MASONRY WALLS WITH BED JONT REINFORCEMENT – A TRIAL OF DESCRIPTION OF THE PROBLEM WITH FIRST PROPOSITION OF DESIGN METHOD

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Nowadays a large number of new types of masonry units, especially many types of vertically perforated hollow bricks and blocks are being in use. Sometimes, it is necessary to enhance the compressive strength of masonry made using such material by reason of preferred smaller thickness of the walls what is connected with building erecting costs reduction. Using of bed joint reinforcement is one of the methods of masonry properties improvement. European Masonry Code EN 1996-1-1:2005 (Eurocode 6) recommends using of steel prefabricated bed joint reinforcement. Requirements for the main four types of such reinforcement are specified in European Standard EN 845-3. In spite of that a lack of calculation methods allowing to take into the account these types of bed joint reinforcement in design practice for load-bearing capacity determination of mainly vertically compressed masonry walls is still observed. In Chapter 8 of Eurocode 6 covers only the general recommendations of bed join reinforcement using for masonry properties enhancement only based on the minimal reinforcement percentage – without possibility of calculation of the effectiveness of using them.

Author, based on the long tradition and wide experience of using in many countries of Middle-East Europe, Russia and China bed joint reinforcement in case of masonry columns, discusses the problem in relation to masonry walls. The confining effect of using such reinforcement referring to the strain state in bed joints is analysed and discussed. Additionally, the first proposition of the design method for masonry walls with some types of bed joint reinforcement (orthogonal meshwork and truss type reinforcement) is presented. Proposed analytical calculation method was compared with results of tests of masonry walls made of clay bricks, carried out at the Silesian University of Technology.

Keywords: Compression; bed joint reinforcement; state of stress; state of strain; load-bearing capacity

INTRODUCTION

In case of typical housing with wall load-bearing system, masonry walls are mainly subjected to vertical loads (death and live loads), connected with self weight of the structures and loads transmitted from other structural elements, like floors and roof structure. In this situation sometimes the total compressive forces (stresses) can attain high values. From the other side, nowadays a large number of masonry unit’s types are being in use, especially many types of vertically perforated hollow bricks and blocks, characterised by not so high compressive strength. Therefore, in order to avoid erecting buildings with thick walls and avoid higher building costs (i.e. cost of additional amount material and brickwork) it is necessary to enhance the compressive strength of masonry. One of the methods, which can be applied, is using bed joint reinforcement. In European Standard EN 845-3:2003 the recommended types
of metallic prefabricated bed joint reinforcement are specified. Unfortunately, a lack of calculation methods allowed to take into the account these bed joint reinforcement in design practice for determination of load-bearing capacity of mainly vertically compressed masonry walls is still observed. In European Masonry Standard EN 1996-1-1:2005 (Eurocode 6) taking bed joint reinforcement only based on the minimal reinforcement percentage is recommended. Unfortunately, there is not possible to calculate the effectiveness of using this type of reinforcement. As the result of such situation a low number of research works connected with this problem have been carried out. Within the last 30 years more interesting investigations were carried out by Ohler & Göpfert (1982), Hilsdorf & Haartd (1991), Floher & Hilsdorf (1982) and (1984), Ernst (1995), Dajun (1997), Vintzileou (1999) and Drobiec (2004). The results of these investigations were not unequivocal and were mainly concerned masonry columns (not walls). Generally, the positive effect of reinforcement using on load-bearing capacity was observed, but only for some types of bed joint reinforcement, mainly in form of welded or woven orthogonal meshes and circular stirrups with vertical rods (mixed reinforcement). The load-bearing capacity enhancement varied between 13% and 47% in relation to the type of masonry units and shapes of used reinforcement. Only tests carried out by Vintzileou (1999) of compressed columns built of clay hollow bricks and reinforced using steel meshes, have shown lower load-bearing capacity than in unreinforced specimens. Using of bed joint reinforcement for enhancement of load-bearing capacity on compression in case of masonry columns had a long tradition and is accepted in national standards (further and new editions still being obligatory in use) in many countries of Middle-East Europe, e.g. Poland (former masonry codes up to PN-B-3002:2007), Russia (up to last version of code SNiP II-22-81 (2000)) and China (GBJ3-88 (1988)). Author, based on tradition and wide experience using this type of reinforcement discusses the problem of confining effect of such reinforcement in connection with state of strains in bed joints and proposes the design method, which may be use in calculation of masonry walls. Proposed design formulae concern masonry walls with orthogonal and truss type steel bed joint reinforcement. This analytical calculation method was compared with tests results of masonry walls made of clay bricks, carried out at Silesian University of Technology.

SHORT DESCRIPTION OF THE METHOD SPECIFIED IN POLISH MASONRY CODE PN-B-03002:2007 FOR BED JOINT REINFORCED MASONRY COLUMNS

As it was mentioned above, design procedures for bed joint reinforced masonry columns were most incorporated in many former national standards in Middle- East European countries, as well as Russian Code SNiP II-22-81 (2000) and Chinese GBJ3-88 (1998) (see Dajun (1997)). Generally, bases of presented calculation (design) method were elaborated more than 50 years ago. The main, accepted simplifying assumptions:
- masonry is a linear-isotropic body and transmitting only compressive stresses;
- tensile stresses are transmitted only by horizontal bed joint reinforcement;
- there is fully adhesion between reinforcing steel wires and mortar;

Method specified in all former Polish Masonry Codes – including last (before introducing the Polish national version of Eurocode 6) edition PN-B-03002:2007 in this paper is presented. Generally, it is possible to calculate the load-bearing capacity of masonry columns with bed joint reinforcement in form of steel orthogonal mesh or loops – as it has shown in Figure 1. Derivation of the formula for determination of compressive strength of masonry in bed joints reinforced is based on the principal assumption, that masonry in its volume is subjected to confining effect by steel reinforcement, i.e. there is limiting the expansion in plan
perpendicular to direction of acted compressive load (in horizontal plan). This assumption became truth only when reinforcement placed into bed joints will have adequate intensity in both orthogonal directions (“x” axis and “z” axis – according to notation shown in Figure 1). Also distance (in vertical direction – axis “y”) between bed joints covering reinforcement (marked as “s” distance in Figure 1) should not be so high. Based on the national experience the maximal value of distance “s” should not exceed:
- 500 mm and smaller of the cross-section dimensions, i.e. $s \leq \min (t; b)$ – in case of masonry column made of units of 80 mm high or more;
- 300 mm – in case of masonry made of clay or Ca-Si bricks and blocks of height not exceeds 80 mm.

This design method for bed joint reinforced columns has been detailed presented and discussed in paper Drobiec & Kubica (2008). Generally, the compressive strength of such confined bed joint reinforced masonry ($f_r$), may be taken as a sum of compressive strength of unreinforced masonry in direction perpendicular to bed joints ($f_y$) and additional vertical stresses ($\Delta \sigma_y$) connected with transferring horizontal tensile stresses by bed joint reinforcement:

$$f_r = f_y + \Delta \sigma_y$$

The value of additional vertical stresses ($\Delta \sigma_y$) is determined based on the Hooks’ law and taking into consideration the equilibrium state of strains and stresses in horizontal cross-section of the column. Design value of compressive strength of axially compressed masonry columns with bed joint reinforcement as shown in Figure 1, ($f_{dr}$), (mainly made of masonry units group 1 – acc. to Eurocode 6 classification) may be calculated as the sum of design strength of unreinforced masonry ($f_d$) and component connecting with load-bearing capacity of bed joint reinforcement:

$$f_{dr} = f_d + 2 \rho_m \cdot f_{yd} \left(1 - \frac{e}{y'}\right) \leq 2f_d$$

where: $\rho_m$ – volume reinforcement ratio, $\rho_m = \frac{A_m (a_1 + a_2)}{a_1 \cdot a_2 \cdot s}$.
For columns with rectangular cross-section \((t \neq b)\), equation (2) has modified form:

\[
f_{dr} = f_d + 2 \rho_m \cdot f_{ya} \frac{(b \cdot a_2 + t \cdot a_1)}{\sqrt{(t + b)(a_1 + a_2)}} \left(1 - 2 \frac{e}{y}\right) \leq 2 f_d
\]

where \((\nu)\) is the Poisson’s ratio for masonry (usually taken as \(\nu = 0.25\)); dimensions \((t)\) and \((b)\) – as shown in Figure 1. Equation (3) may be use only in case of masonry columns whose cross-section dimensions fulfill the relationship: \(0.5 \leq b/t \leq 2\).

Presented above design method taking bed joint reinforcement into account in load-bearing capacity determination of masonry columns subjected to compressive loads by using of modified compressive strength of reinforced masonry \((f_{dr})\) is simple, sensible and useful in design practice and is still accepted in Poland, Russia and China for longer than 50 years.

**PROPOSED DESIGN METHOD FOR BED JOINT REINFORCED MASONRY WALLS**

Using of the above-mentioned and discussed formulae (2) and (3) for determination of the compressive strength \((f_{dr})\) of masonry walls with bed joint reinforcement (i.e. when length of the masonry structural element \(b\) exceeds 1.0 m or the \(0.5 \leq b/t \leq 2\) relationship is not fulfilled) is not correct. In case of masonry wall, different types of the bed joint reinforcement than shown in Figure 1, are being in us. According to requirements specified in second part of Eurocode 6 and European Standard EN 845-3:2003, in case of masonry walls, the prefabricated steel bed joint reinforcement (truss type, ladder type, woven wire meshwork or expanded metal meshwork) or orthogonal steel meshes should be use. In Figure 2 three more popular in real building practice, types of bed joint reinforcement were presented. Proposed design method in case of bed joint reinforced masonry walls is based on presented above assumptions and formulae elaborated for masonry columns and pillars between window openings. According to Hilsdorf’s model, the determination of the compressive strength of bed joint reinforced masonry walls \((f_{dr})\) should take into consideration the confining influence of bed joint reinforcement on horizontal mortar deformations. Similarly, like in case of masonry columns in masonry wall subjected to compressive forces (stresses) in vertical direction, according to Hook’s law in horizontal plan are appeared deformations and accompanied them tensile stresses \((\sigma_x)\) and \((\sigma_z)\). Integrating these stresses by unity area of the wall (by vertical cross-section) is assumed unity (per height unity) values of tensile forces \((N_x)\) and \((N_z)\). Taken the assumption that Poisson’s ratio values in horizontal plain are similarly equal \((\nu_x \approx \nu_y \approx \nu)\), tensile forces \((N_x)\) and \((N_z)\) may be expressed as:

\[
N_x = \nu \cdot \Delta \sigma_y \frac{E_y}{E_z} t \cdot s \quad \text{and} \quad N_z = \nu \cdot \Delta \sigma_y \frac{E_z}{E_y} l \cdot s
\]

**EQUATION (3)**
where \((l)\) is the length of analysed part of the wall (usually taken as 1.0 m), whereas \((E_x), (E_y),\) and \((E_z)\) – values of modulus of elasticity of masonry in directions according to individual axes – see notation given in Figure 2.

\[ N_x = F_x \quad \text{and} \quad N_z = F_z \] (4b)

In case of ladder type reinforcement (shown in Figure 2b) or rectangular steel meshwork (Figure 2c) determination of tensile capacity of the bed joint reinforcement for both horizontal
directions is easy. Situation became a little complicated in case of truss type reinforcement (see Figure 2a). In this type of reinforcement only distance between welding points (distance “b” in Figure 2a) is a constant value. It is connected with the production process of such reinforcement. As the result, for different distances between two longitudinal rods (distance “a” shown in Figure 2a) different values of inclined angle (α) are achieved.

The tensile capacity of the bed joint reinforcement for longitudinal axis “x” and transverse axis “z” (see notations given in Figure 4) can be calculated as

\[
F_x = \sum_i F_{x,i} = \sum_i n_{x,i} A_{x,i} f_{y,d,z,i} \cos \alpha_i \quad F_z = \sum_i F_{z,i} = \sum_i n_{z,i} A_{z,i} f_{y,d,z,i} \sin \alpha_i
\]

where: \((n_{x,i})\) and \((n_{z,i})\) – number of bars in corresponding axis direction; \((A_{x,i})\) and \((A_{z,i})\) – cross-section area of single reinforcing bar; \((f_{y,d,x,i})\) and \((f_{y,d,z,i})\) – yield strength of reinforcing bars steel and \((\alpha_i)\) is an angle between reinforcing bar axis and longitudinal axis of the wall (“x” axis) – see notation given in Figure 2a.

Rearranging equations (4a) and taking into account equation (4b) and relationships (5) the following formulae for additional vertical stresses \((\Delta \sigma_{y,i})\) determination is receiving:

\[
\Delta \sigma_{y,x} = \alpha_E \frac{\sum_i n_{x,i} A_{x,i} f_{y,d,x,i} \cos \alpha_i}{t \cdot s} \quad \Delta \sigma_{y,z} = \alpha_E \frac{\sum_i n_{z,i} A_{z,i} f_{y,d,z,i} \sin \alpha_i}{t \cdot s}
\]

where \((\alpha_E)\) is the elastic orthotropy coefficient, calculated as \(\alpha_E = \frac{E_y}{\nu E_{x,z}}\) and \((\nu)\) is the mean value of Poisson’s ratio for unreinforced masonry.

These formulae are valid only when the suitable adhesive between steel reinforcement and covering them mortar is guaranteed. From investigations carried out during last 20 years at the Faculty of Civil Engineering of Silesian University of Technology may be taken that in case of common joints (with thickness between 12 and 15 mm) and general purpose mortar a lack of adhesion between reinforcing steel and mortar is usually not observed. Some different behaviour was noted for bed joint reinforced masonry walls build with thin bed joints, when is necessary to use two mortar layers for good reinforcement covering. As the result of such approach the total thickness (including thickness of reinforcing steel rods and two layers of mortar covering) of thin joints is receiving between 5 and 6 mm. This problem was presented in relation to masonry walls subjected to shearing by Kubica & Kluža (2011). So high value of the joint thickness is nor compatible with Eurocode 6 requirements and is not accepted by Standardising Bodies in some European Countries. Additionally, in case of prefabricated steel truss type or ladder type reinforcement using is necessary to assure adequate strength of the welded connections between main, longitudinal rods or flat bars and jointed them together transverse or zigzag wires. Up to now, during tests carried out in different research centres no problem with these connections was recorded.

Based on the analytical analysis carried out in accordance with earlier presented for masonry columns (see equation (1)), the substitute compressive strength of bed joint reinforced masonry in wall type structures \((f_{dr})\) may be determined as a sum of compressive strength of unreinforced masonry \((f_d)\) and minor value \((\min (\Delta \sigma_{y,z}; \Delta \sigma_{y,x}))\) of additional vertical stresses connected with adequate reinforcement capacity in directions of “x” and “z” axis:

\[
f_{dr} = f_d + \min \left\{ \frac{\Delta \sigma_{y,x}}{\Delta \sigma_{y,z}} = f_d + \min \left\{ \frac{\alpha_E}{t \cdot s} \frac{\sum_i n_{x,i} A_{x,i} f_{y,d,x,i} \cos \alpha_i}{t \cdot s} \right. \right. \\
\left. \left. \frac{\alpha_E}{t \cdot s} \frac{\sum_i n_{z,i} A_{z,i} f_{y,d,z,i} \sin \alpha_i}{t \cdot s} \right. \right. \right\}
\]
In this approach it is assumed that at the ultimate state cracks can appear in typical form of vertical cracks (shown in Figure 3a) when tensile stresses exceed the reinforced masonry strength in direction parallel to plan of the wall (“x” axis) or by internal longitudinal crack – as shown in Figure 3b. This second mode of failure will appear when tensile stresses exceed the reinforced masonry strength in direction perpendicular to the wall (“z” axis). From safety point of view this failure is dangerous because crack appearance and its development for long time from outside are not visible.

![Figure 3: Two possible failure modes of vertical compressed masonry walls with bed joint reinforcement: a) – dividing of the wall by set of vertical cracks; b) – internal longitudinal crack appearance separating the wall into two leafs](image)

Taking into consideration the geometrical relations specified in Figure 2, the general formula (6) may be expressed in two main forms. In case of masonry walls with orthogonal shape bed joint reinforcement, like ladder prefabricated type (shown in Figure 2b) or steel meshwork (see Figure 2c), the compressive substitute compressive strength of bed joint reinforced masonry in wall type structures ($f_{dr}$) may be calculated as:

$$f_{dr} = f_a + \min \left\{ \frac{A_{sa,x}f_{yd,x}}{a \cdot s}, \frac{A_{sa,z}f_{yd,z}}{t \cdot s} \right\} \tag{7}$$

where ($A_{sa,x}$), ($A_{sa,z}$) and ($f_{yd,x}$), ($f_{yd,z}$) are the cross-sections area and values of yield strength of one reinforcing rod for direction of “x” axis and “z” axis, as appropriate, while ($a$),($b$),($s$) are geometrically data – specified in Figure 2.

When bed joint reinforcement has truss shape (like presented in Figure 2a) the compressive strength ($f_{dr}$) may be determined from following formula:

$$f_{dr} = f_a + \min \left\{ \frac{A_{sa,x}f_{yd,x}}{a \cdot s} + \frac{A_{sa,z}f_{yd,z}\cos \alpha}{t \cdot s}, \frac{A_{sa,x}f_{yd,x}\sin \alpha}{b \cdot s} \right\} \tag{8}$$

where ($A_{sa,x}$) and ($f_{yd,x}$) are the cross-section area and yield strength of the zigzag rod; ($t$) is the thickness of the wall. Other values as specified above and in Figure 2a.

Formulae (7) and (8) were compared with results of test carried out in Poland by Drobiec (2004). Within these investigations the influence of different types and reinforcement ratios of bed joint reinforcement on the behaviour and failure mode of in-plane loaded masonry walls was investigated. All tested specimens (masonry wallettes) were built using solid clay bricks...
and cement-lime mortar (strength class M7) and had a rectangular shape with dimensions 1415 mm × 1290 mm and were 250 mm thick. Totally, five different types of the bed joint reinforcement were tested: two unconnected longitudinal bars with diameter 6 mm, two unconnected longitudinal spiral rods with diameter 6 mm (not analysed in presented paper, because there is not typical bed joint reinforcement), woven mesh with diameter 4 mm and opening size of 40×40 mm, welded mesh with diameter 1.2 mm and opening size of 12 × 12 mm and finally truss type prefabricated bed joint reinforcement with bar diameter of 5 mm. Furthermore, two different reinforcement ratios were investigated, \( \rho = 0.05\% \) and \( \rho = 0.1\% \). As a reference, a series of unreinforced specimens were also tested. The comparison of \( (f_{dr}) \) values calculated using formulae (7) and (8) with test data and observed types of failure mode (schematically shown in Figure 3) is presenting in Table 1. Generally, analytically determined values were significantly lower than obtained from tests. Quite good correlation of tests results with valued calculated using formula (7) was observed for masonry walls reinforced using woven orthogonal meshwork, where diameter of steel rods was \( \phi = 4 \) mm, what has given the reinforcement ratio similar to \( \rho_m \approx 0.1\% \). That is reflected on that confining influence of bed joint reinforcement on deformation in horizontal directions is observed only for higher values of reinforcement ratio. Lower percentages, e.g. \( \rho_m \approx 0.05\% \) specified in Eurocode 6 in case of masonry walls mainly subjected to compressive loads practically gave not influences on improving of material properties and enhancement of load-bearing capacity of wall. Proposed formula (7) should not be use of steel welded meshwork made of small diameter rods. More test data are required for calibration of this formula. Comparison of calculated using formula (8) values of \( (f_{dr}) \) strength with test results obtained for specimens with truss type prefabricated steel bed joint reinforcement has shown significant differences (see Table 1). In such cases the confining influence of the strong longitudinal bars is enhancing the reinforcement capacity not only in axis parallel to plain of the wall, but also in direction perpendicular to the wall. As the result, the limitation of tensile strains in zigzag connecting bars is observed. By author, such phenomenon may be taking into consideration by introducing reinforcement confining factor \( (\eta_{xz}) \) determined based on the total reinforcement capacity for both directions (“x” and “z” axis) and reinforcing wires capacity in direction of “z” axis:

\[
\eta_{xz} = \frac{a \cdot t (A_{sa,xx}f_{yd,xx} \sin \alpha)}{b (t \cdot A_{sa,xfy,d,x} + a \cdot A_{sa,xx}f_{yd,xx} \cos \alpha)}
\]  

(9)

where \( (a) \) is the distance between both longitudinal bars and \( (b) \) is the length of the projection of the zigzag wire between welding points on longitudinal axis “x”, see Figure 2a. Modified formula for \( (f_{dr}) \) strength determination in the case of using truss type bed joint reinforcement can be expressed as

\[
f_{dr,MOD} = f_d + \min \left\{ \begin{array}{c}
\frac{A_{sa,xx}f_{y,d,xx} + A_{sa,xx}f_{y,d,xx} \cos \alpha}{a \cdot s} \quad \frac{t \cdot s}{A_{sa,xx}f_{yd,xx} \sin \alpha} \\
\eta_{xx} \frac{A_{sa,xfy,d,x} + a \cdot A_{sa,xx}f_{yd,xx} \cos \alpha}{b \cdot s}
\end{array} \right\}
\]  

(10)

Using such modified relationship, calculated values \( (f_{dr,MOD})^{calc} \) in case of percentage ratio \( \rho_m \approx 0.1\% \), are quite similar to obtained from tests (see two last rows in last column in Table 1). For smaller reinforcement density, the experimental results are significantly lower than calculated using equation (10).
Table 1: Comparison of calculated ($f_{calc}^{dr}$) and mean tests’ ($f_{test}^{dr}$, $f_{test}^{ur}$, $f_{calc}^{ur}$) values of compressive strength of masonry in case of walls with different typed of bed joint reinforcement in relation to compressive strength of unreinforced masonry ($f_{test}^{ur}$, $f_{calc}^{ur}$)

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<th>Observed failure mode</th>
<th>$s$ [mm]</th>
<th>$\rho_m$ [%]</th>
<th>$f_{test}^{ur,mean}$ [N/mm$^2$]</th>
<th>$f_{test}^{dr,mean}$ [N/mm$^2$]</th>
<th>$f_{calc}^{dr}$ [N/mm$^2$]</th>
<th>$f_{calc}^{ur}$ [N/mm$^2$]</th>
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SUMMARY AND CONCLUSIONS

Presented method for analytically determination of load-bearing capacity of masonry walls with bed joint reinforcement, because of still low number of available test data, is not yet good calibrated. The main problems are connected with many different types of reinforcement possible to use in case of masonry walls, as well as not so clear recognizing of their confining influence. Based on the literature review, results of presented above theoretical analysis and experimental results, the following general conclusions may be formulated:

(i) a significant lack of knowledge and design procedures for reinforced masonry walls subjected to compressive loads is observed;

(ii) proposed method was positively verified with test data for using reinforcement density not lower than $\rho_m \approx 0.1$%;

(iii) bed joint reinforced masonry walls may be calculated using proposed method, but it is necessary to make additional verification and calibration them by test data, as well as determination of maximal vertical distance of reinforced bed joints masonry, especially walls build of other than solid clay brick, masonry units;

(iv) in case of using bed joint reinforcement in form of rectangular steel meshwork, proposed method may be use only in situation when diameter of reinforcing rods in both orthogonal directions is not less than $\phi = 3$ mm;

(v) in case of too low reinforcement capacity in direction perpendicular to plan of the wall in relation to such capacity in opposite (perpendicular) direction it is possible to achieve failure mode by internal longitudinal crack – not expected from safety point of view.

REFERENCES


