WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945
DOI: 10.24425/ace.2023.145255
ARCHIVES OF CIVIL ENGINEERING
Vol. LXIX ISSUE 2 2023
pp. 97 –110

Research paper

FRP strengthening of AAC masonry walls – comparative analysis and discussion selected calculation methods

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Abstract: The use of FRP materials as external reinforcement of masonry structures has been recognized as an effective and minimally invasive method of wall strengthening. The available literature and research reports confirm the positive effect of the strip-like arrangement of composites with a horizontal, diagonal and – as shown in the paper – vertical configuration. The problem here is the proper estimation of the benefits of such FRP reinforcement, namely determining the real increase in shear strength. The paper described selected calculation procedures that can be found in the available literature (proprietary solutions), as well as in the published guidelines for the design of masonry walls strengthening using FRP materials. The results of experimental tests of sheared masonry walls made of AAC blocks and strengthened using vertical strips of carbon and glass fibres are briefly presented. Finally, based on the presented formulae, the values of the theoretical shear force resulted from the FRP contribution were calculated and detailed discussed.

The comparison of the experimental and theoretical shear forces showed that only one of the presented calculation methods gave a high agreement of the results for both carbon and glass sheets. In addition, it was noticed that in two cases the effects of strengthening – depending on the material used – drastically differed, which was not observed in the research.

Keywords: comparative analysis, diagonal compression, FRP strengthening, masonry walls, vertical strips

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1. Introduction

Modern methods of enhancement of the shear properties of masonry structures use non-metallic materials in form of external wall reinforcement. Nowadays, two main groups of strengthening systems based on various types of composites and their application on masonry substrate can be distinguished. The first one, analysed in this paper, is a FRP (Fibre Reinforced Polymer) system, that uses the strip-like arrangement of the laminate or woven nets glued on the masonry surface. The most commonly strip arrangement is horizontal – parallel to the bed joints, which corresponds to the classic reinforcement of the joints – or diagonal referring to the main tensile stresses in the sheared wall. The application of vertical strengthening strips is used less frequently, as some researchers consider it ineffective and ignored in the calculations [1, 2]. However, as the author's own research [3, 4], briefly presented in this paper, shows such an assumption as ineffective.

The second, relatively new system involves placing the composite material – in form of fibres (FRM: Fibre Reinforced Mortar) or textiles (TRM: Textile Reinforced Mortar) – on the mineral mortar. The material is placed on the entire surface of the wall on one or both sides.

The positive influence of FRP reinforcement applied on various types of masonry walls is already well known. This type of strengthening significantly delays the cracking moment, but most of all causes a significant increase in shear capacity and deformation of the walls [5–8].

Increasing the shear capacity of masonry walls is especially important in areas where there are significant ground movements, for example the places with intensive mining exploitation. In this case, wall reinforcements are preventive measures that are already performed while the building is being erected. Therefore, the assessment of the effectiveness of the proposed strengthening solution requires the determination of the increase of load-bearing capacity results from FRP contribution. Unfortunately, this issue is not an easy one, despite the existence of several original calculation procedures and national guidelines. The literature [9–11] shows a comparison of the load-bearing capacity of walls made of ceramic (clay) units strengthened with the FRP system, determined in laboratory test and calculated according to the selected calculation procedures. There are significant differences in the obtained values, which proves that the available calculation formulae are often fitted to specific research cases and do not constitute universal calculation methods. Therefore, the correct estimation of the load-bearing capacity requires an individual analysis of the suitability of the available formulae and the determination of the most appropriate in a given strengthening case. Such procedure is presented in this paper, where the load-bearing capacity resulting from the FRP contribution is calculated and compared with experimental results of walls strengthened using vertically applied CFRP and GFRP strips.

2. Calculation methods

Generally, the shear capacity of strengthened masonry wall is the sum of the original masonry shear capacity and the external reinforcement effect. The calculation of original shear capacity of unstrengthened wall is omitted in this paper, while the focus is on determining the strengthening contribution. The reinforcement – in form of FRP laminates or sheets – is glued on the masonry surface in different strip configurations. The available calculation procedures refer mainly to the horizontal arrangement of the reinforcement, however, in some cases the diagonal or horizontal strip arrangements are also included.

In all proposed calculation methods the FRP influence is reduced taking into account different issues descending form their non-ductile behaviour, and the system of internal forces in the structure is mostly based on the truss model.

For simplicity's sake the basic symbols repeated in the formulae were adopted with the same designation regardless of those presented in the original sources, namely: A_{frp} – total area of the FRP material, f_{frp}, ε_{frp}, E_{frp} – tensile strength, strain and elastic modulus of FRP material provided by the manufacture, respectively, ρ_{frp} – reinforcement ratio computed on the panel section, t_{frp} – thickness of FRP material, l – appropriate dimension of the masonry, d – distance from extreme compression fibre to centroid of tension reinforcement.

2.1. Authorial calculation procedure

Initially, the prediction of FRP contribution in a shear capacity of masonry wall was adopted from formulations for masonry reinforced with steel bars. Assuming that the FRP reinforcement acts as external reinforcement, these relationships could be used to estimate the load-bearing capacity of a wall with horizontally arranged reinforcement [7, 9]. A very simplified calculation formula was proposed in 1993 by Tomaževič et al. [1]:

$$V_{\text{FRP}} = 0.4 A_{\text{frp}} f_{\text{frp}} \tag{2.1}$$

Another approach that involves the actual stiffness of the reinforcement, was proposed by Triantafillou et al. [2]. The calculation model adopted here was based on the assumptions specified when calculating the bearing capacity of RC elements strengthened with FRP [12]:

$$V_{\text{FRP}} = \frac{0.7}{\gamma_{\text{frp}}} \rho_{\text{frp}} E_{\text{frp}} \varepsilon_{\text{frp},e} l t \tag{2.2}$$

where: γ_{frp} – partial safety factor for FRP in axial tension (1.15 for CFRP, and 1.25 for GFRP), $\varepsilon_{\text{frp},e}$ – effective FRP strain adopted for masonry structures according to the experimental verifications [2]:

$$\varepsilon_{\text{frp},e} = 0.0119 - 0.0205(\rho_r E_{\text{frp}}) + 0.0104 \left(\rho_r E_{\text{frp}}\right)^2 \tag{2.3}$$

In both of these formulae (2.1) and (2.2), the authors made the assumption that the contribution of vertical FRP reinforcement is negligible.

In the case of reinforcement with horizontal, diagonal or both FRP sheet configurations an analytical approach is proposed by Wang et al. [13]. The shear contribution provided by FRP material is calculated taking into account the horizontal (marked as "s") and diagonal (marked as "x") direction of the strengthening and expressed in effective working coefficients ξ_s and ξ_x. Proposed calculation formula is:

$$V_{\text{FRP}} = E_{\text{frp}} \varepsilon_{\text{frp}} \left[\xi_s n_s A_{1-\text{frp},s} + \xi_x n_x A_{1-\text{frp},x} \left(\cos\theta + 0.2 \sin\theta\right)\right] \tag{2.4}$$

where: $n_{s(x)}$, $A_{1-frp,s(x)}$ – number and single cross section of FRP in horizontal (s) and diagonal (x) direction, respectively, ε_{frp} – expressed in [%], θ – angle of tensile diagonal to horizontal direction, $\xi_{s(x)}$ – effective working coefficients for horizontal and diagonal direction, which amounted to:

$$\xi_s = -0.245 \ln\left(\rho_{\text{frp}}\right) - 0.128 \tag{2.5}$$

$$\xi_x = -0.411 \ln\left(\rho_{\text{frp}}\right) - 0.107 \tag{2.6}$$

The procedure proposed by Garbin et al. [14] was an introduction to the later effective American guidelines ACI 440.7 [15]. A methodology for calculation the shear resistance of masonry walls strengthened with FRP system under in-plane load based on the strength designed approach of reinforced masonry member given in the Building Code Requirements for Masonry Structures ACI 530.1-02 [16]. Following this document, when the failure of the masonry compression struts is avoided, the shear resistance provided by FRP system is determined as:

$$V_{\text{frp}} = 0.5\frac{A_f f_{\text{fe}} d}{s} \tag{2.7}$$

where: A_f – area of the FRP reinforcement working in tension, s – distance between FRP in the vertical direction in the presence of horizontal reinforcement, f_{fe} – effective design strength of FRP reinforcement calculated as:

$$f_{\text{fe}} = k_m f_{\text{fu}} = k_m C_E f_{\text{frp}} \tag{2.8}$$

where: k_m – factor for different strengthening systems: 0.65 for FRP laminates glued using epoxy, according to the Table 2 in [14]), f_{fu} – design tensile strength of FRP, C_E – environmental reduction factor (0.95 for CFRP and 0.75 or GFR for internal exposition, according to the Table 8.1 [15] or Table 1 in [14]).

Additionally, work [14] contains a simplified method of calculating the shear resistance provided by the FRP system placed only in the horizontal or vertical direction:

$$V_{\text{frp}} = k_v A_f f_{\text{fu}} \tag{2.9}$$

where: k_v – factor accounts for the orientation angle of the fibres with respect to the direction of the failure surface opening (assumed equal to 45°); in absence of a comprehensive experimental campaign it is taken for different strengthening systems related to the FRP and masonry wall application (0.3 for FRP laminate glued using epoxy on both surface of concrete masonry – Table 4 in [14]).

2.2. Available guidelines

In 2001 the ICBO ES published a document AC125: Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fibre-Reinforced Polymer (FRP), Composite Systems [17]. In this document the nominal shear strength enhancement for rectangular masonry wall sections of depth H parallel to the direction of applied shear force, with fibre on both sides of the wall at an angle θ to the members' axis, shall be calculated as:

$$V_{sj} = 2t_{\text{frp}} f_j H \sin^2\theta \tag{2.10}$$

where: f_j – hoop stress in FRP material limited by an appropriate reduction of tensile strength according to:

$$f_j = 0.004E_{\text{frp}} \le 0.75 f_{\text{frp}} \tag{2.11}$$

Detailed document has been prepared by National Research Council (Rome) in 2004 as CNR – DT 200/2004: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures [18] and then revised in 2013 [19]. In the updated design guide the calculation procedure for increasing the shear capacity of masonry wall by applying FRP to both sides with fibres placed parallel to the shear direction has been given. The FRP contribution in shear capacity is calculated as:

$$V_f = \frac{1}{\gamma_{\text{Rd}}} 0.6d \left(E_f \varepsilon_{\text{fd}}\right) 2t_{\text{frp}} \frac{b_f}{p_f} \tag{2.12}$$

where: γ_{Rd} – partial factor: 1.20 for shear (Table 3-1 in [19]), ε_{fd} – design strain of FRP reinforcement, b_f – width of FRP strips, p_f – center-to-center spacing of FRP strips measured orthogonally to the direction of the force.

A significant difficulty here is the definition of design strain, which is defined taking into account the mode of FRP failure. Two cases are analysed here – exceeding the ultimate tensile strain ε_{frp} (damage of the fibres itself) or exceeding the debonding strain ε_{fdd} (delamination of the FRP). Therefore, the design strain is taken as:

$$\varepsilon_{\text{fd}} = \min\left\{\eta_a \frac{\varepsilon_{\text{frp}}}{\gamma_f};\ \varepsilon_{\text{fdd}}\right\} \tag{2.13}$$

where: η_a – environmental conversion factor for different exposure and FRP (Table 3-2 in [19]): 0.95 for CFRP, 0.75 for GFRP in internal exposure, γ_f – partial factor: 1.10 for FRP laminate (point 3.4.1 in [19]); ε_{fdd} – strain before debonding calculated as:

$$\varepsilon_{\text{fdd}} = \frac{\alpha f_{\text{fdd}}}{E_f} \tag{2.14}$$

where: α – factor between 1.0 and 2.0; this factor does not appear in the document from 2004 [18]; for optimal bond length it can be taken as 1.5; f_{fdd} – design bond strength expressed as:

$$f_{\text{fdd}} = \frac{1}{\gamma_{f,d}} \sqrt{\frac{2E_f \Gamma_{\text{Fd}}}{t_f}} \tag{2.15}$$

where: $\gamma_{f,d}$ – partial factor: 1.20 (point 3-1 in [19]), Γ_{Fd} – design value of the fracture energy computed as:

$$\Gamma_{\text{Fd}} = \frac{k_b k_G}{\text{FC}} \sqrt{f_{\text{bm}} f_{\text{btm}}} \tag{2.16}$$

where: k_b – geometrical factor, k_G – corrective factor, dependent on the type of masonry, FC – confidence factor amounted to 1.2, f_{bm}, f_{btm} – average compressive and tensile strength of masonry blocks, respectively; in absence of experimental data, the tensile strength can be computed as $0.1 f_{\mathrm{bm}}$.

Determining the geometric factor requires knowledge of the bond strength distribution area (b) and can be taken according to the Fig. 1. Then the factor can be calculated as:

$$k_b = \sqrt{\frac{3 - b_f/b}{1 + b_f/b}} \tag{2.17}$$

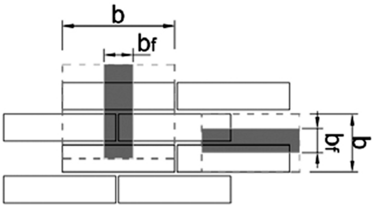

Fig. 1. Bond strength distribution for masonry wall [19]

The second corrective factor (k_G) is given as a specific value for a given type of material. Unfortunately, these values are determined for masonry specific to Italy: perforated brick– 0.031 mm, tuff – 0.048 mm and calcarenite and Lecce stones – 0.012 mm. Therefore, it cannot be clearly applied to other types of masonry. However, the analysis of the previously published document [18] made it possible to calculate the characteristic fracture energy using the simplify Eq. (2.18). The conversion from the characteristic fracture energy to the design value – given in [19] – can be done by adopting the factor $1/FC$ from the Eq. (2.16).

$$\Gamma_{kd} = c_1 \sqrt{f_{\mathrm{bm}} f_{\mathrm{btm}}} \tag{2.18}$$

where: c_1 – experimentally determined coefficient that can be assume as 0.015.

American Concrete Institute in 2010 published Guide for the Design and Construction of Externally Bonded Fibre-Reinforced Polymer System for Strengthening Unreinforced Masonry Structures – ACI 440.7R-10 [15]. According this document the surface mounted FRP contribution to the shear strength can be determined as:

$$V_{\mathrm{frp}} = p_{\mathrm{fv}} w_f \frac{d_v}{s_f} \tag{2.19}$$

where: p_{fv} – force per unit width for FRP system, w_f – width of FRP strips, d_v – effective masonry depth for shear calculations given as minimum value of the wall dimensions, s_f – spacing of FRP strips.

The force p_{fv} that the FRP system transfers to the masonry must satisfy the limitation:

$$p_{\mathrm{fv}} = n t_f f_{\mathrm{fe}} \leq 260\ \mathrm{N/mm} \tag{2.20}$$

where: n – number of plies of FRP laminates, t_f – nominal thickness of one ply of FRP reinforcement, f_{fe} – effective stress level in FRP reinforcement calculated as:

$$f_{\text{fe}} = E_{\text{frp}}\varepsilon_{\text{fe}} \tag{2.21}$$

where: E_f – tensile modulus of elasticity of FRP, ε_{fe} – effective strain in FRP reinforcement calculated as:

$$\varepsilon_{\text{fe}} = \kappa_v \varepsilon_{\text{frp}} \leq C_E \varepsilon_{\text{frp}} \tag{2.22}$$

where: κ_v – bond-depended coefficient for shear taken based on ω_f index (0.40 for $\omega_f \leq 0.2$, $0.64 - 1.2\omega_f$ for $0.2 < \omega_f \leq 0.45$ and 0.1 for $\omega_f > 0.45$), C_E – environmental factor as in Eq. (2.17).

The ω_f index is defined as:

$$\omega_f = \frac{1}{85}\frac{A_{\text{frp}}E_{\text{frp}}}{A_n\sqrt{f'_m}} \tag{2.23}$$

where: A_n – area of panel section, f'_m – specified masonry compression strength in [MPa].

3. Laboratory tests – results

Experimental verification of the effectiveness of vertical FRP reinforcement was carried out on walls with dimensions of 900 × 805 × 240 mm made of aerated concrete blocks (AAC). The mean value of the compressive strength of the masonry blocks was tested according to EN 772-1 standard [20], while the mean value of the compressive strength of masonry walls was tested according to EN 1052-1 standard [21]. Both values are given in Table 1. These walls were made using very popular erecting method with thin bed joints and unfilled head joints. Unfortunately, this technology has a very unfavourable effect in the case of sheared wall, tested in a diagonal compression scheme. Each time the appearance of the first crack was tantamount to the damage of the element and it was initiated at the intersection of the bed and the infilled head joints. It is visible on the map obtained from the optical measurement in the form of the strain concentration recorded just before the failure (Fig. 2a). Due to this fact, the walls were strengthened using carbon and glass sheets, fastening – in a vertical arrangement – unfilled head joints. The FRP strips distribution is shown in Fig. 2b. All elements were tested under diagonal compression (Fig. 2c) – according Rilem LUMB 6 standard [22].

The use of such a bilateral reinforcement resulted in an increase in shear stresses by approximately 50% when using CFRP strips and over 60% in the case of GFRP strips. In addition, the wall reinforced with the CFRP material showed an increase in stiffness in the uncracked phase, which was not observed at application of GFRP sheets. The behaviour of strengthened and unstrengthened walls is shown analysing the relative stresses – deformation relationships (Fig. 3).

In both cases, after cracking the walls, a further increase in the load was followed until the maximum load-bearing capacity was achieved. The in-plane deformability of all strengthened walls also increased significantly in comparison with unstrengthened walls.

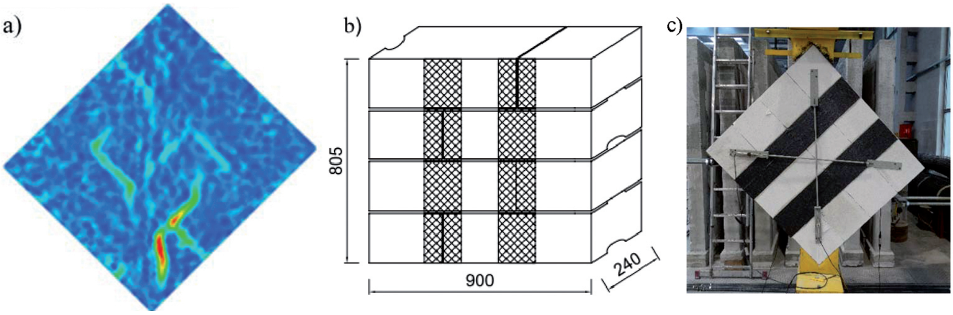

Fig. 2. The characterization of the tested walls: a) the strain concentration in unstrengthened wall, b) arrangements of the FRP strips, c) strengthened wall in test stand

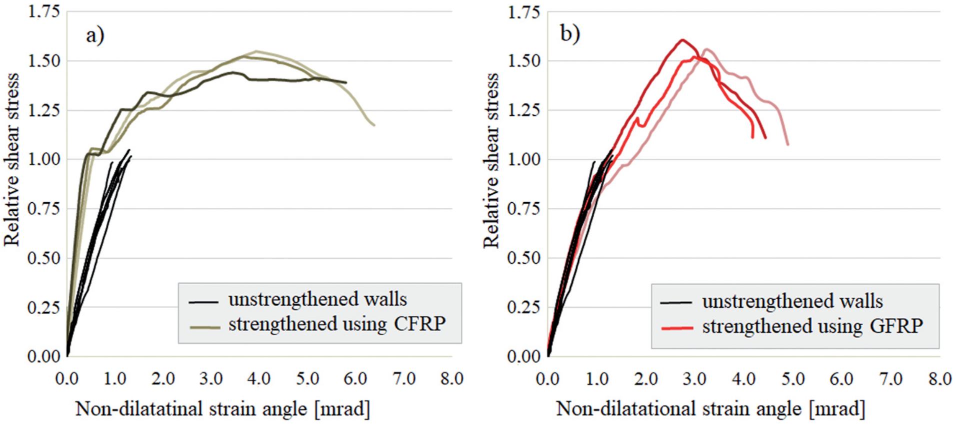

Fig. 3. Comparison of relative stress – deformation relationships for unstrengthened walls and wall strengthened using: a) CFRP strips, b) GFRP strips

4. Calculation of FRP contribution

The application of vertical FRP reinforcement on the masonry walls made of ACC blocks resulted in a noticeable increase in the maximum shearing force of the tested models. More deformable glass sheets allowed for an average force increase of 60.2 kN and rigid carbon sheets by 48.5 kN in relation to the value of the failure load (amounted to 107 kN) of the unstrengthened walls. Those increases were considered to be shear strength resulted from FRP contribution. It should be noted that these values contradict the claim that the effect of vertical reinforcement of masonry walls should be considered negligible in analysis [1, 2].

In most of the cited procedures, only vertical FRP reinforcement is taking into account, however, due to the obtained laboratory results, it was decided to apply the available calculation procedures, disregarding the direction of the FRP arrangement.

The masonry wall parameters are given in Table 1. The basic geometrical and strength properties of FRP material are summarized in Table 2. The remaining value required in the analysis are the result of calculations based on the following information.

Table 1. Parameters of the masonry wall

Parameters	Height [mm]	Length [mm]	Thickness [mm]	Compressive strength of masonry wall [MPa]	Compressive strength of masonry blocks [MPa]
Masonry wall	815	900	240	3.51	4.65

Table 2. Properties characterizing the FRP strengthening

Parameters	Width [mm]	Spacing [mm]	Nominal thickness [mm]	E-modulus [kN/mm^2]	Ultimate strength [N/mm^2]	Ultimate elongation [%]
CFRP strips	150	300	0.117	240	3800	1.55
GFRP strips	200	300	0.154	73	2400	4.5

The value of shear force specifying strengthening effect were calculated in accordance with the procedures described in point 2 (omitting the calculations based on AC125 [17]) and compared with the laboratory results – Fig. 4 for CFRP sheets and Fig. 5 for GFRP sheets. In both figures, the red bar and line represent the values obtained in laboratory tests.

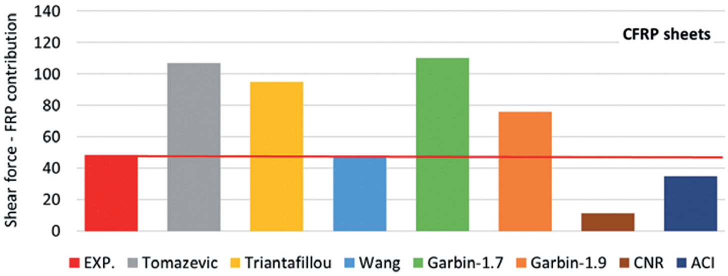

Fig. 4. Comparison of CFRP contribution in shear force from experimental and analytical calculations

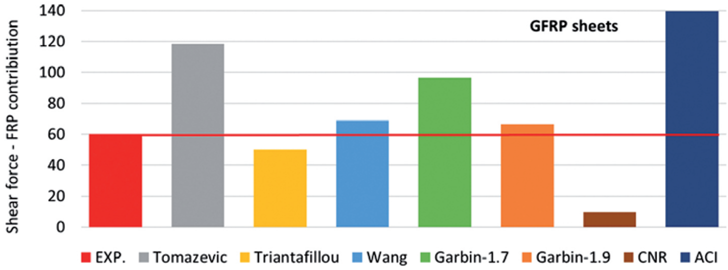

Fig. 5. Comparison of GFRP contribution in shear force from experimental and analytical calculations

5. Discussion

The comparisons presented in Chapter 4 are very interesting in two aspects. Firstly, there are large discrepancies in the calculated values for a given type of reinforcement, and secondly – more interesting – in two cases there were huge differences in calculations depending on the FRP material used.

The use of a very simplified approach proposed by Tomaževič – Eq. (2.1) – significantly overstates the obtained theoretical values, both for carbon and glass sheets. The assumption of reducing the maximum load-bearing capacity of the strengthening material to 40% is still too small in the analysed case. It is evident that the reduction level should depend on the mode of failure, and more specifically the level of usage of the composite upon failure. The observed failure was FRP detachment due to the damage of the masonry structure. Thus, the level of usage of the composite itself at the time of failure is much lower than the 40% adopted here.

The formula (2.2) proposed by Triantafillou uses the effective strains, calculated from an empirical relationship (based on experimental data) including the elastic modulus of composite. In the case of CFRP material, a fairly high level of sheets usage is obtained (0.67), as the calculated effective strain is 1.05% in relation to the maximum – 1.5%. Thus, the stresses in the sheet are almost 2500 MPa, which in turn leads to a high value of shear force resulting from the CFRP effect. Unfortunately, this value is almost twice as high as that obtained in the tests. Therefore – in the case of CFRP sheets – estimation with this method gives significantly overestimated values resulting from relatively high material usage. In the case of glass sheets, the calculated effective strain was 1.11%, but comparing them to the ultimate strain (4.5%), this gives a low level of GFRP usage (0.25). The stresses in the composite are only 800 MPa, which results in a relatively low shear force (ca. 50 kN). This is only about 15% lower than the experimental value. Therefore, it can be concluded that this formula may be appropriate for materials with a low modulus of elasticity, which leads to a low level of their usage – what occurs in presented research – and gives values similar to those obtained in the laboratory tests.

The calculation of the FRP contribution according to the Wang formula – Eq. (2.4) – in which only the vertical/horizontal strips were analysed (the section concerning diagonal strips was omitted), gives a very good estimation of the shear forces in relation to the values measured in the tests. High compliance was obtained for both CFRP and GFRP sheets, although in the latter case the force was approx. 10% higher than the experimental one. The formula (2.5) based on empirical relationships that determine the effective working coefficient related to the reinforcement ratio. In general, the formula is based on the maximum usage of the composite, assuming the value of deformations in [%], and the calculated coefficient very accurately matched the reality. It can be assumed that this method – despite the fact that it is used for horizontal reinforcement – perfectly defines the FRP effect in the case of vertical reinforcement uses in presented laboratory tests.

The method proposed by Garbin et al., preceding the ACI standard [15], provides formula for calculating the shear force that results from the work of tensile horizontal reinforcement, with the existence of FRP reinforcement in both directions – Eq. (2.7). There is an effective design strength of FRP, which is reduced due to the reinforcement application (FRP laminate or NSM bars, absence of puffy) and environmental condition (different for various materials). However, the determination of shear strength from Eq. (2.7) gives much overstated values – green bars in Fig. 4 and 5. This results from a slight reduction in the maximum stresses in the FRP sheets, as it is assumed here that the FRP strips are cooperated in two directions (which is not true in the laboratory tests). However, this document [14] also proposes a calculation procedure that assumes the use of reinforcement in one direction, either horizontally or vertically. In this formula (2.9), the reduction coefficient k_v was introduced, amounting to 0.3 in the analysed case, with the simultaneous limitation of the level of stress reduction in the FRP material. As shown in Fig. 4, this reduction is sufficient for a weaker material (GFRP sheets), because the values obtained in the calculations are slightly higher than the experimental ones (by about 10%). Unfortunately, it is too small when using strong carbon sheets because the shear force calculated is approximately 60% higher than the force obtained in the laboratory tests (Fig. 3).

The calculation procedure included in AC125 [17] does not allow its use in the case of vertically arranged reinforcement. The formula (2.1) requires the calculation of the value of $sin^2\theta$, where θ denotes the angle between the reinforcement and the members' axis, and in the analysed case this angle is 0°. An interesting observation here is the fact that Eq. (2.10) does not contain information about the geometrical parameters of the applied reinforcement (number of strips, their width or spacing), which means that the intensity of the reinforcement is completely ignored.

Contrary to AC125, the analysis of the FRP contribution in shear strength according to CNR-2013 [19] contains very detailed geometrical characteristics of the reinforcement arrangement. Despite the determination of the spacing and width of the strips, it requires the calculation of the k_b coefficient, which determines the area of the strip's cooperation with the masonry wall. These guidelines do not specify the arrangement of the reinforcement, so they can also be used for vertical FRP stripes. Unfortunately, in order to calculate the fracture energy Eq. (2.16), it requires the corrective factor (k_G) that depends on the type of masonry, and the standard gives its value only for selected materials (perforated brick masonry, tuff and calcarenite or Lecce stones masonry). Due to the lack of this coefficient for analysed material (AAC blocks), it was decided to adopt the formula to calculate fracture energy from the earlier edition of the standard [12] – Eq. (2.18). In this document the fracture energy is generally determined without taking into account a specific masonry units. As can be seen from Figs. 3 and 4, the shear force values are negligible and amount to about 12 kN, regardless of the FRP material. The proposed calculation formula, despite its detail and taking into account many aspects, gives very low values, which are safe, but too far from the actual values (in this case).

The last calculation procedure included in the American guidelines [15] also does not distinguish between the arrangement of the reinforcement, so it can be fully useful in the analysed case. The method of calculating shear strength is very simple, it only requires the determination of the unit strength that the FRP system transfers to the masonry (p_{fv}) – Eq. (2.20). The usage of the reinforcement by determining the effective strain in FRP is also limited here. In the case of carbon sheets, the force obtained from calculations is about 25% lower than that obtained in the tests, but in the case of glass sheets it is 132% higher. The huge difference obtained for various materials results from the method of calculating the effective stresses, and more precisely the k_v coefficient (bond-depended coefficient). The range of the k_v coefficient is very large, ranging from 0.1 to 0.4. In the case of CFRP material, it is 0.1, which gives a low deformation in the strip (0.0016) and makes the unit force of 87 kN/mm. In the case of glass sheets the k_v is 0.29 (so it is almost 3 times higher), which translates into much greater deformations (0.013) and a huge unit force of 290 kN/mm (this value must be limited to 260 kN/mm). Therefore, the method of determining the k_v coefficient causes such a large difference in the shear strength values, which are 35 kN for CFRP and 139 kN for GFRP strips. Therefore, it should be acknowledged that despite the use of the actual parameters of the reinforcement and the wall (contained in Eq. (2.23), the value of bond-depended coefficient is crucial and in the analysed case, it is not appropriate.

6. Conclusions

The aim of the presented comparative analysis was to check the possibility of applying the available procedures for calculating the shear forces that determine the impact of FRP strengthening. The basis for the analysis were the results of laboratory tests of masonry wall made of AAC blocks and strengthened with vertical CFRP and GFRP sheets. It was decided to adapt these calculation methods, despite the fact that in many cases the authors stated that the proposed formulae only applied to the horizontal or diagonal arrangement of the reinforcement. The author's own research confirmed a significant increase in the shear force when using vertical stripes made of FRP materials.

The presented comparisons (Figs. 4 and 5) show that only one proposed calculation method – proposed by Wang et al. [13] – allowed for obtaining a high agreement between the theoretical and experimental results, both for CFRP and GFRP sheets. Good compliance was also obtained according to the Garbin et al. – Eq. (2.9) – but only for reinforcement made using GFRP strips. In the case of CFRP strips, the theoretical value was significantly overstated (about 60%) in relation to the experiment. Of course, one should be fully aware that this compliance has been demonstrated only for the analysed case and should be confirmed in subsequent research.

An interesting observation resulting from the conducted analyses was a very large difference in the obtained shear forces depending on the strengthening material. This was noted with the procedure defined by Triantafillou [2] and ACI standard [15].

A large discrepancy of other theoretical values with those obtained in the laboratory tests is probably due to the fact that most formulae are based on empirically defined values or coefficients, determined for a specific type of masonry walls (mainly ceramic units). Therefore, it is very difficult to refer them directly to strengthening the wall made of AAC blocks that are quite different in deformability than the typical masonry units.

The key issue that must be correctly defined in the calculation procedure is the reduction of maximum stresses appearing in the strengthening material at failure. The level of achieved strains (stresses) results mainly from the mode of failure of strengthened wall – delamination of FRP or tensile failure of FRP. However, it is almost impossible to classify this due to the huge variety of base material (masonry structures) and type of reinforcement available.

As can be seen from the presented analyses, the expected increase in load-bearing capacity resulting from FRP contribution should not be taken uncritical and without prior checking, even if the calculation are based on the applicable standards, because they were probably determine on strictly defined assumptions obtained from specific laboratory tests.

Acknowledgements

This publication is supported under the Rector's pro-quality grant. Silesian University of Technology, 03/060/RGJ21/1012.

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Wzmocnienia ścian z bloczków ABK materiałami FRP – analiza porównawcza i dyskusja wybranych metod obliczeniowych

Słowa kluczowe: analiza porównawcza, pionowe pasy, ściany murowane, ukośne ściskanie, wzmocnienie typu FRP

Streszczenie:

Zastosowanie materiałów FRP jako zewnętrznego zbrojenia konstrukcji murowanych jest skuteczną i mało inwazyjną metodą wzmacniania ścian. Dostępna literatura potwierdza pozytywny wpływ kompozytów układanych pasmowo, w konfiguracji poziomej, ukośnej i – jak pokazano w artykule – pionowej. Problemem jest tu właściwe oszacowanie korzyści płynących z takiego zbrojenia, a dokładniej, określenie rzeczywistego wzrostu nośności na ścinanie wzmocnionej ściany.

W artykule opisano wybrane procedury obliczeniowe dostępne w literaturze (rozwiązania autorskie), a także w opublikowanych wytycznych do projektowania wzmocnień ścian murowanych materiałami FRP. Pokrótce przedstawiono też wyniki własnych badań laboratoryjnych ścian murowanych z bloczków AAC poddanych ścinaniu, które wzmocniono pionowymi pasami z włókien węglowych i szklanych. Ostatecznie, na podstawie przedstawionych wzorów, obliczono i szczegółowo omówiono wartości teoretycznej siły ścinającej wynikającej z udziału FRP.

Porównanie doświadczalnych i teoretycznych sił ścinających wykazało, że tylko jedna z przedstawionych metod obliczeniowych pozwala na uzyskanie dobrej zgodności wyników zarówno dla pasm CFRP, jak i GFRP. Ponadto zauważono, że w dwóch przypadkach wartości siły ścinającej, w zależności od użytego materiału, znacząco się różniły, czego nie zaobserwowano w badaniach.

2022-07-15, Revised: 2022-08-18