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Moment transfer factors for column-supported cast-in-situ hollow core slabs[*]

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Abstract: Hollow core slabs are becoming of increasing interest as the construction industry attempts to minimise the impact of its activities on the environment. By forming voids in the interior of a concrete slab, the amount of concrete used can be reduced without significantly altering the capacity of the structure. In this study, we examined the inner force transfer mechanism of a column-supported cast-in-situ hollow core slab using finite element analysis. Both a hollow core slab and the corresponding solid slab were analysed using ANSYS and the results were compared. The orientation of the tube fillers causes the stiffness of the hollow slab to be orthotropic, potentially changing the distribution of load carried in the two orthogonal directions. Both the cross-section's moments in the column strip and near the columns in the hollow core slab become larger than that in the solid floor. As well, the cross-section's stiffness along the tube arrangement direction is larger than that of the radial cross-section, which causes the direction along the hole of the hollow core slab to carry more moment than the radial direction. The conversion factors of the two directions are proposed from the comparison for four typical areas of the hollow core slab, as are the moment distribution coefficients.

Key words: Reinforced concrete, Cast-in-situ, Hollow core slab, Tube filler, Finite element analysis
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1 Introduction

The impact of the construction industry on the environment is becoming an increasing global concern. In particular, the contribution of cement production to carbon emissions has come under scrutiny. In turn this has raised interest in methods of increasing the efficiency of concrete usage. Much of the load resisted by a concrete structure is the weight of the structure itself. Reducing the weight of the structure not only saves concrete directly, but also potentially allows reduced structural sections, as the dead load is correspondingly reduced. Hollow concrete floors are therefore, becoming of increasing interest in building construction. By forming voids in the interior of a concrete slab, the amount of concrete used can be reduced without significantly altering the capacity of the structure.

The cast-in-situ hollow core slab was first suggested by Leopold MOLLER in the 1960s, and was named the B-Z system (Fertigteil-Vertrieb Gmbh, Mannheim, 1965). This cellular hollow core slab structure was studied through a series of experiments performed by Franz (1965). A method

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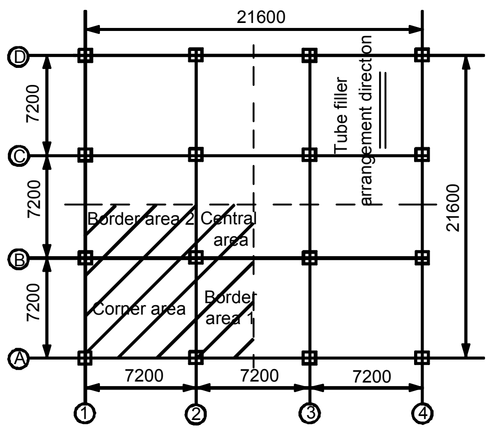
for designing the hollow core slab structure under static load by computing the equivalent solid floor with the same stiffness as the hollow core slab was developed. Hendler (1968) presented another approach where required thickness values of the hollow core slab were determined for different spans and loads. These values took into account bending deformation, however, they were not based on an experimental study. Elliot and Clark (1982) proposed and verified a stiffness coefficient formula for the circular voided concrete slab through elastic testing and finite element analysis. This formula allows computation of the stiffness of equivalent beams for GBF (one type of thin wall composite pipe with high strength) tube filler hollow core slabs. Takabatake and Yanagisawa (1996) proposed a numerical method for analysing hollow slabs with circular and rectangular holes. This method can be used for calculating holes of arbitrary configuration, taking into account bending deformation and transverse shear deformation at the same time.

Mo (2003) performed finite element analysis and an experimental study of side-supported cast-in-situ hollow concrete floors. Kim *et al.* (2010) studied the flexural capacities of one-way hollow slab with donut type hollow sphere, and Hegger (2009) and Hegger *et al.* (2010) conducted finite element analyses of shear-loaded precast hollow-core slabs on different supports. Truderung *et al.* (2010) studied the shear capacity of dry-cast extruded precast/prestressed hollow core slabs. Chung *et al.* (2010) found that the current design provisions for concrete solid slabs are applicable to hollow slabs, without significant modification, for the evaluation of flexural strength and initial stiffness essential to the serviceability check. Also, others (Gao, 2003; Girhammar and Pajarib, 2008; Rahman *et al*., 2009; Feng, 2009; Chang *et al*., 2010; Li *et al*., 2011) have studied hollow core slabs, but very little work has been done with respect to column-supported cast-in-situ hollow concrete floors. The most difficult aspect of these slabs is the analysis of the floor system. The state of stress and strain distribution within the hollow core slab can only be successfully obtained through analysis; although, the overall deformation of the slab can be observed in experiments. The design of the hollow core slab has to be carried out despite a lack of research results.

The hollow core slab system can be analysed via a 3D finite element model with fine meshing. From this model the stress and moment distribution of the floor can be obtained under working load. This paper deals with the performance evaluation of column supported cast-in-situ slabs with voids formed through the inclusion of tube fillers.

2 Numerical models

To compare the behaviour of a typical column-supported hollow slab with its solid counterpart, a particular slab of typical dimensions was adopted. The layout of the slab and columns is shown in Fig. 1a. A quarter of the floor was chosen as the numerical model and each floor model was subjected to a vertical uniformly distributed load of magnitude 0.01 N/mm^2.



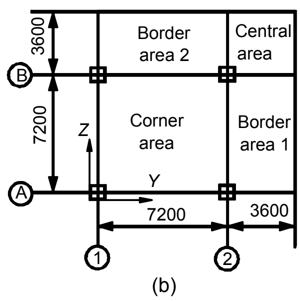


Fig. 1 Floor system model indicating four kinds of typical areas (unit: mm)
(a) The whole floor system model; (b) One fourth of the floor system model. A, B, C, D, 1, 2, 3, and 4 are the construction position axes

The dimensions of the floor system are 21.6 m×21.6 m (Fig. 1a). Each panel of the slab is 7200 mm ×7200 mm. There are three panels in each direction, leading to a total of nine slab panels. The dimension of each column cross-section is 600 mm×600 mm.

The thickness of the floor is 300 mm, and all the tube fillers are aligned along one direction, which will be denoted the *Z* direction, as indicated in Fig. 1b. The diameter of the hole formed by tube filler is 200 mm, and the tube filler's length is 900 mm. The rib width between adjacent fillers in each direction is 100 mm, so that the distance between the centres of the holes formed by tube fillers is 300 mm. Fig. 1a also shows four kinds of typical areas in the model. Due to the symmetry, one fourth of the floor system has been modelled numerically, as illustrated in Fig. 1b. Figs. 2a and 2b show cross-sections of the hollow slab along two directions. a-a′ and 1-1′ are typical cross lines. Solid 45, which is a 3D solid element type, has been chosen for setting up the models. The finite element models of the two floor systems are illustrated in Figs. 3a and 3b.

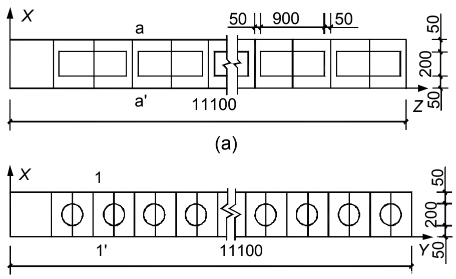


Fig. 2   Section along (a) radial direction (*Y* direction) and (b) tube direction (*Z* direction)

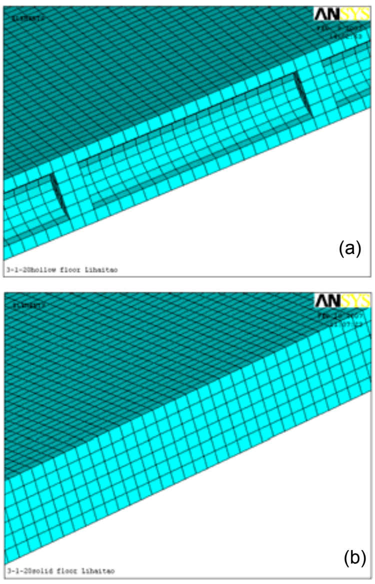


Fig. 3   Hollow core slab (a) and solid slab (b) finite element model

3 Moment analysis

Designers work with moments rather than normal stresses, and slab design is often done using moments resulting from elastic analysis. In this section, the distributions of elastic moments in the hollow and solid slabs are compared to see if there are significant differences. The moments are synthesized by numerical methods from the stress calculated by ANSYS (Wang, 2007).

Moment comparisons along different axes in different typical areas have been performed. The moment for the radial direction of the cross-section is compared along several lines parallel to the *Z* axis, while the moment for the tube direction of the cross-section is compared along several lines parallel to the *Y* axis.

3.1 Moments in the corner area

The moment comparison along different cross lines in the corner areas is presented in Fig. 4. As expected, in comparison to the solid slab, the hollow slab carries more of the load (Figs. 4d and 4e) in the tube direction and less (Figs. 4a and 4b) in the radial direction in the hollow core area, whereas the solid slab carries equal load in each direction. This is evident at the middle of the span where the maximum positive moment in the direction across the tubes is about 20% less than that in the solid floor (Figs. 4a and 4b). Along the column lines, the moments are slightly higher in the hollow core slab in both directions, while at the middle of the span in the direction along the tubes the moment is increased by about 8% (Fig. 4f).

3.2 Moments in border area 1

The moment comparison along different typical position axes in the border area 1 can be seen from Fig. 5. Due to the symmetry, only one half of the floor system has been compared with each other. Similar to the corner area, the hollow slab carries more of the load (Figs. 5e and 5f) in the *Z* direction and less (Figs. 5a and 5b) in the *Y* direction in the hollow core area in both directions whereas the solid slab carries an equal load in each direction. The maximum positive moment in the *Y* direction at the middle of the span is about 22% less than the

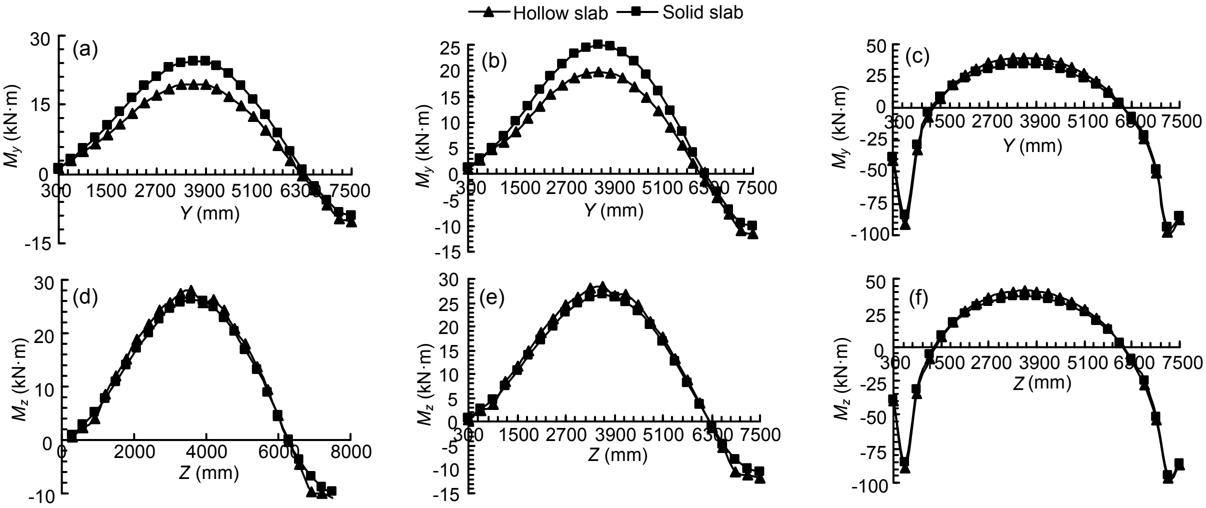


Fig. 4 Moment comparisons along various lines in the corner area

(a) Z=3300 mm axis; (b) Z=4500 mm axis; (c) Z=7500 mm axis; (d) Y=3300 mm axis; (e) Y=4500 mm axis; (f) Y=7500 mm axis

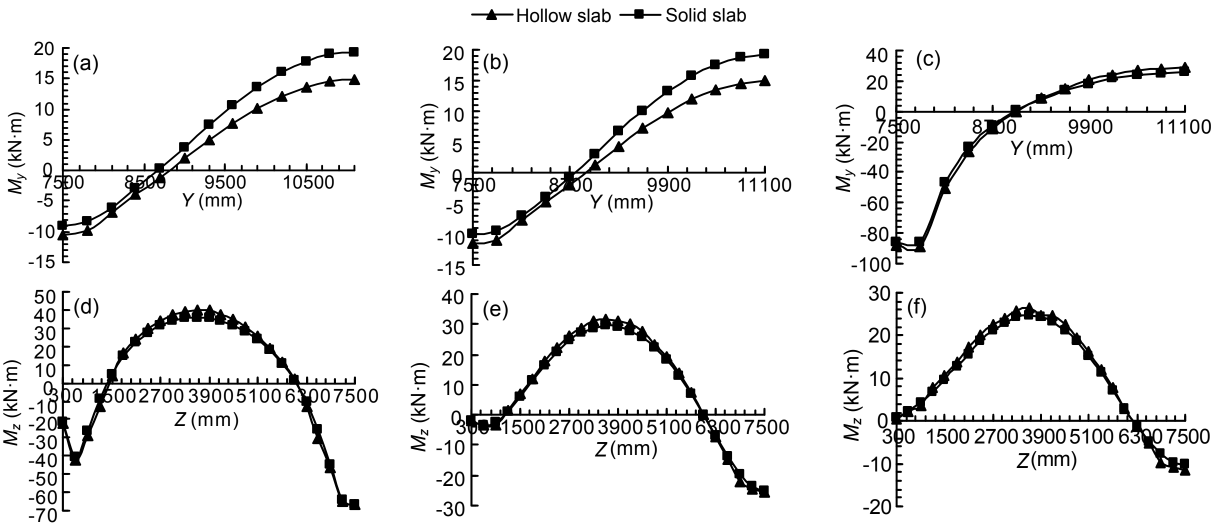


Fig. 5 Moment comparisons along different axis in the border area 1

(a) Z=3300 mm axis; (b) Z=4500 mm axis; (c) Z=7500 mm axis; (d) Y=8100 mm axis; (e) Y=9300 mm axis; (f) Y=10500 mm axis

moment in the solid floor (Figs. 5a and 5b). Along the column lines, the moments are slightly higher in the hollow core slab in both directions, while at the middle of the span in the Y direction the moment is increased by about 12% (Fig. 5c).

3.3 Moment of the border area 2

The moment comparison along different typical axis in the border area 2 can be seen from Fig. 6. Only one half of the floor system has been compared in the border area 2 because of symmetry. The hollow slab carries more of the load (Figs. 6d and 6e) in the Z direction and less (Figs. 6b and 6c) in the Y direction in the hollow core area in both directions whereas the solid slab carries equal load in each direction. The maximum positive moment in the Y direction at the middle of the span is about 22% less than the moment in the solid floor (Figs. 6b and 6c). Along the column lines, the moments are slightly higher in the hollow core slab in both directions, while at the middle of the span in the Y direction the moment is increased by about 8% (Fig. 6f).

3.4 Moment of the central area

Fig. 7 shows the moment comparison along different typical axis in the central area. Due to the symmetry, one quarter of the floor system has been compared in the central area. Similar as other areas, the hollow slab carries more of the load (Figs. 7e and 7f) in the *Z* direction and less (Figs. 7b and 7c) in the *Y* direction in the hollow core area in both directions, whereas the solid slab carries equal load in each direction. The maximum positive moment in the *Y* direction at the middle of the span is about 21% less than that in the solid floor (Figs. 7b and 7c). Along the column lines the moments are slightly higher in the hollow core slab in both directions, while at the middle of the span in the *Y* direction the moment is increased by about 10% (Fig. 7d).

It can be seen from Figs. 4–7 that, the moment distribution of the hollow core slab changed because of the arrangement of the tube fillers compared with the corresponding solid floor. Both the moments' absolute values near the support along the *Y* and *Z* directions of the hollow core slab are larger than those of the solid floor. However, in the middle span, most parts of the moment value along the *Y* direction

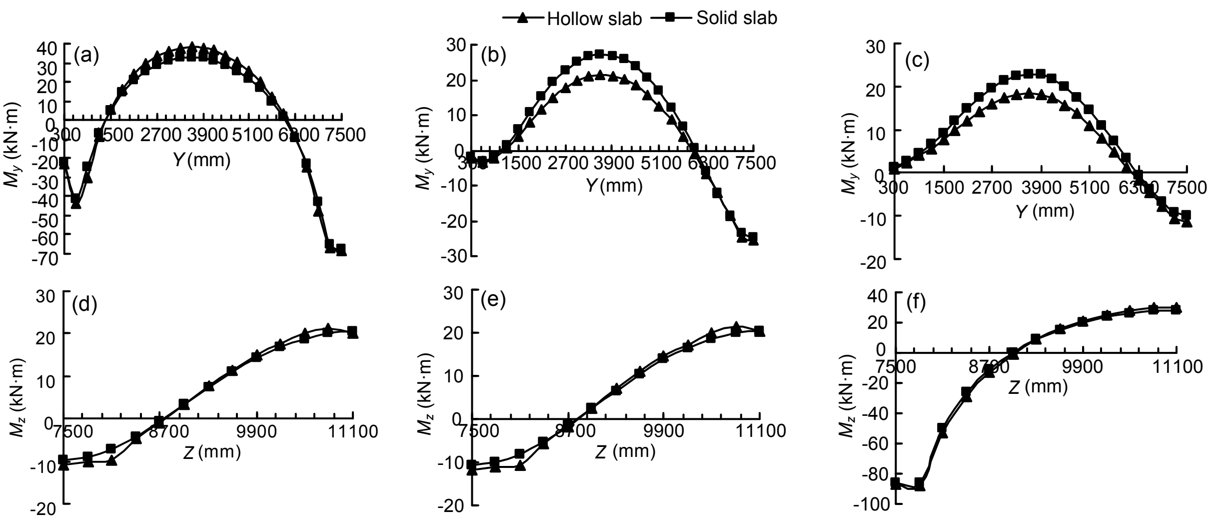


Fig. 6 Moment comparisons along different axis in the border area 2
(a) Z=8100 mm axis; (b) Z=9300 mm axis; (c) Z=10 500 mm axis; (d) Y=3300 mm axis; (e) Y=4500 mm axis; (f) Y=7500 mm axis

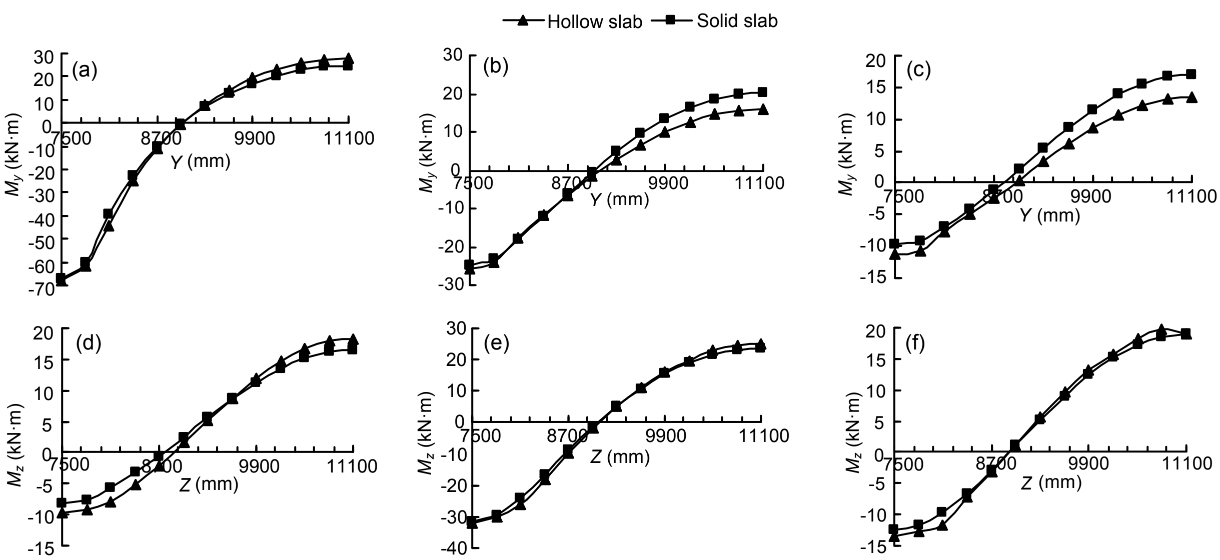


Fig. 7 Moment comparisons along different axis in the central area
(a) Z=8100 mm axis; (b) Z=9300 mm axis; (c) Z=10 500 mm axis; (d) Y=7500 mm axis; (e) Y=9300 mm axis; (f) Y=10 500 mm axis

become larger except that few special parts' moment (lies between the hollow part and solid part, Fig. 2) decreases (because of the stress concentration caused by a sudden weakness of the cross-section), compared with the corresponding solid floor, while all parts of the moment value along the Z direction increase.

It can also be seen that, in all typical areas, the moment value along the Y direction of the hollow core slab in the column strip is larger than that of the solid floor (Figs. 4c, 5c, 6a, and 7a). However, the moment value along the Z direction in the middle strip of the hollow core slab is smaller than that of the solid floor (Figs. 4a and 4b, Figs. 5a and 5b, Figs. 6b and 6c, Figs. 7b and 7c), and the moment near the columns in the hollow core slab is larger than that in the solid floor (Table 1). The reason is that the existence of the tube fillers weakens the floor cross-section's stiffness, and changes the inner mechanics distribution of the floor. Because some stress of the hollow areas is transferred to the solid areas, the solid areas have to partake in more moment. When designing the hollow core slab, these parts should be strengthened by adding more reinforcement to prevent early destruction.

Also, in all typical areas, the cross-section moment value along the Z direction of the hollow core slab in all strips is larger than that of the corresponding solid floor (Figs. 4d–4f, Figs. 5d–5f, Figs. 6d–6f, and Figs. 7d–7f). The reason is that the cross-section's stiffness along the tuber arrangement direction is larger than that of the radial cross-section because of the tube fillers' existence. The stiffness difference between the two directions resulted in the redistribution of the moment, and the cross-section along Z direction can carry much more moment than the radial cross-section in the hollow core slab.

4 Strip moment analysis

One direction is the radial direction, and the other is along the tube arrangement direction. The results can be seen from Tables 2 and 3.

As shown in Tables 2 and 3, although the strip moment values of the column-supported tube filler cast-in-situ reinforced concrete floor and that of the corresponding solid floor are close, there is some difference in the local part. Furthermore, the difference in some places is even large. That is to

Table 1 Maximum moment comparison near the columns

Slab	Maximum moment (kN·m)							
	Near corner column Z_1		Near border column Z_2		Near inner column Z_3		Near border column Z_4	
	Y direction	Z direction	Y direction	Z direction	Y direction	Z direction	Y direction	Z direction
Hollow core slab	59.53	57.83	91.59	88.99	97.59	96.39	48.85	48.37
Solid floor	55.32	55.45	84.60	84.70	94.43	94.44	47.15	47.22
Distinction percentage	7.61%	4.29%	8.26%	5.06%	3.35%	2.06%	3.61%	2.43%

Y direction is the radial direction, Z direction is the hole direction

Table 2 Strip moment comparison of the corner area

Strip		Strip moment (kN·m)							
		Y direction				Z direction			
		Support (side)	Middle span	Inner support	Total moment	Support (side)	Middle span	Inner support	Total moment
Column strip (border)	Hollow	−64.36	57.35	−93.57	136.32	−62.69	70.48	−92.76	148.21
	Solid	−60.05	60.23	−90.38	135.45	−59.98	65.30	−90.14	140.36
Middle strip	Hollow	5.07	74.59	−49.99	97.05	3.84	99.35	−50.68	122.77
	Solid	6.66	91.09	−45.06	110.29	5.11	97.51	−46.77	118.34
Column strip (inner)	Hollow	−64.14	54.36	−106.46	139.66	−62.13	69.28	−105.12	152.90
	Solid	−59.62	57.68	−103.79	139.38	−59.33	62.48	−103.25	143.76
Total moment	Hollow	−123.43	186.30	−250.01	373.03	−120.97	239.11	−248.56	423.88
	Solid	−113.01	209.01	−239.23	385.13	−114.20	225.28	−240.16	402.46

Y direction is the radial direction, Z direction is the hole direction. Hollow represents for hollow core slab and solid stands for solid floor

Table 3 Strip moment comparison of the border and central area

Strip			Strip moment (kN·m)						
			Y direction			*Z* direction			
			Support (side)	Middle span	Total moment	Support (side)	Middle span	Inner support	Total moment
Border area 1	Column strip (border)	Hollow	−88.20	44.20	132.40	−60.54	66.96	−98.07	146.27
		Solid	−87.34	47.07	134.41	−57.96	60.62	−96.80	138.00
	Middle strip	Hollow	−49.77	57.81	107.58	1.37	47.44	−25.54	59.52
		Solid	−45.07	71.67	116.74	1.86	46.15	−23.61	57.02
	Column strip (inner)	Hollow	−100.2	41.05	141.25				
		Solid	−97.72	43.97	141.70				
	Total moment (James and James, 2009)	Hollow	−238.17	143.06	381.23	−59.17	114.40	−123.60	205.78
		Solid	−230.14	162.72	392.85	−56.10	106.76	−120.41	195.02
Border area 2	Column strip (border)	Hollow	−62.48	52.93	−99.42	133.88	−87.26	54.49	141.75
		Solid	−58.18	55.87	−97.24	133.59	−84.79	51.16	135.94
	Middle strip	Hollow	1.836	35.42	−25.34	47.17	−50.44	77.09	127.53
		Solid	2.505	42.83	−22.90	53.03	−46.75	76.43	123.18
	Column strip (inner)	Hollow					−98.88	52.20	151.08
		Solid					−97.16	47.96	145.12
	Total moment	Hollow	−60.64	88.35	−124.76	181.05	−236.58	183.77	420.36
		Solid	−55.68	98.70	−120.15	186.62	−228.70	175.54	404.24
Central area	Column strip	Hollow	−93.06	39.54	132.61	−98.22	49.87		148.09
		Solid	−91.11	42.15	133.26	−96.83	45.94		142.76
	Middle strip	Hollow	−23.82	23.63	47.45	−30.59	37.15		67.73
		Solid	−21.74	29.70	51.44	−28.89	36.08		64.97
	Total moment	Hollow	−116.89	63.17	180.06	−128.81	87.02		215.83
		Solid	−112.84	71.85	184.70	−125.72	82.02		207.73

Y direction is the radial direction, *Z* direction is the hole direction. Hollow represents for hollow core slab and solid stands for solid floor

say, the overall distribution of the inner forces is closer between the two kinds of floor systems, but not exactly the same, and an obvious difference does exist in some parts. The strip moment along the *Y* and *Z* directions of the hollow core slab are not equal. The minus moment in the support of the column strip increases along the two directions. Particularly, the minus moment in the inner support of the middle strip bears a larger increase (10.94% along the *Y* direction and 8.34% along the *Z* direction). As for the moment along the *Y* direction, not only the plus moment of the column strip, but also that of the middle strip decreases in all typical areas compared with those of the solid floor. However, as for the moment along the *Z* direction, both the plus moment of the column strip and that of the middle strip increase.

Also, from Table 2 for the corner area, the total statical moment along the two directions of the hollow core slab is 373.03+423.88=796.91 kN·m, while the total statical moment along the two directions of the hollow core slab is 385.12+402.46=787.58 kN·m, and the difference between them is 1.17%. The two are equal, considering the calculation allowance inaccuracy. The total statical moment along the *Y* direction of the hollow core slab decreases 3.14% and the total statical moment along the *Z* direction increases 5.32% compared with those of the solid floor, which demonstrates the anisotropic characteristics of the hollow core slab. From Table 3, it can be seen that the total statical moments along two directions are not the same for other typical areas. We can conclude that the moment coefficients of the hollow core slab are not the same as the solid floor for direct design method, and new moment coefficients of the hollow core slab need to be proposed.

From the moment comparisons between the two floor systems, the conversion factors of the two directions can be obtained for four typical areas of the hollow core slab, which can be referred to Table 4. Referring to the moment coefficients of the solid floor (ACI Committee 318, 2005) and according to the finite element results comparison, both the moment transfer coefficients of the critical cross-sections for different areas in different directions of solid floor and the hollow core slab can be obtained, which can be seen from Table 5.

Note: (1) When one side of the calculation strip is the floor side, the middle strip of the area will be divided into half, and one is close to the floor side, the other is close to the middle of the floor. The value outside of the bracket is the moment coefficient of the half middle strip close to the floor side and the value in the bracket is the moment coefficient of the half middle strip close to the middle of the floor. (2) Due to symmetry, only the coefficients of one fourth of the floor have been given in the table.

5 Conclusions

Both a hollow core slab and the corresponding solid slab were analysed using ANSYS, and the results were compared. Although the law of the inner force distribution of the hollow core slab is similar to that of the corresponding solid floor, there is still a great difference between them. The cavity weakened the cross-section stiffness of the hollow core slab, and simultaneously some inner stress of the hollow area transfers to the solid area. Also, both the cross-section moment in the column strip and near the columns in the hollow core slab becomes larger than that in the solid floor. Additionally, the stress between the tube filler and the solid hidden beam increases because of the existence of the cavity,

Table 4 Conversion factors for four typical areas

Cross-section	Conversion factor			
	Corner area	Border area 1	Border area 2	Central area
Radial cross-section	0.959	0.958	0.968	0.968
Hole direction cross-section	1.042	1.042	1.032	1.032

Table 5 Moment transfer coefficients of four typical areas

Strip			Moment transfer coefficient							
			Corner area		Border area 1		Border area 2		Central area	
			Y direction	*Z* direction	*Y* direction	*Z* direction	*Y* direction	*Z* direction	*Y* direction	*Z* direction
Column strip (border)	Support (side)	Hollow	0.291	0.262						
		Solid	0.260	0.260						
	Middle span	Hollow	0.290	0.306	0.192			0.205		
		Solid	0.296	0.298	0.199			0.200		
	Support (inner)	Hollow	0.589	0.540	0.534			0.506		
		Solid	0.555	0.551	0.519			0.512		
Middle strip	Support (side)	Hollow	0 (0)	0 (0)		0 (0)	0 (0)			
		Solid	0 (0)	0 (0)		0 (0)	0 (0)			
	Middle span	Hollow	0.188 (0.099)	0.216 (0.113)	0.126 (0.068)	0.107	0.0943	0.145 (0.076)	0.0557	0.0729
		Solid	0.224 (0.117)	0.222 (0.116)	0.151 (0.083)	0.1101	0.1103	0.150 (0.080)	0.0685	0.0751
	Support (inner)	Hollow	0.164 (0.076)	0.153 (0.071)	0.148 (0.070)	0.0707	0.0765	0.143 (0.065)	0.0667	0.0782
		Solid	0.145 (0.067)	0.149 (0.069)	0.131 (0.062)	0.0691	0.0673	0.138 (0.061)	0.0597	0.0756
Column strip (inner)	Support (side)	Hollow	0.149	0.132		0.129	0.145			
		Solid	0.132	0.132		0.129	0.128			
	Middle span	Hollow	0.145	0.157	0.097	0.152	0.141	0.102	0.093	0.098
		Solid	0.149	0.149	0.102	0.145	0.144	0.100	0.097	0.096
	Support (inner)	Hollow	0.312	0.283	0.287	0.258	0.285	0.259	0.262	0.250
		Solid	0.295	0.293	0.275	0.269	0.271	0.260	0.253	0.253

and so does the stress located in the thinnest position up and down the tube filler. These positions should be strengthened during the course of designing. As well, the cross-section's stiffness along the tube arrangement direction is larger than that of the radial cross-section, which causes the direction along the hole of the hollow core slab to carry more moment than the radial direction. Both of the conversion factors of the two directions and the moment transfer coefficients are proposed from the comparison for four typical areas of the hollow core slab.

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