MASONRY WALLS AND COLUMNS WITH BED JOINT REINFORCEMENT SUBJECTED TO VERTICAL LOADS – PROPOSITION OF DESIGN METHOD

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SUMMARY

For many years, different types of bed joint reinforcement have been in use in masonry load-bearing structures – also in case of walls and columns subjected to mainly compressive loads. Usually the positive influence of using such reinforcement on the load bearing capacity of these types of structures is accepted. Unfortunately, methods are not available to take this into consideration in design. In Eurocode 6 we can find only some detail requirements concerning the values of the minimum bed joint reinforcement for masonry structures under compressive loads where the reinforcement is provided to enhance the strength of the member.
In this paper, based on the Polish (and other East European countries) experience, the design method for vertically loaded masonry walls and columns with bed joint reinforcement is presented and discussed. The design rules and formulae are verified by test data.

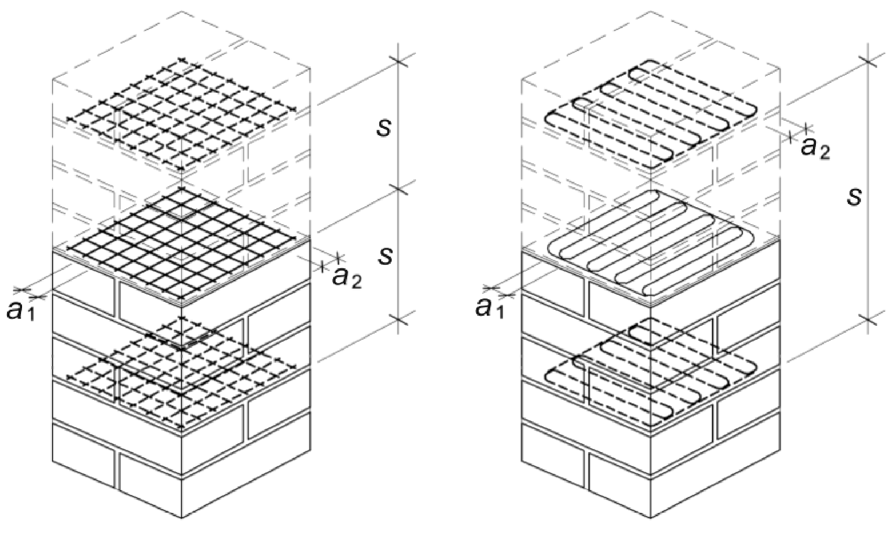
INTRODUCTION

Generally in Europe, the use of bed joint reinforcement in masonry load-bearing columns and walls subjected to compressive loads in the direction perpendicular to bed joints practically doesn't exist in design practice. As the result, a significant lack of suitable design methods and requirements are observed – even in Eurocode 6. Moreover, only a low number of research works connected with this problem have been carried out.
Within the last 20 years interesting investigations were carried out by Ohler and Göpfert 1982, Hilsdorf and Haartd 1991, Floher and Hilsdorf 1982 and 1984 or Ernst 1995 and in Greece by Vintzileou 1999. The results of these investigations were not unequivocal. The positive effect of reinforcement on load-bearing capacity was observed, but only for some types of bed joint reinforcement, mainly in form of welded or woven meshes and circular stirrups. The load bearing capacity enhancement varied between 13% and 24% in relation to the type of masonry units in Ohler 1982 tests to 30% – 47% for masonry columns reinforced in bed joints by steel meshes and built of clay hollow blocks, calcium-silica blocks and light aggregate concrete blocks - Floher and Hilsdorf 1982 and 1984.
Quite different results were obtained by Vintzileou 1999 in tests of compressed masonry columns built of clay hollow bricks and reinforced by steel meshes. In these investigations all reinforced specimens were characterised by lower load-bearing capacity than in unreinforced specimens.

Wider investigations of masonry walls build of 6 types of masonry units and 8 types of bed joint reinforcement were carried out by Floher and Hilsdorf 1982 and 1984. These were very extensive investigations. Much more positive influence (up to 20%) of using of mesh type reinforcement than truss type was observed. Also Ernst 1995 was tested 13 masonry wall specimens built of clay hollow blocks (5 unreinforced; 3 with infilled vertical voids; 3 with bed joint reinforced and 2 with bed joint and additional vertical reinforcement). Masonry walls with infilled vertical voids had 15%-20% greater load-bearing capacity that unreinforced. Elements with bed joint reinforcement had a similar capacity enhancement. Introducing vertical reinforcement involved ca. 50% growth of ultimate load.
One of the wider investigations of behaviour and load bearing capacity of bed joint reinforced masonry walls was carried out in Poland by Drobiec 2004. In this investigation, 45 tested specimens (masonry wallettes), built with solid clay bricks and 5 types of bed joint reinforcement (longitudinal rods, spiral rods, welded and woven meshes) were tested. The influence of the use of two reinforcing bars not connected to each other gave a negative influence on behaviour and load resistance, but with mesh type reinforcement and prefabricated truss type bed joint reinforcement – the influence was positive. The load capacity was ca. 25% to 40% higher than for unreinforced reference elements.
As it was shown above, generally the use of bed joint reinforcement has a positive influence on behaviour and load-bearing capacity of masonry structures under compression. Therefore it is sensible to make use of that fact in design practice, but how to do that?

DESIGN METHOD

A certain method can be adopted from the Polish masonry code PN-B-03002:2007, which incorporated the design procedure of such reinforced masonry structures from the Russian (earlier Soviet) building code SNiP II-22-81 2000. This method has a long history and has been in use in Central European countries since the first half of last century. Generally, it is used to calculate the load-bearing capacity of masonry columns and walls with bed joint reinforcement in form of mesh or loop – as shown in Fig.1.



a) mesh type reinforcement b) loop type reinforcement
Figure 1. Masonry columns with bed joint reinforcement (according to PN-B-03002:2007)

According to the method, the load-bearing capacity (at Ultimate Limit State) in cross-section (i) of the masonry column or wall can be determined using the following general formula:

$$N_{Sd,i} \leq N_{Rd,i} = \phi_i \cdot A_i \cdot f_{dr} \qquad (1)$$

where:
- $N_{Sd,i}$ – design, vertical compressive force in analysed cross-section;
- $N_{Rd,i}$ – load-bearing capacity in analysed cross-section;
- ϕ_i – load-bearing capacity reduction factor;
- A_i – cross-sectional area of calculated column or part of the wall;
- f_{dr} – design value of masonry with bed joint reinforcement.

The design value of compressive strength of masonry with bed joint reinforcement (f_{dr}) of axially compressed masonry columns (made of masonry units group 1 – according to Eurocode 6 classification) is given as:

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

where:
- ρ_m – reinforcing ratio determined as proportion of reinforcement to masonry volume; $\rho_m = \frac{A_{sa}(a_1 + a_2)}{a_1 \cdot a_2 \cdot s}$;
- A_{sa} – cross-sectional area of one wire of mesh or loop;
- a_1, a_2 – dimensions of mesh holes or loops; measured in axis (as in Fig.1);
- s – vertical spacing between bed joints with reinforcement (Fig.1a); in case of loop type of reinforcement (Fig.1b) – distance between bed joints with this same direction of the reinforcement;
- f_{yd} – design value of tensile strength of the reinforcing steel;
- e – design value of total eccentricity;
- y – distance between centre of area of masonry cross-section and the more compressed edge of the section.

Formula (1) is valid in the design of load capacity of masonry columns. But how should it be modified for calculation of masonry walls with bed joint reinforcement?

To give an answer to the question, a suitable analysis of the internal stress distribution in a compressed element is necessary. It is assumed that under acting vertical forces **N** masonry element has displacement in vertical direction ε_y, and in the horizontal direction deformations of the edges in relation to mid point of the cross-section are ε_x and ε_z. These both horizontal displacements are associated with normal tensile stresses in the reinforcement σ_x and σ_z – see scheme shown in Fig.2.
Bases of presented calculation (design) method were elaborated more than 50 years ago. The main simplifying assumption is acceptance that:

- masonry is an linear-isotropic body and transmitting only compressive stresses;
- tensile stresses are transmitted by horizontal bed joint reinforcement.

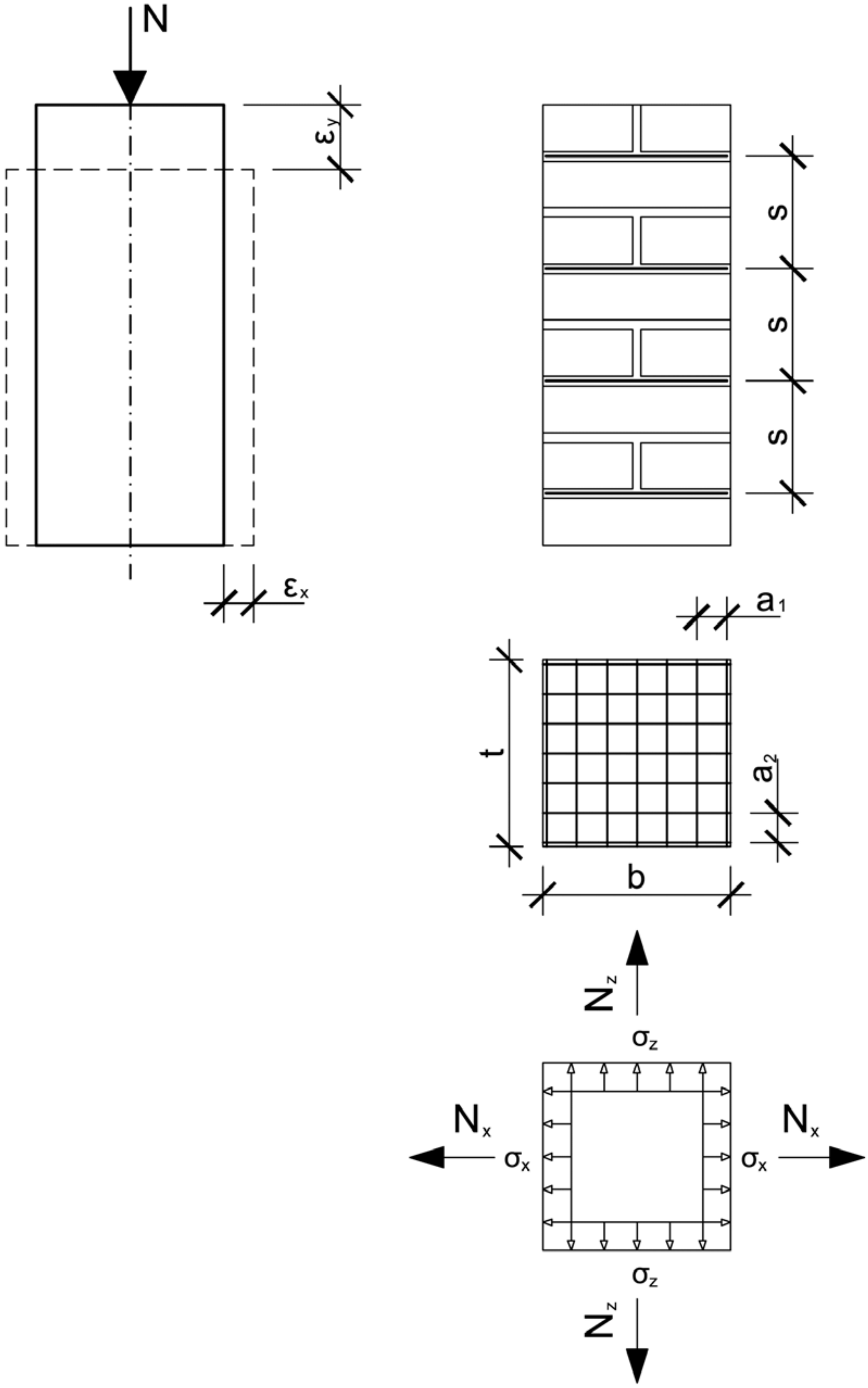


Figure 2. Scheme of horizontal forces and stresses

In simply elastic analysis, the horizontal forces at each level of reinforcement can be determined as:

$$N_x = \sigma_x \cdot t \cdot s \;; \qquad N_z = \sigma_z \cdot b \cdot s \tag{3}$$

The total horizontal force is

$$(N_x + N_z) = (\sigma_x \cdot t \cdot s + \sigma_z \cdot b \cdot s) = \left(\nu_x \cdot \frac{\sigma_y}{E_y} \cdot E_x \cdot t + \nu_z \cdot \frac{\sigma_y}{E_y} \cdot E_z \cdot b \right) s \tag{4a}$$

where: σ_y – vertical normal stress;

σ_x, σ_z – horizontal stresses in both orthogonal directions (X and Z);

ν_x, ν_z – Poisson's ratio in both orthogonal directions (X and Z);

E_x, E_z, E_y – modulus of elasticity for three directions.

For isotropic body ($E_x = E_z = E_y$ and $\nu_x = \nu_z = \nu_y = \nu$) the total horizontal force is

$$(N_x + N_z) = (\sigma_x \cdot t \cdot s + \sigma_z \cdot b \cdot s) = \nu \sigma_y (t + b) s \tag{4b}$$

The maximum force transmitted by reinforcement (F_A) may be calculated as

$$F_A = A_{sa} \left(\frac{b}{a_1} + \frac{t}{a_2} \right) f_{yd} \tag{5}$$

where: A_{sa} – cross-sectional area of one wire of the mesh.

Taking that the total horizontal force should be transmitted by reinforcement and for (4b) = (5) is obtained:

$$\nu \sigma_y (t + b) s = A_{sa} \left(\frac{b}{a_1} + \frac{t}{a_2} \right) f_{yd} \tag{6}$$

After conversion of equation (6) the vertical (perpendicular to bed joints) normal stress (σ_y) can be determine as:

$$\sigma_y = \frac{A_{sa} \left(\frac{b}{a_1} + \frac{t}{a_2} \right) f_{yd}}{\nu (t + b) s} = \frac{A_{sa} (b a_2 + t a_1) f_{yd}}{a_1 a_2 \nu (t + b) s} \tag{7}$$

and taking that reinforcement density (ρ_m) is equal to the proportion of the reinforcement volume (V_r) to volume of masonry (V_m):

$$\rho_m = \frac{V_r}{V_m} = \frac{A_{sa} (a_1 + a_2)}{a_1 a_2 s} \tag{8}$$

the normal stress (σ_y) is represented by the following formula:

$$\sigma_y = \rho_m f_{yd} \frac{(ba_2 + ta_1)}{\nu((t+b)(a_1 + a_2))} \tag{9}$$

In case of rectangular square cross-section of masonry column (b = t) and taking Poisson's ratio $\nu = 0.25$ (as for an isotropic material) the growth of compressive vertical normal stresses (σ_y) may be determined as:

$$\sigma_y = 2\rho_m f_{yd} \tag{10}$$

then the compressive strength of masonry with bed joints (f_{dr}) can be calculated as

$$f_{dr} = f_d + 2\rho_m \cdot f_{yd} \tag{11}$$

In all Polish masonry codes (since 1955) such formula was incorporated and being in use in design practice. Taking into account the influence of the eccentricity on strength of bed joint reinforced masonry, the finally version of formula (11) as given in (2) is obtained. Moreover, is taken, that such determined strength (f_{dr}) should not exceed $2f_d$ (double compressive strength of unreinforced masonry).

Formula (2) concerns determination of compressive strength of bed joint reinforced masonry in case of rectangular cross-section where b = t. For masonry walls (when $b \neq t$) is also possible to use (f_{dr}) determined from equation (2) but modified as follow:

$$f_{dr} = f_d + 2\rho_m \cdot f_{yd} \frac{(b \cdot a_2 + t \cdot a_2)}{\nu((t+b)(a_1 + a_2))}\left(1 - 2\frac{e}{y}\right) \le 2f_d \tag{12}$$

COMPARISON OF COMPRESSIVE STRENGTH OF BED JOINT REINFORCED MASONRY WITH TEST DATA

The comparison of the f_{dr}/f_d ratio where f_{dr} is calculated from equation (2) or (12) with test data (taken from Haardt and Hilsdorf 1999, Ohler and Göpfert 1982, Ernst 1995[1] and 1995[2], Vintzileou 1999, Adamski 1949, Dajun 1997, Kreüger 1918, Withey 1934 and Xingzhi and Chuxian 1982) for different values of reinforcement density ρ in case of masonry columns is shown in Fig.3, but for walls (tests carried out by Drobiec 2004, Flohrer and Hilsdorf 1982 and 1984) – in Fig.4.

It is easy to notice, that calculated values of f_{dr} are quite safe, especially for reinforcement ratio lower than 0.6% and without usage of reinforcement as two bars not connected to each other (see Fig.3). In case of masonry walls with bed joint reinforcement the number of available data is still small, but it appears from Fig.3 & 4 that higher values of reinforcement density ρ (over 0.4%) have little effect on compressive strength.

For masonry walls, the comparison of the calculated load-bearing capacity enhancement (using formula (10)) in relation to different types of steel (three different yield points) with some available test data is shown in Fig.5.

In tests carried out by Drobiec 2004 masonry specimens were made of clay solid bricks and cement-lime mortar, whereas in Floher and Hilsdorf 1982 and 1984 investigations were built

of calcium-silica masonry units and cement or cement-lime mortar. In this figure, only the results for masonry walls reinforced by reinforcement compatible with EN 845:2003 regulations are presented.

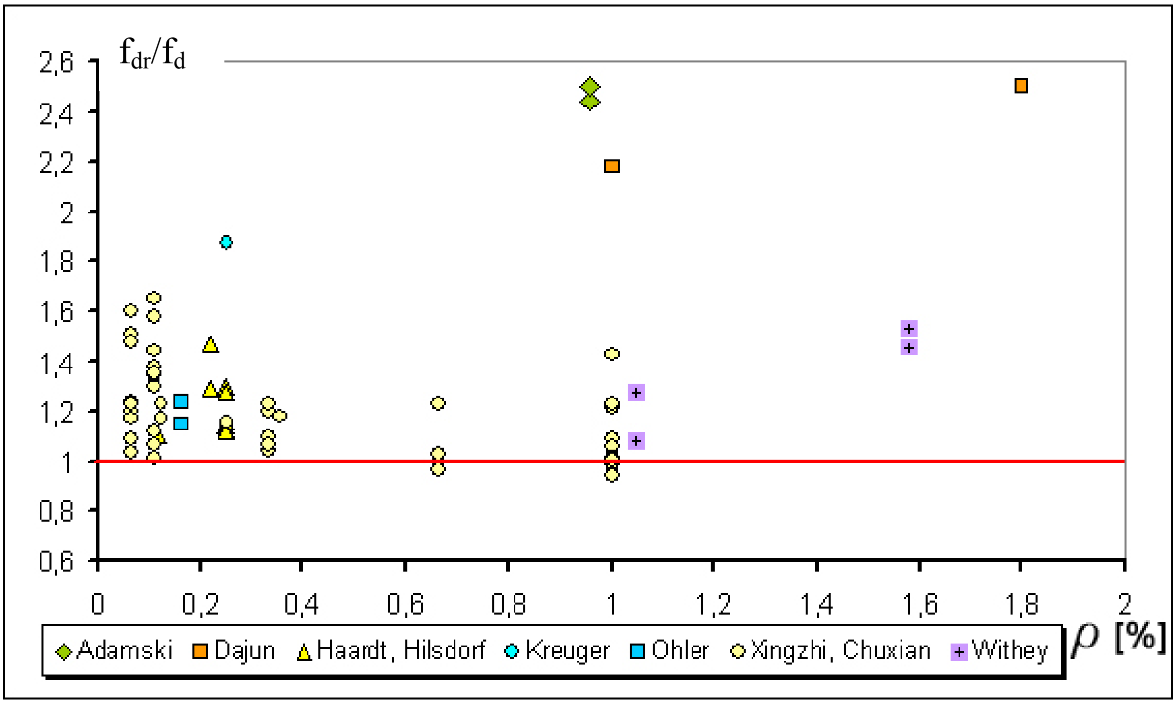


Figure 3. The comparison of the f_{dr}/f_d ratio with test data for different reinforcement density ρ for masonry columns

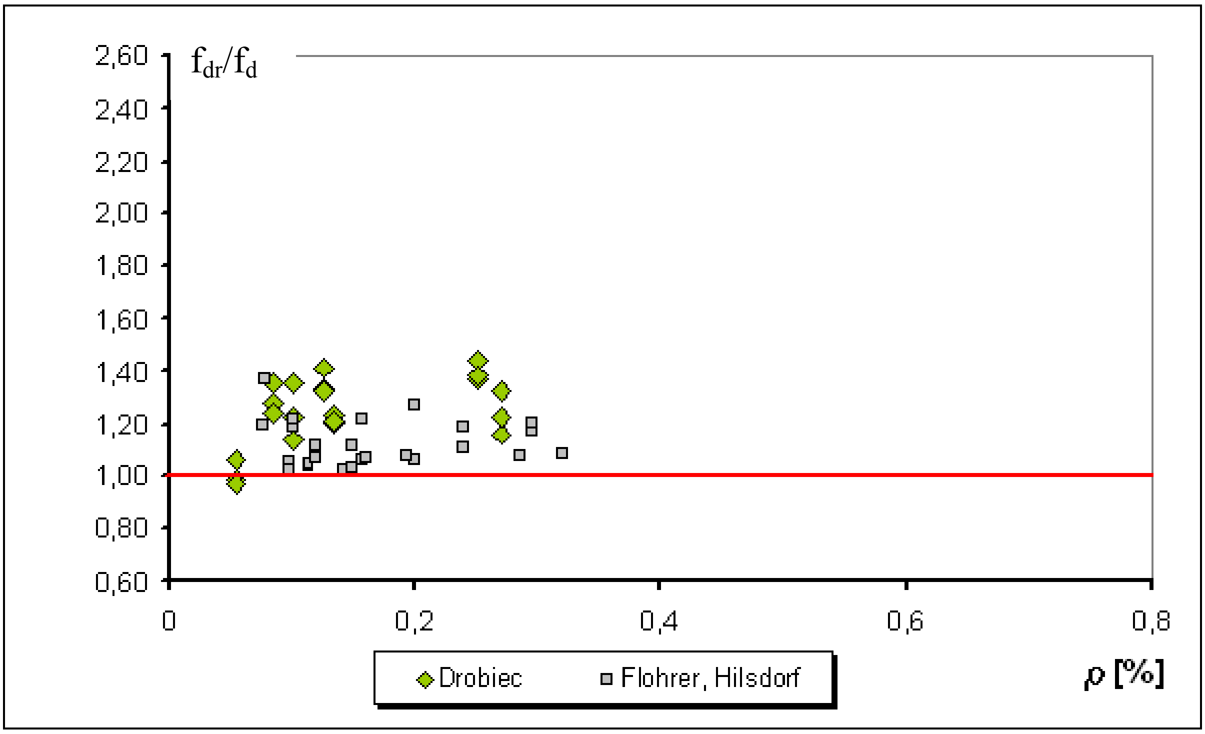


Figure 4. The comparison of the f_{dr}/f_d ratio with test data for different reinforcement density ρ for masonry walls

According to carried out by Drobiec 2004 tests of masonry wallettes reinforced by two longitudinal steel rods with diameter ϕ6mm and truss type prefabricated reinforcement in any case at failure steel was not yield in main longitudinal rods with diameter ϕ6mm. Only in zigzag wires (with diameter ϕ3.7mm) the lateral strains were larger and steel was yield.

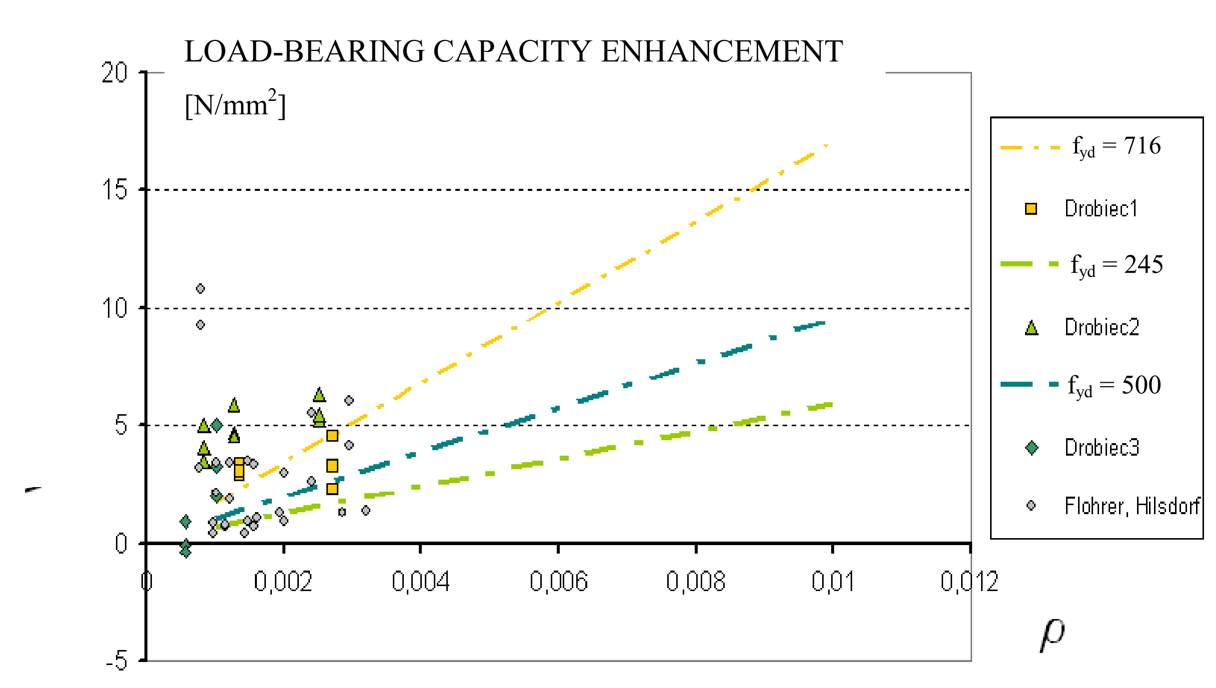


Figure 5. The comparison with test data the load-bearing capacity enhancement calculated using formula (10) in relation to different types of steel

It is very easy to notice, that in case of steel with very high mechanical parameters (yield point over 500 N/mm^2) the theoretically calculated load-bearing capacity is greater than test values. Such situation is dangerous from design point of view because there is no capacity reserve in construction – failure can be occur by exceeding the compressive stresses in masonry and steel will not yield. Therefore, according to presented investigations, especially carried out by Drobiec 2004, the necessity of steel parameters limitation is apparent.

The problem concerns only the level of such limitation. For example, in Chinese standard GBJ3-88, where these method of f_{dr} calculation is also incorporated, the values of the yield point for the steel of bed joint reinforcement should not exceed $f_{yd} \leq 320$ N/mm^2. Based on analysed test data, this limitation is completely well-grounded.

SUMMARY AND CONCLUSIONS

Presented simple method taking bed joint reinforcement into account in load-bearing capacity determination of masonry columns and walls subjected to compressive loads by use of modified compressive strength of masonry may be sensible and useful in design practice.

Practically, in quite similar form this method is in use in Polish and some other Central European and other (e.g. in China) countries. Long (over 50 years) period of their usage – without any known problems – is quite convincing argument for more wide dissemination. Of course, there is necessary to specify all conditions and requirements for safe usage of presented design method.

Based on all analysis and comments presented above, the following conclusions can be formulated:

1. Proposed method taking into account of bed joint reinforcement in determination load-bearing capacity of subjected to compressive loads masonry columns and walls by using of modified compressive strength of masonry is safe from Ultimate Limit State analysis and may be use in design practice.
2. Described above calculation procedure may be use in design of masonry columns and walls made of masonry units group 1 (according to Eurocode 6 classification) with general purpose mortar.
3. Bed joint reinforcement should be in form of steel welded or woven mesh or loop type (like shown in Fig.1b). Use of other types of bed joint reinforcement and types of joints (e.g. thin bed joints) is for the time being not possible.
4. It could be accepted that presented method is recommended only for reinforcement steel with yield point not exceeded 350 N/mm^2.
5. More universal usage of proposed procedure required further both theoretical and experimental investigations.

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