loading condition in the fill direction. The limitations from both loading conditions should overlap. Figure 4 combines the graphs from Table 1 and the design aid graph in Fig. 3. It is noted that the limitations related to the upward loading conditions are independent of the opening angle. Any arch curvature can be combined with a mid-span width (*M*) inside the limited area (envelope), and the maximum opening angle can be checked following the curved lines.

A new parameter (see α in Fig. 5) is introduced that defines the asymmetry about the longitudinal axis for inclined anticlastic membranes. Having different scales in the arches and maintaining the width of the panel (i.e., arches are parallel), the inclination angle (α in Fig. 5) is formed between the horizontal line and the line that connects between the peaks of the 2 arches. A detailed explanation is provided by Hong et al. (2018) to find the relationships between the parameters that are needed for the design.

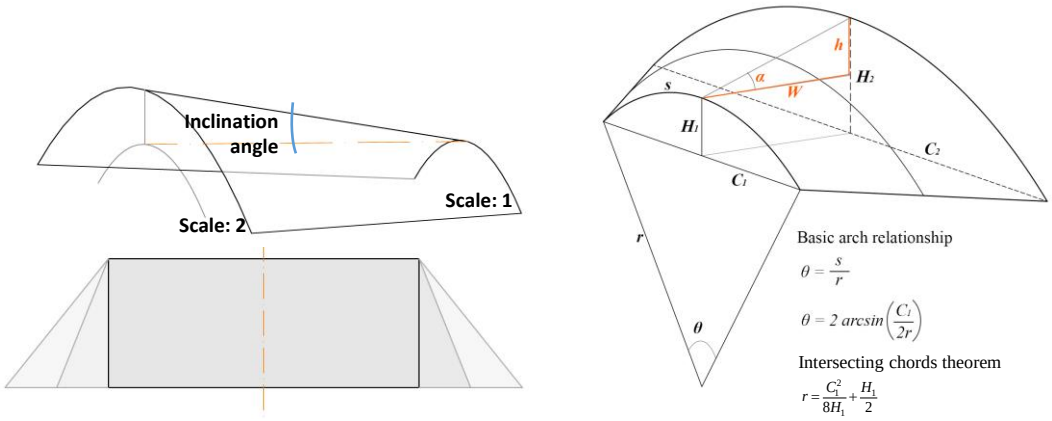

Fig. 5 Parameters defining scale of larger arch in consideration of inclination angle between two arches

Table 2 Design aid for maximum inclination angle (α) of inclined membranes

Width (m)		2	3	4	5	6	7	8	9
m = slope		0.216	0.227	0.256	0.306	0.319	0.319	0.319	0.319
Arch curvature									
n = max. stress inclination 0º (kN/m)	9.5	11.99	12.98	15.13	17.27	19.43	21.05	22.69	24.33
	19	12.49	13.74	16.12	18.51	20.89	22.56	24.23	25.9
	28.5	13.15	14.72	17.27	19.82	22.37	23.91	25.44	26.96
	38	13.75	15.62	18.17	20.72	23.27	24.58	25.88	27.18
	47	14.09	16.14	18.49	20.85	23.21	24.24	25.28	26.32
	56	14.25	16.37	18.38	20.39	22.41	23.17	23.93	24.7
	65	14.31	16.42	17.99	19.5	21.02	21.62	22.22	22.82
	74	14.34	16.37	17.44	18.36	19.27	19.8	20.33	20.85
Max. inclination angle α (degrees)	9.5	58.0	50.9	36.7	23.7	16.0	10.9	5.8	
	19	55.7	47.5	32.8	19.7	11.4	6.2	0.9	-4.3
	28.5	52.7	43.2	28.3	15.4	6.8	1.9	-2.9	-7.6
	38	49.9	39.2	24.8	12.4	3.9	-0.2	-4.2	-8.3
	47	48.3	36.9	23.6	12.0	4.1	0.9	-2.4	-5.6
	56	47.6	35.9	24.0	13.5	6.6	4.2	1.9	-0.5
	65	47.3	35.7	25.5	16.4	11.0	9.1	7.2	5.3
	74	47.2	35.9	27.7	20.1	16.5	14.8	13.2	11.5

All the parameters that influence the design of inclined anticlastic membranes were analyzed, including the arch curvature (θ), height (H_1), and width of the panel (W). Then, a computational parametric study on inclined anticlastic membranes was performed. Table 2 summarizes the values found from the analysis. As shown in the table, some combinations result in a negative inclination angle (α), which means that for that combination, inclined membranes may wrinkle with larger curvatures and wider membranes; thus, the models that wrinkle should also be removed from the safe combination cases. Finally, the developed design aid for inclined anticlastic tension membranes is graphically illustrated in Fig. 6.

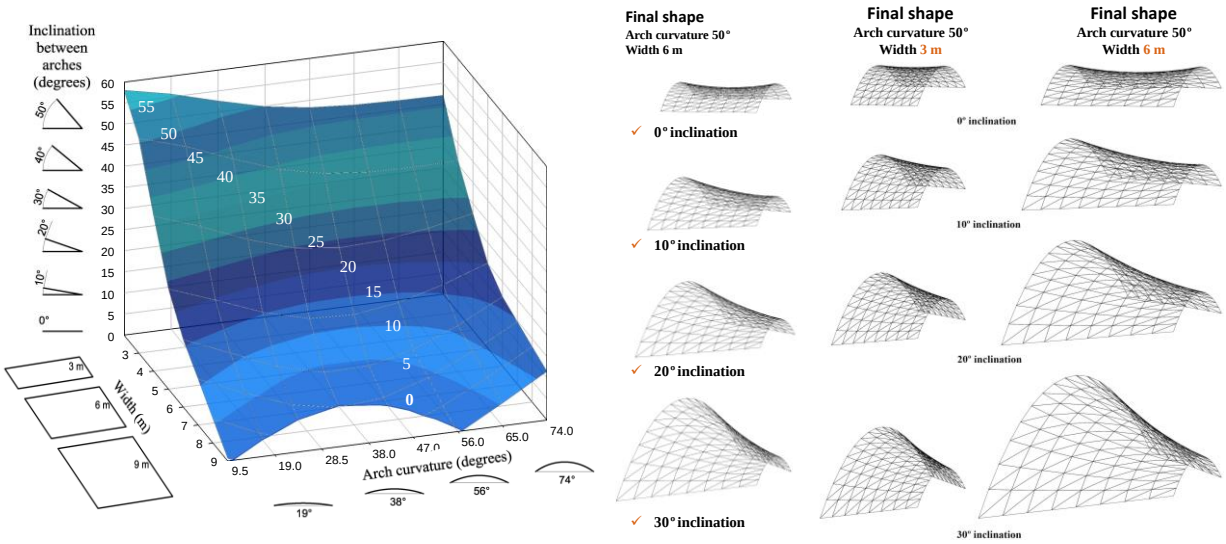

Fig. 6 Design aid for inclined anticlastic membrane tension structures and final design examples

As a result of the parametric study, the following findings were obtained:

1) The proposed trapezoid-shaped membranes have the same limitations as the regular membranes with the same width as that at the mid-span of the trapezoid-shaped membrane, regardless of the opening angle, because the maximum stress is always reached at the mid-span of the membrane.
2) However, the opening angle is limited by the behavior of the structure under downward loading in the fill direction. For the same arch curvature, the increase of the stress under downward loading in the fill direction is linear with the constant rate, and the same rate can be applied to any width.
3) The most critical case for inclined anticlastic membranes is observed under the upward loading in the fill direction. When the inclination angle is increased, the incremental rate of the stress in the fill direction under upward loading differs according to the membrane width.
4) However, the increasing rate is similar for different arch curvatures when the width is constant. This finding indicates that the maximum stress tends

to be reached across the transverse section at the mid-span region, which applies for all membranes regardless of the arch curvature, because the inclination angle is only dependent on the width of the membrane.

3. SUMMARY AND REMARKS

Descriptions for anticlastic tension membrane supported by two nonparallel or asymmetric circular arches and two parallel straight non-equal length edge beams are provided. This membrane is not synclastic but attached to arched and straight edge beams on all four sides. The primary outcomes are somewhat specific, because the initial prestressing force per width is fixed to be 5 kN/m and some other parameters are fixed as well.

The authors have exploited the developed computational program to investigate various cases of regular and irregular anticlastic membranes including trapezoid-shaped or inclined panels, and developed the design aid charts and tables. Such a computational development process should be emphasized, as similar approaches can be taken for further study by the authors and other researchers. The developed design aid itself is also meaningful and is a valuable contribution to the design practice, as it gives general ideas for practicing engineers and helps them get started designing anticlastic tension membrane structures.

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