical cross-section (Fig. 14). In this case, the average tensile stress obtains the much higher value when the reduced peaks of stress concentrations reach the material strength (Fig. 14), giving the cohesive (in polymer) – adhesive failure mode (Fig. 9f). This failure mode is especially advantageous in the case of repair of historical masonries, because does not cause failure of the heritage substrate, strengthening simultaneously the heritage structure [15], [19].

IV. REPAIR OF MASONRY WALL USING HIGHLY DEFORMABLE POLYMER PM

Repair of cracked masonries by injection using highly deformable polymer makes a repair joint in a place of crack of complex properties. Polymer of hyperelastic characteristic (local stress in polymer is nonlinearly dependent on polymer strain) causes various stress level dependent on crack width [12]. Even local exceeding of polymer strength (disruption of one polymer unit) do not activate of a brittle damage mechanism, because the ductile characteristic of polymer allows for stress redistribution in polymer in the surrounding of damage.

A. Shear test of masonry wall in laboratory

Efficiency of highly deformable repair material was checked during laboratory research. A shear test on a cracked clay brick masonry wall, repaired using polymer PM, was carried out at the Silesian University of Technology in Poland. The wall with rectangular shape and overall dimensions 1.40 × 1.41 m (length × height) and thickness 0.25 m was made by qualified bricklayers using clay bricks (with
compressive strength $f_c = 15$ MPa) and cement-lime mortar (with compressive strength $f_m = 7.2$ MPa). It was subjected to horizontal shearing in one cycle into the test stand shown in Fig. 15 and described in [21]. The values of horizontal shear forces and in-plane displacements were recorded. The masonry specimen pre-compressed vertically with stress level of 0.7 MPa was loaded up to failure with a horizontal force. The diagonally cracked masonry wall was strengthened by polymer PM injection, and after curing of polymer was again sheared horizontally up to failure (Fig. 16). The final damage occurred only in the polymer joint (important in the case of heritage masonries) and the form of failure allows for second filling of voids, appeared in the damaged flexible joint (Fig. 16).

Fig. 15. View on the test stand for horizontal shearing with pre-compressed masonry wall (laboratory of the Silesian University of Technology)

Results obtained from the shear tests are presented in form of diagrams and compared each other in the table (Fig. 17), where appropriate comparison of the specimens work is done at the moment of cracking (up to points A and C). They showed that repair of cracked masonry wall by injecting using the highly deformable polymer PM restores up to 95% of the original masonry strength, but increases ultimate shear strain over 10 times and energy dissipation capacity 14 times (areas under curves). A huge amount of ductility was introduced in damaged masonry structure in comparison to the original one (it is important especially in seismic areas), what is in agreement with assumptions of the Flexible Joint Method dedicated to historical masonries [15].

B. Dynamic tests of masonry building in situ

Efficiency of highly deformable repair material was also examined on small masonry building during dynamic damage tests in situ. The original structure was damaged by a caterpillar. Ultimate dynamic forces were generated in the corner of the building at the roof level. The structure was about to collapse after the action and had to be rectified what caused appearance of new cracks (Fig. 18).

Fig. 16. Tested masonry specimen in succeeding fazes of work: with diagonal crack, with the polymer joint filling the crack and with the damaged highly deformable joint made of polymer PM

Fig. 17. Comparison of the test results for the unreinforced (URM) and the polymer reinforced masonry (PRM) specimens

<table>
<thead>
<tr>
<th></th>
<th>Unreinforced Masonry (URM)</th>
<th>Polymer Reinforced Masonry (PRM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of stress (MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the moment of cracking (up to point A and C)</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Shear strain (γ)</td>
<td>1.70</td>
<td>1.40</td>
</tr>
<tr>
<td>Energy dissipation</td>
<td>14.92</td>
<td>1.04</td>
</tr>
</tbody>
</table>

B. Dynamic tests of masonry building in situ

Efficiency of highly deformable repair material was also examined on small masonry building during dynamic damage tests in situ. The original structure was damaged by a caterpillar. Ultimate dynamic forces were generated in the corner of the building at the roof level. The structure was about to collapse after the action and had to be rectified what caused appearance of new cracks (Fig. 18).
The cracked building was repaired by injection using highly deformable polymer PM (Fig. 5) and a brick-polymer composite [12] constructed in places of wide cracks (Fig. 19), also using highly deformable polymer PM as injection.

The repaired building was examined using a harmonic excitation of the 60 second duration for each excited frequency in the band of 6 – 30 Hz. As a dynamic exciter Vibrosejs MARC IV of 20 T mass was used (Fig. 20). The Vibrosejs excited vertical vibrations at the soil surface at the distance of 15 m in front of the masonry building. The analysis of the building response was carried out for horizontal accelerations measured on the sensor, localized at the top corner of the masonry [14]. It should be noticed that such damaged building (Fig. 18) bonded using the highly deformable polymer PM survived the horizontal harmonic vibration with the first resonant frequency of 10 Hz. The maximum acceleration amplitude measured at the top of the building [14] during the first resonant frequency reached the value of 30 cm/s² (Fig. 20). There was no additional damage on the repaired masonry building after the vibration tests what confirms efficiency of the applied repair method.

Dynamic destructive test using caterpillar, hitting the repaired building at the roof level again, showed that the strength of the highly deformable repair joint is higher than the original masonry. After the huge hit of the caterpillar a new crack appeared in a new form (Fig. 22), different from the primary damage (Fig. 18). Moreover, the polymer joint caused closing of the newly appeared crack during unloading of the structure. The disrupted part of the wall of triangle shape was moving like on rubber braces during following hits (Fig. 22).
The destructive test showed that the polymer reduces stress concentrations and introduces the huge amount of capacity of the cracked masonry structure to absorb the input energy. It should be mentioned that new damages went only through new masonry areas, not through the polymer bonded cracks (Fig. 19 and 23). Finally, the last huge hit collapsed the repaired masonry structure but the polymer PM kept fast together pieces of wall during the damage process (Fig. 24).

V. SINGLE LAP SHEAR TEST OF BRICKS WITH BONDED FRP STRIPS

Comparison of bonding efficiency in the aspect of ultimate shear loads, carried by adhesives of low and high deformability bonding FRP composites to brick units, is presented using specimens tested in the Single Lap Shear Test (SLST). The specimens were first failure in the shear test, and next repaired by bonding again of the detached FRP strips.

A. Shear Test up to Failure of Specimens with Stiff Epoxy Adhesive (lowly deformable)

Single Lap Shear Tests were carried out on the bricks Rosso Vivo - A6R55W (of dimension 250×120×55 mm³) strengthened by the CFRP (CARBON UNIDIR 320 HT240) strips bonded on the stiff epoxy resin adhesive (SATURANT HM) and by the SRP (STEEL 3X2-B 12-12-500) strips bonded on the stiff epoxy resin adhesive (SATURANT HMT). These tests (Fig. 25a) were done at the Cracow University of Technology in frame of the RILEM TC223MSC activity and were described in details in [13]. The tensile strength of the CFRP and the SRP was $f_t = 2735$ MPa and $f_t = 2997$ MPa, respectively (after [13]). The tensile strength of the Rosso Vivo brick, determined during the pull-off test, was $f_t = 1.03$ MPa. Epoxy resins (HM, HMT) and the brick
(A6R55W) were characterized by the Young’s module

\[ E = 1308 \text{ MPa (HM), } E = 1605 \text{ MPa (HMT) and } E = 5756 \text{ MPa, respectively (after [13]). The ultimate} \]

elongations of the epoxy resins adhesives HM and HMT are \( \varepsilon_u = 3.8\% \) and \( \varepsilon_u = 3.1\% \) respectively.

The only failure mode of the CFRP and SRP strips bonded on epoxy adhesives was the strip detachment with the removal of a thin layer of the brick material (Fig. 25b). The mean value of the ultimate loads of the CFRP specimens (C1 – C5) was 6.28 kN (C.o.V. 7.4\%) and of the SRP specimens (S1 – S5) 6.72 kN (C.o.V. 10.4\%), obtained for the primary tests of the specimens with the epoxy adhesive. The measured ultimate loads of the CFRP and SRP specimens with the epoxy adhesive \( F_E \) are given in Tables VI + VII for 10 tested bricks.

![Fig. 25. Single Lap shear test of the A6R55W brick strengthened with the CFRP strip: test set-up (a), the failure mode in the case of the use of stiff epoxy adhesive layer (b), the failure surface with primer before repair (c)](image)

**TABLE VI.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( F_E ) (kN)</th>
<th>( F_P ) (kN)</th>
<th>( F_P/F_E ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>5.78</td>
<td>8.60</td>
<td>149</td>
</tr>
<tr>
<td>C2</td>
<td>6.81</td>
<td>8.81</td>
<td>129</td>
</tr>
<tr>
<td>C3</td>
<td>6.69</td>
<td>9.48</td>
<td>142</td>
</tr>
<tr>
<td>C4</td>
<td>5.88</td>
<td>8.57</td>
<td>146</td>
</tr>
<tr>
<td>C5</td>
<td>6.25</td>
<td>9.38</td>
<td>150</td>
</tr>
<tr>
<td>Mean value (MPa)</td>
<td>6.28</td>
<td>8.97</td>
<td>143</td>
</tr>
<tr>
<td>C.o.V. (%)</td>
<td>7.39</td>
<td>4.83</td>
<td>-</td>
</tr>
</tbody>
</table>

**B. Shear Test up to Failure of Specimens Repaired using Flexible Polymer Adhesive (highly deformable)**

The tested up to failure specimens (mentioned above) were repaired using the flexible polyurethane adhesive of high deformability made of the polymer PS (after primer application - Fig. 25c) and the same SLSTs were repeated. The characteristics of the polymer PS were: the tensile strength \( f_t = 1.48 \text{ MPa, the Young’s modulus } E = 8 \text{ MPa and the} \]

ultimate elongations \( \varepsilon_u = 45\% \) (after [17]). The failure mode of the repaired CFRP and SRP specimens was of new rough type, engaging deeper part of the brick surface (Fig. 26 and 27).

![Fig. 26. Normalized ultimate load values \( F_P/F_E \) (normalization to the load of the epoxy specimen – 100\%), presented for the specimens with CFRP strips (left) and failure mode of the repaired CFRP specimen (right)](image)

![Fig. 27. Normalized ultimate load values \( F_P/F_E \) (normalization to the load of the epoxy specimen – 100\%), presented for the specimens with SRP strips (left) and failure mode of the repaired SRP specimen (right)](image)

The mean value of the ultimate loads of the CFRP specimens (C1 – C5) was 8.97 kN (C.o.V. 4.8\%) and of the SRP specimens (S1 – S5) 14.58 kN (C.o.V. 13.4\%), obtained for the secondary tests of the specimens with the polymer PS adhesive. The measured ultimate loads of the CFRP and SRP specimens with the polymer PS adhesive \( F_P \) are given in Tables VI + VII for 10 tested bricks.
C. Discussion of Obtained Results

In the case of repair using the polymer PS, there was observed relatively huge increase of the ultimate loads of the repaired specimens. The mean value of the ultimate load of the CFRP specimens bonded on polymer PS is higher about 43 % ($F_{FP}/F_E = 143\%$) than the same bonded on the epoxy resin. Similarly, there was found over double load increase ($F_{FP}/F_E = 217\%$) of the ultimate load of the SRP specimens bonded on the polymer PS.

This phenomenon results from reduction of the peaks of stress concentration by the highly deformable polymer PS and by the shear stress redistribution along the whole bond length. It was confirmed by numerical analysis presented in [17], where the SLSTs were modeled in the FEM code ABAQUS. There were calculated shear stress distributions in the brick substrate for the ultimate loads of the specimen C3 (Fig. 28).

The maps of shear stress confirm that in the case of epoxy adhesive, the peak of shear stress concentration (about 1.5 MPa) causes damage of the brick substrate close to the loaded composite end at the relatively low load level ($F_E = 6.69$ kN). On the other hand, the polymer PS adhesive redistributes the shear stress more evenly along the whole bond length and is able withstanding the shear stress level up to 2.0 MPa before damage of the brick substrate at much higher load level ($F_P = 9.48$ kN).

The distribution of the shear stress along the bond length is proportional to the strains distribution, measured by strain gauges at the strips of the specimen C3 (Fig. 29). It confirms that the shear stress distribution in the case of the highly deformed adhesive (polymer PS) is more even than in the case of barely deformed adhesive (epoxy resin). It is also visible that the shear stress distribution is characterized by higher stress values (higher strains) for the polymer PS adhesives than for the epoxy one, obtained for the same load levels. Detailed analysis of this phenomenon was presented in [17], [20]. The presented results indicate that application of a flexible polymer adhesive in the FRP strengthening system allows increasing significantly the ultimate load of the strengthening system.

VI. REPAIR OF MASONRY WALL USING GFRP GRID BONDED ON HIGHLY DEFORMABLE POLYMER PS

Efficiency of highly deformable adhesive polymer PS was examined during laboratory research. A shear test on a cracked clay brick masonry wall pre-compressed vertically...
with stress level of 0.25 MPa (similar as described in Chapter IV.A) was carried out at the Silesian University of Technology in Poland using composite strengthening. The composite was made of four layers of glass fiber grids, fixed to the both surfaces of the masonry (after crack appearing) using polymer PS [12].

Fig. 30. View on the test stand for horizontal shearing with pre-compressed masonry wall strengthened with composite mats (laboratory of the Silesian University of Technology)

Fig. 31. Tested masonry specimen strengthened by the glass-polymer composite mats, constructed and fixed to the both surfaces of the masonry by using the polymer PS

The composite mats in the form of diagonal bands were fixed without filling the crack (Fig. 30), so local destruction of masonry in the crack surrounding caused by the high level of stress concentrations was expected. The final damage occurred only in the composite in form of glass fiber rupture. Inspection of the bond indicated very good adhesion of flexible polymer to masonry substrate after fiber failure (Fig. 31).

Results obtained from the shear tests are presented in form of diagrams [12] and compared each other in the table (Fig. 32), where appropriate comparison of the specimens work is done at the moment of cracking (up to points A and C). They showed that strength of the repaired masonry specimen exceeds 133% of the original one (the polymer diagram was cut in point C because of the displacement sensor limitation). Similarly as in the case of the research described in Chapter IV.A, increase of the ultimate shear strain was higher over 12 times and increase of energy dissipation capacity over 16 times.

Fig. 32. Comparison of the test results for the unreinforced and the reinforced masonry specimen using glass-polymer composite mat (the GPRM diagram was cut in the point C because of the sensor limitation)

VII. CONCLUSIONS

Flexible structural joints (repair injects, bonding adhesives) are able carrying and transferring loads under large deformations. Such ability have newly constructed stable polyurethane materials (polymers PT, PST, PM and PS), which characteristics are different from the traditionally using stiff and brittle bonding materials (epoxy resin, lime and cement mortars) of low deformability. Flexible joints are characterized by: low Young’s modulus (from 0.1 MPa up to 800 MPa), high deformability (from 2% up to 1000%) and elaso-visco-plastic mechanical behavior.

The increase ratios of tensile strength were determined and compared each other for two repair cases of masonry elements. Firstly, masonry units (bricks) were failure in the four point bending test and next were repaired using various bonding materials and tested in the bending test again. This kind of test was chosen, because the shape of the stress distribution in the bending element cross-section generates the highest level of tensile stress at the bottom of tested specimens. Secondly, the Single Lap Shear Tests on bricks strengthened using the CFRP and SRP strips were carried out. There were tested specimens with the strips bonded on stiff and flexible adhesives. In both repair cases, higher strength increase ratio was obtained after repair using the polymer flexible joints made of highly deformed polymers.

Repair and strengthening of weak masonries is connected in majority with bonding of cracked masonry elements (using injection) or with improving of the global structural strength
by external bonding of FRP composites. Typically, if the stiff and brittle materials of low deformability (epoxy resins, lime and cement mortars) are used as the bonding inject or adhesive, the stress concentration peaks occur being responsible for relatively low strength of the bonding joint.

The new flexible approach in bonding of masonries was proposed few years ago and many researches on polymer flexible joints have been carried out in the laboratory and natural scales till now, demonstrating the efficiency of the proposed bonding (repair) method. Application of new bonding materials of lower stiffness and higher deformability causes reduction of stress concentrations, leading to avoiding of the micro cracks generation at the low load level. This phenomenon allows increasing the strength of the repaired masonry much better (in comparison to the primary strength of the masonry) than the traditionally using stiff, brittle and barely deformable bonding materials. The flexible polymers can be especially useful in the case of masonries in seismic areas, where high deformability, ductility and dissipation energy is required. They can help also in the case of repair of historical masonries, because this kind of structures is constructed of weak structural materials, which are vulnerable to stress concentrations. The flexible polymer joints decrease peaks of stress and redistribute the uneven stresses, protecting locally the weak masonry material against overcoming of its strength by the stress peaks and against generating of the initial cracks, responsible for activation of the damage process.

Above conclusions were confirmed by two kinds of the comparative tests on stiff and flexible bonding materials. The results of the tests on specimens with various bonding materials joining disrupted bricks (simulating cracks repair) indicated that repair of cracks in masonries by the use of the cement mortar or the epoxy resin is less effective (taking into consideration the load level) than using of flexible polymers. The same results were obtained in the case of the single lap shear tests, carried out using the epoxy and polymer adhesives. These starting tests explain usefulness of the flexible polymer joints of high deformability and point that further researches on properties of flexible polymers in masonry applications are needed and worth to do, especially on rheological and durability aspects.

The presented innovative bonding technology is able protecting architectural value of structures because it assures the rule of minimum intervention (is compatible with masonries form the mechanical point of view) without significant intervention in elevation of buildings and can be easily hidden under conservation materials, making durable joint of aesthetic external appearance fitted to the surroundings.

Moreover, the highly deformable polymer joints and adhesives were examined in laboratory on the medium scale cracked masonry walls and in situ on the cracked masonry building. The tests showed effectiveness and advantages in the use of highly deformable bonding polymers as the repair material of damaged masonries in cases of static and dynamic loads. The destructive tests showed that polymer joints reduce stress concentrations and introduce the huge amount of capacity to the cracked masonry structure to absorb the input energy. Presented tests point also that the polymer bonded masonry could be able to survive an earthquake better than an original masonry, but it should be confirmed during tests on shaking tables.

Acknowledgment

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References

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Dr. Kwiecień is a member of: Global Science and Technology Forum (GSTF), International Institute for FRP in Construction (IIFC), European Association of Earthquake Engineering (EAEE), two RILEM Committees (TC 223 MSC and TC CSM).