MODERN BUILDING
MATERIALS, STRUCTURES
AND TECHNIQUES

http://www.vgtu.lt/en/editions/proceedings

May 19–21, 2010, Vilnius, Lithuania
The 10th International Conference

Faculty of Civil Engineering
Vilnius Gediminas Technical University
Saulėtekio ave. 11, LT-10223 Vilnius, Lithuania
Phone +370 5 2745243, Fax +370 5 2745016
E-mail: *statkon@vgtu.lt*

IMPACT OF MOISTER-TEMPERATURE ACTIONS ON CHARACTER OF BEHAVIOUR OF EXTERNAL LAYERS OF LAYERED WALLS WITH FLEXIBLE TIES

Bronius Jonaitis[1], Gediminas Marčiukaitis[2], Juozas Valivonis[3]

Vilnius Gediminas Technical University, Saulėtekio ave. 11, LT-10223 Vilnius, Lithuania
E-mail: [1]broniusjonait@gmail.com; [2]gelz@vgtu.lt; [3]juozas.valivonis@vgtu.lt

Abstract. The article discusses influence of flexural ties on behaviour of external finishing-protective layer under the action of temperature-moisture movements. Forces and their distribution calculation results according to the finite element method in the external layer subjected to the action of temperature and moisture are presented. It is determined by investigations that even flexible ties restrain deformations imposed by temperature and shrinkage herewith tensile stress in the layer capable to cause its cracking.

Keywords: layered wall, temperature moister deformations (movements), flexible ties, restrain.

1. Introduction

Layered walls are used in many buildings since such structure gives opportunity to make it of desired operational properties. Purpose of the external layer of a wall with the thermal insulating layer is to protect the later from various external actions. Often the internal layer is solid, i. e., made of one type material, while the external layer may be of several different layers connected with various ties: adhesion bond or mechanical ones. Structural solutions of external layers connected with the internal layer by the flexural ties in the most cases are as shown below (Fig 1).

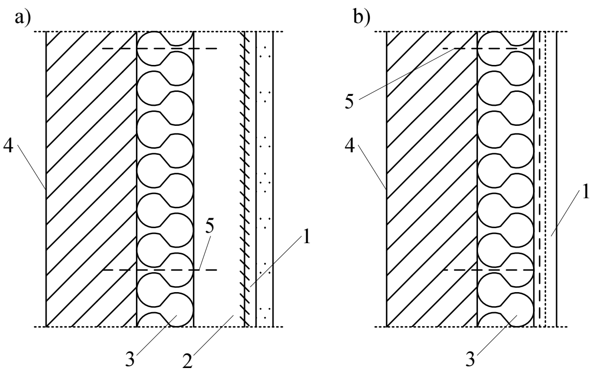

Fig 1. Structural diagrams of walls with flexible ties: with finishing layer (a) and with thin-layer plaster (b), 1 – external layered plaster cover; 2 – stiff external layer with finishing plaster coating; 3 – thermal insulating layer; 4 – internal bearing layer; 5 – flexible ties

In the case of flexible ties vertical loads usually are transmitted directly to the internal (4) bearing layers (Fig 1). Our investigations show (Marčiukaitis 1999) that due to the flexible ties actions caused by temperature, moisture and horizontal loads may be transmitted from a layer to the other one. The flexible ties joint the external layers together for their joint action increasing their stiffness. Wall stiffness in this case depends on the stiffness of the external layers, on number and distribution of the flexible ties.

As mentioned above, solutions of layered walls can be various (Fig 1), in one case the external protective – finishing layer (2) may be made of materials with different properties: masonry or concrete, finishing layer – plaster (1) and paint, the later can be up to 1 mm in thickness (Fig 1 a), in another case – the external finishing plaster layer (1) is directly placed on the thermal insulation layer (polystyrene or rock wool plates). In this case on the thermal layer (3) 7–10 mm thick primer, then about 10 mm thick of special mortar levelling layer and finishing 4–7 mm thick cement mortar layer are placed. The finishing layer may be mortar of special composition and colour or it may be painted. All said layers are made of different materials in their origin, composition and structure; therefore they are of different physical and mechanical properties which affect interaction of these layers. Construction type of walls is selected with regards to an array of economical aspects (Zavadskas *et al.* 2008).

Our investigations (Marčiukaitis 1999, 2001, 2000) indicate that external actions – temperature and moisture – affect greatly state and appearance of building external walls. Finishing layer surface colour influence greatly the percipience of sun radiation and therefore the surface may heat up to quite high temperature. Frequently it induces various defects – spallling, cracking. Investigations indicate that in the wall of one colour these defects are less than in the wall of another colour. Al this is due to deformations induced by sun radiation and moisture.

Observations show that character and size of deteriorations depend on structural solution of external layer of layered masonry walls. Stiffness of external layer made of masonry units and plaster (Fig 1 a) is substantially higher than that of external layer made of polystyrene and plaster layer (Fig 1 b). In the first case deformation properties of plaster and that of layer from masonry units are different and therefore temperature – moisture induced deformations in the layers are restrained. In the second case elasticity modulus of thermal insulation layer (polystyrene) is substantial less than mortar elasticity modulus and therefore deformations of plaster are less restrained than in the first case. Investigations point out that apparently visible defects, as cracking, in the main external layers are more numerous in „a" type (Fig 1 a) structures than that in the „b" type (Fig 1 b). This difference can be explained by the difference in elasticity moduli of interfacing layers.

Nevertheless in practical design and analysis of layered wall these actions mostly are not taken in to account. Distances between movement joints in layered masonry external facing layer made of masonry units are taken of the same value as in a solid wall of defined length without allowance for the affect of ties for general behaviour (during deformation) when deformational properties of layers differ.

In the code for design of masonry structures STR 2.05.09:2005 Technical Regulation for Construction. Design of Masonry Structures and Eurocode 6, it is indicated that in load bearing masonry walls temperature and shrinkage movement joints have to be installed in places where concentration of said movements is possible leading to excessive masonry cracking. Distance between said joints, as a rule, shall be selected by calculation. Additionally, the maximum distances between movement joints allowed without calculation for unreinforced external walls are specified. There are no additional requirements for installation of the said movement joints in facing layers. It is stated in many cases that deformations of the external layers are restrained by stiff ties only while the flexible ties allow free deformations of the layers in both horizontal and vertical directions. But as investigations (Marčiukaitis 1999) show such approach is not correct since external layer deformations mostly are more or less restrained depending on type and stiffness of the ties (Peters 2005).

In practice numerous cases are met when vertical, sometimes and horizontal, cracks appear in relatively stiff external layers at distances not specified in the design code.

2. General stress and strain analysis in external layers of walls due to changes in temperature and moisture

Distribution of stress and strain between external wall layers in the cross-section due to temperature and moisture depends on stiffness of ties between the layers and material properties and on duration of action as well. When the change in moisture and temperature is sudden distribution along the thickness is not even, when action time is longer – even (continuous). In the first case greater strain difference in the external layer is obtained which may induce external layer surface cracking. Strain and stress distribution according to the depth of a layered wall with rigid ties or of its external layer can be calculated using method proposed by us (Marčiukaitis 1999, 2001). According to this method when deformation of layers due to moister and temperature are known, assuming that ties between layers (brick or block headers, adhesion of mortar with putty and paint) and all deformations in interfacing plane are equal, from conditions of equilibrium of all forces acting in the separate layers, bending moments and axial forces in layers are found. When moments and axial forces are known stress is calculated:

$$\sigma_i = \frac{M \cdot y_i \cdot E_i}{D} \pm \frac{N_i}{A_m} . \qquad (1)$$

Stiffness D of the layered cross-section:

$$D = \sum_{i=1}^{n} E_i I_i \ , \qquad (2)$$

here n – number of layers; $E_i I_i$ – material elasticity modulus and the second moment of area of the layer i cross-section, M_y and N_i – acting forces, bending moment and axial force respectively, A_m – external layer cross-section area.

Often shape of a building wall in the plan is nonlinear, some its lengths are long and ratio of EI/l is substantially less than it of the others intersecting walls (Fig 2).

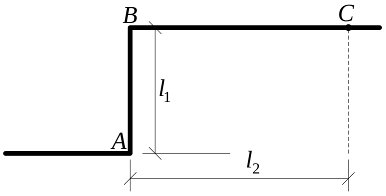

Fig 2. Diagram of facade external layer horizontal section

It is accepted that walls and foundation are rigidly joined then displacement between wall and foundation does not take place. Therefore, value of expansion deformations due to moister and temperature varies from zero (at the level of the contact with foundation) up to the maximum value (at a particular height). This change in all directions of the wall is different and depends on many factors that will be analysed in next section.

For approximate determination of developed forced and their distribution along the walls a wall section ABC is taken (Fig 2). Since the wall in BC direction is substantially longer than that of AB then it is accepted that the wall is built in at the point A and at the point C does not deflects. Then such conditional diagram is obtained (Fig 3).

If linear member is assumed then its deformations due to temperature and moister is

$$\varepsilon_{\Theta} = \varepsilon_T + \varepsilon_{sh} = \alpha_T \Delta T + \varepsilon_{sh} \, , \tag{3}$$

here α_T – coefficient of thermal expansion; ε_{sh} – moisture deformations.

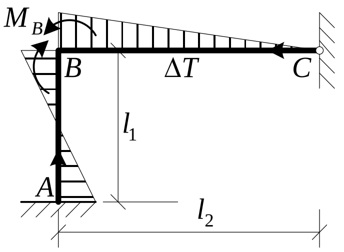

Fig 3. Diagram of presumable distribution of forces in external layers of walls due to temperature and moister movements

Stress imposed by restrained change is

$$\sigma_{\Theta} = \left(\alpha_T \Delta T + \varepsilon_{sh} \right) E_{cm} \, . \tag{4}$$

But such stress state is obtained when external layer of the wall in horizontal plane is broken in shape. As it is shown in Fig 3, not only axial forces but and bending moment are obtained as well. Cracking depends mostly on bending moments and it is easy to prove that their maximum values are at the intersections of the walls. Using classical conditions of structural analysis and assuming that cross-sections and material of all external layers are the same, the maximum moments act at points A and B and can be determined by formulae:

$$M_A = \frac{3}{2} EI \left[\frac{1}{l_1 \left(n + 0.75 \right)} \left(\frac{1}{n} + 3n + n^2 \right) \right] \varepsilon_{\Theta} \, , \tag{5}$$

$$M_B = \frac{3}{2} EI \left[\left(3n^2 + 1 \right) \left(\frac{1}{n^2 + 0.75n} \right) \right] \varepsilon_{\Theta} \, , \tag{6}$$

here n – the ratio of lengths of intersecting external layers of walls, i. e. $l_2 = nl_1$; Θ – change in temperature and moisture deformations determined by formula 4.

But at particular ratio of EI/l the external layer of the wall may curve and bending moment due to elongation caused by temperature can even change its direction. Additionally, in the case of flexible ties transition of external layer displacement to another layer is possible, i. e. restraint of displacements takes place. It is demonstrated by some our investigations (Marčiukaitis 1999, 2000). Considering that the wall deforms not in one but in three directions: x – horizontal (along the wall) direction; y – transverse direction and z – vertical one, the said diagram for determination of forces does not reflect complete deformation character. With reference to theoretical investigations in stability of plates (shells) (Bhatt 1999; Gambhir 2004; Godoy 2000) the maximum moments may act not at intersection point of bars.

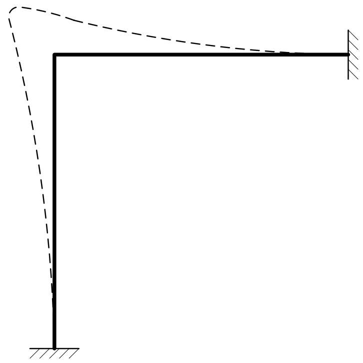

Fig 4. Possible distribution of deformations in external layers of walls due to temperature-moisture actions

Diagram of deformation distribution in external layers (Fig 4) shows that moment at the edge of a wall or further from it may produce deformations greater than allowed ones. In relation to moment value and cross-section stiffness deformation is

$$\varepsilon_{\Theta} = \frac{M \cdot t}{2D} \, , \tag{7}$$

here $D = IE$ – external layer of a wall stiffness; t – layer thickness.

Deformation diagram (Fig 4) and investigations indicate that the maximum moment may be located at some distance from the intersection point. In this case ties between the external layer and the main load bearing layer (Fig 5) may have substantial influence. Free expansion of external layers elongating due to temperature is impeded by tension ties since the main layer almost does not elongate. These forces in the ties distort deformation of the external layer.

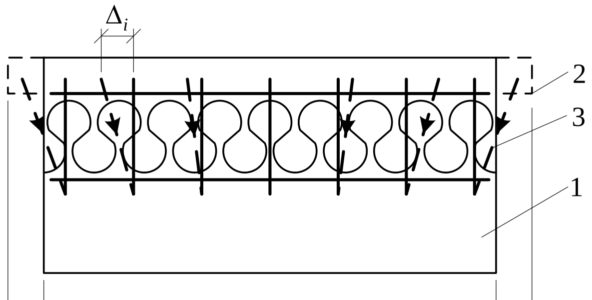

Fig 5. Influence of flexible ties on redistribution of forcer between ties: 1 – load bearing (stiff) layer; 2 – external layer; 3 – flexible ties

The closer to the end of the wall the greater forces in ties develop and the change in bending moment value is sharper. Practical observations show that in the walls of similar structure vertical cracks appear near the corners of the walls.

3. Numerical modelling of state for external layers of walls

For more accurate stress-strain state evaluation for external layer of layered wall subjected to the action of temperature – moisture movements an analytic investigation was performed, i. e. forces were calculated and their distribution determined.

Stress – strain state analysis for facing layer of layered wall subjected to the action of temperature and shrinkage deformations was made using numerical modelling.

The goal of analysis – investigation in influence of flexible ties on stress-strain state of the facing layer subjected to the action of temperature and moisture.

For investigation a solid (continuous) finite element of slab was used assuming masonry deformation characteristics – elasticity modulus $E = 2.4\times10^4$ N/mm^2 ($0.8E_{cm}$), Poisson's ratio ($\nu = 0.25$). Diagram for analysis is presented in Fig 6.

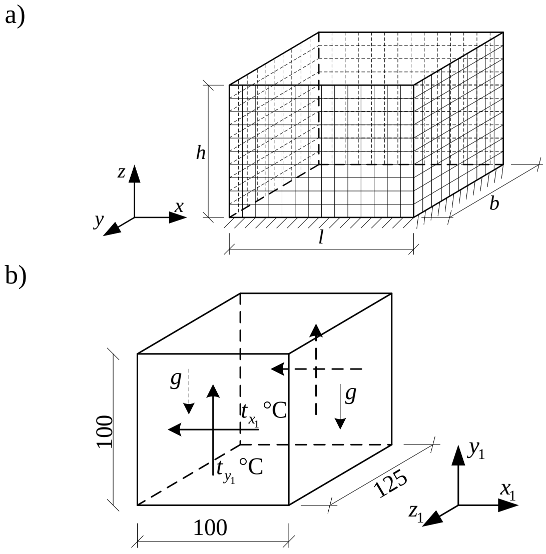

Fig 6. Diagram for analysis: layout of external facing layer of walls for a building (a), finite element measurements and loading diagram (b)

Stress – strain state of an external wall facing layer comprising a closed contour of height $h = 3$ m, width $b = 4$ m, length $l = 6$; 9; 12; 18 and 24 m respectively.

Making model for analysis it was assumed that facing layers are supported on foundation. At the level of foundation displacements of joints are restrained in directions of local axes x_1, y_1 and z_1. The facing layer of the wall is joined by flexible ties (5 mm in diameter) with the internal load bearing layer. Number of flexible ties was assumed 4 pieces per one square meter and they were distributed in chequered way. Actions taken in to account: facing layer self weight and temperature – moisture deformations. Temperature – moisture action is estimated by subjecting finite elements to equivalent temperature assuming that facing layer is heated from both sided equally, i. e. $t_{1x1} = t_{2x1}$ ir $t_{1y1} = t_{2y1}$. In analysis of stress – strain state temperature difference winter–summer was taken, i. e. $t_{1x1} = t_{2x1} = t_{1y1} = t_{2y1} = \Delta t$.

Design difference of mean temperatures Δt during service life of buildings for the external layer can be assumed according to well – known formulae:

$$\Delta t = 0.5\left(t_{m,s,\min} - t_{m,s,\max}\right) - A_w - t_c\,, \tag{8}$$

here $t_{m,s,\min}$ and $t_{m,s,\max}$ – the minimum (January) and the maximum (July) (or these of the coldest and the hottest day) temperatures respectively; A_w – equivalent temperature of sorption moisture (at varying relative moisture); t_c – shrinkage of structure.

Plane stress state problem is solved. Since the moisture – temperature action causes relatively not great stress and in this case plastic deformations in masonry do not appear, the problem is solved assuming that masonry behaves elastically, i. e. linear – elastic analysis is performed.

Software bundle „LIRA“ was used for stress calculation and their distribution determination.

Forces in finite elements and displacements of finite element joints were calculated.

4. Numerical modelling results and their analysis

Character of deformations in the horizontal direction (out-of-plane) of wall external layer in a separate top strip of a rectangular in plan building, and herewith distribution of moments acting in the same direction were verified in the first place. Deformation distribution (Figs 7 and 8) shows clearly that the maximum bending moments act near to the wall corners. Analysis of these results indicates that distribution of forces is substantially affected by the flexible ties. It proves assumptions used (Figs 3 and 4).

Comparison of force and deformation distributions shown in Figs 7 and 8 indicates that with receding from the middle length of the wall layer engagement of the ties in the common action increases (Figs 5 and 7b) and herewith not being able to deform freely, bending moments in the layer grow and the general character of deformation changes. It is visually demonstrated in Figs 7 and 8 by deformation distribution character and comparison of curves for cases when there are no flexible ties between the layers (a) and when there are ties (b).

External wall layers are perpendicular to each other and rigidly joined to foundation and therefore hinder each other from free deformation both along the length of the wall and along its height. Deformation character and herewith stress state are affected by the flexible ties as well. It is pointed out by deformation character in all directions of all walls for a building of (6×6 m) in plan and 3 m high shown in Fig 8.

External layer state was analysed for buildings of various rectangular plans: 6×6; 6×9; 6×12; 6×18; 6×24 m. All were 3 m high. Obtained result revealed that the bending moments at the top of the layer vary almost similarly irrespective to the ratio of the wall lengths. It is also demonstrated and by graphs of relationships between moments M_y and l_2 in Fig 9. They almost coincide for any ratio of wall lengths.

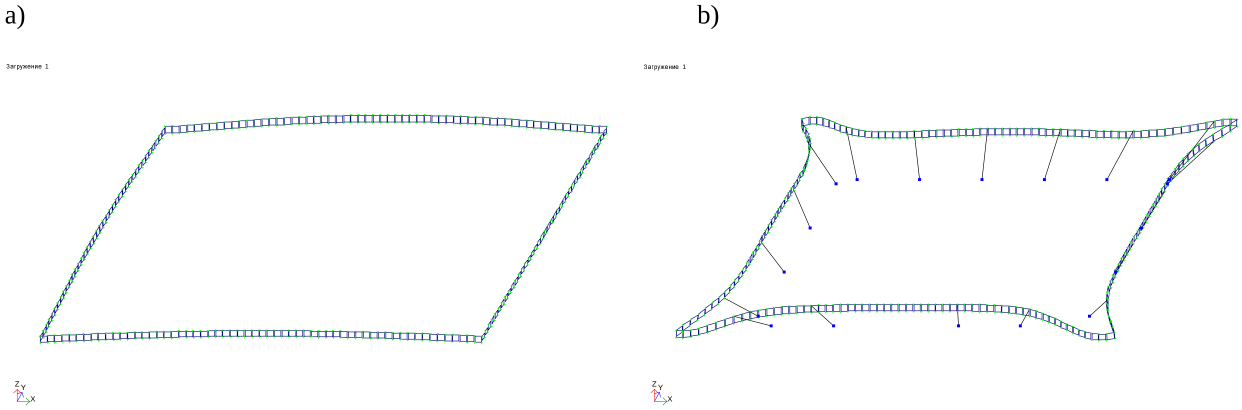

Fig 7. External layer horizontal deformations in the top strip of a wall:
a – when there is no flexible ties between the layers and b – when there are ties

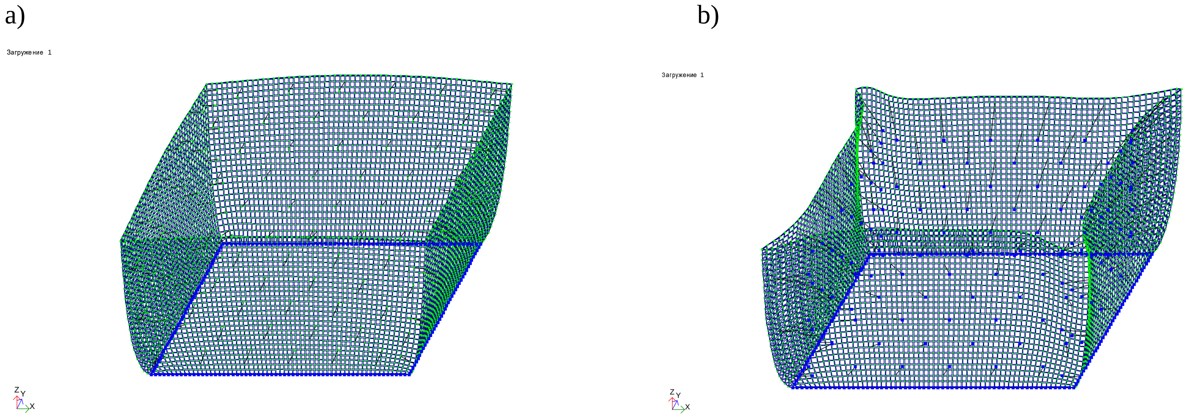

Fig 8. General character of horizontal deformation distribution in external layer of walls
for a building of 4.0×6.0×3.0 m: a – when there is no ties between the layers and b – when there are ties

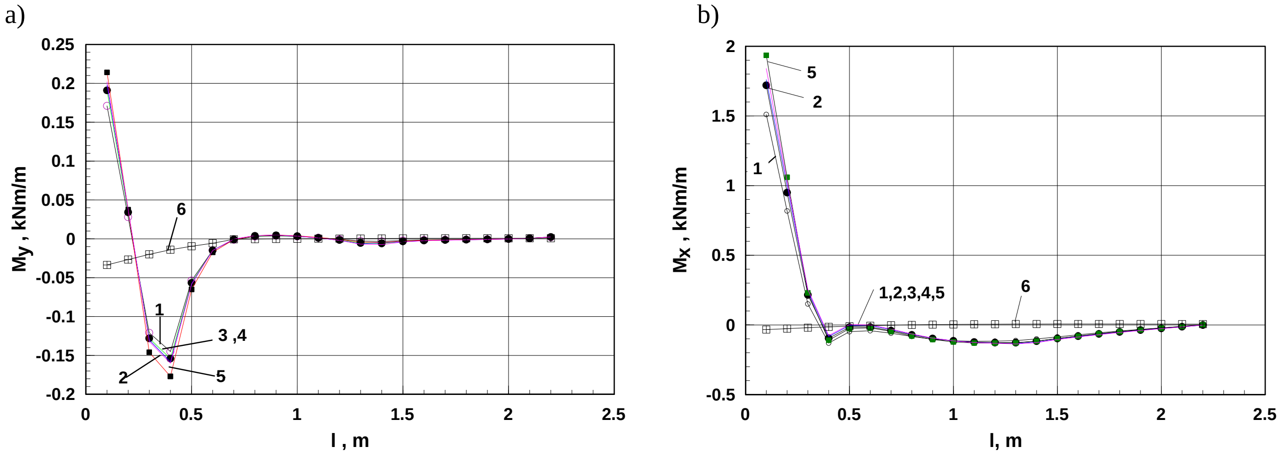

Fig 9. Variation in external layer bending moments M_y – (a) and M_x – (b) M_y – (a) and
M_x – (b) in respect of wall length l when flexible ties are provided:
1 – l = 6 m, 2 – l = 9 m , 3 – l = 12 m, 4 – l = 18 m, 5 – l = 24 m, and when the ties are not provided 6 – l = 6 m

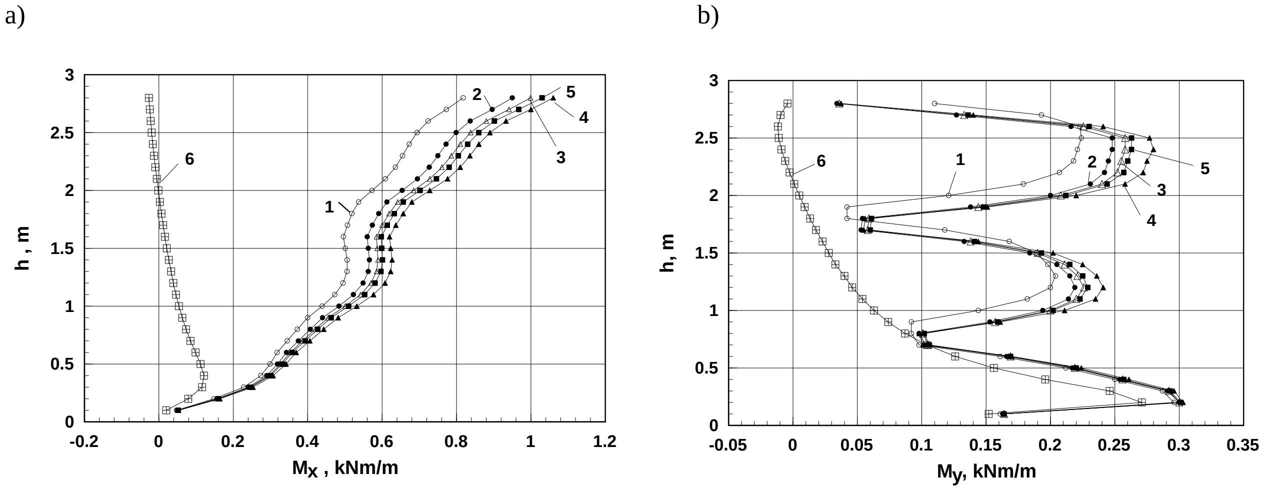

Fig 10. Variation of moments M_x (a) and M_y (b) in relation to the height of the wall, when there are flexible ties: 1 – l = 6 m, 2 – l = 9 m, 3 – l = 12 m, 4 – l= 18 m, 5 – l = 24 m and there is no flexible ties 6 – l = 6 m

When there is no flexible ties between the layers bending moments in external facing layer at wall ends (at the joint of intersection of walls) are not substantial, while the bending moments at the same section increases when the layers are joined with the ties (Fig 9). It proves the fact that the reason why in the most cases vertical cracks appears in external layer of the walls near their corners is that influence of the flexible ties on deformations of the layer is not taken into account, i. e. restraint of temperature – moisture deformations of layers by the flexible ties is not accounted for.

The general volumetric deformation of planes of wall layers demonstrates (Fig 8) that bending moments vary in direction of other axis as well. Analysis of moment variation according to the height of the wall (at the section of 0.5 m from the intersection axis of the walls) shows (Fig 10) that the moments increase in different way with the height when the external layers are not joined with the internal load bearing layer and when between them flexible ties are provided.

When ties between the layer are not provided moments in the zone near the foundation increase but forward they decrease and about at 1/3 of the height change direction (sign) but they are insignificant. However distribution of forces is different one when the flexible ties between the layers are provided. Variation of moments in respect to the height is different depending on the length of the wall. If the external layer is not joined to the bearing one, moment variation according to the height is insignificant then when the ties are provided the variation is significant. Throughout the height of 3 m the moment M_x increases from zero up to 1.2 kNm/m (Fig 10 a).

Some uneven variation of moments according to the directions of axes (Fig 10) may be explained by influence of ties provided in particular section of the wall according to the length or height (herewith in the area of the finite element).

Effect of ties to the moment distribution character is pointed out by the fact that in a wall without the ties distribution of moments is even while in sections at the ties and between them there are significant changes in moment values (Fig 10), like in a continuous beam or slab supported on in chequered way arranged supports.

General deformation variation character (Fig 10) demonstrates different almost even increase in moment values with the wall (layer) length in the direction of axis x. E. g., at the height of 0.5 m above foundation moments are almost equal irrespective of the wall length. However at the top of the layer they differ in 35 % comparing wall layers of 6 m and of 24 m long. It may be explained by effect of axial forces. The longer the wall the smaller its stiffness $\left(EI/l\right)$ and probability of buckling increases since influence of displacement restraint at foundation level on this deformation reduces with increase in the wall height. Moreover, the moments M_x may cause stress exceeding masonry tensile strength resulting in opening of horizontal cracks.

Conclusions

1. Layers of masonry layered walls deform differently under the action of temperature and moisture and deformations of the external facing – protective layer are restraint by the flexible ties. It depends on the shape of the building, quantity, stiffness and distribution of flexible ties.
2. Restraint by flexible ties of external layer deformations due to temperature and moister action produces bending moments in both vertical and horizontal directions which may inflict in the layer tensile stress exceeding limit values and herewith vertical and horizontal cracks can appear.
3. The maximum bending moments in respect to the vertical and the horizontal axes are obtained at a distance of 0.2 – 0.4 m from the intersection of the walls. Observations of masonry buildings in service show that cracks in external layers of masonry walls

mostly appear in the zones near the corners of the walls (at wall intersections).

4. Provisions of the code for design of masonry structures for distances between temperature – moisture movement joints that can be taken without calculation may be applied to facing walls (facing layers) only in the case when they are not joined to the bearing layers with ties. It is recommended selection of movement joint layout for the external layer joined to the bearing layer with the flexible ties to accomplish by calculations with account for quantity, stiffness and distribution of the flexible joints.

References

Bhatt, P. 1999. *Structures*. UK, Longman. 597 p.

Eurocode 6. Design of masonry structures – Part 1–1: General rules for reinforced and unreinforced masonry structures.

Gambhir, M. L. 2004. *Stability analysis and design of structures*. Berlin – New-York. 535 p.

Godoy, L. A. 2000. *Theory of elastic stability*. Tailor&Francis Group. 433 p.

Hendry, A. W.; Fhalaf, E. M. 2003. *Masonry Wall Construction*. Taylor&Francis Group. 117 p.

Kollar, L. 1999. *Stability in engineering practice*. London, Taylor&Francis Group. 454 p.

Marčiukaitis, G.; Popov, V. 1999. Estimation of multilayered wall slenderness depending on behaviour of flexible ties. *Statyba* 5(1): 219–226.

Marčiukaitis, G.; Zabulionis, D. 2000. Influence of composition of mortar mixture on strength and deformability of external walls, *Statyba* [Civil Engineering] 6(2): 76–81.

Marčiukaitis, G. 2001. Shrinkage influence on stresstrain state of composite masonry members, *Statyba* [Civil Engineering] 7(1): 177–183.

Peters, H. R. 2005. *Richting bauen mit Ziegel*. Stuttgart: Fraunhofer IRB Verlag. 232 p.

STR 2.05.09:2005. *Statybos techninis reglamentas. Mūrinių konstrukcijų projektavimas* [Technical regulation of Building Design of masonry structures]. 58 p.

Zavadskas, E. K.; Kaklauskas, A.; Turskis, Z.; Tamašauskienė, J. 2008. Selection of the effective dwelling house walls by applying attribute values determined at intervals, *Journal of Civil Engineering and Management* 14(2): 85–93. doi:10.3846/1392-3730.2008.14.3