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WRINKLING AT THE FAILURE OF MEMBRANE STRUCTURES

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Abstract:

A physical and a numerical model were worked out to examine the failure of a membrane structure. The wrinkling phenomenon was noticeable in some situations. This experiment leads to further questions: which are the most characteristic disposition parameters and how they set up the balance of the surrounding parts of the slack regions.

Keywords:

wrinkling, membrane structures, tent, failure

1 INTRODUCTION

Membrane structures are used in many engineering fields, especially in architecture. The prestressed membrane structures are quite commonly used as roofs, as they can span large distances. Fabric materials can only carry tension, but no compression or bending. An unsuitable shape, inappropriate distribution of tension or overloading could cause local buckling situations, called wrinkles.

The failure of the membrane structure can change the distribution of tension which results in some parts becoming wrinkled. The buckled and slack parts are unstable in some aspects (for example in wind), but they may support the structure like perimeter cables. So it's important to define the location of the wrinkled parts.

2 THE WRINKLING PHENOMENON

Tensile structures are made of thin fabric material. Fabric materials have negligible bending stiffness, therefore the critical load is very low, that in effect they can carry no compression. Wrinkling is a local buckling situation and it is noticeable where compression would occur if the material had bending stiffness. The direction of the wrinkles is perpendicular to the direction of the compression. The structure transforms into a new equilibrium shape which only has tension in its points.

3 THE FIRST MODELS AND EXAMINATIONS

3.1 Frames

The easiest way to examine a tensile structure is stretching a textile on a rigid frame. In order to approximate the ratio of the elements of a real structure, the thinner material the better. Besides thickness, the flexibility is also an important attribute. Flexible polyester materials or nylon stockings are suitable in these aspects.

The generation of an appropriate distribution of tension is supported by an ortogonal net drawn on the textile. This net also gives further information about the failures as well.

Failures are situations, where a crack is created in the original distribution of tension. The structure tries to restore the stresses and responds with a new shape.

3.1.1 Cut on the frame

The first situation is a cut on the frame. The edge of the textile at the missing frame is wrinkled and behaving like a perimeter cable. This cable balances the structur. When a cable is stitched to the edge of the textile, the wrinkling phenomenon isn't noticeable. This examination shows that there is a connection between the wrinkles and the perimeter cables.

Figure 1: Wrinkled edge

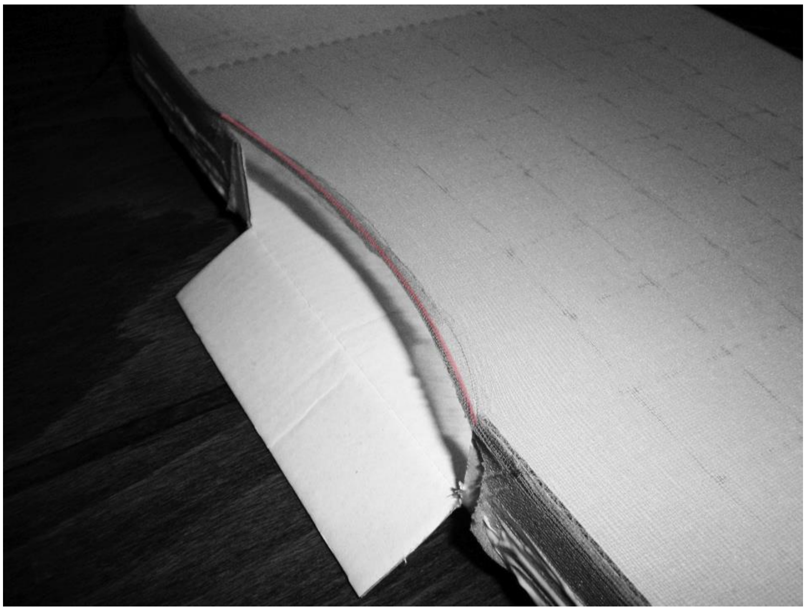

Figure 2: Edge with cable without wrinkling

3.1.2 Split in the textile

The second failure is a split in the textile. Similar wrinkled edges occure as in the previous situation. The shape and the direction of the split affects the bending. Circle shaped splits cause no wrinkled edges, circles seem to be the most favorable form of split for the structure. Splits in the weft and warp make different wrinkles.

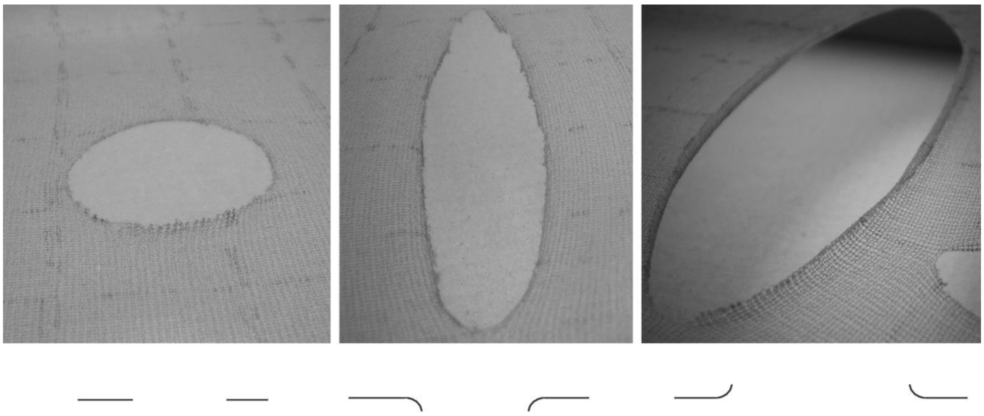

Figure 3: A circle and two different directions

3.1.3 Explanation and conclusion

The connection of the wrinkles and the perimeter cables is demonstrated with the frame examinations. The edge of the textile is streched to 180°. The tension from this streching wrinkles the edge, and the edge transforms to a new shape. The tension is the distribution load for the edge. If the distribution of tension has the same value at each point, the direction of the stress vector is perpendicular to the tangent of curved edge. The theoratical shape of the edge would be a semi-circle, but the deformed lines affect the distribution of the stress vectors, therefore the new shape differs from a perfect arch.

Making an unwrinkled edge is possible by stiching a perimeter cable to the edge with the shape of a semi-circle.

3.2 Tents

In architecture, the most common tensile structures are tents. Tents are more complex than frames and suitable to examine the wrinkles. The tent stands on a plywood board with pin-joint connections. A fabric material is streched above a regular polygon between the central pole and the corners. There is a column and two cables in each corner.

Figure 4: Tent with 12 corners

3.2.1 Edges

The behaviour of the edges is similar to the wrinkled edge examination (1.3.1). If no perimeter cables are stitched into the edges, wrinkles will replace them. Creating a tent with unwrinkled edges is possible by choosing a cutting pattern with curved edges and sewing a cable into the edge.

Figure 5: Edge without a perimeter cable

3.2.2 Removed corners and cables

Removing a cable changes the distribution of forces between the supporting elements. The structure stays in a statically indeterminate state. The pin-joint connection between the corner's column and the board can carry no bending, therefore the column moves to the direction of the another cable (Figure 6.). The wrinkle is a catenary curve between the disturbed corner and the next corner.

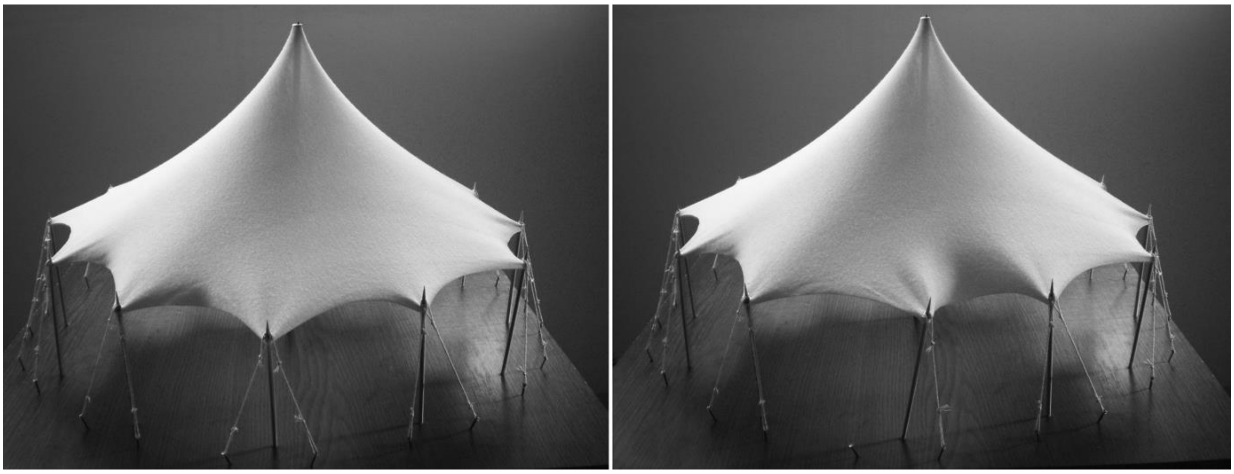

Figure 6: Removing a cable

Removing one corner is a similar situation to the wrinkled edge situations. A missing corner changes the polygon and creates a new unsupported edge. The wrinkle connects the two corners next to the missing corner with a parabolic line. The textile over the semi-circle is taut and excluded from the equilibrium of the structure.

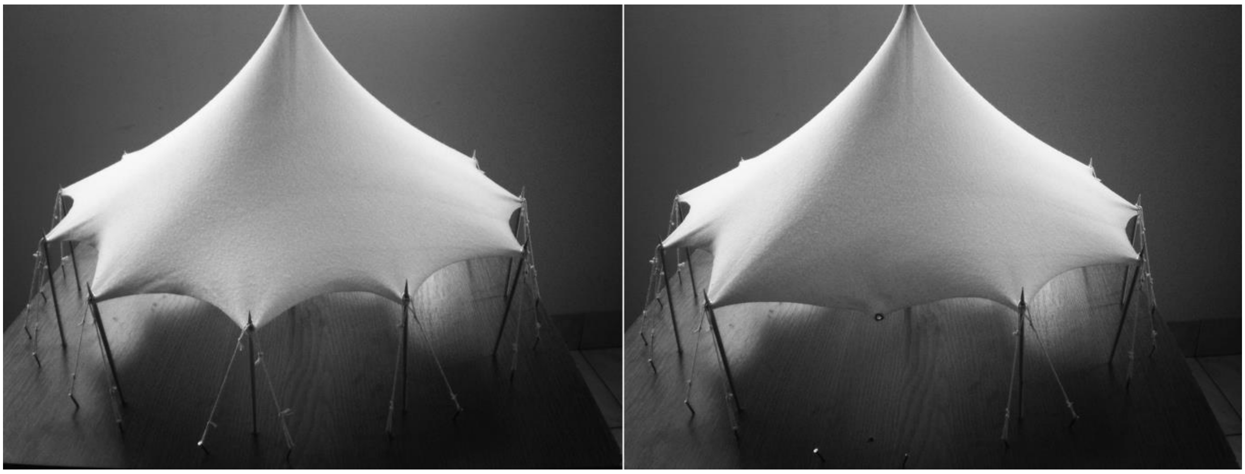

Figure 7: Removing a corner

Removing corners and cables at the same time makes more complex wrinkles.

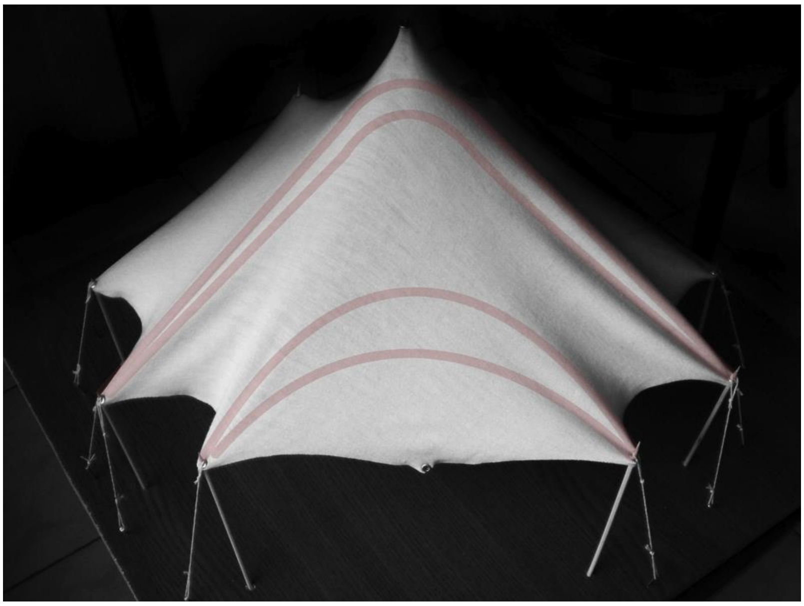

Figure 8: Removing a corner and 2 cables

4 THE FINAL PHYSICAL MODEL

A physical model is the result of the first examinations, using the experiences with the previous models and materials.

4.1 Configuration

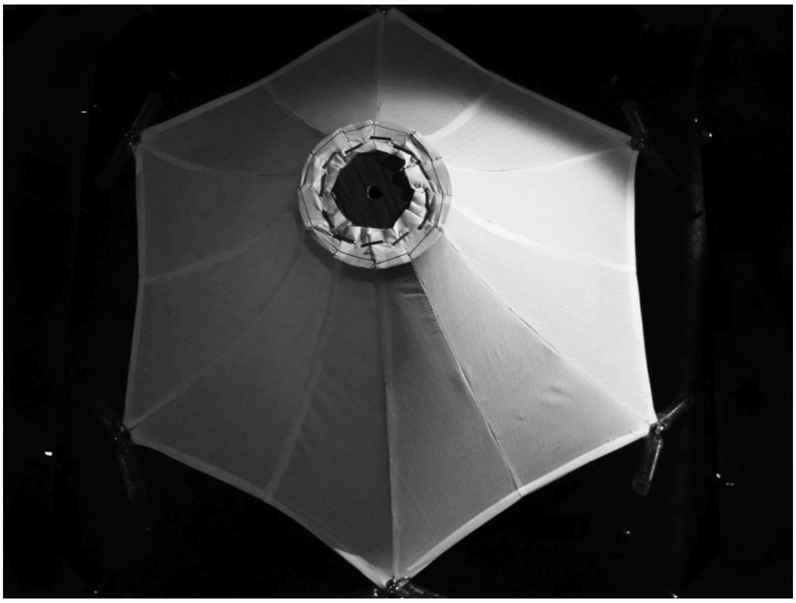

Figure 9: The model

The model is on a 65x65 plywood board. It is a Pelikan-membrane with 6 corners and a central pole. Each corner supported by a column and 2 nylon cables.

The cables run down to the board in a fixed angle, which are secured by a ring screw anchored to the board. Each cable is linked with a spring balance to measure the stress. Twelve classical guitar tuners are fixed to the edges of the board to adjust and monitor the force in the cables.

The central pole is linked with another spring balance to measure the compression. The columns and the pole are standing in recesses constituting a pin-joint connection with the board, therefore these elements can't take bending. If they were fixed columns with the ability to take bending, they would carry horizontal forces and isolate some parts of the membrane forbidding them from contributing in the overall equilibrium of the structure.

4.2 Membrane

The cutting pattern is generated from a Pelikan membrane shape. Twelve elements of this pattern are stiched together with light polyester yarn. According to this, 2 elements are connected at the corners, which are the most strained parts of the structure. The experiments destroyed these parts first. The connection of the middle pole and the membrane is a similar problematic situation. The textile is stitched on a wooden disk, which is in a pin-joint connection with the pole.

Three kinds of textile are used with different attributes. The strongest one is made of cotton and examined by the Department of Polymer Engineering. With the attributes of this material, it is possible to compare the experiences with the numerical calculations. The other two materials are made of the same kind of polyester, but one of them is coated with PVC film. For real constructions the common materials are coated textiles, for example PVC-coated polyester or PTFE-coated fiberglass.

Each edge has a perimeter cable stitched into the textile. In real constructions these cables play an important role in the distribution of tension. However in this model, the bending stiffness of the sewed connection is comparable with the bending stiffness of the cable. Sewing supports the perimeter without the cable. The supporting phenomenon of the sewing is noticeable at the sides during the examination of the failures as well.

4.3 Installation

Figure 10: One of the guitar tuners

Making the appropriate distribution of tension is important. The guitar tuners enable us to increase the tension in the cables gradually and simultaneously. Otherwise other balanced situations could occur with inadequate (usually assymetric) shape. These shapes often come with winkled parts, so they are inadequate to examine the wrinkling at the failures. Different shapes can have the same value of tension in the cables and compression in the middle pole. However the behaviour of these shapes are inappropriate in loaded situations.

5 COLLAPSE

Collapse is a situation where some supporting elements are removed as in the previous tent examinations. If two cables are removed from a corner, the column will become exluded from playing a role in the overall equilibrium of the structure. Therefore there are two kinds of failures in a corner: removing one cable or removing all of the supporting elements.

There are 3 examination steps. The first step is to predict the location of the wrinkled parts with approximations, considering the previous experiences. The next step is to make numerical calculations with a program using a nonlinear analysis to make precise calculations. The final step is a comparison between the calculations and the model.

5.1 Missing corners

The aim is to find the most stressed cables, because they are the origin of the wrinkles. The wrinkle is a catenary curve between two heavily stressed corners.

5.1.1 Prediction

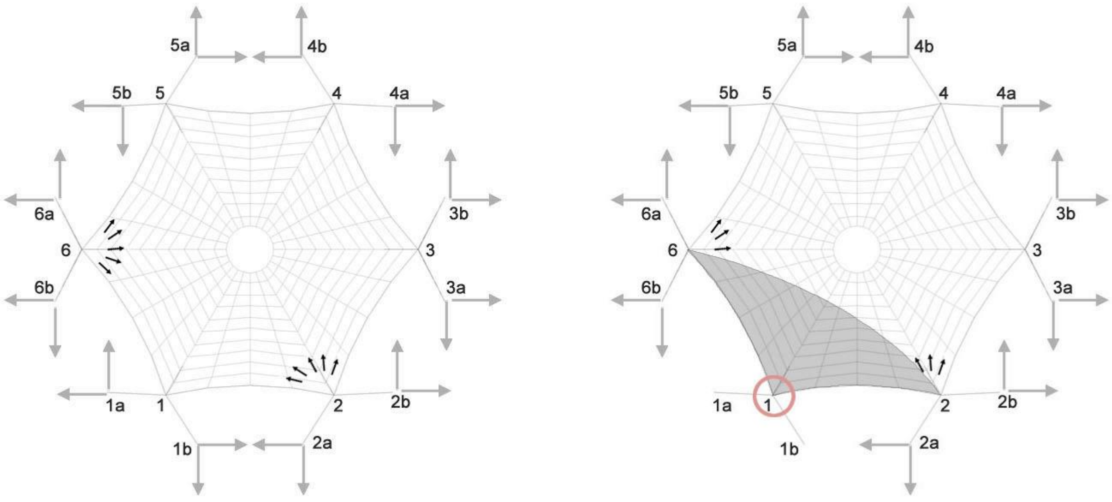

Figure 11: Before and after removing a corner

A missing corner is increasing the stress in the next and the previous cables. When a corner is removed, the cables next to it loose the corner's support. As a result, the wrinkle is a connecting catenary curve between the corners next to the removed corner.

Removing more than 1 corner is similar. For example: removing '1' and '4'. In this case, the heavily stressed cables are: '6b', '2a', '5a', '3b'. The wrinkles are running from '6b' to '2a', and from '5a' to '3b'.

5.1.2 Numerical calculation

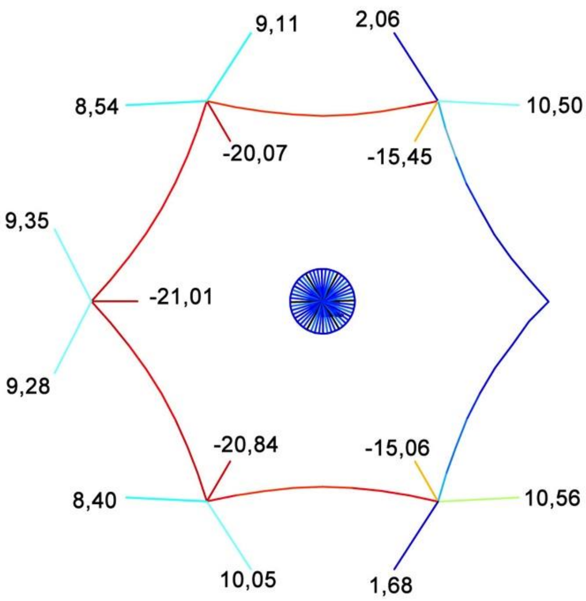

Figure 12: Numerical calculation with one missing corner

5.1.3 Physical model

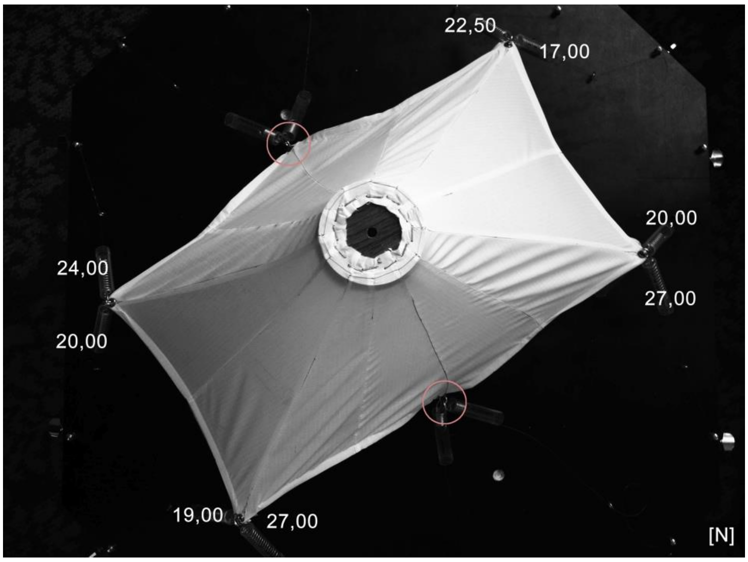

Figure 13: 2 missing corners

Initially, there were 25N in the spring balances. The wrinkles are quite noticeable . They start from the heavily stressed corners, but the stitched connections are too rigid to transmit them, therefore most of the wrinkles break at the first stitched connection.

5.2 Missing cables

Removing a cable moves the disturbed corner to the side. The aim is to find the direction of this movement, because the wrinkle starts from the disturbed corner and runs to the next corner in this direction.

5.2.1 1 cable

If a cable is removed from a corner, its pair has to take heavier loads. The corner moves to the side.

For example: '1a' is removed. '1b' become a heavily stressed cable. The corner moves to the left and this movement tense '6b' and decrease the stress in '2b'.

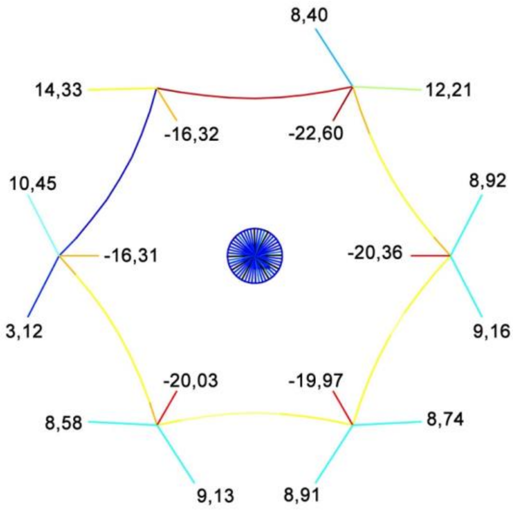

Figure 14: 1 removed cable

5.2.2 2 or more cables

Two removed cables next to each other in the same corner is discussed in the previous section.

If the 2 cables are not in the same corner, they behave similar to the 1 removed cable situation. The corners move from each other to the another direction.

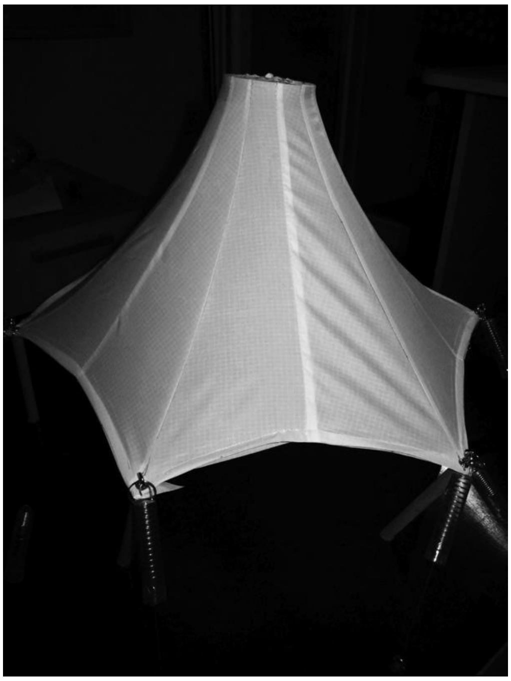

Figure 15: 2 removed cables next to each other

The wrinkles are catenary lines between the disturbed corner and the next corner in the direction of the movement of the disturbed corner.

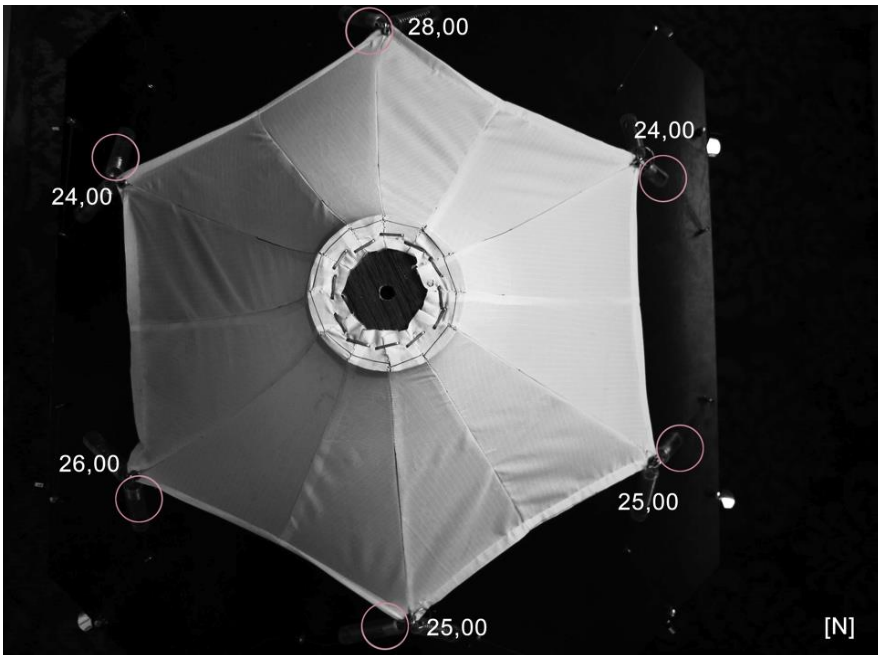

Figure 16: 6 removed cables

5.3 Combined situations

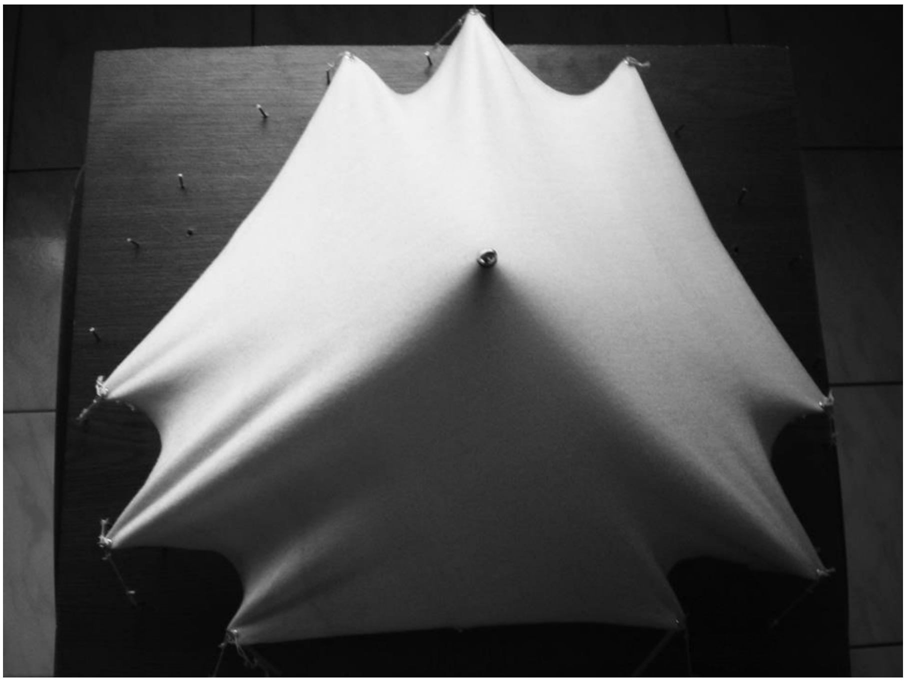

Figure 17: Combined situation

The rules are the same. In this example 3 corners and 6 cables are removed. The wrinkles are catenary lines between the heavily stressed corners or between the disturbed corners and the next corner in the direction of the disturbed corner's movement.

6 CONCLUSION

These examinations lead to further questions and problems. After solving the problems which occured during the numerical calculations, more details can be examined. This paper only deals with the position of the wrinkles. The next step could be the examination of the behaviour of the wrinkled tents in loaded situations, or the examination of the shape of the wrinkles.

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