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Experimental and Numerical Analysis of the Edge Effect for Corrugated and Honeycomb Fiberboard

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As the two typical structural paper packaging materials, corrugated fiberboard and honeycomb paperboard occupy an important position in the field of logistics packaging. Up to now, numerous studies were focused on the properties of the above sandwich paperboards. However, the issue of their edgewise compressive strength has reached no consensus yet. The objective of this study is to investigate the edge effect and the influence on edgewise compressive strength of the two sandwich paperboards by experimental and numerical simulation methods. Firstly, the standard size specimens of the two sandwich paperboards were made based on the machining direction (MD) and cross-machining direction (CD), and the edgewise compressive strength experiments were carried out. Secondly, the finite element models of corrugated fiberboard and honeycomb paperboard were constructed using the same material, comprehensive weight and thickness, while the numerical assessment on edgewise compressive strength of CD and MD of the models were analyzed, respectively. Finally, measures to restrain the edge effect were taken, and the edge enhancement finite element models of the two paperboards were eleborated. The buckling analysis was carried out based on the numerical method. The results obtained suggest that the edge effect is one of the major factors controlling the edgewise compression strength of corrugated fiberboard and honeycomb paperboard.

Keywords: corrugated fiberboard, honeycomb paperboard, edge effect, edgewise compressive strength, buckling analysis, numerical simulation.

Introduction. Nowadays, as environment-friendly materials, sandwich paperboards have been widely used in the packaging industry. Corrugated fiberboard and honeycomb paperboard are both periodic, array-shape and complicated spatial thin-walled structures. The cross section of corrugated paperboard CD is composed of several complete corrugated structures and two incomplete corrugated structures on both sides, while the cross section of MD is composed of several cantilever structures (Fig. 1). Both cross sections of honeycomb paperboard CD and MD are composed of incomplete cellular structures (Fig. 2). Therefore, it is very important to study the edge effect of the sandwich paperboard.

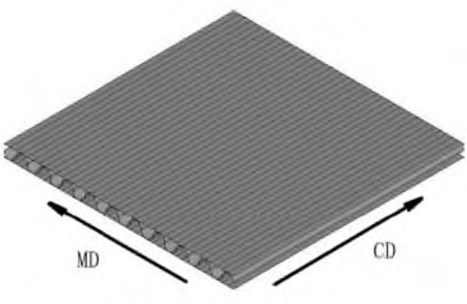

Fig. 1. Structure of corrugated paperboard.

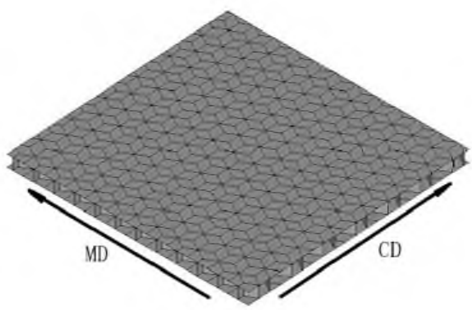

Fig. 2. Structure of honeycomb paperboard.

Although an extensive research has been carried on the edgewise compressive strength of sandwich paperboard, there is still no unified opinion on the mechanical properties of corrugated fiberboard and honeycomb paperboard [1–5]. By means of the numerical analysis, the edgewise compressive strength of large-size specimens of corrugated and honeycomb fiberboard was analyzed [6–8]. The results suggested that for the large-size specimens, the edgewise compressive strength of honeycomb cardboard was higher than that of corrugated cardboard, but no edge effect of sandwich paperboard has been revealed yet. The aim of this paper is to reveal the edge effect of sandwich paperboard by means of the experiment and simulation analysis.

1. **Methods.**

1.1. ***Edgewise Compressive Strength Test of Sandwich Paperboards***. A flute corrugated paperboard and a honeycomb paperboard with thickness of 6mm were selected. According to GB/T6546-1998, the 25×100 mm size specimens of the two sandwich paperboards in both CD and MD were cut randomly. Then the specimens were subjected to the thermal and humidity treatments according to GB10739. The edgewise compressive strength test was carried on the treated specimens with 12.5 + 2.5 mm/min displacement speed. The results are listed in Table 1.

T a b l e 1

Results of Edgewise Strength Test (N)

Specimen number	Flute-corrugated fiberboard		Honeycomb paperboard	
	MD	CD	MD	CD
1	75	422	478	305
2	76	477	563	396
3	124	461	566	391
4	43	441	505	420
5	117	421	400	383
6	138	476	568	200
7	115	453	535	450
8	50	447	577	408
9	50	440	630	441
10	71	457	562	283
11	114	453	420	382
12	102	444	541	468
13	105	410	546	430
Average	90.8	446.3	530.1	381.3
Standard deviation	31.5	20.1	64.4	75.9
Coefficient of variance	**34.8**	**4.5**	**12.2**	**19.9**

1.2. ***Numerical Simulation of Sandwich Paperboard***. The testing results of edgewise compressive strength were interfered by many factors, such as the fluctuation of temperature and humidity, the error of measuring system and specimens (such as uneven edges, error of height and length, sandwich board defects, etc.). In order to eliminate the influence of nonstructural factors, numerical models of corrugated and honeycomb fiberboard were established with ANSYS software [9]. The edgewise crush resistance of the models were calculated based on the buckling criterion. By means of numerical simulation, factors, such as the material, quantification, specimen size and dimension variations of honeycomb and corrugated fiberboard can be controlled. So the structural effect on edgewise compressive strength was decoupled.

1.2.1. *Materials*. In order to eliminate the impact of material selection, the same material was used in the numerical models of honeycomb and corrugated paperboard. Parameters of the paperboard used in the numerical models are shown in Table 2 [10].

Table 2

Parameters of Paperboard

Young modulus (MPa)			Shear modulus (MPa)			Poisson's ratio			Thickness (mm)	G, g/m^2
E_x	E_y	E_z	G_{xy}	G_{xz}	G_{yz}	μ_{xy}	μ_{xz}	μ_{yz}		
7600	4020	38	2140	20	70	0.34	0.01	0.01	0.269	200

1.2.2. *Paper Consumption*. In the numerical models, the corrugated fiberboard and honeycomb paperboard should utilize the same paper consumption. Based on the criterion of the same paper consumption, the hexagonal side of honeycomb paperboard is to be calculated according to the relative density of corrugated paperboard. According to the structure of corrugated fiberboard, the relative density of A flute-type corrugated paperboard is presented as

$$P_w = \frac{(2L+2\pi h)G}{Lh}, \tag{1}$$

where h is the thickness of corrugated paperboard, L is the period length of A flute, and G is the paper weight.

According to the structure of honeycomb paperboard, the relative density of honeycomb paperboard is presented as

$$P_f = \frac{(6\sqrt{3}a+8h)G}{3\sqrt{3}ah}, \tag{2}$$

where h is the honeycomb paperboard thickness, which is the same as the thickness of corrugated fiberboard, and a is the length of hexagonal side.

Let $P_f = P_w$, formula (3) can be derived:

$$\frac{(2L+2\pi h)G}{Lh} = \frac{(6\sqrt{3}a+8h)G}{3\sqrt{3}ah}. \tag{3}$$

Suppose the height of A flute is 5 mm, then $L = 2h = 10$ mm. According to Eq. (3), the result of $a = 4.9$ mm can be obtained.

1.2.3. *Simulation Models*. In order to reveal the edge effect of sandwich paperboard, three kinds of finite element models, including edge effect, edge enhancement, and large-scale edge enhancement models were elaborated.

The size of edge effect model was 25×100 mm. The cutting scheme of the edge effect model of corrugated paperboard and honeycomb paperboard were shown in are shown in Figs. 3 and 4, respectively. It can be seen from Figs. 3 and 4 that the different cutting position lead to different edge structures. The honeycomb paperboard and corrugated paperboard are all space array structures. If the cutting position of one side is controlled, the cutting position of the other side is automatically determined. According to Fig. 3, five edge effect models of corrugated paperboard in MD can be built, in which MD1 is the same as MD5. With one short side controlled according to Fig. 3, five edge effect models of corrugated paperboard in CD can also be built, in which CD1 is the same as CD5. According to Fig. 4, five edge effect models of honeycomb paperboard in MD and CD can be constructed, respectively. There is a total of twenty edge effect models.

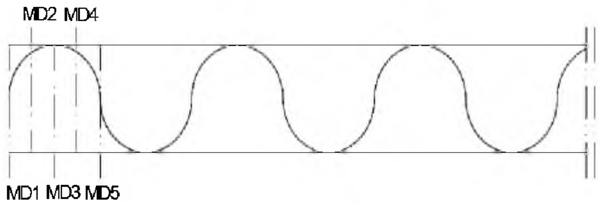

Fig. 3. Cutting scheme of corrugated paperboard.

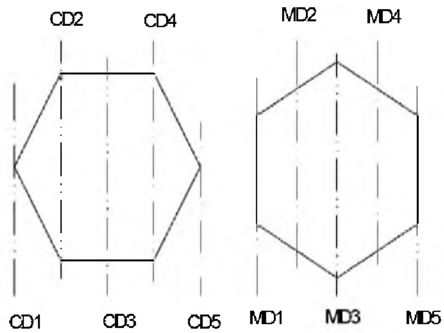

Fig. 4. Cutting scheme of honeycomb paperboard.

Selecting CD1 and MD1 from the edge effect models of honeycomb and corrugated paperboard, and repairing the four edges of each models, the edge effect enhancement model can be established. The total number of edge enhancement effect models is four.

Since the scale of engineering application is generally much larger than the standard specimen size, the large-scale edge enhancement model is applied to study the size and edge effects on the edgewise compressive strength of sandwich paperboard. There were four large scale edge enhancement effects models, and the model size was 200×100 mm. The geometry of edge effect model of corrugated fiberboard CD1 is shown in Fig. 5. The geometries of edge effect model of corrugated fiberboard CD1, edge enhancement model corresponding to CD1 and large-size edge enhancement model corresponding to CD1 are shown in Figs. 5–7, respectively.

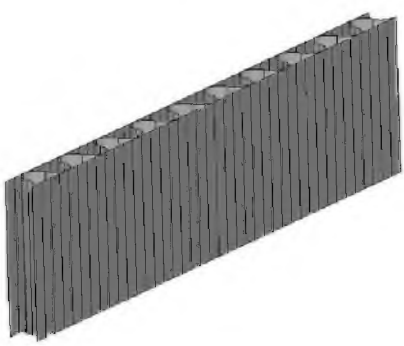

Fig. 5. Edge effect model geometry.

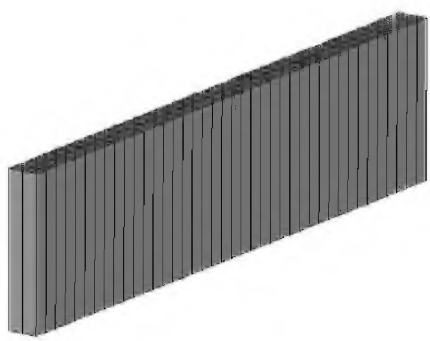

Fig. 6. Edge effect enhancement model geometry.

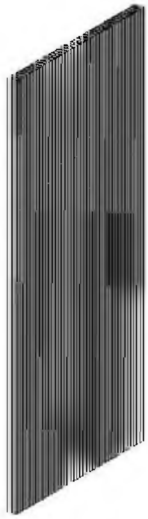

Fig. 7. Geometry of the large-size model.

The element SHELL63 is used in the numerical simulation models. All the thickness of the front, back plate and core of A flute corrugated and honeycomb paperboard are 0.269 mm. It is assumed that there is no failure in the binder, so the latter was not explicitly simulated. Constrains and loads condition should simulate the actual situation as close as possible. In the finite element models, it is supposed that the displacements of y direction of all the bottom nodes is zero. The pre-load of 1 N on $-y$ direction is applied to each node of the top edge. The eigenvalue buckling analysis was applied to the models respectively. The loads and constraints of the modes are shown in Fig. 8.

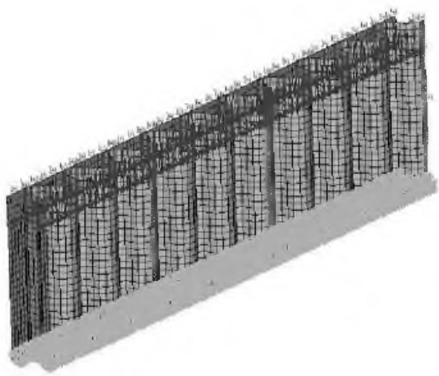

Fig. 8. Finite element model and constraints.

2. **Results**.

2.1. ***Results of Edgewise Compressive Strength***. The test results of edgewise compressive strength of A flute corrugated fiberboard and honeycomb paperboard are shown in Table 1. The data in Table 1 indicate that for the corrugated paperboard, the coefficients of variation of edgewise compressive strength (CVECS) in CD and MD are 4.5 and 34.8%, respectively. For the honeycomb cardboard, CVECS in MD and CD are about 12.2 and 19.9%, respectively. Therefore, the specimen of corrugated paperboard in CD has a small edge effect, the specimen of corrugated paperboard in MD and that of honeycomb paperboard in both CD and MD have an obviously large edge effect.

2.2. ***Simulation Results***.

2.2.1. *Results of Edge Effect Models of Corrugated Paperboard*. For the edge effect models of A flute corrugated paperboard, the buckling loads are shown in Table 3. The results suggest the buckling load in CD is higher than in MD, which is in accordance with the experimental results tabulated in Table 1. The buckling loads of different models are strongly fluctuated in both CD and MD. The results also reveal the existence of edge effect. The buckling modes of corrugated paperboard of edge effect model in MD1 and CD1 are shown in Figs. 9 and 10, respectively. Figure 9 shows that the buckling of MD model mainly occurs near the bearing area. Figure 10 shows that buckling of CD model mainly occurs near the side edge. It can be concluded that the edge effect of MD is significantly stronger than that of CD. It can be concluded that the edge effect of CD is mainly caused by MD.

Table 3

Buckling Load of A Flute Corrugated fiberboard (N)

Order	MD (25×100 mm)					CD (25×100 mm)				
	MD1	MD2	MD3	MD4	MD5	CD1	CD2	CD3	CD4	CD5
First order	90.4	124.1	178.8	69.1	90.4	551.3	407.4	1095.2	407.4	551.3
Second order	97.1	133.2	192.5	74.6	97.1	551.3	657.0	1096.0	657.0	551.3
Third order	109.4	148.5	214.4	85.3	109.4	896.1	762.8	1111.8	762.8	896.1
Fourth order	125.5	166.8	237.5	100.6	125.5	896.1	786.0	1112.7	786.0	896.1
Fifth order	146.2	188.4	261.8	121.3	146.2	919.8	1053.6	1128.3	1053.6	919.8

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Fig. 9. Buckling mode of A flute corrugated paperboard of edge effect model MD1. Here and Figs. 10–16: (a) first mode; (b) second mode; (c) third mode; (d) fourth mode; (e) fifth mode.

2.2.2. *Results of Edge Effect Models of Honeycomb Paperboard*. For honeycomb paperboard, the buckling loads of edge effect models are shown in Table 4. The compressive strength of CD is close to MD. The buckling loads of different models also exhibit a significant fluctuation in both CD and MD directions. This also indicates the existence of edge effect of honeycomb paperboard. By comparing the data in Tables 3 and 4, the compressive capacity of honeycomb paperboard in both CD and MD is close to the CD but higher than the MD of corrugated paperboard.

Table 4

Buckling Load of Honeycomb Paperboard (N)

Order	MD (25×100 mm)					CD (25×100 mm)				
	MD1	MD2	MD3	MD4	MD5	CD1	CD2	CD3	CD4	CD5
First order	905.0	1174.6	997.4	755.8	1035.6	658.4	1463.2	1341.6	1009.5	974.9
Second order	910.3	1177.3	1210.9	792.9	1040.9	665.2	1480.8	1347.8	1017.5	1012.5
Third order	922.1	1191.6	1318.1	1032.5	1049.7	685.0	1548	1351.5	1034.9	1028.6
Fourth order	925.6	1195.8	1377.5	1037.7	1064.9	1430.3	1659.1	1360.0	1041.2	1054.5
Fifth order	936	1208.2	1407.9	1043.7	1073.7	1509	1687.8	1363.9	1056.6	1063.1

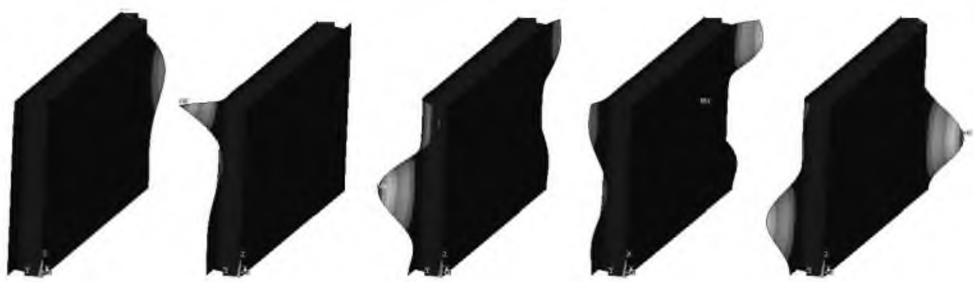

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Fig. 10. Buckling mode of A flute corrugated paperboard of edge effect model CD1.

The buckling modes of honeycomb paperboard of edge effect models MD1 and CD1 are shown in Figs. 11 and 12, respectively. The buckling of honeycomb paperboard in MD and CD mainly appears near the bearing surface, and sometimes occurs at the side edge parts.

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Fig. 11. Buckling mode of honeycomb paperboard of the edge effect model MD1.

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Fig. 12. Buckling mode of honeycomb paperboard of the edge effect model CD1.

2.2.3. *Predicted Results of Edge Enhancement Models*. The results of edge enhancement models of corrugated paperboard and honeycomb paperboard are shown in Table 5. For the 25×100 mm edge enhancement model, the buckling load of honeycomb paperboard is higher than that of corrugated paperboard. For the large-size edge enhancement model (200×100 mm), the first-order buckling loads of the two sandwich paperboards are close, but the higher-order buckling loads of honeycomb paperboard are higher than those of corrugated paperboard. Therefore, the compressive strength of honeycomb paperboard is superior to corrugated board under the condition of the restrained edge effect.

Table 5

Buckling Load of Edge Enhancement Model (N)

Order	A flute corrugated fiberboard				Honeycomb fiberboard			
	25×100 mm		200×100 mm		25×100 mm		200×100 mm	
	MD	CD	MD	CD	MD	CD	MD	CD
First order	615	1884	130	117	2399	2742	124	130
Second order	672	1885	440	1023	2410	2754	1088	1137
Third order	742	1912	452	1897	2426	2756	2389	2470
Fourth order	750	1913	457	1897	2435	2759	2403	2530
Fifth order	799	1915	466	1908	2459	2765	2416	2611

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Fig. 13. Buckling mode of corrugated paperboard of the edge enhancement model MD.

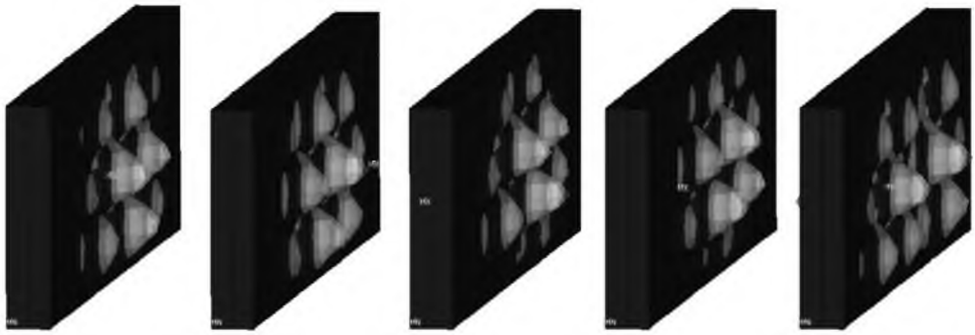

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Fig. 14. Buckling mode of corrugated paperboard of the edge enhancement model CD.

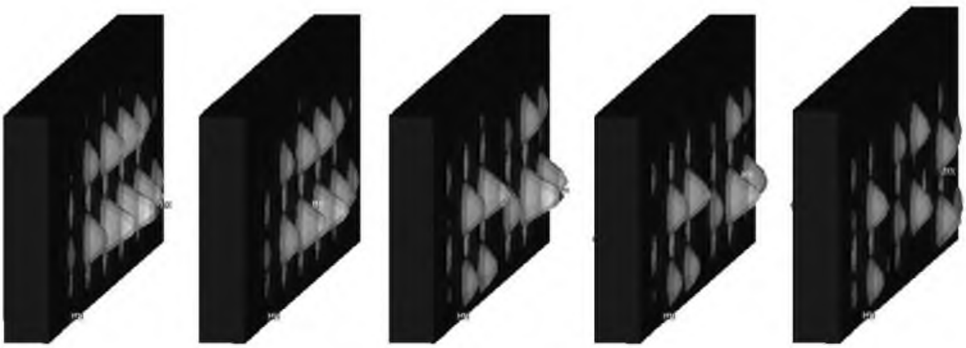

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Fig. 15. Buckling mode of honeycomb paperboard of the edge enhancement model MD.

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Fig. 16. Buckling mode of honeycomb paperboard of the edge enhancement model CD.

The buckling modes of edge enhancement model of corrugated paperboard are shown in Figs. 13 (MD) and 14 (CD). Figures 15 (MD) and 16 (CD) are the buckling modes of edge enhancement models of honeycomb paperboard. Figures 13–16 show that the buckling area is far away from the loading field. The results indicate that the edge enhancement model can effectively restrain the edge effect. The buckling modes of large-size edge enhancement models are similar to those of edge enhancement models.

Conclusions

1. The experimental and simulation results show that the edge effect is one of the major factors to affect the edgewise compressive strength of sandwich paperboards. For the corrugated fiberboard, the edge effect on MD is significantly stronger than that of CD. The edge effect of honeycomb paperboard for CD and MD is similar, which is stronger than that for CD, but weaker than that for MD of the corrugated fiberboard.

2. The finite element results of the edge enhancement model show that, under the condition restrained edge effect, the honeycomb paperboard has larger edgewise compressive strength than that of corrugated fiberboard.

3. Edge effect is one of the defects of the sandwich paperboards, which has affected the wide application of sandwich paperboards. Edge enhancement process will increase manufacturing costs. It is generally carried out in the packaging container forming process. In the practical application of the logistics packaging industry, especially the design of the paper tray and honeycomb paperboard boxes, a variety of technical measures has been adopted to enhance the edge of the sandwich paperboards. The results of this study are instrumental for more comprehensive understanding and reasonable application of the sandwich paperboards.

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