Reduced Scale Model Test on Cable Membrane Roof of Shanghai Expo Central Axis

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Abstract
In this paper a reduced scale model test on cable membrane roof of Shanghai Expo Central Axis is introduced. The membrane pre-stresses, cable forces and membrane geometry at the initial state are carefully inspected. Numerical form-finding analysis is also carried out and its result is compared with the inspecton. The behaviors of the membrane roof under breaking of cables are observed. Test proves the practicability of the project in aspects of system safety, analysis and inspection.

Keywords: Cable membrane structures, reduced scale model test, numerical analysis, pre-tension and geometry inspection.

1. Introduction
The "Central axis" is one of the five permanent buildings for 2010 Shanghai EXPO, which is shown in Figure.1. The roof covering the "Central axis"is a huge cable membrane structure with about 80m width and 1000m length supported on side masts, middle masts and steel grid shells with "free form" shapes. The membrane material is PTFE with 1.2mm.

Figure 1: Permanent buildings of 2010 Shanghai EXPO

For the test model the scale is taken as 1:40. The membrane material is taken as NAIZIL(type-1) with *200g/m²* weight, *550N/mm* warp stiffness and *500N/mm* woof stiffness. The cutting pattern of membrane surface is shown in Figure.2.

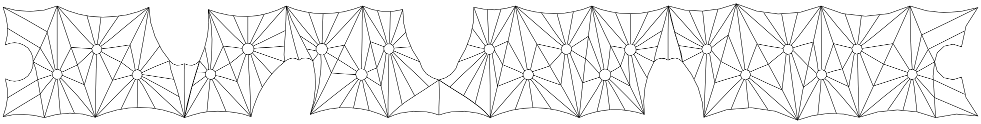

Figure 2: Cutting pattern of the model membrane surface

Wire rope with 4mm diameter is chosen as cables. ϕ20×2 stainless steel tube is taken as the masts. The pin-jointed ends of cables and masts can be seen in Figure.3.

Figure 3: Pin-joints of the ends of cables and masts in test model

The pre-stress with the target value *1.0kN/m* is introduced into the model to get its initial pre-stressed state, as seen in Figure.4.

Figure 4: Pre-stressed initial state of the model

The aims of the model test are to check the realizing possibility of pre-tensioning, the roof behaviors in case of cutting of cables, the reasonability of numerical form-finding analysis, and the possibility of inspection of cable forces and membrane stresses.

2. Inspection devices adopted in the model test

The pre-stresses of the membrane roof, the pre-tensions of the cables and the spatial geometry are inspected in the model test.

The membrane stresses can be calculated according to its relationships with the normal pressure on the membrane surface and the corresponding maximum membrane displacement. Based on this principle a special patent device for inspecting the pre-stress of the membrane roof was designed and invented (Sun and Zhang [1]), which consists of the vacuum pump and laser displacement sensor, shown as in Figure.5.

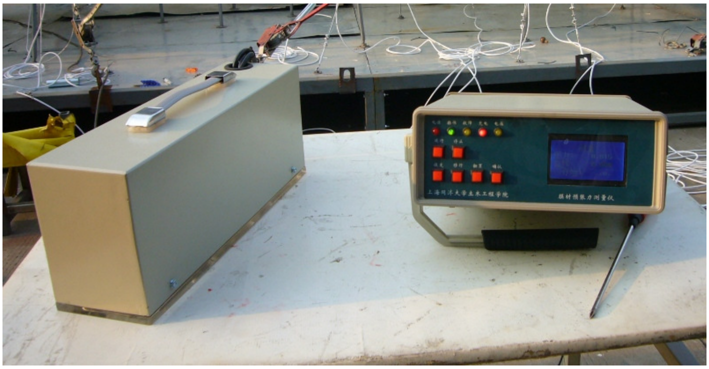

Figure 5: Device for inspecting pre-stresses of membrane

The cable forces are inspected according to the elasto-magnetic principle. With the use of double coils the forces of the inspected steel cables or bars will have relationships with the output voltage of the electricity current under given input voltage, seen as in Figure.6. The patent device was then designed to inspect the cable forces (Chen and Zhang [2]), which consists of the EM sensor and the oscillograph, as seen in Figure.7.

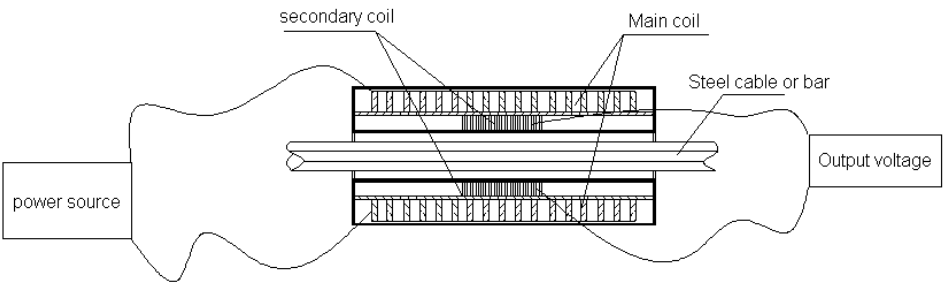

Figure 6: Working principle of EM sensor

Figure 7: EM sensor and voltage oscillograph

The spatial geometry of the model is measured by transit instrument shown as in Figure.8.

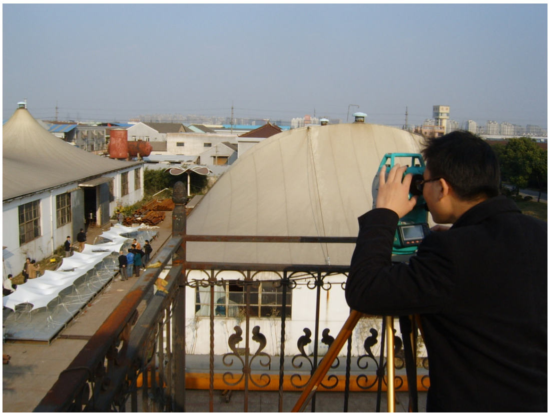

Figure 8: Spatial geometry measurement with use of transit instrument

3. Comparison of form-finding analysis results with the inspection

3.1. Membrane geometry of the model

Form-finding analysis is carried out by using nonlinear finite element method (Zhang [3]). To make comparison of the analysis with the inspection 67 points on the membrane surface are selected as seen in Figure.9.

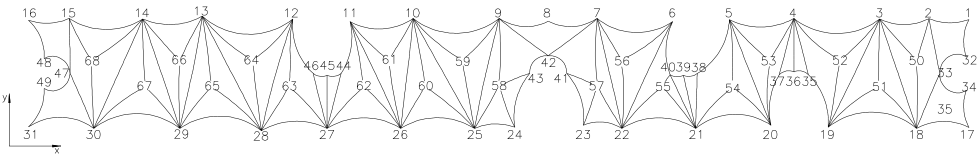

Figure 9: Numbering of the geometry inspection points

The spatial coordinates of the inspection points obtained from numerical analysis and inspection are compared and listed in Table.1, in which Δ means the error of the analysis magnitude minus the inspection.

No.	X		Y		Z	
	Δx (mm)	error (%)	Δy (mm)	error (%)	Δz (mm)	error (%)
1	78.8	5.4	86.9	3.7	2.0	0.2
3	8.0	0.6	15.2	0.6	-7.0	-0.8
5	15.3	1.1	34.3	1.4	0	0.0
7	32.2	2.2	-25.4	-1.1	-12.0	-1.3
9	31.6	2.2	-37.1	-1.6	-13.0	-1.4
11	1.0	0.1	4.8	0.2	-24.0	-2.7
13	27.1	1.9	24.7	1.0	74.0	8.2
15	-40.9	-2.8	77.0	3.2	6.0	0.7
17	54.2	3.7	-14.4	-0.6	-36.0	-4.0
19	-17.4	-1.2	0.9	0.0	-25.0	-2.8
21	23.0	1.6	-80.4	-3.4	-17.0	-1.9
23	-8.1	-0.6	-16.9	-0.7	-36.0	-4.0
25	52.6	3.6	-76.1	-3.2	-10.0	-1.1
27	-11.9	-0.8	-79.2	-3.3	-14.0	-1.6
29	-34.5	-2.4	-42.8	-1.8	-5.0	-0.6
31	-39.5	-2.7	-77.1	-3.3	19.0	2.1
33	6.2	0.4	7.3	0.3	-16.2	-1.8
35	-12.0	-0.8	0.4	0.0	-11.5	-1.3
37	26.1	1.8	-4.5	-0.2	-11.5	-1.3
39	21.7	1.5	-10.0	-0.4	-21.8	-2.4
41	5.4	0.4	-28.9	-1.2	-0.5	-0.1
43	1.4	0.1	-45.8	-1.9	-7.5	-0.8
45	-12.1	-0.8	-23.3	-1.0	-14.4	-1.6
47	-21.3	-1.5	20.3	0.9	12.3	1.4
49	-1.1	-0.1	-13.8	-0.6	3.7	0.4
51	76.3	5.3	36.5	1.5	62.0	6.9
53	43.0	3.0	-14.0	-0.6	10.7	1.2
55	32.8	2.3	-24.2	-1.0	-21.5	-2.4
57	18.4	1.3	-29.3	-1.2	-19.2	-2.1
59	58.5	4.0	-76.6	-3.2	45.3	5.0
61	31.8	2.2	-71.0	-3.0	62.6	7.0
63	22.0	1.5	-60.4	-2.5	15.3	1.7
65	-11.1	-0.8	-35.1	-1.5	63.1	7.0
67	-7.9	-0.5	-0.8	0.0	33.2	3.7

No.	X		Y		Z	
	Δx（mm）	error（%）	Δy（mm）	error（%）	Δz（mm）	error（%）
2	47.7	3.3	65.8	2.8	3.0	0.3
4	−0.7	0.0	66.0	2.8	9.0	1.0
6	18.9	1.3	25.7	1.1	−13.0	−1.4
8	0	0.0	0	0.0	0	0.0
10	26.8	1.8	57.8	2.4	−19.0	−2.1
12	0.2	0.0	−14.2	−0.6	−13.0	−1.4
14	6.8	0.5	16.8	0.7	−94.0	−10.4
16	−41.8	−2.9	63.9	2.7	7.0	0.8
18	3.7	0.3	21.5	0.9	−29.0	−3.2
20	28.9	2.0	−49.2	−2.1	−35.0	−3.9
22	41.4	2.9	58.7	2.5	−13.0	−1.4
24	111.0	7.6	−60.0	−2.5	−3.0	−0.3
26	10.2	0.7	−61.1	−2.6	−17.0	−1.9
28	−32.3	−2.2	−85.0	−3.6	−14.0	−1.6
30	−27.1	−1.9	−15.1	−0.6	−13.0	−1.4
32	−10.7	−0.7	24.4	1.0	−15.8	−1.8
34	6.1	0.4	22.9	1.0	−25.8	−2.9
36	17.0	1.2	6.5	0.3	−6.8	−0.8
38	19.3	1.3	−13.2	−0.6	−17.2	−1.9
40	11.9	0.8	—3.9	−0.2	−15.8	−1.8
42	3.7	0.3	−45.1	−1.9	−15.9	−1.8
44	−3.2	−0.2	−11.2	−0.5	−18.2	−2.0
46	−2.1	−0.1	−22.4	−0.9	−18.2	−2.0
48	−25.7	−1.8	−7.3	−0.3	−0.3	0.0
50	62.7	4.3	32.1	1.4	27.0	3.0
52	32.9	2.3	34.4	1.5	41.9	4.7
54	22.4	1.5	−20.7	−0.9	10.6	1.2
56	−1.8	−0.1	−48.6	−2.1	−8.7	−1.0
58	76.9	5.3	−54.7	−2.3	−0.8	−0.1
60	56.9	3.9	−88.2	−3.7	39.6	4.4
62	14.0	1.0	−57.7	−2.4	22.9	2.5
64	9.7	0.7	−64.8	−2.7	89.7	10.0
66	−23.1	−1.6	−26.6	−1.1	48.2	5.4
68	−29.1	−2.0	11.0	0.5	17.8	2.0

Table 2: The error of analysis coordinates minus the inspection

It can be seen from Table.1 that form finding analysis can satisfactorily predict the geometry of the model.

3.2. Cable forces of the model

The cables are numbered as in Figure.10 for inspection of cable forces.

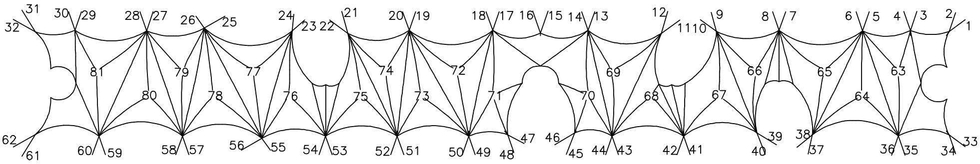

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Figure 10: Cable numbering for inspection of cable forces

The cable forces in the model are inspected by EM sensors shown in Figure.7. Its results and the comparison with the form finding analysis results are shown in Figure.11.

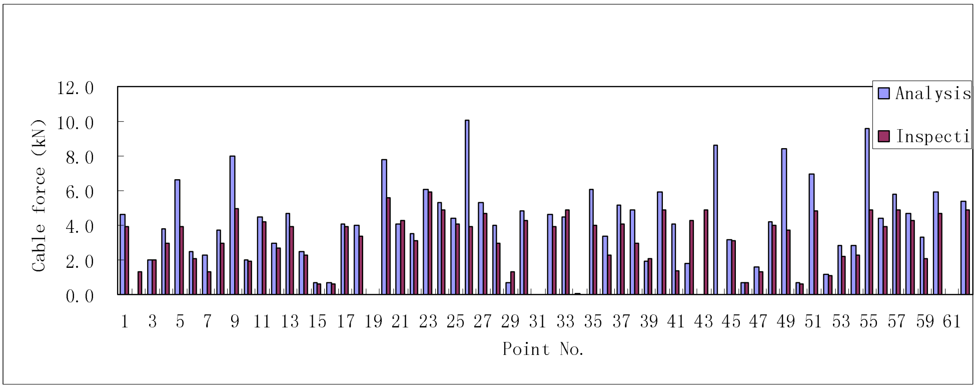

Figure 11: Cable forces from inspection and form finding analysis

It can be seen from Figure.11 that the inspected cable forces are with the same trends of the form finding analysis results and most of them are close to each other.

3.3. Membrane stresses of the model

On membrane surface of the model 35 points are selected for inspection of the stresses, seen as in Figure.12.

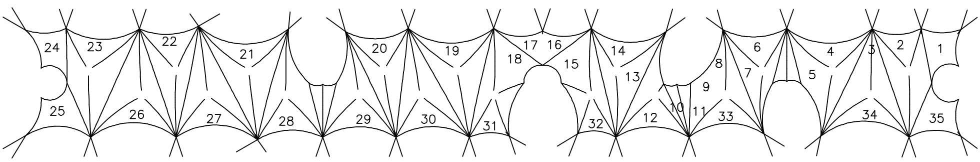

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Figure 12: Stress inspection points on membrane surface

The design target value of the membrane pre-stresses is *1.0kN/m*. Stress distribution on membrane surface of the model from form finding analysis is shown in Figure.13. It can be seen that the stresses from analysis with the range of *0.811-1.018kN/m* can fulfill the design desire.

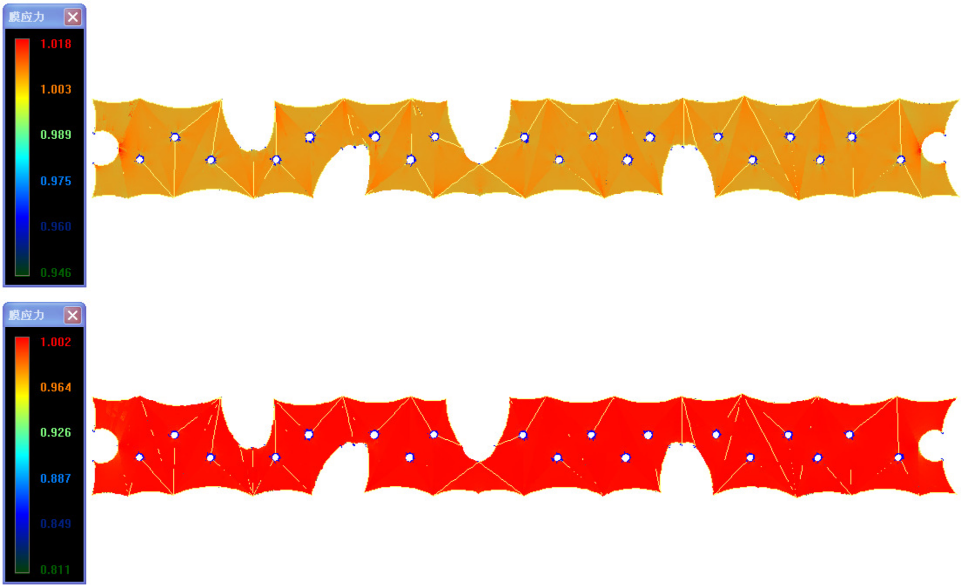
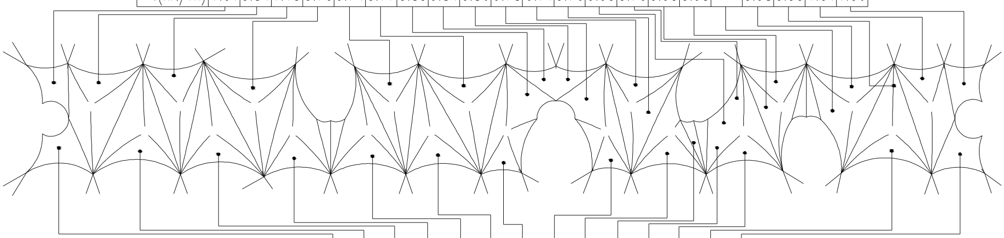


Figure 13: Membrane stresses of the model from form finding analysis

With the device shown in Figure.5 we can inspect the real membrane stresses of the model. Figure.14 shows the inspected stress values. It can be seen that the real stresses are in the range of *0.74-1.15kN/m*, which is quite close to the results from the analysis.

径向(kN/m)	0.75		0.81	0.75					0.79								0.85	0.82	0.87	1.08	1.08
环向(kN/m)	1.01	0.84	1.15	0.76	0.74	0.77	0.89	0.84	0.86	0.78	0.71	0.76	0.93	0.76	0.95	0.95		0.98	0.90	1.01	1.06



径向(kN/m)	0.78										1.14			0.81
环向(kN/m)	1.02	0.94	0.86	1.03	0.88	0.82	0.79	1.15	1.09	1.01		0.84	0.82	0.85

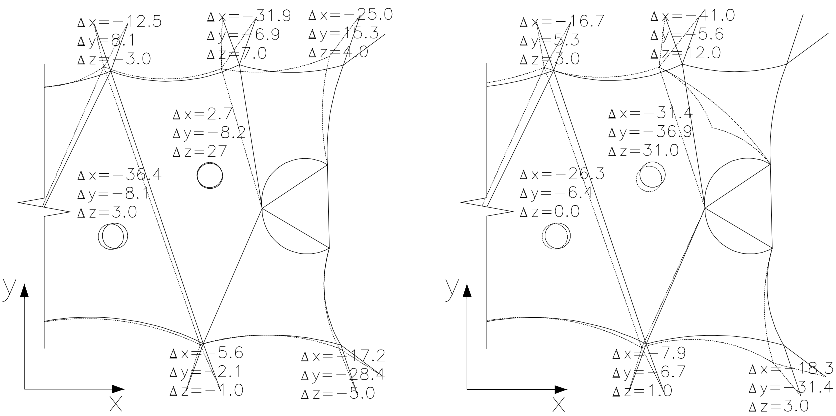
Figure 14: Inspected membrane stresses of the model

4. Behaviors of the model under breaking of cables

Cables at the corner and at the sides are cut to observe the behaviors of the model. Figure.15 shows the membrane shape under breaking of one and two corner cables (cable No.1 and cable No.2). Figure.16 shows the corresponding geometry displacements.

Breaking of cable No.1 Breaking of cables No.1 and No.2

Figure 15: Model behaviors under breaking of corner cables



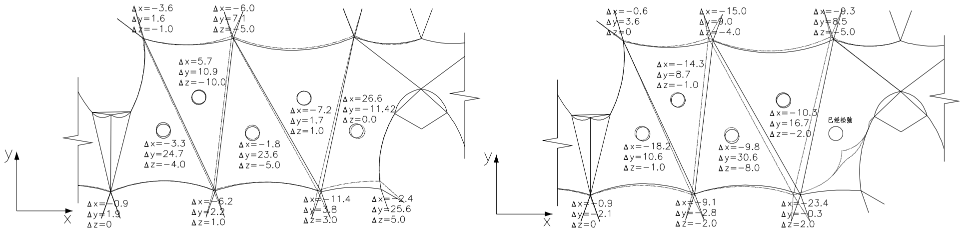
Breaking of cable No.1 Breaking of cables No.1 and No.2

Figure 16: Geometry displacements of the model under breaking of corner cables

Figure.17 shows the membrane shape under breaking of one and two side cables (cable No.48 and cable No.47). Figure.18 shows the corresponding geometry displacements.

Breaking of cable No.48 Breaking of cables No.48 and No.47

Figure 17: Model behaviors under breaking of side cables



Breaking of cable No.48 Breaking of cables No.48 and No.47

Figure 18: Model behaviors under breaking of side cables

It can be seen from Figures.15-18 that the masts connected with the cut cables will have an obvious moving under cutting of cables and the local zone on membrane surface near the cut cables will relax. But the total membrane system of the model will find a new equilibrium state with the redistribution of the internal forces after the breaking of one cable or two cables and will not crash down.

5. Conclusions

Model test shows that the existing numerical form finding analysis methods based on finite element theory can satisfactorily predict the initial pre-stressed state of cable membrane structures. Membrane stresses and cable forces can be inspected with sufficient accuracy by special devices, which can be expected to be adopted in real structures. Cable membrane structure like the roof for "Central axis" is statically indeterminate system with redundant freedoms, so that it will keep stable under breaking of one cable or two cables after redistribution of internal forces.

Acknowledgement

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