WOOD RESEARCH
62 (5): 2017
815-824

# CALCULATION OF HONEYCOMB PAPERBOARD FLAT CRUSH RESISTANCE

Zbigniew Kołakowski
Technical University of Lodz , Faculty of Mechanical Engineering
Department of Material Strength
Lodz, Poland

Włodzimierz Szewczyk, Gabriela Kmita-Fudalej
Technical University of Lodz, Institute of Papermaking
and Printing
Lodz, Poland

(Received September 2016)

## ABSTRACT

The article presents calculation methods for flat-crush resistance (*FCT*) of honeycomb paperboard. The calculations were made on the bases of mechanical properties of the material that is, paper used for core production and shape of its cells. The methods presented in the article allow to calculate the *FCT* for the cores with the cells of the theoretical hexagon shape as well as of the real shape. The correctness of the methods proposed was verified by the comparison of calculation results with the results of *FCT* measurements for boards of different core height.

KEYWORDS: Honeycomb paperboard, flat crush test.

## INTRODUCTION

When comparing to wood, board and other multi-layer products with honeycomb board cores have many advantages, such as:

- low specific weight,
- high strength and stiffness in relations to specific weight,
- possibility to produce from fibrous materials of different basis weight and different composition,
- recyclability,
- good insulation, thermal and acoustic properties (Bitzer 1997, Barboutis et al. 2005).

One of the basic mechanical properties determined for honeycomb paperboard is flat-crush resistance determining a maximum pressure value applied perpendicularly to the board surface which it can transfer when compressing with forces perpendicular to its surface. The board core cells usually have the hexagon shape similar to the regular hexagon. Perpendicular setting of the core walls to the top liners causes that at the moment of reaching maximum flat-crush resistance it is slightly deformed when compared to the corrugated board. Owing to this fact it is a stiff and light construction material. Honeycomb paperboard is very often used combined with oriented standard board (OSB). Due to its advantages, the honeycomb paper cores are more and more often used instead of wood for production of packaging, furniture, doors or even car upholstery (Fig. 1).

a) b) c)

*Fig. 1: Application of honeycomb paperboard cores: a) box (Commercial materials Eltete 2016), b) filling of furniture boards (Commercial materials Egger 2014), c) doors (Commercial materials Kadimex 2014).*

The method presented for determination of honeycomb paperboard flat-crush resistance is based on stability of thin-walled isotropic plates (Brzozka 1965, Gere 2004, Krolak 1990, Timoshenko and Woinowsky-Krieger 1959) and orthotropic plates (Altenbach et al. 2001, 2004, Carlsson and Byron 1997, Jones 1999, Kołakowski and Kowal-Michalska 1999). The formulas presented for the *FCT* calculations were discussed in details in (Kołakowski 2003, 2004, Kołakowski and Mania 2007).

## MATERIAL AND METHODS

The tests were performed for 17 boards with height *H* ranging from 8 mm to 65 mm. The boards were made from paper with basis weight of 135 $g \cdot m^{-2}$ and thickness of 0.2 mm. Paper with basis weight of 135 $g \cdot m^{-2}$ was used both for the cores and the top liners. The square shaped test pieces with surface of 100 $cm^2$ were crushed. Compression of the board test pieces was carried out on the Zwick strength testing machine with force range up to 10 kN using two different apparatuses. One with two plates, fixed rigidly, with parallel surfaces having pressure on the test pieces. The other one with bottom plate fixed rigidly and the top plate fixed articulately. When testing the plates were getting close to each other at the speed of 12.5 $mm \cdot min^{-1}$.

### Cell geometric parameters

The article analyses two shapes of honeycomb cells: the theoretical one in the form of regular hexagon (Fig. 2) and the real one present in the board manufactured in industrial conditions, shown in Fig. 3.

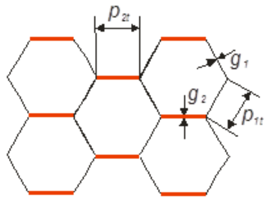

*Fig. 2: Theoretical cell in the shape of regular hexagon.*

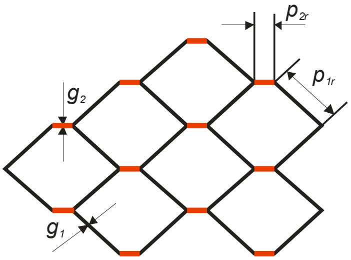

*Fig. 3: Cell in the real shape.*

In case of the regular hexagon shape, a diameter of a circle inscribed in the hexagon, given by a board manufacturer, was used for calculations, $d$ = 15 mm, on bases of which the cell side length was calculated $p_t = p_{1t} = p_{2t}$.

Knowing the side length of a regular hexagon, the cell area $A_{kt}$ was determined from known relationship:

$$A_{kt} = \frac{3 \cdot p_t^2 \cdot \sqrt{3}}{2} \tag{1}$$

On the basis of knowing an area of one cell, the number of cells on 1 $m^2$ of board $I_{kt}$ was determined.

The length of single cells $D_{p1t}$ and the total length of double walls $D_{p2t}$ on 1 $m^2$ of board, were calculated from the relationship:

$$D_{p_{1t}} = p_t \cdot 2 \cdot I_{kt} \tag{2}$$

$$D_{p_{2t}} = p_t \cdot I_{kt} \tag{3}$$

For calculation of an area of the real cells, parameters shown in Fig. 4 were used.

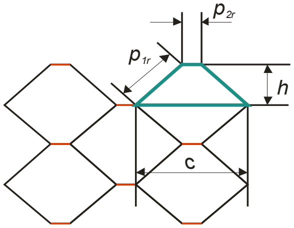

*Fig. 4: Geometric parameters of real cell.*

The geometric parameters of the cells with the real shape were determined as average values from 20 measurements.

The area of the real cell $A_{kr}$ was calculated using the following formula:

$$A_{kr} = (c + p_{2r}) \cdot h \tag{4}$$

Knowing the cell area, the number of the real cells $I_{kr}$ on 1 m$^2$ of the board was calculated.

Length $D_{p1r}$ of the walls with thickness $g_1$ and length $D_{p2r}$ of the walls with thickness $g_2$,

on 1 m$^2$ of the board were calculated from formulas (5, 6) analogically to the regular hexagon shaped cells:

$$D_{p_{1r}} = p_{1r} \cdot 2 \cdot I_{kr} \tag{5}$$

$$D_{p_{2r}} = p_{2r} \cdot I_{kr} \tag{6}$$

The number of the regular hexagon shaped cells on 1 m$^2$ of the board $I_{kt}$ was different from the number of the cells in the real shape $I_{kr}$.

## Calculation of *FCT* for the board with the cells with the theoretical shape

For the cells with the theoretical shape of the regular hexagon, using measured Young's moduli for the paper used for the production of the cores, the method of approximate assessment of *FCT* values was proposed. It was assumed that in each hexagonal theoretical cell, each wall has thickness $g_1$ and three walls co-operate independently.

Critical force $P_{cr}$ per one cell, when the work of three walls with thickness of $g_1$ is taken into account (Kołakowski 2003, 2004, Kołakowski and Mania 2007) is:

$$P_{cr} = \sigma_{cr} 3 g_1 p_t = \frac{\pi^2 g_1^3}{p_t} \sqrt{E_{MD} E_{CD}} \tag{7}$$

where: $\sigma_{cr}$ - stress causing loss of load capacity of one cell wall,
$E_{MD}$ - Young's modulus for paper in machine direction,
$E_{CD}$ - Young's modulus for paper in cross direction.

As one of the cell walls has thickness $g_2 = 2g_1$, formula (7) was modified by correction factor of stiffness $\alpha$, which can be determined experimentally.

Considering formula (7), the board resistance to the *FCT* can be calculated from:

$$FCT = I_{kt}\, \alpha\, P_{cr} = \alpha\, I_{kt} \frac{\pi^2 g_1^3}{p_t} \sqrt{E_{MD} E_{CD}} \tag{8}$$

where: $\alpha$ - coefficient of elastic fixing of the walls of a single cell, where $1 \le \alpha \le 1.3$ .

## Calculation of *FCT* for the board with the cells with the real shape

When determining the load capacity of each wall, possible buckling or crashing were considered.

Using measured values of Young's moduli for the paper for the production of the cores, linear loading of a given wall $Nw_i$, causing loss of its loading capacity as a result of buckling were calculated using the following formula:

$$Nw_i = \beta\, \sigma_{cri}\, g_i = \beta \frac{\pi^2 g_i^3}{3p_i^2}\sqrt{E_{CD}E_{MD}} \tag{9}$$

where: $\sigma_{cri}$ - stress causing the loss of the loading capacity of one board wall (adequately for each wall),

$g_i$ - thickness of a given wall (adequately for the walls with single and double thickness $g_1$ and $g_2$ were substituted),

$p_i$ - length of a given wall (adequately for each wall $p_{1r}$, $p_{2r}$ were substituted),

$\beta$ - coefficient taking into account an increase in stiffness of honeycomb walls results of buckling in place of joining with neighboring walls. On the bases of the tests of the boards in this article it was assumed that $\beta$ = 2.

The linear loading, which a given wall can transfer in case of losing the load capacity as a result of crushing $Ns_i$ for the walls of thickness $g_1$, was determined from the relationship:

$$Ns_i = SCT_{MD} \tag{10}$$

for walls with thickness $g_2$ from relationship:

$$Ns_i = 2 \cdot SCT_{MD} \tag{11}$$

where: $SCT_{MD}$ - short span compressive test in machine direction of paper used for the core production.

As the maximal loading capacity of a given wall $Nmax_i$ the smaller values from the measured ones were assumed:

$$Nmax_i = min\ (NS_i,\ Nw_i) \tag{12}$$

The *FCT* was calculated as a sum of forces transferred by all the walls on the surface of 1 m$^2$ of the board using formula:

$$FCT = \sum_{i=1}^{n} Nmax_i \cdot p_i \tag{13}$$

where: $n$ - number of the walls on the unit of board surface,

$p_i$ - wall length.

With maximum assessment value of the Flat Crush Resistance *FCTmax*, it was assumed, in accordance with the method of boundary capacity known from strength of materials, that both types of the walls (thickness $g_1$ and thickness $g_2$), at the moment of achieving the maximal *FCT* value, they will transfer maximal value of linear loading $Nmax_i$, which they reach at the moment of the loss of loading capacity. Then the relationship (13) takes the form of:

$$FCTmax = \sum_{i=1}^{n} Nmax_i \cdot p_i \tag{14}$$

With minimum assessment value of the Flat Crush Resistance *FCTmin*, conformity condition of relative deformations of all the walls was considered assuming that $g_2 = 2g_1$ and $p_{1r} \geq p_{2r}$. In this case, the Flat Crush Resistance of the board *FCTmin* can be determined from the relationship:

$$FCTmin = I_{kr}\, \beta \frac{2\pi^2 g_1^3}{3p_{1r}^2}(p_{1r} + p_{2r})\sqrt{E_{MD}E_{CD}} \tag{15}$$

## RESULTS AND DISCUSSION

Wand and Wang (2007) presented the compressive behavior of paper honeycombs and experimental results of the differential thickness of honeycomb paperboard under out-of plane loading.

The results of calculations and experimental studies for two different calculation models were compared. In the first model it was assumed that the collapse is described with critical loading for double-wall honeycomb for elastic condition. Whereas in the other model the collapse appears for rigid-plastic collapse stress.

The models are used for isotropic materials, while orthotropic properties of paper are described by coefficients determined experimentally.

Whereas, a collapse criterion, Muc and Nogowczyk (2005) show critical forces for isotropic model, however not taking paper as orthotropic material into account.

As a collapse criterion, the authors assume the critical forces determined for honeycomb paperboard including orthotropic properties of paper.

The comparison of the measurement and calculation results made for the boards with the regular hexagon shaped cells for different values of coefficient $\alpha$ is presented in Fig. 5.

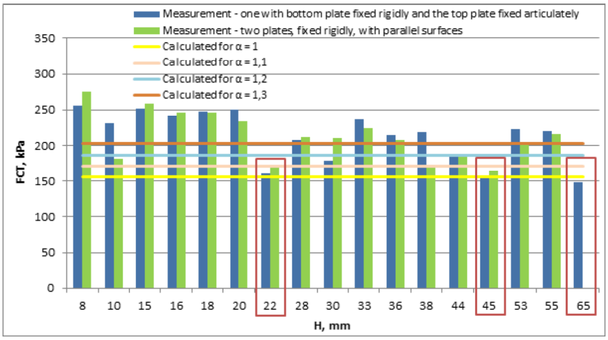

*Fig. 5: Comparison of calculation and measurements results for FCT of the board with the regular hexagon shaped cells – brown frames show the boards where crushing of core walls was observed during production.*

The comparison of measurement and calculation results of maximum assessment of *FCTmax* (14) of the boards with the cells with real shape is presented in Fig. 6.

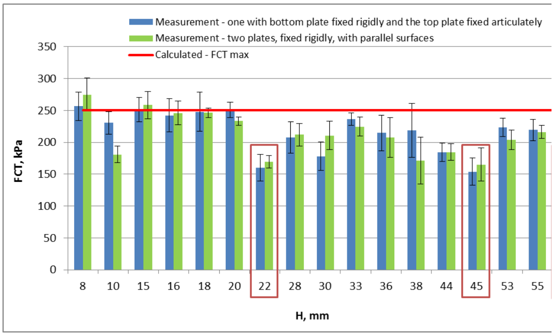

*Fig. 6: Comparison of measurement and calculation results FCTmax (formula 14) – brown frames show the boards where crushing of core walls was observed during production.*

The comparison of measurement and calculation of minimal assessment of *FCTmin* (15) of the boards with the cells with real shape is presented in Fig. 7.

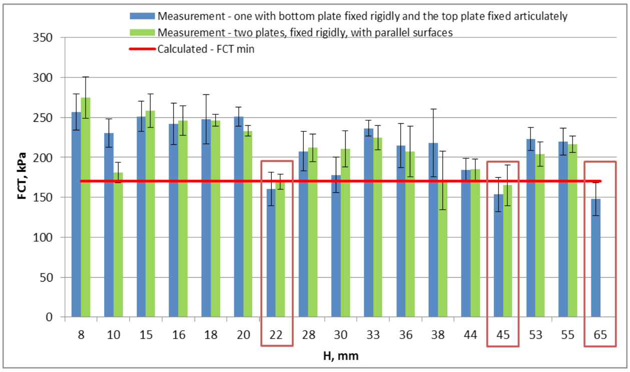

*Fig. 7: Comparison of measurement and calculation results FCTmin (formula 15) – brown frames show the boards where crushing of core walls was observed during production.*

On the basis of the measurements it can be concluded that the differences between the *FCT* values obtained at rigidly and articulately fixed upper plate are random and they are in the range of measurement errors.

The lowest values were obtained in the cases marked in diagrams with frames, in which the cores were crushed during the board production. In these cases, on the walls of the core, visible crushings were seen close to top liners. Despite the fact that with the same cell shape the *FCT* values of each board should be the same, even after eliminating the boards crushed during the production, clear differences are seen in their resistance to the Flat Crush Test. They can be explained by the differences in the resistance of papers used for the production of the cores. When making the core, the papers are un winded simultaneously from several rolls and as it is widely known, the properties of the papers manufactured in different batches can differ significantly.

Comparing the results of measurements and calculations presented in Fig. 5, it can be concluded that, on average, in the tested cases the best representation of the real values is obtained by using coefficient $\alpha$ = 1.3 in the calculations.

The comparison of maximum assessment of the *FCT* with measurements results, presented in Fig. 6 shows, that only in two cases the value of maximum assessment is slightly smaller from the real values, and the difference is smaller from measurement errors.

The values of minimum assessment (Fig. 7) is higher from the value measured only in case of the boards damaged during the manufacturing process.

## CONCLUSIONS

The method of maximum and minimum assessment of the resistance of honeycomb paperboard to flat compression gives good results and can be used if a real shape of the cells with regular shape is known.

If the real shape of the cells is not known, to assess the board resistance to flat crush the method based on the assumption that the cells have the shape of the regular hexagon can be used. In the tested cases the method gives the results in the range between the maximum and minimum assessment.

The accuracy of the measurement results obtained with both methods depends significantly on the correctness of determination of mechanical properties of fibrous material used for the production of the board core.

## REFERENCES

1. Altenbach, H., Altenbach, J., Kissing, W., 2001: Structural analysis of laminate and sandwich beams and plates. An Introduction into the Mechanics of composite, Lubelskie Towarzystwo Naukowe, Lublin, 73 pp.
2. Altenbach, H., Altenbach J., Kissing, W., 2004: Mechanics of Composite Structural Elements, Springer-Verlag Berlin Heidelberg, 458 pp.
3. Barboutis, I., Vassiliou, V., 2005: Strength properties of lightweight paper honeycomb panels for furniture. Proceedings of International Scientific Conference, 10th Anniversary of Engineering Design (Interior and Furniture Design) October 17-18, Sofia, Bulgaria.
4. Bitzer, T., 1997: Honeycomb Technology – Materials, design, manufacturing, applications and testing, London, Chapman & Hall, 230 pp.
5. Brzoska, Z., 1965: Statics and stability of beam and thin-walled structures. PWN (Polish Scientific Publishers), Warsaw, (in Polish).
6. Carlsson, L.A., Byron Pipes, R., 1997: Experimental characterization of advanced composite materials. Lancaster, Bassel, 243 pp.
7. Commercial materials Egger, 2014: More from wood, Zoom light solutions CEE_PL_226924_2014.
8. Commercial materials Eltete, 2016: Transport Packaging Solutions. Honeycomb board. Light and strong, 100% recyclable. Copyright 2016 Eltete TPM Ltd.
9. Commercial materials Kadimex 2014: http://www.kadimex.com.pl/wypelnienia_plaster_miodu.html
10. Gere, J.M., 2004: Mechanics of materials (Six Edition), Brooks/Cole–Thomson Learning, Inc., Belmont USA.
11. Jones, R.M., 1999: Mechanics of composite materials (Second Edition), Taylor&Francis, 507 pp.
12. Kołakowski, Z., Kowal-Michalska, K., 1999: Selected problems of instabilities in composite structures, Technical University of Lodz, A series of monographs.
13. Kołakowski, Z., 2003: About a slightly different look at BCT (O nieco innym spojrzeniu na BCT), Przegląd Papierniczy 59(10): 605-606 (in Polish).
14. Kołakowski, Z., 2004: Determination of the BCT, (Określanie wskaźnika BCT), Przegląd Papierniczy 60(11): 631-632 (in Polish).
15. Kołakowski Z., Mania R., 2007: Closed method of lower bound estimation of the BCT index, (Zmodyfikowana zamknięta metoda oceny z dołu wskaźnika BCT), Opakowanie 7: 49-52 (in Polish).
16. Krolak M. (Ed.), 1990: Post-buckling behaviour and load carrying capacity of thin-walled plate girders, PWN (Polish Scientific Publishers), Warsaw-Lodz (in Polish).
17. Muc A., Nogowczyk R., 2005: Failure modes of sandwich structure with composite faces, (Formy zniszczenia konstrukcji sandwiczowych z okładzinami wykonanymi z kompozytów), Composites (Kompozyty) 5(4): 31-36.
18. Timoshenko S., Woinowsky-Krieger S., 1959: Theory of plates and shells. Mc Graw-Hill Book Company Inc., New-York, Toronto, London, 575 pp.

19. Wang D., Wang Z., 2007: Out-of-plane compressive properties of hexagonal paper honeycombs, Chinese Journal of Mechanical Engineering 20(2):115-119.

Zbigniew Kołakowski*
Technical University of Lodz
Faculty of Mechanical Engineering
Department of Material Strength
1/15 Stefanowskiego St.
90-924 Lodz
Poland
Phone: +48 42 6312423
*Corresponding author: zbigniew.kolakowski@p.lodz.pl

Włodzimierz Szewczyk, Gabriela Kmita-Fudalej
Technical University of Lodz
Institute of Papermaking and Printing
233 Wólczańska St.
90-924 Lodz
Poland
Phone: +48 42 6313810