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Research paper

A Study on Behaviour of V and Trapezoidal Type of Folded Plate Roofs for Fixed and Hinged Boundary Conditions

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Abstract

Folded plate roofs are very useful form of roof structures for spanning large column free areas, which composed of a number of flat thin plates connected to each other. In this paper, linear static analysis is performed to study the behaviour of two types of single span prismatic folded plate roof. Different parameters considered for the study are height, bay width, thickness and varying boundary conditions. The results are obtained in the form of variation of displacement and percentage reduction in displacement for different thickness which are useful for selecting economic sections and predicting stiffness.

Keywords: *Folded Plate roof, Linear static analysis, Prismatic, Displacements, Bay width, Finite element analysis, Stiffness.*

1. Introduction

The Folded Plate roofs (FPR) sometimes called as Hipped Plates, which composed of a series of flat thin plates connected to each other. The folded plates can be of any shape such as V, Trapezoidal, Trough type etc. They are preferred in the place of normal slabs because of its low construction cost for long span, high load carrying capacity and rigidity. They find applications in Auditoriums, Gymnasia etc. Folded Plate Roof can be of concrete, steel and Timber. Concrete Folded Plate roofs are considered for the present investigation. Reduced number of columns can be of an economic advantage where the ground conditions require a expensive piled foundations [1].
Basically, there are two types of folded plate roof namely prismatic and non-prismatic folded plate roofs. Prismatic folded plate roofs are formed by connecting series of rectangular plates and lines of junction remain parallel. Non- prismatic folded plate roofs composed of series of non rectangular plates connected to each other whose plate width goes on changing with span.
The structural action of folded Plate roof can be mainly classified in to two actions i.e. transverse slab action and longitudinal Plate action. The transverse slab action causes bending of slab normal to the plane and reactions produced at the joints are counteracted by plate loads as there are no external support at the joints. These plate loads causes longitudinal bending of slabs in their own plane which is called Longitudinal Plate action.
The main objective of the present study is to investigate the behaviour of two types folded plate roof for various geometrical parameters. The assumptions made in the analysis of folded plate roofs are [2] :i) The structure is monolithic and joints are rigid. ii) Material is elastic, homogeneous and isotropic. iii) In all plates, plane sections remain plane even after bending. iv) The length of each plate is more than twice its width.

1.1 Related Works:

S Haldar and A.H Sheikh analysed bending of high precision composite plate bending element and presented its application to the analysis of isotropic composite folded plates to study the performance of an element in terms of deflection, in-plane forces and bending moments [3]. WojciechGilewski, Jan Pelczynski et al analysed various origami inspired folded plate roofs. They compared the values of maximum displacements and stresses for different types of FPR and proved that V type of FPR gives better results [4]. J.N Bandhyopadhyay and P.K Lad compared different conventional methods of folded plate roof analysis and proved that Simpson's and Witney's methods can be used for the preliminary analysis of FPR [5]. Saurabh Chauhan developed computer programs in MATLAB to analyse folded plate structures for varying cross sectional parameters in order to avoid Simpson's and Witney's methods which are lengthy and verified the results by developing finite element model in ABAQUS [6].

2. Methodology

In the present study, analysis is done for the single span V and Trapezoidal type of folded plate roofs (Fig.1) whose variation of displacement and % reduction in displacement is studied.

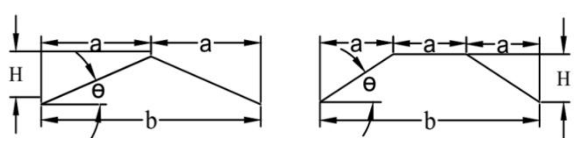

Fig 1: Typical cross section of (i) V type of FPR; (ii) Trapezoidal type of FPR;

Table: 1 Parameters considered for the study

H = Height of FPRThickness	100 to 150	mm
Plan size	20X20	m^2
Span	20	m
Height	L/10, L/15 and L/20	m
Boundary conditions	Fixed and Hinged	
Support spacing	3 to 7	m
Live load	0.4	kN/m^2
Compressive strength of concrete	25	N/mm^2
Density	25	kN/m^3
Young's Modulus	25	GPa
Poisons ratio	0.2	
Mesh size	0.25X0.25	m^2

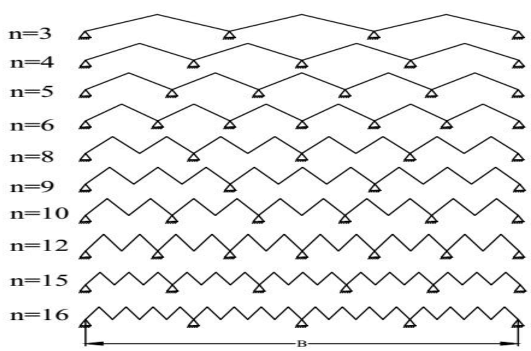

Fig. 2: Cross section of V-type of FPR with different number of bays;
n = Number of bays; B = Total width
b = Bay width; θ = Inclination to horizontal; a = Width of one fold

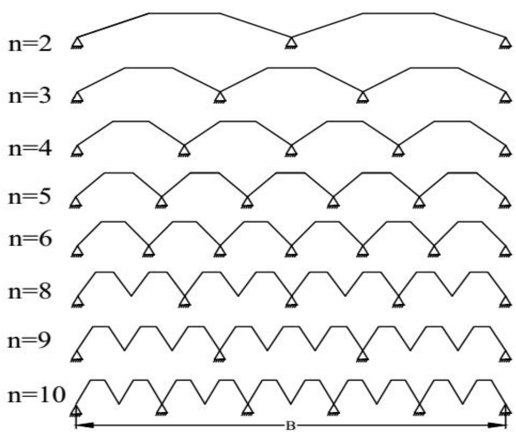

Fig.3: Cross section of Trapezoidal type of FPR with different number of bays;
n = Number of bays; B = Total width

1.2 Selection of Geometries

As per IS: 2210 – 1988 [7], the height of folded plate roof shall be around L/15. Hence heights of L/10, L/15 and L/20 are chosen. The possible number of bays for any assumed height and for any plan size can be calculated by using formula,

$$\theta = tan^{-1}\left(\frac{H}{a}\right) = 30° \; to \; 60° \quad (1)$$

Where, H = L/10 to L/20; L = Span; a = b/2 for V type; a = b/3 for Trapezoidal type (Fig. 1); b = bay width;θ = inclination to horizontal. The number of bays is assumed by trial and error procedure for a fixed total width "B" and any assumed height "H". From the obtained bay width "b", corresponding value of "a" is calculated and substituted in the equation (1) for the constant span. If the obtained inclination to horizontal, "θ" of folded plate roof is other than 30^0 to 60^0, that particular trial model cannot be selected, because if the inclination to horizontal is less than 30^0, the stresses increase and structure becomes inefficient and if the inclination to horizontal is greater than 60^0, the structures becomes uneconomical. The table 2 and table 3 show the possible number of bays for heights 1.0 m, 1.34 m and 2 m. All the number of bays selected in the present investigation is such that the supports are given at every 3 to 7 m for all possible bays and the roof structure is symmetric (Fig. 2 and Fig. 3).

Table 2: Selected geometrical parameters for various heights of V type of FPR

n	H = 1.0		H = 1.34		H = 2	
	b	θ	b	θ	b	θ
3	–	–	–	–	6.67	30.96
4	–	–	–	–	5.00	38.65
5	–	–	4.00	33.8	4.00	45.00
6	3.34	30.98	3.34	39.08	3.34	50.14
8	2.50	38.65	2.50	46.00	2.50	58.00
9	2.23	41.88	2.23	50.24	–	–
10	2.00	45.00	2.00	53.27	–	–
12	1.67	50.14	1.67	58.07	–	–
15	1.34	56.30	–	–	–	–
16	1.25	58.00	–	–	–	–

*n = Number of bays; b= bay width in "m"; H = Height of FPR in "m";
θ = Inclination to horizontal in "degrees"

Table 3: Selected Geometrical parameters for various heights of Trapezoidal type of FPR

n	H = 1.0		H = 1.34		H = 2	
	b	θ	b	θ	b	θ
2	–	–	–	–	10	30.96
3	–	–	6.67	31.08	6.67	53.37
4	5.00	30.96	5.00	38.74	5.00	50.14
5	4.00	36.73	4.00	45.00	4.00	56.30
6	3.34	42	3.34	50.28	–	–
8	2.50	50.17	2.50	58.10	–	–
9	2.23	53.38	–	–	–	–
10	2.00	56.30	–	–	–	–

*n = Number of bays; b= bay width in "m"; H = Height of FPR in "m";
θ = Inclination to horizontal in "degrees"

2.2. Finite Element Analysis

Linear static analysis is carried out using the software SAP 2000 (version 19) and a total of 420 models are analysed for a combination of dead load and live load [7, 8]. The 4 node quadrilateral element with 6 degree of freedom for each node is chosen which has both membrane and bending capabilities.

3. Results and Discussions

In the present study, the displacement for both hinged and fixed boundary conditions are found to have negligible difference for all the cases (Table 4 to 9). Hence all the graphs shown in the present paper refer to hinged boundary conditions (BC). Following Figures show the variation of midspan displacement with thickness for varying heights for the two shapes. It is observed that maximum midspan displacement decreases with increase in thickness for all the heights.

3.1 For V-Type of Folded Plate Roof

Fig. 4 to 6 show that the variation of displacements with thickness for different heights. For heights of 1 m and 1.34 m, the displacement is found to be maximum for 9 bays and minimum for 12 bay (Fig 4 and 5); for height of 2 m, it is found to be maximum for 3 bay and minimum for 6 bay (Fig. 6) for all thickness.

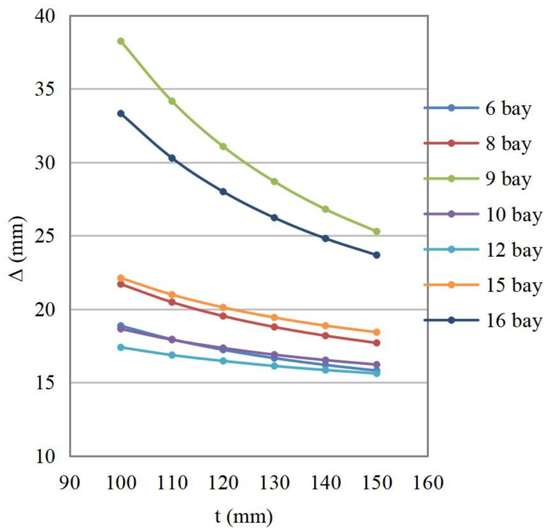

Fig. 4: Variation of displacement (Δ) with thickness (t) for H = 1.0 m in V type of FPR

It is observed that displacement variation of 10 bay and 6 bay is found to be almost same for heights of 1 and 1.34 m (Fig. 4 and Fig. 5). It is also seen that displacement variation of 8 bay and 5 bay is found to be almost same for height of 1.34 m (Fig. 5).

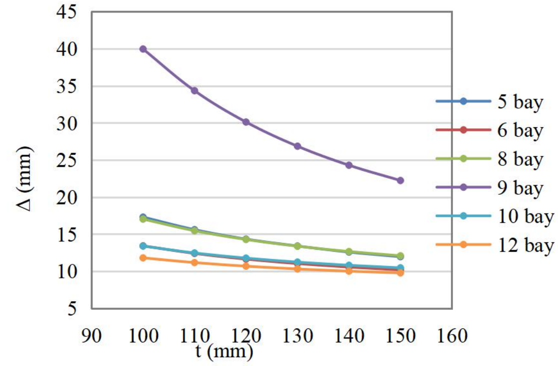

Fig. 5: Variation of displacement (Δ) with thickness (t) for H = 1.34 m in V type of FPR

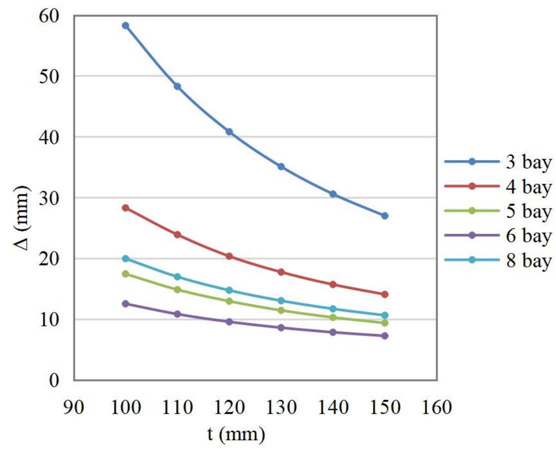

Fig. 6: Variation of displacement (Δ) with thickness (t) for H = 2 m in V type of FPR

Table4: Displacement variation and percentage reduction in displacement from thickness 100 mm to 150 mm for H = L/20 = 1.0 m in V type of FPR

Number of bays	Supports at	Spacing between supports in "m"	Displacement variation in "mm" for Hinged B.C	% Reduction in displacement for Hinged B.C	Displacement variation in "mm" for Fixed B.C	% Reduction in displacement for Fixed B.C
6	Every bay	3.34	18.85 to 15.79	16.23	18.679 to 15.564	16.676
8	Alternate bays	5	21.69 to 17.685	18.46	21.542 to 17.55	18.53
9	At every 3 bay	6.67	38.24 to 25.275	33.9	37.6 to 25	33.5
10	Alternate bays	4	18.638 to 16.208	13.03	18.543 to 16.102	13.16
12	Alternate bays	3.34	17.381 to 15.607	10.20	17.314 to 15.536	10.26
15	At every 3 bays	4	22.103 to 18.413	16.69	21.947 to 18.335	16.45
16	At every 4 bays	5	33.310 to 23.67	28.94	32.776 to 23.468	28.39

Table 5: Displacement variation and percentage reduction in displacement from thickness 100 mm to 150 mm for H = L/15 = 1.34 m in V type of FPR

Number of bays	Supports at	Spacing between supports in "m"	Displacement variation in "mm" for Hinged B.C	% Reduction in displacement for Hinged B.C	Displacement variation in "mm" for Fixed B.C	% Reduction in displacement for Fixed B.C
5	Every bay	4	17.298 to 11.959	30.86	17.135 to 11.811	31.07
6	Every bay	3.34	13.424 to 10.181	24.158	13.325 to 10.078	24.36
8	Alternate bays	5	17.025 to 12.084	29.02	16.823 to 11.937	29.04
9	At every 3 bay	6.67	39.95 to 22.229	44.35	39.786 to 21.786	45.24
10	Alternate bays	4	13.393 to 10.465	21.86	13.263 to 10.397	21.6
12	Alternate bays	3.34	11.803 to 9.770	17.22	11.713 to 9.72	17.015

Table 6: Displacement variation and percentage reduction in displacement from thickness 100 mm to 150 mm for H = L/10 = 2.0 m in V type of FPR

Number of bays	Supports at	Spacing between supports in "m"	Displacement variation in "mm" for Hinged B.C	% Reduction in displacement for Hinged B.C	Displacement variation in "mm" for Fixed B.C	% Reduction in displacement for Fixed B.C
3	Every bay	6.67	58.274 to 27	53.66	56.21 to 26.04	53.03
4	Every bay	5	28.314 to 14.089	50.24	26.918 to 13.8	48.73
5	Every bay	4	17.46 to 9.394	46.19	17.229 to 9.262	46.24

6	Every bay	3.34	12.55 to 7.275	42.03	12.430 to 7.196	42.107
8	Alternate bays	5	19.968 to 10.654	46.64	19.49 to 10.427	46.5

3.2 For Trapezoidal-Type of Folded Plate Roof

Fig. 7 to 9 show that the variation of displacements with thickness for different heights. For all thickness of plates, the maximum and minimum displacements are observed in 9 bay and 6 bay for 1 m height (Fig.7); 3 bay and 6 bay for 1.34 m height (Fig. 8); 2 bay and 5 bay for 2 m height respectively (Fig. 9). It is also observed that the displacement variation of 4 bay and 8 bay is found to be almost same for heights of 1 m and 1.34 m.

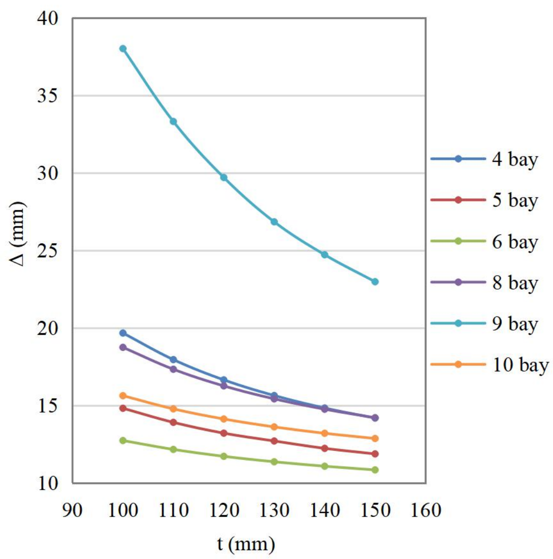

Fig.7: Variation of displacement (Δ) with thickness (t) for H = 1m in Trapezoidal type of FPR

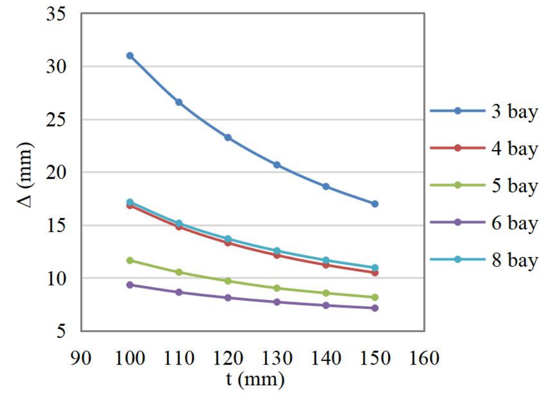

Fig.8: Variation of displacement (Δ) with thickness (t) for H = 1.34 m in Trapezoidal type of FPR

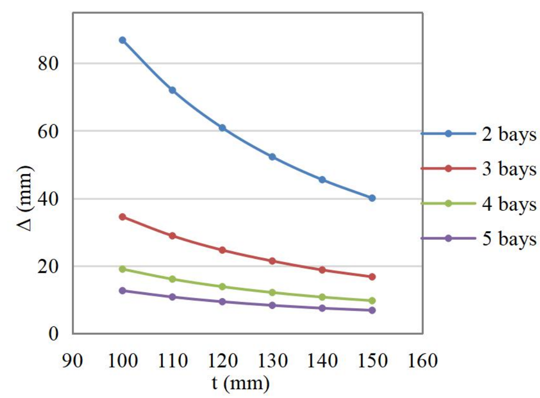

Fig.9: Variation of displacement (Δ) with thickness (t) for H = 2 m in Trapezoidal type of FPR

Table 7: Displacement variation and percentage reduction in displacement from thickness 100 mm to 150 mm for H = L/20 = 1m in trapezoidal type of FPR

Number of bays	Supports at	Spacing between supports in "m"	Displacement variation in "mm" for Hinged B.C	% Reduction in displacement for Hinged B.C	Displacement variation in "mm" for Fixed B.C	% Reduction in displacement for Fixed B.C
4	Every bay	5	19.66 to 14.176	27.89	19.538 to 14	28.34
5	Every bay	4	14.809 to 11.867	19.86	14.719 to 11.763	20.08
6	Every bay	3.34	12.728 to 10.835	14.87	12.673 to 10.757	15.11
8	Alternate bays	5	18.737 to 14.199	24.2	18.634 to 14.150	24.06
9	At every 3 bays	6.67	38 to 22.968	39.55	37.5 to 22.754	39.22
10	Alternate bays	4	15.619 to 12.860	17.66	15.556 to 12.828	17.53

Table 8: Displacement variation and percentage reduction in displacement from thickness 100 mm to 150 mm for H = L/15 = 1.34 m in trapezoidal type of FPR

Number of bays	Supports at	Spacing between supports in "m"	Displacement variation in "mm" for Hinged B.C	%Reduction in displacement for Hinged B.C	Displacement variation in "mm" for Fixed B.C	% Reduction in displacement for Fixed B.C
3	Every bay	6.67	30.979 to 16.986	45.16	30.08 to 16.543	45
4	Every bay	5	16.839 to 10.492	37.69	16.602 to 10.349	37.66
5	Every bay	4	11.649 to 8.169	29.87	11.561 to 8.1045	29.89
6	Every bay	3.34	9.341 to 7.151	23.44	9.303 to 7.110	23.57
8	Alternate bays	5	17.155 to 10.964	36.08	16.929 to 10.877	35.74

Table 9: Displacement variation and percentage reduction in displacement from thickness 100 mm to 150 mm for H = L/10 = 2 m in trapezoidal type of FPR

Number of bays	Supports at	Spacing between supports in "m"	Displacement variation in "mm" for Hinged B.C	% Reduction in displacement for Hinged B.C	Displacement variation in "mm" for Fixed B.C	% Reduction in displacement for Fixed B.C

2	Every bay	10	86.82 to 40.08	53.83	80.89 to 37.39	53.77
3	Every bay	6.67	34.524 to 16.782	51.39	33.04 to 16.09	51.30
4	Every bay	5	19.06 to 9.728	48.96	18.551 to 9.507	48.75
5	Every bay	4	12.692 to 6.882	45.77	12.669 to 6.78	46.48

Table 4 to 9 refer to variation of displacements and percentage reduction in displacement for thickness varying from 100 mm to 150 mm and heights of 1 m, 1.34 m and 2 m for both the shapes. As the stiffness is inversely proportional to the displacement, reduction in displacement and hence increase in stiffness is observed from thickness 100 mm to 150 mm. Percentage reduction in displacement is very much useful in predicting economic sections.

6. Conclusion

In this study, the behaviour of two types of Folded plate roof (V and Trapezoidal) is investigated with reference to displacement and following observations are made:

- Negligible difference in displacement is observed between hinged and fixed boundary conditions for both the shapes.
- Displacement decreases with the increase in thickness for all the heights and corresponding possible number of bays. The rate of decrease in displacement reduces as the thickness increases.
- Economic sections can be chosen when the % reduction of displacement is found to be less.
- The sample design tables are presented in the appendix, which are expected to be useful in the design of folded plate roofs.

Acknowledgement

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APPENDIX

Design Table

Table 10: Design table for V type of FPR with hinged boundary condition

n	t = 130 mm; H= 1.0 m					t = 130 mm; H=1.34 m					t = 130 mm; H=2.0 m				
	s_x		s_y		τ_{xy}	s_x		s_y		τ_{xy}	s_x		s_y		τ_{xy}
	C	T	C	T	—	C	T	C	T	—	C	T	C	T	—
3	—	—	—	—	—	—	—	—	—	—	27.62	3.46	24.35	7.23	11.94
4	—	—	—	—	—	—	—	—	—	—	23.53	3.23	15.88	4.69	8.76
5	—	—	—	—	—	26.86	3.67	11.73	2.82	8.36	22.00	3.00	12.02	3.38	7.38
6	29.20	4.14	10.69	3.86	9.13	24.98	3.47	8.735	2.73	7.26	20.51	2.86	9.78	2.61	6.48
8	45.28	6.31	14.48	7.49	14.06	39.58	5.51	16.08	6.14	11.56	33.12	4.62	19.97	6.16	10.51
9	58.30	8.90	21.49	13.29	17.71	52.65	8.01	24.37	11.92	15.66	—	—	—	—	—
10	40.19	5.79	11.19	6.99	11.72	35.28	5.20	12.25	5.81	10.05	—	—	—	—	—
12	39.67	5.34	10.14	6.35	11.24	34.51	4.85	10.34	5.46	9.82	—	—	—	—	—
15	47.22	7.13	11.12	9.67	13.28	—	—	—	—	—	—	—	—	—	—
16	60.17	8.92	16.17	14.11	17.47	—	—	—	—	—	—	—	—	—	—

*n = Number of bays; s_x= Longitudinal stresses in X direction (MPa) (Along span); s_y= Transverse stresses in Y direction (MPa) (Along width); τ_{xy} = Shear stresses (MPa); C = Compression; T = Tension

Table 11: Design table for Trapezoidal type of FPR with hinged boundary condition

n	t = 130 mm; H= 1.0 m					t = 130 mm; H=1.34 m					t = 130 mm; H=2.0 m				
	s_x		s_y		τ_{xy}	s_x		s_y		τ_{xy}	s_x		s_y		τ_{xy}
	C	T	C	T	—	C	T	C	T	—	C	T	C	T	—
2	—	—	—	—	—	—	—	—	—	—	29.91	4.23	31.04	6.43	16.71
3	—	—	—	—	—	32.18	3.92	20.50	3.10	12.31	24.04	3.11	18.24	3.61	10.42
4	33.29	4.39	13.64	2.89	10.34	28.01	3.69	12.85	2.12	9.02	22.5	2.86	13.23	2.45	8.12
5	29.82	4.05	9.93	3.49	8.68	25.23	3.46	9.20	2.25	7.42	20.20	2.70	10.51	1.85	6.81
6	26.46	3.88	7.62	3.73	7.27	22.48	3.32	7.09	2.54	6.28	—	—	—	—	—
8	43.94	5.83	12.26	6.93	12.48	37.21	5.12	14.55	5.42	11.06	—	—	—	—	—
9	54.39	8.45	18.42	12.17	1.59	—	—	—	—	—	—	—	—	—	—
10	37.17	5.56	9.02	6.47	10.23	—	—	—	—	—	—	—	—	—	—

*n = Number of bays; s_x= Longitudinal stresses in X direction (MPa) (Along span); s_y= Transverse stresses in Y direction (MPa) (Along width); τ_{xy} = Shear stresses (MPa); C = Compression; T = Tension