Table 2. Results of triaxial mortars and brick tests
Tabela 2. Wyniki badań przy obciążeniu trójosiowym

Loading paths	Mortar M1		Mortar M2		Brick B1	
	σ_{ver} [N/mm²]	σ_{rad} [N/mm²]	σ_{ver} [N/mm²]	σ_{rad} [N/mm²]	σ_{ver} [N/mm²]	σ_{rad} [N/mm²]
A	-17,7	-2,1	-6,2	-0,9	-40,5	-2,1
	-26,5	-4,1	-11,4	-1,8	-48,8	-4,1
	-27,3	-6,1	-14,5	-3,1	-52,9	-6,0
B	0,0	-14,4	-1,0	-5,0	0,0	-28,7
	-2,0	-17,1	-1,9	-6,7	-2,0	-31,3
	-4,0	-18,4	-3,0	-8,5	-4,0	-35,4

Material model

Loading paths (A: $\sigma_{rad} > \sigma_{ver}$, B: $\sigma_{ver} > \sigma_{rad}$) are located on the planes inside of the failure surface. The points responsible for mortars or bricks' damaging are situated directly on this surface. When $\sigma_{rad} > \sigma_{ver}$ the Lode angle's value equals $\Theta = 60°$ and the points responsible for mortars or bricks' damaging are situated on compressive meridian. Whereas, when $\sigma_{ver} > \sigma_{rad}$ the Lode angle's value equals $\Theta = 0°$ and the points responsible for mortars or bricks'' damaging are situated on tensile meridian. Owing to the periodicity of deviatoric section the determination of tensile and compressive meridians allows to define the shape of failure surface.

To define the failure surface the uniaxial and triaxial tests results were showed as the points in the octahedral co-ordinate system $\sigma_{oct} - \tau_{oct}$. The points were quadratic function approximated by using least squares method. In this way the equations and graphs of failure surface for mortar M1, M2 brick B1 were made. Failure surface for mortar M3 and brick B2 were recalculated using tests data of previous triaxial tests (M1, M2, B1) – fig. 7.

Both meridians of failure surface should be intersected in the point responsible for triaxial tension strength. The meridians defined on the basis of mortar M1 and brick B1 tests did not intersect σoct axis in the same point. In the presented model the way of the meridians was change. It was done in such a way, to make the compressive meridian intersect the σ_{oct} axis in the place of intersection the tensile meridian, which was estimated on the basis of the tests (fig. 6). This procedure is recommended in the following works [7, 9].

Table 3. Parameters of masonry material model
Tabela 3. Parametry modelu materiałowego

Parameter	Mortar M1	Mortar M2	Brick B1
Parameters of failure surface			
The uniaxial compressive strength f [N/mm²]	11,4	3,5	28,4
The uniaxial tensile strength f_t [N/mm²]	0,5	0,5	1,2
The biaxial compressive strength f_{cc} [N/mm²]	14,4	10,7	28,7
The high-compressive stress point on the tensile meridian [N/mm²]	$\sigma_{okt,1} = 18,5$ $\tau_{okt,1} = 7,5$	$\sigma_{okt,1} = 12,0$ $\sigma_{kt,1} = 3,0$	$\sigma_{okt,1} = 29,7$ $\tau_{okt,1} = 15,0$
The high-compressive stress point on the compressive meridian [N/mm²]	$\sigma_{okt,2} = 14,8$ $\tau_{okt,2} = 10,5$	$\sigma_{okt,2} = 12,0$ $\tau_{okt,2} = 3,0$	$\sigma_{okt,2} = 30,4$ $\tau_{okt,2} = 24,1$

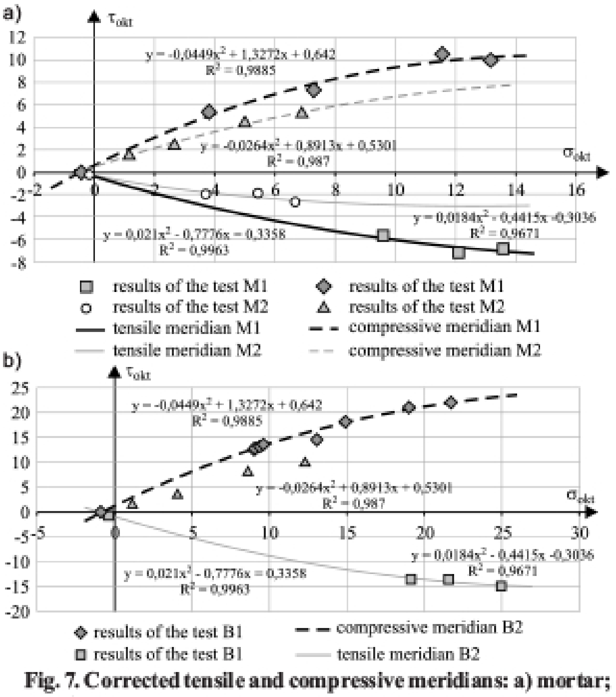

Fig. 7. Corrected tensile and compressive meridians: a) mortar; b) brick

Rys. 7. Skorygowane południki ściskania i rozciągania powierzchni granicznej: a) zaprawy; b) cegły

On the basis of meridians' equations and graphs the last two parameters of Willam-Warnke failure surface were determined. All parameters of failure surface were displayed in table 3.

Apart from defining the failure surface the material model must describe the masonry behaviour in the elastic area. It was assumed that mortar and brick since gaining the failure surface are isotropic materials. Until the load path will be situated inside the failure surface the stiffness matrix is defined by two parameters: modulus of elasticity E and Poisson's ratio ν. The values of E and ν were obtained from the mortars and bricks tests.

Conclusions

The following conclusions may be presented on the basis of conducted analysis:

- Willam-Warnke failure criteria can be established by defining failure surface parameters on the basis of mortar and brick uniaxial and triaxial tests;
- the higher values of constant horizontal compression the higher vertical compressive strength;
- the higher values of constant vertical compression the higher horizontal compressive strength;
- Willam-Warnke failure criteria can be can be determinated using triaxial tests results of same type materials.

References

[1] Chaimoon Kirt, Attard Mario M. 2007, „Modeling of unreinforced masonry walls under shear and compression", *Engineering Structures 29* (9): 2056 – 2068.
[2] Chen W. F. 1982. „Plasticity in reinforced concrete". McGraw-Hill Book Company.
[3] Drobiec Łukasz, Kubica Jan. 2002. „Influence of Some Types of Bed Joint Reinforcement on Mechanical Properties of Masonry Under Compression". *Proceedings of the British Masonry Society*, no. 9: 99 – 104.
[4] Drobiec Łukasz. 2004. „Analiza murów z cegły pełnej ze zbrojeniem w spoinach wspornych poddanych obciążeniom pionowym". Praca doktorska, Gliwice.
[5] Drobiec Łukasz. 2005. „FEM Micro Model of Masonry". *5th International Conference Analytical Models and New Concepts in Concrete and Masonry Structures AMCM*: 1 – 8.
[6] Drobiec Łukasz. 2006. „FEM Micro-Model for Masonry Reinforced in Bed Joints". *Proceedings of the British Masonry Society, no. 10, Published by the Society Stoke-on-Trent.*
[7] Majewski Stanisław. 2004. „MWW3 – elasto-plastic model for concrete". *Archives of Civil Engineering* nr 1: 11 – 43.
[8] Massart T. J., R. H. J. Peerlings, M. G. D. Geers, S. Gottcheiner. 2005. „Mesoscopic modeling of failure in brick masonry accounting for three-dimensional effects". *Engineering Fracture Mechanics* 72 (5): 1238 – 1253.
[9] Willam K. J., Warnke E. P. 1975. „Constitutive models for the triaxial behavior of concrete". *IABSE Proceddings*, vol. 19: 1 – 30.

Przyjęto do druku: 08.09.2016 r.