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DEVELOPING HYDROSTATIC BEEHIVE BRICKWORK

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Abstract

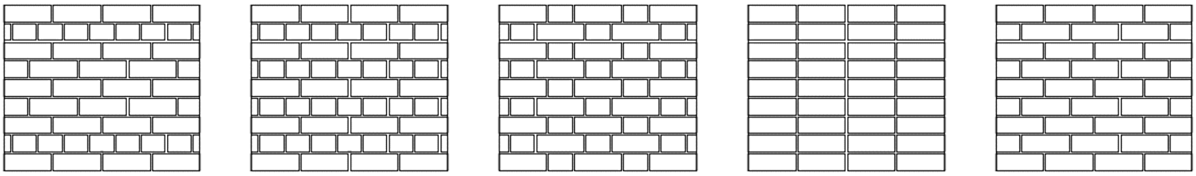
In this paper, a new masonry construction is proposed based on honey beehive cell internal geometry as a unique structure and hydrostatic pressure principle. The considered experimental program involved suggestion, manufacturing, testing and analysis of masonry specimens of honey beehive units' arrangement as well as corresponding specimens of custom arrangement, two classes of cementations bonding mortars are used. Plan strain concept and Saint Venant's principle are adopted to model and assign proper boundary conditions of testing specimens. The significant improvement of masonry construction bearing capacity is confirmed by the obtained results and could be related to the presence of internal or self-confining pressure, which is produced due to the specific internal geometry of proposed honey beehive units' arrangement of hexagonal construction units. The obtained results show that, the masonry specimens of proposed honey beehive arrangement Mode II exhibited higher bearing capacity in term of ultimate and service loads besides stiffness improvement in comparison with the customary arrangement Mode I.

Keywords:

Brick units' arrangement;
Cementitious bonding mortar;
Flexibility;
Hydrostatic pressure;
Masonry construction.

1 Introduction

Brickwork is the traditional construction technique in which the brick units are compiled one on each other with bonding mortar. The behavior of masonry units is different from the behavior of mortar alone or bricks. Dawood, A.O. et al. [1]. It is masonry of bricklayers, using building units and binder mortar. There are many basic structural bonds commonly used in constructional field which create typical patterns of bricks. The units are stone, block or brick, stone, usually being natural form while the artificially units forms are mostly concrete block or bricks which are adobe, fired clay brick, or concrete. Cementitious bonding mortar is usually made from cement, lime, gypsum, or bitumen. The use of units and the adhesive bonding mortar in a combining manner as a construction technique is called masonry construction technique. Various combinations of bricks in the masonry manufacturing can be used. Fig. 1 shows the most customary brick units' arrangements in masonry construction. Lourenço, P.B. [11].



a) b) c) d) e)

Fig. 1: Masonry of various units' arrangements: a) American bond, b) English bond, c) Flemish bond, d) Stack bond, e) Stretcher bond. Lourenço, P.B. [11].

On the other side, a beehive is an enclosed smart structure in which some honey bee species live and raise their young. The beehive's internal structure is a densely packed group of hexagonal prismatic cells made of beeswax, called a honeycomb.

Since long time, many researchers were interested with various structural aspects of masonry construction likewise shear failure mode, local buckling, strengthening technique and loading conditions. Aguilar, V. et al. [2], Alcaino, P. and Santa, H. [3], Anil, O. et al. [6], Arnau, O. et al. [7], Bernat, E. et al. [9], Haach, V. et al. [10], Lourenço, P.B. et al. [12], Penna, M. et al. [14].

In this study, the unique beehive structure, Fig. 2, is utilized besides its compatibility with the hydrostatic concept of uniform distributed stress to suggest, simulate and investigate the proposed honey beehive masonry construction of a new brick configuration and a new brick arrangement.

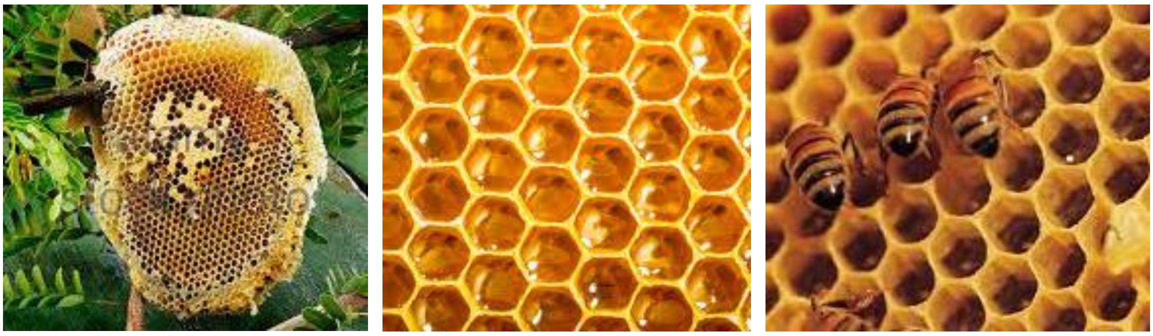
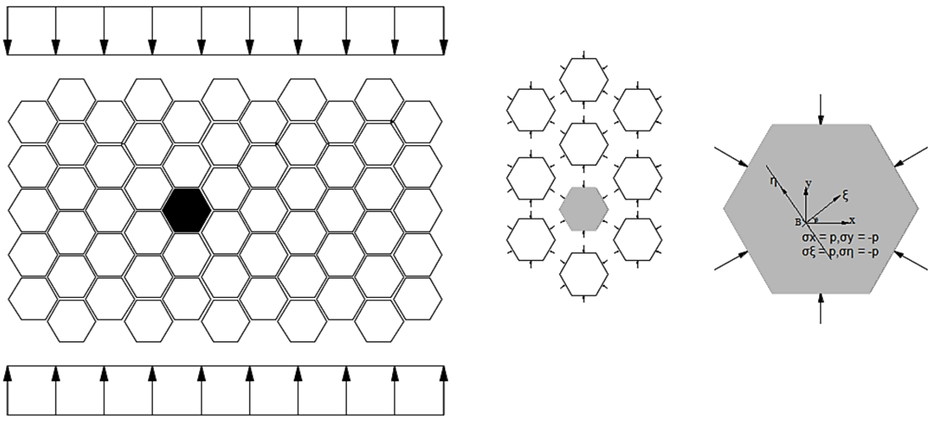


Fig. 2: Honey beehive smart structure.

2 Hydrostatic beehive simulation

Under general conditions, the stress field could be divided into two states, hydrostatic or mean stress σ_m involving only pure compression and deviatoric stress tensor σ'_{ij} which is dominated by representing pure shear. The proposal brickwork internal geometry might eliminate or minimizes deviator stresses which dominated by shear stress and affect the shape change and failure mode, so the proposal internal geometry aims to make the mean stresses as dominated stresses.

The expected internal or self-confining stresses which are produced due to the smart arrangement of honey beehive cell structure could provide a stress state likewise that of a hydrostatic field stress state. The stress flow within the internal structure of the proposed beehive masonry could be simulated using condition similar to the hydrostatic stress state. The visualizing of units as an arbitrary part within a larger is shown in Fig. 3.



a) b) c)

Fig. 3: Hydrostatic simulation of proposed beehive masonry.

In honey beehive arrangement and in the absent of shear resistance between cells, the unit is subjected to a uniform constant pressure p along its periphery. The stresses inside the unit, can be obtained by a specific analysis using stress transformation equation, eq. (1)

$$\sigma_\xi = \sigma_x \cos^2\theta + \sigma_y \sin^2 \theta + 2\tau_{xy} \cos\theta \sin\theta \,,$$

$$\sigma_\eta = \sigma_x \sin^2 \theta + \sigma_y \cos^2\theta - 2\tau_{xy} \cos\theta \sin\theta \,,$$

$$\tau_{\xi\eta} = (\sigma_y - \sigma_x) \cos\theta \sin\theta + \tau_{xy} (\cos 2\theta - \sin 2\theta), \quad (1)$$

which are introduced by Murakami, Y. [13], when an arbitrarily shaped plate of uniform thickness is subjected to a constant pressure, p along its periphery, the normal stress, σ, and the shear stress, τ, are $\sigma = -p$ and $\tau = 0$ throughout the plate, Fig. 4, by visualizing the plate as an arbitrary shaped part within a larger.

a) A plate under in-plan constant stress. b) Visualizing the plate as a part within a larger.

Fig. 4: An arbitrarily shaped plate of uniform thickness.

The plate is subject to a constant pressure p along its periphery. The stresses inside the plate will be $\sigma_x = -p$, $\sigma_y = -p$ and $\tau_{xy} = 0$, at the arbitrary point B on the periphery. The stresses can be obtained from eq. (1)

$$\sigma_\xi = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta + 2\tau_{xy} \cos\theta \sin\theta = -p\cos^2\theta - p\sin^2\theta + 0 = -p$$

$$\tau_{\xi\eta} = (\sigma_y - \sigma_x) \cos\theta \sin\theta + \tau_{xy} (\cos^2\theta - \sin^2\theta) = (-p + p) \cos\theta\sin\theta + 0(\cos^2\theta - \sin^2\theta) = 0$$

The stresses at point A can be expressed in the same way as those at point B. $\sigma = -p$ and $\tau = 0$ at any point and direction within periphery.The analysis results confirmed that to determine the stress state inside a plate, knowing only the boundary conditions and the stress transformation equation and the analysis did not mention the material of the plate besides its uniform thickness.The 2D elementary hydrostatic stress state due to uniform compression loading, and related state of strain based on generalization Hooke’s law are. Sadd, M. [15]:

$$\sigma_{ij} = \begin{bmatrix} -p & 0 \\ 0 & -p \end{bmatrix}, \quad \varepsilon_{ij} = \begin{bmatrix} -\frac{1-2\nu}{E}p & 0 \\ 0 & -\frac{1-2\nu}{E}p \end{bmatrix}. \quad (2)$$

The present of hydrostatic stress state will extremely improve the internal effective compressive strength within the brickwork. Actually, the presented cementitious bonding layer provides shear resistance which affects pure hydrostatic stress and so affects the related improving degree of internal effective compressive strength within the brickwork. The expected improving of a wall bearing capacity of honey beehive units ‘arrangement and the related improving degree of internal effective compressive strength are investigated by the considered experimental program.

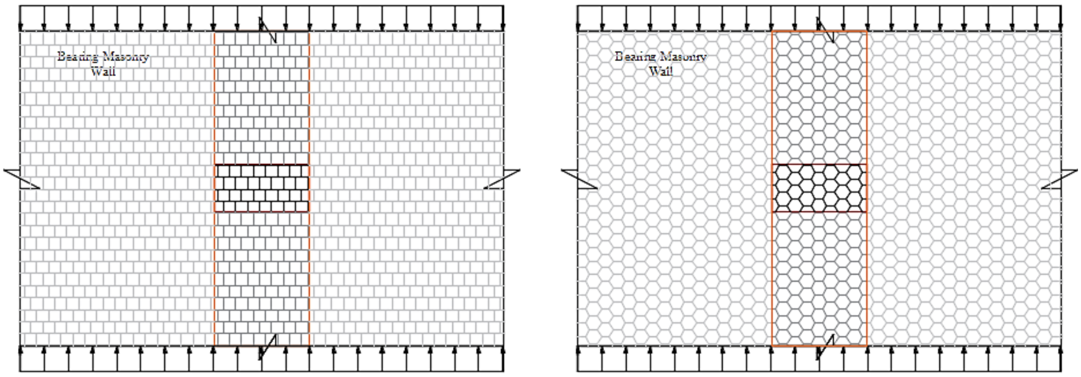
3 Experimental program

3.1 Specimens modeling

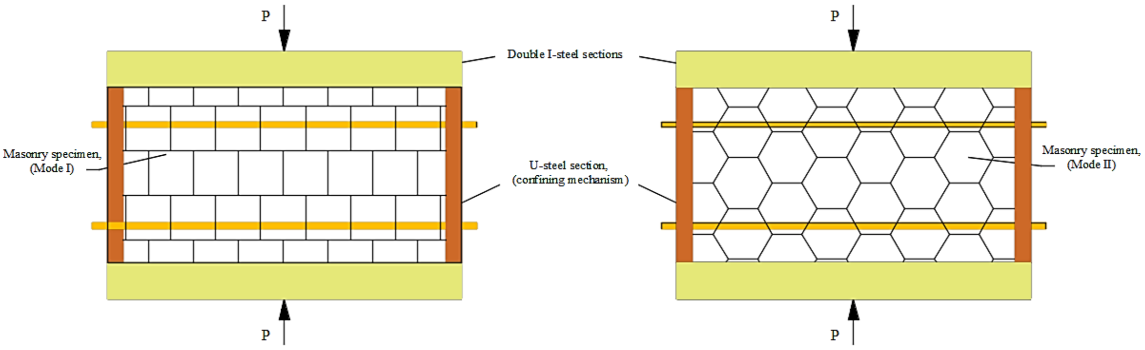
In the masonry construction, the effective loads on the lateral boundaries are independent of the z coordinate. Besides, one dimension is smaller than the other two and under the effect of uniformly distributed load, so the plane strain concept could be the more proper methodology to model the problem and assign related boundary conditions. A strip within masonry construction is considered and extracted in loading direction, basing on the Saint Venant’s principle; the dimension in loading directing is reduced so that the statically equivalent loads are approximately the same [11]. U-section steel supports are used to simulate lateral confining while I-section steel beams are used to apply uniform distributed vertical loads, Fig. 5 depicts specimens modelling. Compression test machine of 5000 kN loading capacity is used; the approximated loading rate is 0.1 kN/s. Electrical strain gauges and LVDT’s are used to measure vertical deformations, normal strain, and vertical shortening.

3.2 Specimens characteristics

Aerated concrete (PAAC) wall construction units. ASTM C – 1389 [4] are used to manufacture masonry construction specimens of two cementitious bonding mortars of significant various flexibility (cement sand mortar and gypsum mortar) using available customary raw materials, Table 1. The cement matrix was designed according to standard procedures of mix design for mortar. The compressive and flexural strengths of each mix determined by 50 mm cubes and 40x40x20 mm prisms were cast and investigated in the same conditions, according to ASTM C109-03[5] and BS 1881part 118-1983 [8] respectively.



a) Brickwork of customary units' arrangement, (Mode I)
b) Brickwork of hexagonal units' arrangement, (Mode II)



c) Masonry specimen, (Mode I)
d) Masonry specimen, (Mode II)

Fig. 5: Specimens modeling based on plan strain concept and Saint Venant's principle.

Table 1: Cementitious bonding mortar classes.

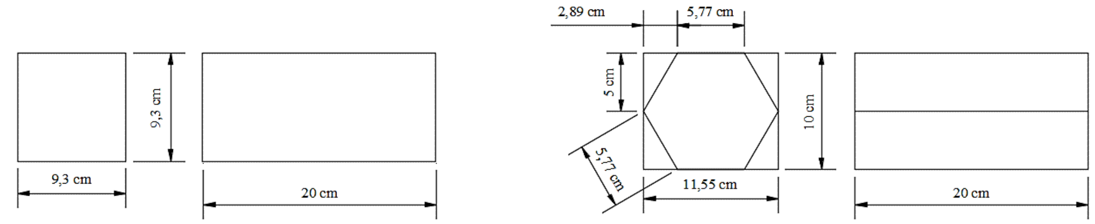
Batch No.	Class	Description	f_m [MPa]	f_r [MPa]	E_m [MPa]
1	A	cement: sand mortar	31.67	6.34	24200
2	B	gypsum mortar	3.00	0.47	1000

Brickwork masonry construction specimens of 800 x 400 x 200 mm were adopted. Four masonry specimens were fabricated and tested throughout this study as shown in Table 2; they are related to two distinguished groups and have two unit types of equivalent cross-section area, Fig. 6 depicts the geometrical description of used construction units. Besides, an unconfined specimen of PAAC is prepared. Masonry specimens' geometrical details are shown in Fig. 7 while Fig 8 illustrates their manufacturing process. The brickwork consists of one layer of Precast Autoclaved Aerated Concrete units.

The improvement of internal effective compressive strength within the brickwork could be assigned by comparative analysis of obtaining effective compressive strength within the brickwork of various units' arrangement modes with that of an unconfined specimen of Precast Autoclaved Aerated Concrete is used, a new proposed dimension are introduced to get a proper matching in geometry properties of different adopted shapes like units volume and their cross section area. Precast Autoclaved Aerated Concrete (PAAC) is a lightweight concrete composed of quartz sand, calcined calcium sulfate, as aggregate and lime and cement as a binder matrix.

Table 2: Specimens description.

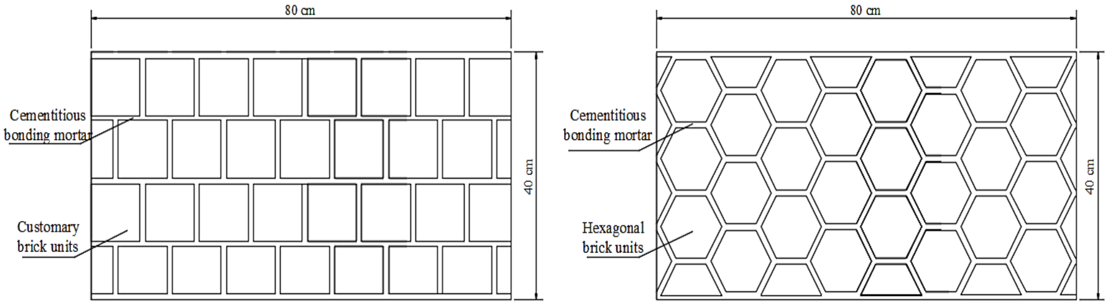
No.	Gr.	Designation	Units arrangement mode	Bonding mortar class	Description
1	1	RB1	Mode I (rectangular-brickwork)	A	Brickwork of customary (rectangular section) brick unit shape
2		RB2		B	
3	2	HB1	Mode II (honey beehive -brickwork)	A	Brickwork of proposed honey cell (hexagonal section) brick unit shape
4		HB2		B	



a) Customary units of equivalent hexagonal unit area

b) Proposed hexagonal units

Fig. 6: Geometrical description of used construction units.



a) Customary units' arrangement, (Mode I)

b) Proposed honey beehive units' arrangement, (Mode II)

Fig. 7: Specimens' geometrical details.

a) b)

Fig. 8: Specimens manufacturing process.

3.3 Test setting

U-steel lateral supports are used to simulate lateral confining while I-section steel beams are used to apply uniform distributed vertical loads. A compression test machine of 5000kN loading capacity is used; the approximated loading rate is 0.1 kN/s. Electrical strain gauges and LVDTs' are used to measure vertical deformations, normal strain, and vertical shortening. Fig. 9 illustrates the test arrangement.

Fig. 9: Test arrangement.

4 Results and discussions

4.1 Comparative analysis

The main aim of considered experimental program is to investigate the proposed fashion of units' arrangement within masonry construction that is associated with the proposed unit's configuration. The test results and corresponding analysis regarding specimens bearing capacity and their deformation response are illustrated in Table 3 and Table 4, respectively. Comparative analysis of proposed arrangement Mode II with customary arrangement Mode I in scope of the ultimate wall bearing capacity, cracking load, load-deformation response, stiffness, plastic deformation and failure modes are achieved. The obtained results show that, the masonry construction of honey beehive arrangement exhibits significant ultimate strength upgrading and stiffness enhancement, the strength increment rating in respect to the corresponding specimens of customary arrangement, varied between 1.30 - 1.87 while the acceptable serviceability of new hexagonal arrangement is confirmed by assigning relatively higher cracking loads in comparison with those of customary arrangement; the upgrading rates vary between 1.80 - 2.74. Fig. 10 clearly depicts comparative view of load-deformation response between customary masonry arrangement Mode I and proposed masonry arrangement (Mode II) of various cementitious bonding mortars. It is clearly shown that the obtained high bearing capacity and high stiffness are related to masonry specimens of cement sand mortar class A, f_m = 31.67 MPa and E_m = 24200 MPa, while the relative best upgrading rates are associated with using gypsum mortar which is characteristics by relatively high flexibility class B, of f_m = 3.00 MPa and E_m = 1000 MPa.

Generally, the brickwork effective compressive strengths f_{ce} are much more than that of unconfined masonry construction of f_{ue} = 0.94 MPa and ε = 0.008, and the specimens of hexagonal arrangement have the best increment rating 1.81-2.21 verse 0.97-1.7 of the corresponding specimens of customary arrangement.

The load-deformation responses of masonry construction of unit arrangement Mode I and Mode II are illustrated in Fig. 11 and 12, respectively. The effect of cementitious bonding mortar class on ultimate wall bearing capacity and stiffness are confirmed where the brickwork of cement sand mortar class A exhibits best ultimate strength 330.66 kN verse 270.10 kN for the corresponding specimen of gypsum mortar class B, respectively; the same finding is observed in the masonry of customary arrangement while the brickworks of flexible mortar class B associated with the best ductility response for both arrangement modes as illustrates in Table 4. For both units' arrangement, the masonry specimens of mortar class B are characteristic by crushing mode, while the corresponding specimens of mortar class A are failed by significant shear mode as shown in Fig. 13 that illustrates comparative failure modes views of hexagonal verse customary masonry arrangement.

The significant improvement of wall bearing capacity is confirmed by the obtained results and could be related to the presence of internal or self-confining pressure, which is produced due to the specific internal geometry of proposed honey beehive units' arrangement of hexagonal construction units.

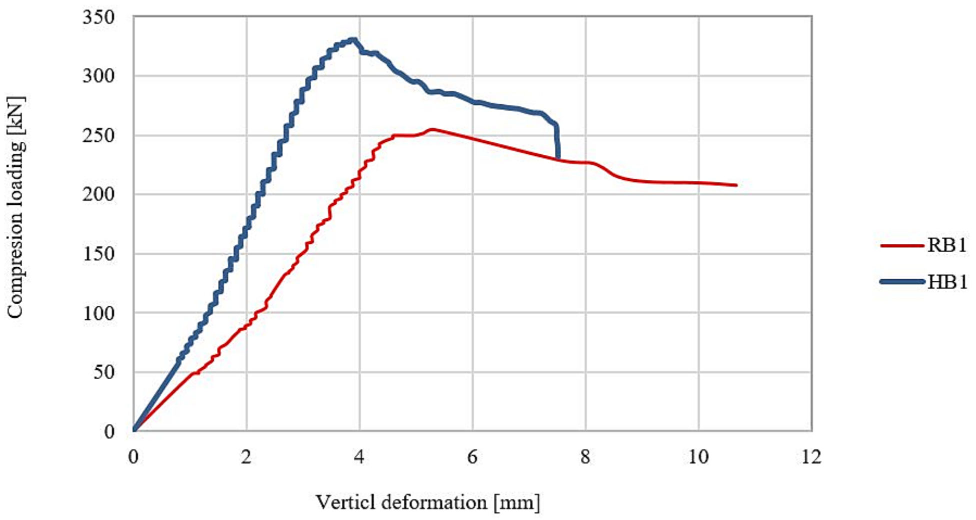
The obtained results could be generalized for other conventional materials as the adopted brickwork building mode is utilized the hydrostatic stress distribution benefit which is related to the effect of in-plan constant stress on a proper boundary condition and independent of materials properties where the stress analysis that introduced by Murakami, Y. [13] confirmed that to determine the stress state inside an element, knowing only the boundary conditions and the stress transformation equation and the analysis did not mention the material of the element besides its uniform thickness.

Table 3: Tested specimen's strength analysis.

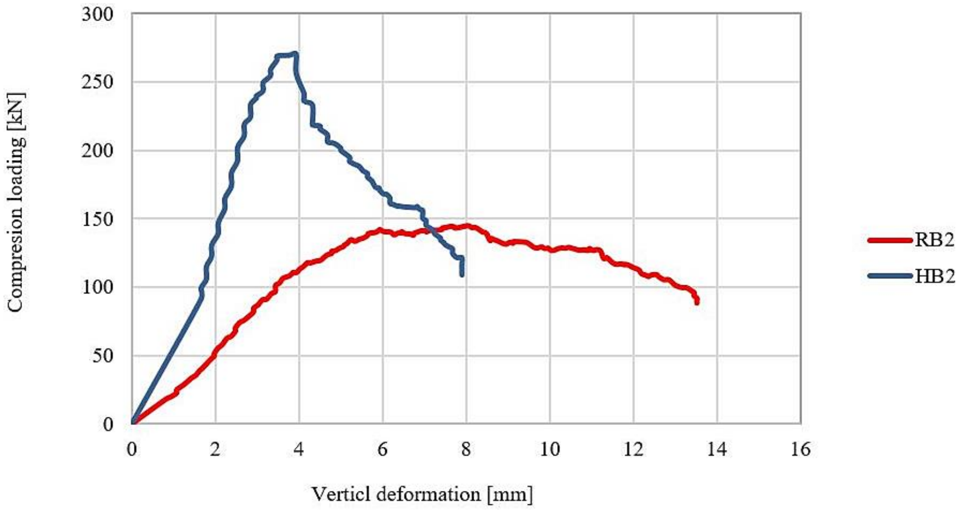
No.	**Gr.**	**Designation**	**Units arrangement mode**	P_u, **[kN]**	f_{ce}, **[MPa]**	P_{cr}, **[kN]**	f_{ce}/f_{ue}	Pu_i / Pu_{RBi}	Pcr_i / Pcr_{RBi}
1	1	RB1	Mode I (rectangular-brickwork)	255.00	1.59	155.00	1.70	1.00	1.00
2		RB2		144.50	0.90	89.80	0.97	1.00	1.00
3	2	HB1	Mode II (honey beehive-brickwork)	330.66	2.07	279.30	2.21	1.30	1.80
4		HB2		270.10	1.69	230.10	1.81	1.87	2.56

Table 4: Tested specimen's deformation analysis.

No.	**Gr.**	**Designation**	**Units arrangement mode**	**Vertical deformation [mm]**	**Longitudinal strain**	$\varepsilon_i/\varepsilon_{uc}$	Δ_i/Δ_{RBi}	$\varepsilon_i/\varepsilon_{RBi}$
1	1	RB1	Mode I (rectangular-brickwork)	10.66	0.01000	1.21	1.00	1.00
3		RB2		13.53	0.00860	1.04	1.00	1.00
4	2	HB1	Mode II (honey beehive -brickwork)	7.52	0.00873	1.06	0.70	0.87
6		HB2		7.90	0.00830	1.01	0.58	0.97



a) Masonry of cementitious bonding mortar class A.



b) Masonry of cementitious bonding mortar class B.

Fig. 10: Comparative analysis of load-deformation response between customary masonry rrangement (Mode I) and proposed masonry arrangement (Mode II).

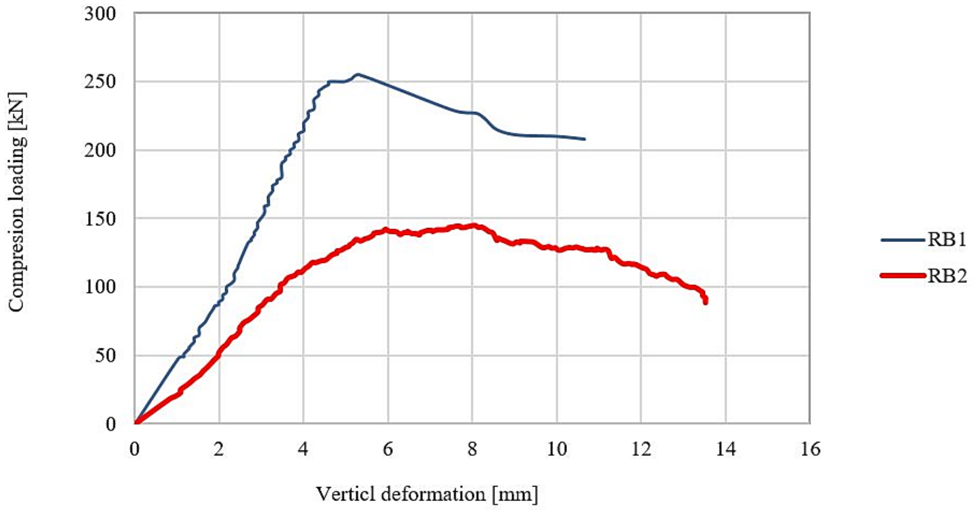


Fig. 11: Load-deformation responses of customary masonry (M635ode I) with different cementitious bonding mortar classes.

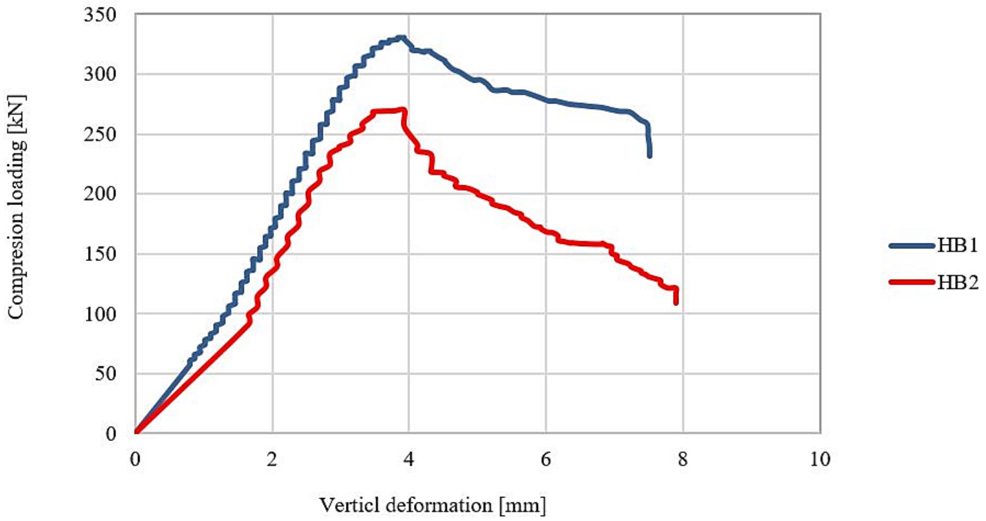
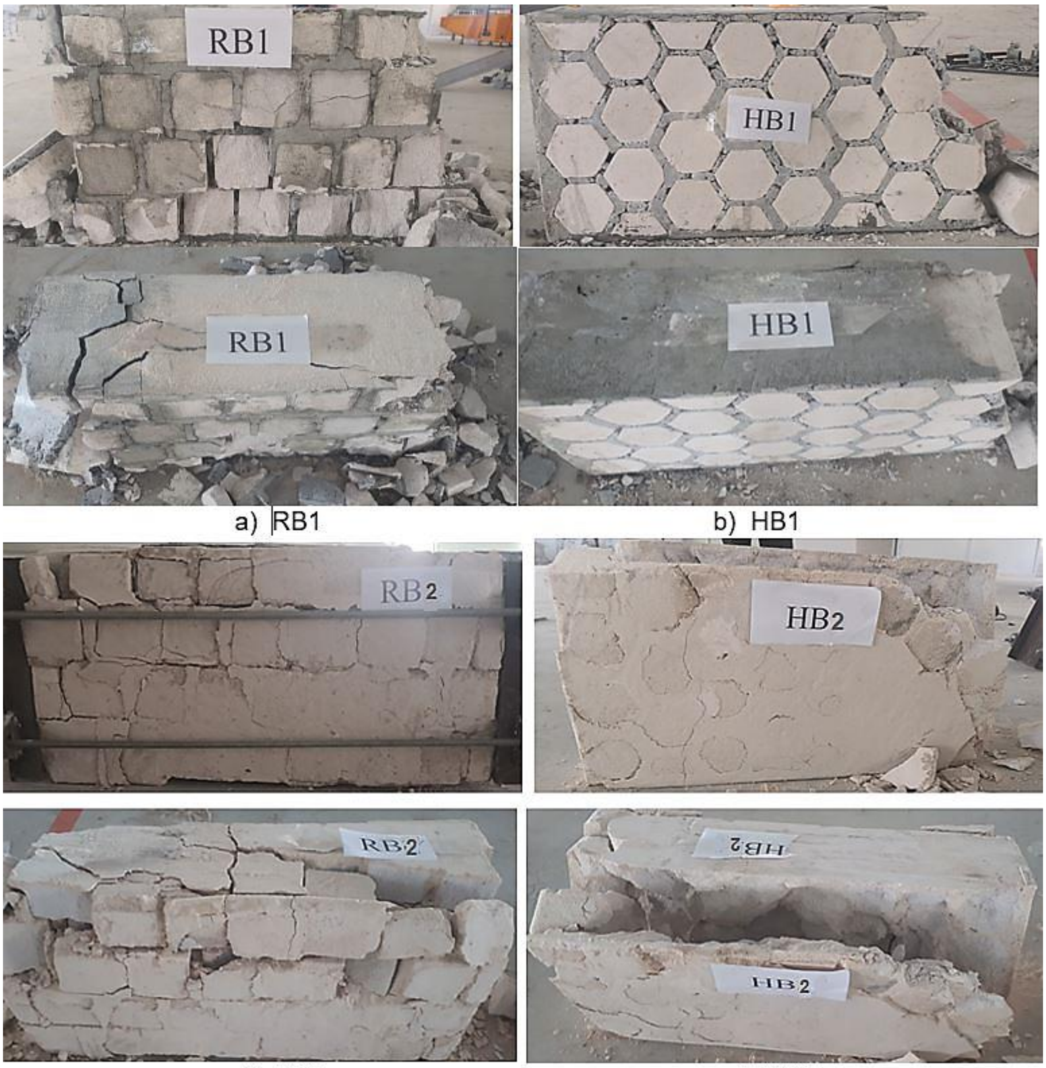


Fig. 12: Load-deformation responses of proposed masonry (Mode II) with different cementitious bonding mortar classes.



a) RB1 b) HB1

c) RB2 d) HB2

Fig. 13: Comparative views of failure modes.

4 Conclusions

The honey beehive structure had been imitated to propose masonry of hexagonal brick units compatible with specific honey beehive units' arrangement. The adopted experimental program clearly stated the following observations:

1) The new masonry construction of the proposed arrangement exhibited significant ultimate strength upgrading and stiffness enhancement, the strength increment rating in respect to corresponding specimens of customary arrangement, varied between 1.30 and 1.87 according to used cementitious bonding mortar class.

2) The best strength upgrading rate is associated with masonry of gypsum mortar which is more flexible in comparing with cement sand mortar.

3) The acceptable serviceability of new hexagonal arrangement is confirmed by assigning relatively higher cracking loads in comparison with those of customary arrangement; the upgrading rates varied between 1.80 and 2.74 according to used cementitious bonding mortar class.

4) The brickwork effective compressive strengths are much more than that of unconfined masonry and the specimens of hexagonal arrangement exhibit the best increment rating in comparison with the corresponding specimens of customary arrangement. The increments rating are 1.81, 2.21 verse 0.97, 1.7 of the corresponding specimens of customary arrangement, respectively.

5) For both units' arrangement modes, the masonry specimens of the relatively high flexible bonding mortar are characteristic by crushing mode, while the corresponding specimens of relatively less flexible bonding mortar failed by significant shear mode.

6) The obtained results could be generalized for other conventional materials as the adopted brickwork building mode is utilized the hydrostatic stress distribution benefit which is related to the effect of in-plan constant stress upon a proper boundary condition and independent of materials properties.

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