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Abstract

The sandwich panels, with plain and shallow grain pressed metal plate as the face sheets, and glass wools, rigid polyurethane foam, and rock wools as core materials, have excellent heat insulation and mechanical behavior, and been used as curtain walls for tall buildings in recent years in China. Since wind load and temperature action are the main actions for curtain walls, the sandwich panels are flexural members. In this paper, the design method and design formula of flexural load-carrying capacity and flexural deflection of a kind of sandwich plates with different metal panel on both sides are discussed and proposed. This proposed method considers the different load types, like uniform load, concentrated load, and temperature action, and different core materials. The FE Method can be verified by comparing on shear force distribution coefficients for different sandwich panels with same metal panels on both sides between FE results and calculated results. Then the FE Method can be used to verify the proposed method for shear force distribution coefficients of sandwich plates with different metal panel on both sides. Finally, the proposed method for bending load-carrying capacities for sandwich plates with different metal panel on both sides is verified using FE Method. These verifies show that the proposed method for shear force distribution coefficients and bending load-carrying capacities for sandwich plates with different metal panel on both sides is safe and suitable.

Introduction

A sandwich (Fig.1) structure consists of two thin face sheets of high strength firmly fixed to a light-weight thick core in between them. This structure

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possesses many features including light weight, high strength, higher bending stiffness, and great heat and heat insulation. Sandwich panel with metal skin panel first were used in aviation field. Some researchers (Hoff and Mautner 1956, Chong and Hartsock 1972) investigated the behavior of sandwich panel with plain metal skin panel. Then sandwich panels were used in architecture field with development of building engineering, researchers main studied the overall deformation, mechanical behavior, and buckling behavior of metal skin panel. Based on classical mechanics, Davies(Davies 1993) proposed the simple formula calculated maximum deflection of mid-span for simply supported sandwich panel using the approximate calculation method. Based on the study on buckling of steel skin panels, Styles et al.(Styles, Compston, and Kalyanasundaram 2008) investigated the buckling behavior and bending behavior of sandwich panel with aluminum skin panel. Jeyakrishnan et al.(Jeyakrishnan, Chockalingam, and Narayanasamy 2013) studied on buckling of honeycomb sandwich panel, and critical buckling load was found to be same for experimental, theoretical and FEA analysis. Ugale et al. (Ugale et al. 2013) studied influencing factor of bending load-carrying capacity and failure mode of three types of thin sandwich panels. Mostafa et al.(Mostafa, Shankar, and Morozov 2013) studied on the flexural behavior and failure mode of composite sandwich panels based on experimental, theoretical, and numerical method. With the development of Chinese architecture recently, the use of sandwich panel in China becomes more and more extensive. Institute of Mechanics of Chinese Academy of Sciences (IMCAS 1977), and Shi et al.(Shi etal. 2006) studied the behavior of sandwich panel based on math and mechanics. Wang et al.(Wang, He, and Tao 1999, Wang and He 2002) studied the buckling behavior of metal panel and bending load-carrying capacity of sandwich panel using experimental and numerical method. A series of experimental researches about sandwich panel with same metal panel on both side have been conducted (Zha 2011). All these researches consider the sandwich with same metal material on both side of panels, but the sandwich with different metal material on both side of panels are more and more used in China for requirement of architecture and there have no provision in Chinese code *Double skin metal faced insulating panels for building* (GB/T 23932-2009, 2009)for calculating bending load-carrying capacities of these sandwich panels, so the bending load-carrying capacity of sandwich panel with different metal skin panel on both sides under uniform load, concentrated load and temperature action are researched in this paper.

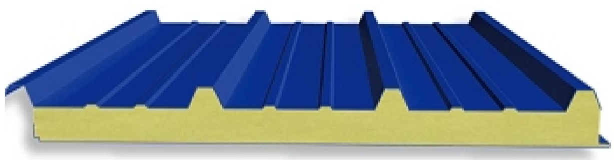

Fig.1 Sandwich panels

Analysis on bending load-carrying capacity of sandwich panel with different metal skin panel on both sides

Basic assumption of deflection and bending capacity for sandwich panels

1) The bending stiffness is only considered the metal skin panel because of less bending stiffness of core material, 2) The shearing deformation is considered the metal skin panel and core material, 3) the sandwich panels are designed to demand the serviceability limit state, so sandwich panel is controlled by deflection of panel and investigated using elastic method, 4） There is no slipping between metal skin panel and core material, 5）The metal skin panel and core material are all linear elastic materials, 6) the deformation of sandwich panel is limited in small deformation.

Analysis method of deflection of sandwich panels

Based on basic assumption of 3) and 6), the deflection of simply support sandwich panel can be analysis using displacement formula of structural mechanics.

$$f=\sum\int\frac{\overline{M}M_p}{EI}ds+\sum\int\frac{\overline{N}N_p}{EA}ds+\sum\int K\frac{\overline{Q}Q_p}{GA}ds+\sum\alpha t_0\int\overline{N}ds+\sum\alpha\frac{\Delta t}{h}\int\overline{M}ds \tag{1}$$

Eq.(1) can be rewritten as eq.(2) because the axial force don't need to consider for bending sandwich panels.

$$f=\sum\int\frac{\overline{M}M_p}{EI}ds+\sum\int K\frac{\overline{Q}Q_p}{GA}ds+\sum\alpha\frac{\Delta t}{h}\int\overline{M}ds \tag{2}$$

The maximum deflection of mid span of sandwich panel under uniform load can be given by integration.

$$f=\frac{5ql^4}{384EI}+\frac{kql^2}{8GA} \tag{3}$$

The maximum deflection of mid span of sandwich panel under concentrate load can be given by integration.

$$f=\frac{Pl^3}{48EI}+\frac{kPl}{4GA} \tag{4}$$

The maximum deflection of mid span of sandwich panel under temperature action can be given by integration.

$$f=\frac{\alpha\Delta tl^2}{8h} \tag{5}$$

Where f、q、l、E、I、G、A、P、h、α、Δt k are the deflection of sandwich panel, uniform load, length of sandwich panel, elastic modulus of sandwich panel, moment of inertial of sandwich panel, shear modulus of sandwich panel, area of sandwich panel, concentrated load, thickness of sandwich panel、linear expansion coefficient of sandwich panel, temperature of top and bottom surface for sandwich panel, cross section shape coefficient

respectively.
The bending stiffness of sandwich panel only considers bending stiffness of top and bottom metal panel based on basic assumption 1). The shearing deformation consider the metal skin panel and core material based on basic assumption 2）and the deformation of the metal skin panel and core material is same, so the deformation of core material is equal to total deformation of sandwich panel. At the same time, the percent of shear force of core material in total shear force of sandwich panel is defined as β which is called shear force distribution coefficient of core material, then deformation of shear can be calculated using shear force and shear stiffness of core material. The deflection of sandwich panel can be calculated using expression (6), (7), and (8).

$$f = \frac{5qbl^4}{384\left(E_t I_t + E_b I_b\right)} + \frac{k\beta qbl^2}{8G_c A_c} \tag{6}$$

$$f = \frac{Pl^3}{48\left(E_t I_t + E_b I_b\right)} + \frac{k\beta Pl}{4G_c A_c} \tag{7}$$

$$f = \frac{\left(k_t t_t - k_b t_b\right) l^2}{8h} \tag{8}$$

Where β is the shear force distribution coefficient, E_t、E_b、I_t、I_b is the elastic modulus and moment of inertial for natural axis of top and bottom metal panel respectively, G_c、A_c is the shear modulus and area of core material, the shear modulus of different core material can be calculated as table 1(Zha 2011), k_t、k_t、t_b、t_b is the linear expansion coefficient and thickness of top and bottom metal panel for sandwich panel respectively.

Table 1 Shear modulus of core meterail G_c

Core material	Shear modulus/*MP*a	Core material	Shear modulus/*MP*a
polyurethane	$1.725(\rho/38)^2$	rock wool	$1.294\text{x}\rho/100$
glass wool	$2.682\text{x}\rho/100$	polystyrene	$2.07(\rho/17.8)^2$
ρ is the density of core material, unit is kg/m^3			

Shear force distribution coefficient of core material

Shear force distribution coefficient of core material for sandwich panel with same metal skin panel on both sides

The shear force distribution coefficient of core material for sandwich panel with same metal skin panel on both side can be express a function about thickness of sandwich panel(h)and thinkness of metal skin panel(t) (GB/T 23932-2009, 2009) .The thickness of metal panel can be used the average value if the thickness of top and bottom panel is different, the unit of h and t is *mm*.

$$\beta = R_1\left(\frac{h}{100}\right)^2 + R_2\frac{h}{100} + R_3 t + R_4 \tag{9}$$

Where the value of coefficient R_1、R_2、R_3、R_4 can be attained from the Table 2(Zha 2011).

Table 2 Value for R_1、R_2、R_3、R_4

Skin panel	Kind of panel	Core material	R_1	R_2	R_3	R_4
Steel panel	wall panel	rock wool, glass wool	0.08	0.021	-0.08	0.63
		polyurethane	0.08	0.021	-0.08	0.72
	roof panel	rock wool, glass wool	-0.2	0.67	-0.2	0.22
		polyurethane	-0.2	0.67	-0.2	0.25
Aluminum panel	wall panel	rock wool, glass wool	-0.3	0.929	-0.035	-0.127
		polyurethane	-0.2	0.785	-0.021	-0.07
	roof panel	rock wool, glass wool	0.091	0.386	-0.072	0.069
		polyurethane	0.029	0.357	0.061	0.062

Verify of FE method

The value for shear force distribution coefficient of sandwich panel can be verified using FE method, which can be attained as Eq.(10).

$$\beta = \frac{\tau A_c}{Q} \tag{10}$$

where τ、Q are the average shear stress of core material and total shear force at the support.

The ABAQUS is used to analysis shear force distribution coefficient, where metal material use thin shell element, core material use solid element, tie is used to consider the constraint of metal panel and core material. The shear force distribution coefficients for sandwich panel with the same metal panel on both side using FE method and code method[13] are shown in table 3,where β_1, β_2 are shear force distribution coefficients calculated using Chinese code and FE analysis, the dimension of sandwich panels and material model can be found in reference(Zha 2011).

Table 3 Comparison on shear force distribution coefficients for sandwich panel with the same metal panel using FE method and code method

Specimen	Calculated results/β_1	FE analysis results/β_2	β_1/β_2
BⅡQ(B)(30)	66.95	77.88	0.8597

BⅣQ(B)(30)	69.95	78.95	0.8860
BⅡQ(B)(40)	67.72	78.14	0.8666
BⅣQ(B)(40)	70.72	79.09	0.8942
BⅡQ(B)(50)	68.65	78.28	0.8770
BⅣQ(B)(50)	71.65	79.21	0.9046
BⅡQ(B)(60)	69.74	78.27	0.8910
BⅣQ(B)(60)	72.74	79.02	0.9205
BⅡQ(B)(80)	72.4	78.10	0.9270
BⅣQ(B)(80)	75.4	78.78	0.9571
BⅡQ(B)(100)	75.7	77.74	0.9738
BⅣQ(B)(100)	78.7	78.22	1.0061
Mean			0.9136
Variance			0.0452
Coefficient of variation			0.0495

Note： B= sandwich panel, Ⅱ= polyurethane, Ⅳ= polystyrene, Q= wall panel, the something in parentheses is the thickness of core material, thickness of steel panel is 0.8mm, length of panel is 2000mm.

Table 3 shows that the shear force distribution coefficient for sandwich panel with same metal panel on both sides using FE method are relate to results using code method and have less coefficient of variation. The FE method can be used to analysis the shear force distribution coefficient of core material.

Shear force distribution coefficients for sandwich panel with different metal panel on both sides

β is shear forece distribution coefficient in Eq. (6)、(7), for sandwich panel with different metal skin panel on both sides of panel, which can be supposed to calculate as eq.(11).

$$\beta = \frac{\beta_t t_t + \beta_b t_b}{t_t + t_b} \qquad (11)$$

where，β_t, β_b are the shear force distribution coefficient of core material for sandwich panel using same metal material liking top and bottom metal panel on both side respectively, t_t, t_b are thickness of metal skin panel for top and bottom metal panel.

FE method can be used to verify the suitable of Eq.(11) because FE method can be investigate the shear force distribution coefficient very well. The shear force distribution coefficients for sandwich panel with different metal panel on both side using FE method and proposed method Eq.(11) are shown in table 4, where，β_{cl}、β_{FE} are the shear force distribution coefficients calculated using proposed method and FE method respectively. panel use steel panel and aluminum panel in top side and bottom side with different thickness, core material use polyurethane and rock wool, thickness of panel(t) use normal thickness 50mm and 100mm，the length of panel is

2000mm and the width of panel is 1000mm. t_s and t_a is the thickness of steel panel and aluminum panel respectively.

Table 4 Comparison on shear force distribution coefficients for sandwich panel with different metal panel on both side using FE method and proposed method

t_s/mm	t_a/mm	t /mm	core material	β_{cl}	β_{FE}	β_{cl} /β_{FE}
1.0	0.3	50	polyurethane	0.5772	0.5963	0.9680
1.0	0.5	50	polyurethane	0.5343	0.5534	0.9655
1.0	0.8	50	polyurethane	0.4861	0.4951	0.9818
0.8	0.3	50	polyurethane	0.5719	0.598	0.9564
0.8	0.5	50	polyurethane	0.5232	0.5487	0.9535
0.8	0.8	50	polyurethane	0.4711	0.4983	0.9454
0.5	0.3	50	polyurethane	0.5439	0.5609	0.9697
0.5	0.5	50	polyurethane	0.4863	0.5123	0.9492
0.5	0.8	50	polyurethane	0.4306	0.4478	0.9616
0.3	0.3	50	polyurethane	0.4964	0.5139	0.9659
0.3	0.5	50	polyurethane	0.4362	0.4551	0.9585
0.3	0.8	50	polyurethane	0.3841	0.3902	0.9844
1.0	0.3	100	polyurethane	0.6874	0.6995	0.9827
1.0	0.5	100	polyurethane	0.6622	0.6829	0.9697
1.0	0.8	100	polyurethane	0.6331	0.651	0.9725
0.8	0.3	100	polyurethane	0.6893	0.6958	0.9907
0.8	0.5	100	polyurethane	0.6599	0.67	0.9849
0.8	0.8	100	polyurethane	0.6276	0.6398	0.9809
0.5	0.3	100	polyurethane	0.6789	0.6907	0.9829
0.5	0.5	100	polyurethane	0.6428	0.6652	0.9663
0.5	0.8	100	polyurethane	0.6070	0.6178	0.9825
0.3	0.3	100	polyurethane	0.6529	0.6676	0.9780
0.3	0.5	100	polyurethane	0.6142	0.6129	1.0021
0.3	0.8	100	polyurethane	0.5797	0.5808	0.9981
1.0	0.3	50	rock wool	0.5739	0.5912	0.9707
1.0	0.5	50	rock wool	0.5287	0.5492	0.9627
1.0	0.8	50	rock wool	0.4767	0.4961	0.9609
0.8	0.3	50	rock wool	0.5680	0.5969	0.9516
0.8	0.5	50	rock wool	0.5167	0.5381	0.9602
0.8	0.8	50	rock wool	0.4605	0.4817	0.9560
0.5	0.3	50	rock wool	0.5386	0.5445	0.9892
0.5	0.5	50	rock wool	0.4778	0.4889	0.9773
0.5	0.8	50	rock wool	0.4176	0.4378	0.9539
0.3	0.3	50	rock wool	0.4893	0.5131	0.9536
0.3	0.5	50	rock wool	0.4256	0.4458	0.9547
0.3	0.8	50	rock wool	0.3687	0.3898	0.9459
1.0	0.3	100	rock wool	0.6834	0.6821	1.0019
1.0	0.5	100	rock wool	0.6555	0.6598	0.9935
1.0	0.8	100	rock wool	0.6223	0.6508	0.9562

0.8	0.3	100	rock wool	0.6846	0.695	0.9850
0.8	0.5	100	rock wool	0.6522	0.6608	0.9870
0.8	0.8	100	rock wool	0.6155	0.6123	1.0052
0.5	0.3	100	rock wool	0.6724	0.6759	0.9948
0.5	0.5	100	rock wool	0.6328	0.6501	0.9734
0.5	0.8	100	rock wool	0.5921	0.6008	0.9855
0.3	0.3	100	rock wool	0.6443	0.6548	0.9840
0.3	0.5	100	rock wool	0.6017	0.6186	0.9727
0.3	0.8	100	rock wool	0.5621	0.5854	0.9602
Mean						0.9727
Variance						0.0161
Coefficient of variation						0.0165

Table 4 shows that the shear force distribution coefficient for sandwich panel with different metal panel on both sides using proposed method are relate to results using FE method and have less coefficient of variation. The proposed method is safe and suitable which can be used to calculate the shear force distribution coefficient of core material.

Calculated formula of bending load-carrying capacity of sandwich panel with different metal panel on both sides

Based on formula (6) and (7), the calculated formula of bending load-carrying capacity for sandwich panel with different metal skin panel on both sides under uniform distributed loading and concentrated load at mid-span can be attained as follows:

$$p \le \frac{[f]}{\dfrac{5bl^4}{384\left(E_t I_t + E_b I_b\right)} + \dfrac{k\beta bl^2}{8G_c A_c}} \tag{12}$$

$$p \le \frac{[f]}{\dfrac{l^3}{48\left(E_t I_t + E_b I_b\right)} + \dfrac{k\beta l}{4G_c A_c}} \tag{13}$$

Based on a selected allowable bending deflection of [*f*]= *l*/200 and of cross section shape coefficient *k*=6/5, Eq.(12) and (13) can be generalized as follows:

$$p \le \frac{1}{bl\left(\dfrac{2.6l^2}{E_t I_t + E_b I_b} + \dfrac{30\beta}{G_c A_c}\right)} \tag{14}$$

$$p \le \frac{1}{\dfrac{4.2l^2}{E_t I_t + E_b I_b} + \dfrac{60\beta}{G_c A_c}} \tag{15}$$

The bending load-carrying capacities for sandwich panel with different metal panel on both side under uniform distributed loading and concentrated load at mid-span can be calculated using formula (14) and (15) and the FE method can be used to verify the suitable of proposed method. The bending load-carrying capacities for sandwich panel with different metal panel on both side using FE method and proposed method is shown in table 5, where P_{cl} and P_{FE} are the shear force distribution coefficients calculated using proposed method and FE method respectively. The panel use steel panel and aluminum panel in top side and bottom side with different thickness, core material use polyurethane and rock wool, thickness of panel use normal thickness 50mm and 100mm，the length of panel is 2000mm and the width of panel is 1000mm.

Table 5 Comparison on bending load-carrying capacities for sandwich panel with different metal panel on both side between FE method and proposed method

t_s/mm	t_a/mm	t /mm	core material	P_{cl} /kN/m	P_{FE} /kN/m	P_{cl}/P_{FE}
1.0	0.3	50	polyurethane	1.97	2.05	0.96
1.0	0.5	50	polyurethane	2.12	2.26	0.94
1.0	0.8	50	polyurethane	2.32	2.47	0.94
0.8	0.3	50	polyurethane	1.86	1.94	0.96
0.8	0.5	50	polyurethane	2.02	2.11	0.96
0.8	0.8	50	polyurethane	2.24	2.33	0.96
0.5	0.3	50	polyurethane	1.65	1.78	0.93
0.5	0.5	50	polyurethane	1.83	1.91	0.96
0.5	0.8	50	polyurethane	2.08	2.16	0.96
0.3	0.3	50	polyurethane	1.40	1.47	0.95
0.3	0.5	50	polyurethane	1.62	1.69	0.96
0.3	0.8	50	polyurethane	1.90	1.98	0.96
1.0	0.3	100	polyurethane	3.97	4.06	0.98
1.0	0.5	100	polyurethane	4.13	4.21	0.98
1.0	0.8	100	polyurethane	4.34	4.42	0.98
0.8	0.3	100	polyurethane	3.84	3.79	1.01
0.8	0.5	100	polyurethane	4.02	4.28	0.94
0.8	0.8	100	polyurethane	4.26	4.14	1.03
0.5	0.3	100	polyurethane	3.58	3.63	0.99
0.5	0.5	100	polyurethane	3.82	3.67	1.04
0.5	0.8	100	polyurethane	4.11	4.18	0.98
0.3	0.3	100	polyurethane	3.28	3.45	0.95
0.3	0.5	100	polyurethane	3.58	3.63	0.99
0.3	0.8	100	polyurethane	3.95	4.03	0.98
1.0	0.3	50	rock wool	1.70	1.81	0.94
1.0	0.5	50	rock wool	1.83	1.88	0.97
1.0	0.8	50	rock wool	2.02	2.06	0.98
0.8	0.3	50	rock wool	1.62	1.71	0.95
0.8	0.5	50	rock wool	1.77	1.85	0.96
0.8	0.8	50	rock wool	1.98	2.06	0.96

0.5	0.3	50	rock wool	1.47	1.56	0.94
0.5	0.5	50	rock wool	1.64	1.71	0.96
0.5	0.8	50	rock wool	1.88	1.95	0.96
0.3	0.3	50	rock wool	1.28	1.37	0.93
0.3	0.5	50	rock wool	1.48	1.59	0.93
0.3	0.8	50	rock wool	1.75	1.83	0.96
1.0	0.3	100	rock wool	3.33	3.55	0.94
1.0	0.5	100	rock wool	3.48	3.66	0.95
1.0	0.8	100	rock wool	3.68	3.86	0.95
0.8	0.3	100	rock wool	3.24	3.31	0.98
0.8	0.5	100	rock wool	3.41	3.5	0.97
0.8	0.8	100	rock wool	3.63	3.92	0.93
0.5	0.3	100	rock wool	3.06	3.14	0.97
0.5	0.5	100	rock wool	3.28	3.33	0.98
0.5	0.8	100	rock wool	3.56	3.37	1.06
0.3	0.3	100	rock wool	2.86	2.91	0.98
0.3	0.5	100	rock wool	3.14	3.42	0.92
0.3	0.8	100	rock wool	3.46	3.66	0.95
Mean						0.9649
Variance						0.0281
Coefficient of variation						0.0291

Table 5 shows that the bending load-carrying capacities for sandwich panel with different metal panel on both sides using proposed method are relate to results using FE method and have less coefficient of variation. The proposed method is safe and suitable, which can be used in curtain engineering to calculate the bending load-carrying capacities for sandwich panel with different metal panel on both sides.

Conclusion

The follow conclusions are attained by the analysis on the bending load-carrying capacities for sandwich panels with different metal panel on both sides.

1)The deflection and bending load-carrying capacities for sandwich panels with different metal panel on both sides are attained based on the classical beam theory.

2)The shear force distribution coefficient for sandwich panels with different metal panel on both sides is proposed based on FE analysis.

3)The proposed method used to calculate the bending load-carrying capacities for sandwich panel with different metal panel on both sides is safe and suitable .

Notation

The following symbols are used in this paper:

f	=	deflection of sandwich panel,
q	=	uniform load,
l	=	length of sandwich panel,
E	=	elastic modulus of sandwich panel,
I	=	moment of inertial of sandwich panel,
G	=	shear modulus of sandwich panel,
A	=	area of sandwich panel,
P	=	concentrated load,
h	=	thickness of sandwich panel,
α	=	linear expansion coefficient of sandwich panel,
Δt	=	temperature of top and bottom surface for sandwich panel,
k	=	cross section shape coefficient,
β	=	shear force distribution coefficient,
E_t	=	elastic modulus for natural axis of top,
E_b	=	elastic modulus bottom metal panel,
I_t	=	moment of inertial for natural axis of top metal panel,
I_b	=	moment of inertial for natural axis of bottom metal panel,
G_c	=	the shear modulus of core material,
A_c	=	area of core material,
k_t	=	the linear expansion coefficient of top metal panel for sandwich panel,
k_b	=	the linear expansion coefficient bottom metal panel for sandwich panel,
t_t	=	the thickness of top metal panel for sandwich panel,
t_b	=	the thickness of bottom metal panel for sandwich panel,
P	=	the density of core material,
h	=	thickness of sandwich panel,
t	=	thickness of metal skin panel,
τ	=	average shear stress of core material at the support,
Q	=	total shear force at the support,
β_t	=	shear force distribution coefficient of core material for sandwich panel using same metal material liking top metal panel on both side,
β_b	=	shear force distribution coefficient of core material for sandwich panel using same metal material liking bottom metal panel on both side,
β_{cl}	=	shear force distribution coefficients calculated using proposed method and FE method,
β_{FE}	=	shear force distribution coefficients calculated using proposed method and FE method,
P_{cl}	=	shear force distribution coefficients calculated using proposed method,
P_{FE}	=	shear force distribution coefficients calculated using FE method.

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