ENERGY APPROACH IN ANALYSIS OF MASONRY COLUMNS CONFINED WITH GFRP MESH BONDED ON STIFF AND FLEXIBLE ADHESIVES

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ABSTRACT

Application of FRP confinement system improves strength of the masonry column but also changes their dynamic response. Moreover, stiff (mineral and epoxy) adhesives, used in the strengthening of masonry columns, do not protect enough strengthening fibres against the damage caused by pressure of sharp fragments of masonry columns, especially during structural degradation under static and dynamic action. This stress concentration effect can be reduced by the use of polymer flexible adhesives.

The paper presents results of static and dynamic testing of five masonry columns: one of them unconfined and four of them strengthened, using confinement made of GFRP mesh. Confinement was bonded to the masonry columns on mineral, epoxy and two kinds of polymer adhesives. Specimens were tested first dynamically to find influence of various types of confinement on differences in their dynamic response. Next, all the specimens were investigated during a compression test up to failure using a universal machine. Analyses of the static and dynamic tests of the specimens were carried out using energy approach. Comparison of obtained results allowed presenting dynamic effectiveness of various types of adhesives in the case of confining application in earthquake protection, and also allowed calculating damage energy ratio of tested solutions. Finally, all specimens were tested statically up to failure with observation of damage energy. Obtained post-critical damage energy of specimens (important for safety of structure) was compared.

Keywords: Masonry columns, GFRP confinement, Dynamic testing, Stiff and flexible adhesives

1. INTRODUCTION

1.1. Vulnerability of masonry columns

Masonry columns are structural elements that are vulnerable to dynamic forces and usually do not have enough post-critical damage energy, because of their brittleness. It is visible especially in cases of earthquakes, where horizontal and vertical dynamic loads exceed strength of masonry columns and collapse mechanism is rapid. Overload of this kind of structural elements has often catastrophic consequences thus methods of columns capacity improvement are wanted. From the safety point of view, not only strength is taken into consideration in case of earthquake but also ductility (deformability) and damping properties are important. Brittle failure of masonry columns is the problem that should be eliminated in seismic areas.

1.2. Confining of masonry columns

Confinement system of masonry column using FRP composites is one of the most effective innovative techniques of repair and protection. This strengthening method is based on various kinds of FRP composites made of carbon, glass, aramide or basalt fibers, produced in form of mesh, bars, laminates or mats. Many tests were performed by scientists to find the most effective combination of strengthening system consisting of FRP composites and various kinds of adhesives \([1-3]\). The most popular are mineral and epoxy adhesives but these materials are of brittle behavior. Stiff (mineral) and

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very stiff (epoxy) adhesives, using in strengthening of masonry columns, do not protect enough of strengthening fibers against the damage caused by pressure of sharp fragments of masonry columns [4-5] during structural degradation. This is the reason of low efficiency in taking advantage of fibers capacity, because of stress concentration appearance. The other aspect of confining is the dynamic behavior of strengthened columns. Confinement systems change dynamic properties of existing columns which influence their dynamic response.

1.3. Influence of stiff and flexible adhesives fixing FRP composites

Strengthening of existing brittle masonry columns at earthquake areas is typical protection against dynamic forces. Using of brittle adhesives does not protect the FRP against sharp fragments of masonry [4] and causes stiffening of columns, increasing resonance frequency of them. As a solution to this problem the use of polymer flexible adhesives is proposed which allow reducing peak stresses [6] and do not change significantly dynamic properties of strengthened masonry columns [7]. Typically, strengthening confinement systems are tested in static investigations and dynamic tests are carried out sporadically. The research presented in this paper show how innovative technology of confining, based on flexible polymer adhesives modifies dynamic properties in comparison to traditional stiff ones., GFRP meshes are very popular from the economic point of view, thus this kind of fibers was applied in tested specimens, presented in this paper.

2. CONFINING OF MASONRY COLUMNS WITH GFRP MESH

2.1. Description of tested columns

Five specimens were tested dynamically and next statically up to failure, which were constructed in form of masonry columns of dimension 250 × 250 × 500 mm. They consisted of 7 brick layers of thickness 65 mm made of the Polish Bonarka brick, joined with cement mortar layers of thickness 7.5 mm made of Izolbet. One column was tested without strengthening and four of them were strengthened using confinement made of GFRP mesh, bonded to masonry specimens with stiff and flexible adhesives. Stiff adhesives were made of stiff mineral cement mortar Izolbet and of stiff epoxy resin Sikadur 30. Flexible adhesives were made of hard flexible polymer PT and of middle flexible polymer PS. The view of one of the columns and of the applied GFRP mesh was presented in Fig. 1.

2.2. Materials properties

A pull-off test using cylinder of diameter 50 mm was used to obtain tensile strength of bricks (the average value from 6 specimens was 2.06 MPa with the coefficient of variation CoV of 17.5%) and mortar (the average value from 6 specimens was 1.23 MPa with the CoV of 7.3%). Additionally, three-point bending tests were also done. Brick specimens (20 units) of dimension 250 × 120 × 65 mm were bending at the support distance of 20 cm, resulting in the average value of 2.09 MPa with the
CoV of 19.1%. The same test (according to EN 998-2 [8]) was carried out for the mortar specimens of dimension 40 × 40 × 160 mm, by bending them at the support distance of 10 cm. The obtained average value of tensile strength for 6 units was 3.16 MPa with the CoV of 10.4%. The average compression strength of bricks (4 specimens) of dimension 250 × 120 × 65 mm was 23.3 MPa with the CoV of 16.7% and of mortar (12 specimens) of dimension 40 × 40 × 40 mm was 15.9 MPa with the CoV of 7.3%. The economy and popular GFRP mesh (147 g/m²), used in civil engineering for warming of masonry buildings, was applied. This kind of GFRP meshes is constructed of glass fibers of type E of following parameters: $\rho = 25$ kN/m³, tensile strength of 1 700 MPa, Young modulus of 72 000 MPa and ultimate strain of 0.10%. Cross-section of fiber weaves in the X direction was $158 \cdot 10^{-6}$ m²/m and in the Y direction is $187 \cdot 10^{-6}$ m²/m. Each of the four tested specimens were confined with 4 layers of the GFRP mesh, bonded using various kinds of adhesives (Fig. 1).

2.3. Properties of stiff and flexible adhesives

The stiff mineral adhesive (cement mortar Izolbet) properties were characterized above. The stiff epoxy adhesive (Sikadur 30) had the following properties: the Young modulus of 12 800 MPa, tensile strength of 28 MPa, shear strength of 18 MPa, adhesion > 4 MPa and ultimate strain of 0.22%. The hard flexible adhesive (polymer PT) had the following properties: the Young modulus of 600 MPa, tensile strength of 18 MPa, shear strength of 18 MPa, adhesion > 5 MPa and ultimate strain of 10%. The middle flexible adhesive (polymer PS) had the following properties: the Young modulus of 8 MPa, tensile strength of 2.2 MPa, shear strength of 0.8 MPa, adhesion of 2.5 MPa and ultimate strain of 45%.

3. MASONRY COLUMNS TESTED DYNAMICALLY

3.1. Test description

Five masonry specimens fixed elastically at the bottom were excited using of a modal hammer. At the top of columns, an additional mass of 35 kg was joined, to increase a dynamic response of the masonry specimen. Impulse excitations were generated at the top of the tested columns in a horizontal direction and dynamic responses of specimens were measured using two accelerometers (one at the top and one at the bottom of each column) – Fig. 2. There were used the accelerometers 356B18 PCB,
the modal hammer PCB 086D50 and the recording system LMS SCADAS MOBILE, collecting in time domain data of excitation impulse forces and acceleration responses at the top and at the bottom of columns (Fig. 2). The sampling frequency was 2048 samples/second. Each specimen was excited by the modal hammer 10 times and the most representative signal had been chosen for analysis. To avoid influence of bottom vibration on the rest of the tested column, the specimen’s responses were corrected in frequency domain according to equation (1).

\[
\left| \ddot{X}(\omega) \right| = \left| \ddot{X}(\omega)_{\text{top}} \right| - \left| \ddot{X}(\omega)_{\text{bottom}} \right|
\]

(1)

where: \( \left| \ddot{X}(\omega) \right| \) = real acceleration frequency characteristic (FFT) at the column top,
\( \left| \ddot{X}(\omega)_{\text{top}} \right| \) = measured acceleration frequency characteristic (FFT) at the column top,
\( \left| \ddot{X}(\omega)_{\text{bottom}} \right| \) = measured acceleration frequency characteristic (FFT) at the column bottom.
\( \omega \) = natural angular frequency in [rad/s]

3.2. Measurement data analysis
Tested specimens are shortly named in brackets: masonry column without confinement (Z), confined column with polymer PT adhesive (Z_S_PT), confined column with mortar adhesive (Z_S_Z), confined column with epoxy adhesive (Z_S_30) and confined column with polymer PS adhesive (Z_S_PS). Signals without noise (modified according to equation (1)) of each specimen were selected for analysis. The force and acceleration signals in time-domain were analyzed using the Fast Fourier Transform (FFT). The frequency characteristics (FFT) for the exemplary unconfined masonry column – specimen (Z) are presented in Fig. 3. One of them is the force characteristic of modal hammer impulse \( |F(\omega)| \) and the second one is real acceleration characteristic (according to equation (1)) at the top of specimen \( |\ddot{X}(\omega)| \). Similar pairs of the frequency characteristics (FFT) were obtained also for confined masonry columns. The obtained in frequency domain characteristics of the impact force and of the horizontal acceleration allowed determining [7, 9] the modulus of the inertance function \( I(\omega) \), given by equation (2) and the modulus of the compliance (receptance) function \( A(\omega) \) according to equation (3). These dynamic characteristics are presented in Fig. 4 for each tested specimen, to compare them each other. The diagrams allowed finding dominant response frequencies of each specimen (Z – 14 Hz, Z_S_PT – 14 Hz, Z_S_Z – 27 Hz, Z_S_30 – 22 Hz, Z_S_PS – 19 Hz), indicating their stiffness increase after confining (resonant frequency increase).

\[
|I(\omega)| = \frac{\left| \ddot{X}(\omega) \right|}{|F(\omega)|}
\]

(2)

\[
|A(\omega)| = \frac{|I(\omega)|}{\omega^2}
\]

(3)
3.3. Potential energy of tested specimens

The dynamic excitation (seismic) energy is transmitted to the structure and it is balanced by capacity of the structure to absorb this energy. It is possible to determine the input energy in the moment when the velocity of structure is equal zero. In this case, the input energy \( E_i \) equals the sum of [7]: the kinetic energy \( E_k = 0 \), the potential energy \( E_p \) (reaching the maximum and representing reversible elastic deformation), damping energy \( E_d \) (which is dissipated through the mechanism of viscous damping) and irreversible hysteretic energy \( E_h \) (absorbed by the structure through controlled nonlinear deformations). Assuming that only vibrations in the elastic range of columns are taken into consideration, the equation of energy balance can be written in form (4). Thus, the input energy \( E_i \) acting for tested columns (for real structure at low level of dynamic excitation) is balanced only by maximum potential energy \( E_{p}\max \) and damping energy \( E_d \).

\[
E_i(\dot{X} = 0) = \{E_k = 0\} + \{E_k = 0\} + E_{p}\max + E_d
\]

\[
|E_p(\omega)| = \frac{1}{2\omega^2} \left[ \left| \bar{X}(\omega) \right|^2 \right]
\]

\[
\xi = \frac{\Delta \omega}{2\omega_r}
\]

Fig. 5 Comparison of normalized potential energy \( |E_p(\omega)|_{\text{normalized}} \) (left) and of normalized damping coefficients \( \xi_{\text{normalized}} \), calculated for the tested masonry columns

Calculation of the potential energy for the tested columns was carried out for their resonant frequencies. The modulus of the potential energy \( |E_p(\omega)| \) is given by equation (5), which was derived from equations presented in [7]. The obtained values for the confined masonry columns were normalized to the value calculated for the unconfined masonry column (Z) and presented in Fig. 5. The comparison of them shows that confining of masonry column with GFRP mesh bonded on
adhesives of different stiffness, causes reduction of column ability to absorbing input energy through potential energy $E_p$. More disadvantageous kind of confining is using of stiff cement mortar adhesive and very stiff epoxy adhesive, which reduce this ability to about 6-8 times, whereas more advantageous from the analyzed cases is confining with adhesives made of polymers PT and PS, which reduced this ability about only 2 times.

3.4. **Damping energy of tested specimens**
Damping energy $E_d$ is proportional to the damping coefficient $\xi$, which was determined for the tested specimens using the half-power bandwidth method for the dominant resonant frequencies. This method uses the compliance function $A(\omega)$ presented in Fig. 4. The damping coefficients $\xi$ were calculated from equation (6), using the compliance function diagrams of tested columns. The values of $\Delta\omega$ correspond to the widths of the compliance curves, measured at the amplitude levels equal to the maximum amplitudes at the resonant frequencies $\omega_k$ divided by $\sqrt{2}$. To compare damping properties of tested masonry columns, the obtained values of the damping coefficient $\xi$ determined for the confined masonry columns were normalized to the value calculated for the unconfined masonry column ($Z$). As previously, the confinement reduces damping properties of masonry columns. The most disadvantageous is using of cement mortar adhesive, which reduces damping energy almost 5 times, whereas the most advantageous is using of polymer PT adhesive, which reduces damping energy about 1.5 times (Fig. 5).

3.5. **Comments on dynamic properties of confinement**
It should be underlined that confining of masonry columns is disadvantageous from the dynamic response point of view (in the elastic range of vibration). The increase of internal forces in confined masonry columns, caused by increase of dynamic response, is equalized by higher strength properties of the strengthened column cross-section in comparison to the unconfined column. The carried out dynamic tests, on masonry columns confined with GFRP mesh bonded on adhesives of different stiffness showed that applying flexible adhesives is more advantageous than stiff ones. It is valid, when the structure response to a dynamic excitation working in the elastic range of vibration. Potential energy as well as damping energy receives higher values in the case of flexible polymer adhesives than in the case of stiff adhesives.

4. **STATIC COMPRESSION TEST OF MASONRY COLUMNS**

4.1. **Test description**
The tested dynamically masonry columns were compressed up to failure under static load. The research was carried out at Cracow University of Technology, using the universal testing machine Zwick Z6000, which is able to generate the compression load of 6000 kN (Fig 6). The compression tests of all masonry columns were realized with constant displacement ratio of 0.5 mm/min. The obtained stress-strain curves are presented in Fig. 6.

![Fig. 6 Universal testing machine Zwick Z6000 (left), view of the tested confined masonry column (middle) and the stress-strain diagram presenting comparison of results obtained for five tested specimens (right)](image)

4.2. **Static compression test results**
Their comparison indicates that strengthening characteristic of the masonry column, after confining them with four layers of GFRP mesh, is dependent on a kind of adhesive layer. The more flexible
adhesive (comp. the Young module and the ultimate strains of the applied adhesives) the higher strength and the column stiffness are. The scale of strength increase represents the comparison of the obtained maximum stress, normalized to the stress value of the unconfined column (Z). It confirms the previous conclusion that the highest strength (Fig. 7) was obtained for the most flexible polymer PS adhesives (Z_S_PS) and the lowest one for the most stiff cement mortar adhesive (Z_S_Z). Similar observations were found during comparison of the damage energy (proportional to the area measured under the stress-strain curves up to the maximum stress). Their values, normalized to the damage energy value of the unconfined column (Z), are compared in Fig. 7.

![Graph showing comparison of maximum stress and damage energy normalized to unconfined column](image)

**Fig. 7** Comparison of the values of maximum stress and of the damage energy, normalized to the values obtained for unconfined column

The global strength increase of the tested column is not so high after confinement, because the masonry columns were made of the Bonarka bricks of high strength and the glass mesh confinement was not so strong. Such disproportion was designed to emphasis the influence of the adhesive layer properties on failure process of glass fibers. These both materials are of brittle characteristic and are vulnerable to stress concentration phenomenon [6]. Usually, the increase of the masonry columns after confinement is higher (2-3 times – after [5]) if bricks of lower strength and FRP composites of higher strength are taken into cooperation.

4.3. **Stress concentration generated by sharp pieces of bricks**

In the case of nonlinear deformations of confined masonry columns, absorption by irreversible hysteretic energy $E_h$ is activated, when internal damage of masonry column occurs. The structure ability to absorb deformation energy increases considerably in this state, because the confinement protects the inner vertical cracks of masonry column against expansion, also increasing ductility and global strength of the column. Unfortunately, the broken and sharp pieces of masonry, acts on the brittle confinement structure from inside and stress concentrations cause damage of FRP fibers. In the case of the masonry columns of rectangular cross-section, the highest stresses concentrate in corners, causing failure modes presented for the tested specimens in Fig. 8. The failure mode of columns with stiff and flexible adhesive is similar (Fig. 9), but the flexible adhesives (withstanding of large deformations) protects the FRP fibers against damage more efficiently than the brittle stiff adhesives.

![Images of masonry columns](image)

**Fig. 8** Failure modes of the tested masonry columns
The mechanism of stress concentration reduction by flexible adhesive (in contact with FRP composite) was described in [10]. It is known [11] that shear and normal stress concentrations appear in adhesive and FRP composite in the place of crack occurrence, also in the case of masonry column (Fig. 10). If the adhesive is brittle and stiff (epoxy, cement mortar), the crack propagates through it immediately (Fig. 10b), generating high stress directly to FRP composite. In the case of flexible adhesive (polymer PT and PS), the same load level does not cause propagation of the crack through polymer adhesive, which dissipates energy at the crack tip by ductile deformation (Fig. 10c). This mechanism protected the GFRP mesh, resulting in higher strength of the specimens with the flexible adhesives.

5. CONCLUSIONS

The technology of confining using flexible polymer adhesives is an innovative method, proposed for application in strengthening of masonry columns with FRP composites. Two kinds of polymer adhesives made of polyurethane mass were applied for bonding of the GFRP mesh to masonry columns tested under dynamic and static loads. Similar ones were tested, applying two kinds of stiff adhesives. The comparison of results obtained for specimens with stiff (epoxy and cement mortar) and flexible (polymer PT and PS) adhesives showed that the use of flexible adhesives in confining, reduces stress concentrations, better protecting FRP composites and causing an increase of strength of the confined masonry columns, than stiff and brittle adhesives.

The dynamic tests carried out allowed presenting dynamic effectiveness of various types of adhesives in case of confining application in earthquake protection. The obtained results indicate that applying flexible adhesives is more advantageous than stiff ones, when the structure response to dynamic excitation, working in the elastic range of vibration. It was observed in the cases of damping and potential energy (possible to absorb by the confined masonry column). Historical masonries would take advantage of the flexible bonding, but the durability aspect has to be investigated.

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