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(UN)FOLDING THE MEMBRANE IN THE DEPLOYABLE DEMONSTRATOR OF CONTEX-T

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Abstract. The paper presents a system, made out of foldable 'kinked' beams and a membrane skin, based on a concept referring to origami. The anticlastic curvature of the membrane is obtained by transforming flat triangular parts into space. The following research question is considered: can the foldable system be stable in intermediate configurations? To obtain a well-tensioned membrane in the intermediate positions, the belts connecting the membrane to the frame can be released or increased in tension.

A full scale 'demonstrator' has been built within the frame of IP-project Contex-T[8]. Although the deployment - rotating the 'kinked' beams about the central axis - was feasible, the tensioning and structural behaviour of the membrane, attached in the nodes of the frame, was not yet thoroughly examined.

For that reason one single unit has been analysed. Forces and deformations in the membrane are verified for different opening angles using integrated models including the membrane, connecting belts and 'kinked' beams (for the frame).

The results of the experimental investigations and numerical models are compared and occurring discrepancies are clarified.

1 GENERAL CONCEPT

The study of the deployable circular demonstrator is part of a more general research topic to expand the possibilities of high tenacity coated textiles for adaptable lightweight constructions, such as simple retractable canopies and kinematic facades for shading or movable roofs with large free spans.

The concept of the deployable structure with a foldable membrane skin is based on a foldable paper model[1,2,4], as shown in Figure 1. The foldable model consists of a series of triangles, connected at their edges by continuous joints, allowing each triangle to rotate relative to its neighbouring triangle. The foldable model can fold into a flat stack and unfold into a predetermined three-dimensional configuration, with a corrugated surface: a circular dome. The folds moving outwards are called ridge or mountain folds, the folds going inwards are the valley folds.

The demonstrator (which fits in half a sphere with a radius of 4.25m), built in the frame of the IP-project Contex-T *Textile Architecture - Textile Structures and Buildings of the Future*[5,6,8] is made out of 14 identical triangular panels and 2 boundary panels (see lower part of Figure 1).

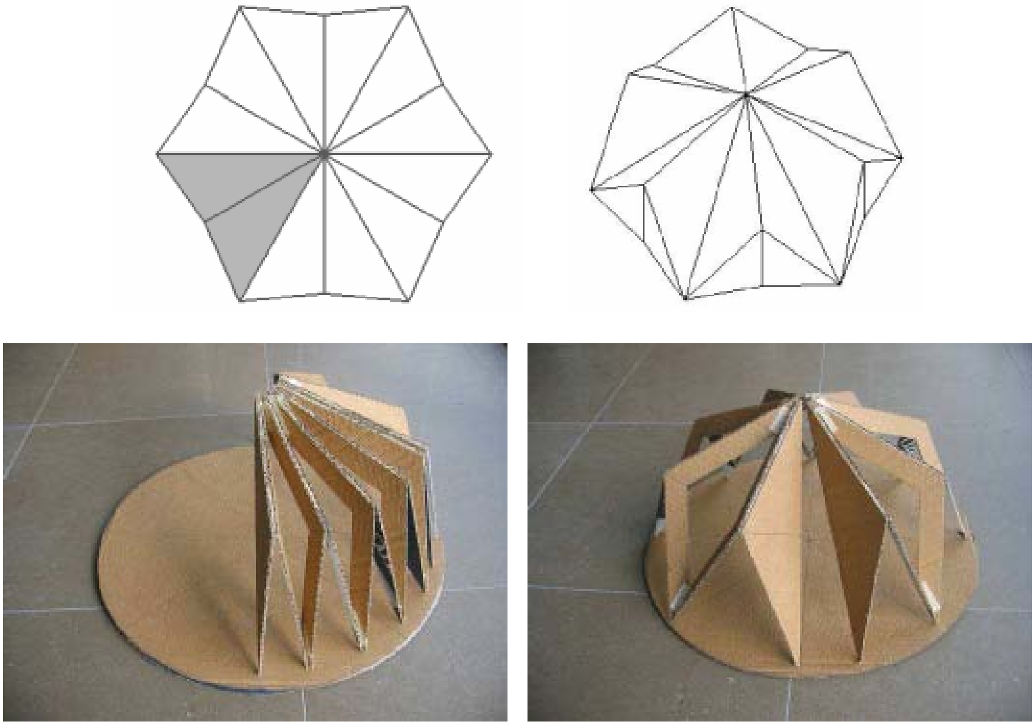

Figure 1: Upper: Origami concept (unfolded)[1]; Lower left: Folded paper model, Right: Deployed

Two units (consisting of four triangles) are fixed in the unfolded configuration and act as the stiff core for the foldable parts: the apex of the dome is supported by these two units.

2 EXPERIMENTAL VERIFICATIONS

2.1 First prototype: one quarter

A first experimental set up of one quarter of the system was analysed[3] and realised at the Vrije Universiteit Brussel (Figure 2). The frame was made of steel profiles with a 50mmx50mmx5mm section. The folding hinges were made by means of hollow tubular axes.

Figure 2: Setup: a. the frame b. the frame with the membrane

The membrane (in this case a PVC-coated polyester membrane from Contex-T partner Sioen) was only attached in the nodes of the steel frame: in the top, at mid height and in the corner points at ground level. Ridge, valley and boundary belts were foreseen to tension the membrane.

The feasibility of folding the frame from 100% open to 30% was approved (see Figure 3).

Figure 3: Top node a. deployed b. folded

2.2 The Contex-T demonstrator

The full scale demonstrator has been built by Contex-T partner IASO with the following simplifications: (i) the system opens along the ridge instead of along the valley line, (ii) only the long diagonals of the membrane units (valley line) can be adjusted to influence the pre-tension and (iii) the cut-out of the boundary curves was increased.

A standard PVC-coated polyester membrane was used (686gr/m^2, strength in the warp direction: 322kg/5cm (64.4kN/m) and in the weft direction: 291kg/5cm (58.2kN/m)) reinforced with stitched vectran and polyester belts.

The two fixed units were placed on site and connected to the concrete base platform. The other elements (on wheels) were joined. Once all elements were attached, the position of the apex of the dome was lower than theoretically foreseen and the system did not appear stable. A connection point was placed in the central position at ground level and all movable elements are attached to this point by means of thin cables (see Figure 5) which control the rotation of the units. When folding, the different units tilt in a different way, depending on the sequence of folding (Figure 4).

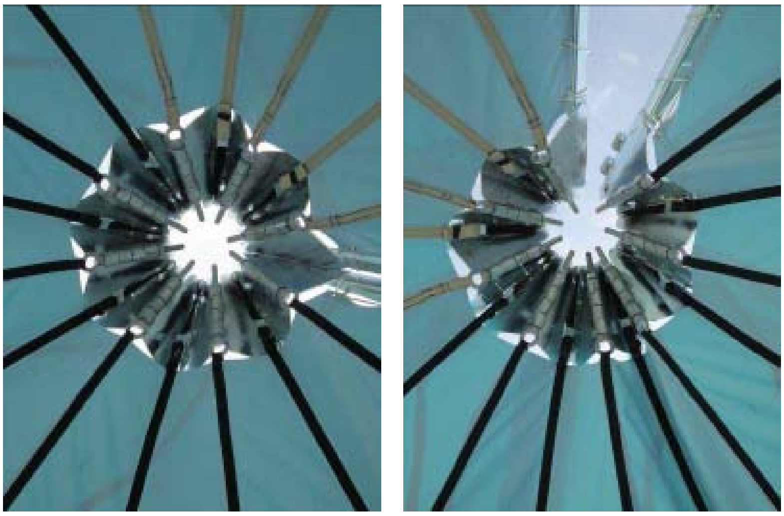

Figure 4. Top node. a. closed configuration b. one unit folded

Figure 5. Overall view: a. closed configuration b. one unit folded

The design considered a slightly tensioned membrane (pretension ~0.1 kN/m) in the unfolded configuration. When folding the structure, the distance between ridge and valley line decreases and the membrane becomes slack. Thus, a higher pretension is required in the unfolded configuration to keep the membrane tensioned in the different intermediate configurations between completely unfolded and folded.

To obtain a better insight in the structural behaviour of this foldable structure, one unit is investigated in more detail during (un)folding.

3 STUDY OF A SINGLE UNIT

3.1 Numerical Analysis

The form finding of the membrane model is done with the approximation of a cable net and the force density method[7] (EASY software from Technet[9]). Two triangles with a base of 6m and an apex angle of 120° are joined along their base and placed with an opening angle of 20°. Next, the equilibrium shape is calculated for a pretension of 1kN/m in the two directions of the net (Figure 6).

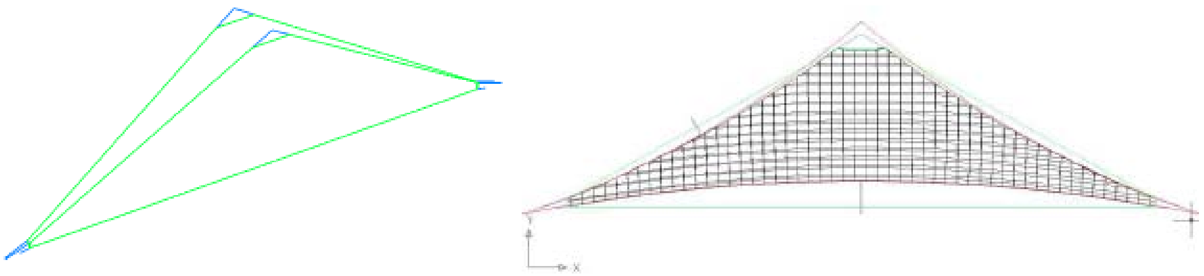

Figure 6. The single unit: a. the system lines b. tensioned equilibrium shape

Two kinked beams are added to this membrane unit, the model is transferred to the EASYbeam software[9] and is calculated for different opening angles (20° to 90°, steps of 10°).

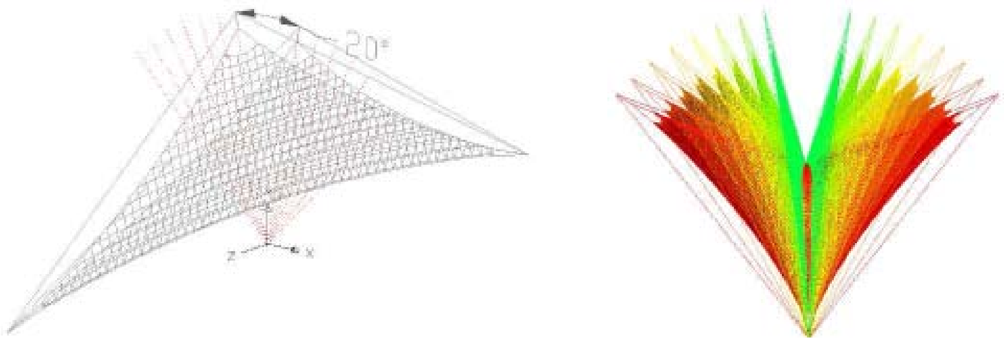

Figure 7. The (un)folding: a. variation of the opening angle from 20° to 90° b. superposed models

In the integrated numeric model (membrane, belts and frame), the evolution of the membrane stresses as well as the forces in the belts can be verified (Figure 8). When folding from an opening angle of 90° to 20° the maximum force in the valley belt decreases from 26.4kN to 23.8kN and the maximum membrane stress decreases from 10.8kN/m to 2.1kN/m.

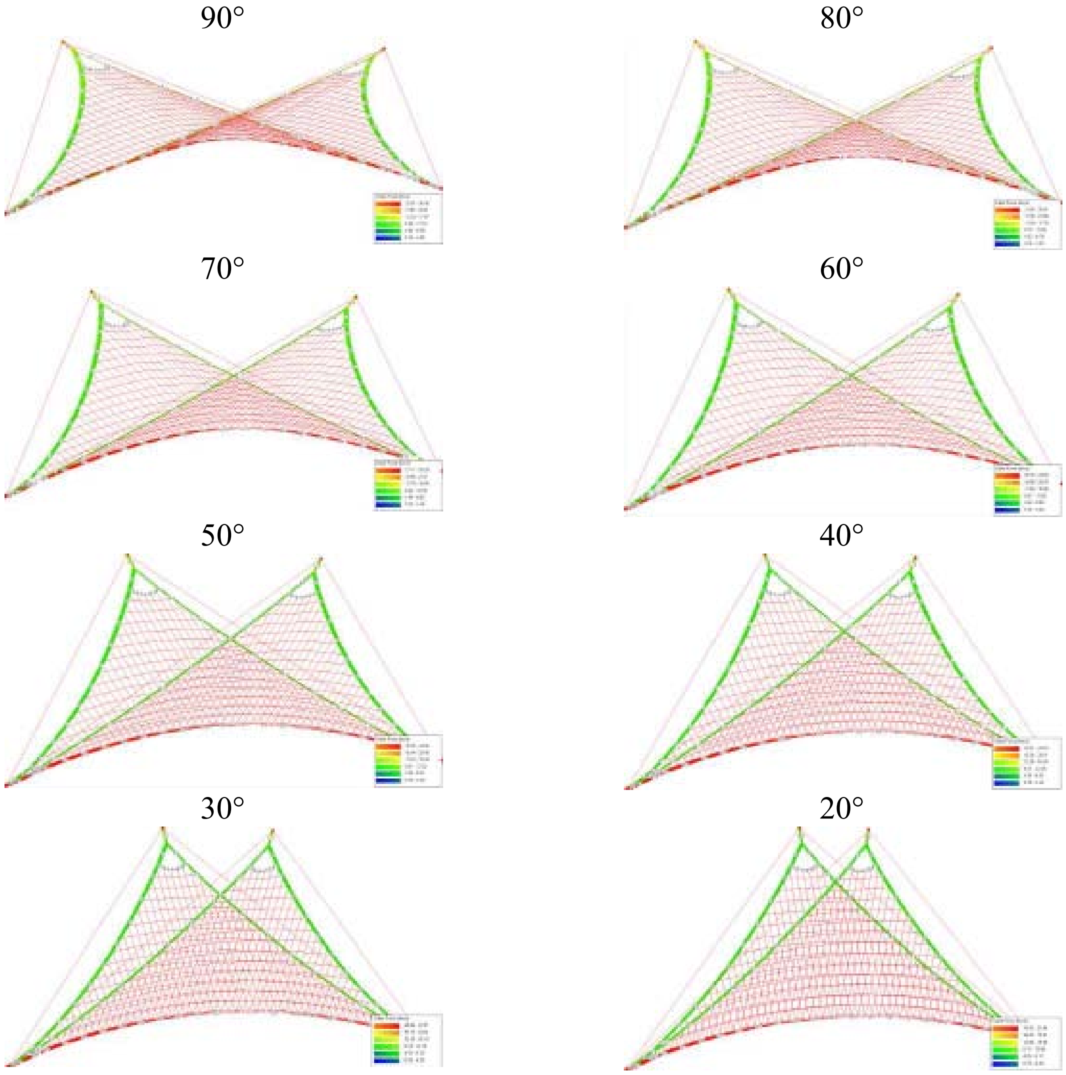

Figure 8. Equilibrium shape of the same membrane for different opening angles

3.2 Fabrication

A PVC-coated polyester membrane (Sioen T2107, 1050gr/m^2, strength in warp and weft direction: 4000N/5cm (80kN/m)) was applied in the fabrication of one unit. Compensation was neglected since on the one hand it is a small membrane with a pre-tension of only 1kN/m and on the other hand the length of each connection belt is adjustable. The foldable unit is made from two triangles (base 6m, apex 120°, weft-direction perpendicular to the base) from which circular cut-outs were made along the borders (sag 5%). The borders have been reinforced with a double polyester belt (strength 20kN). The fabrication was done by Carpro (Figure 9).

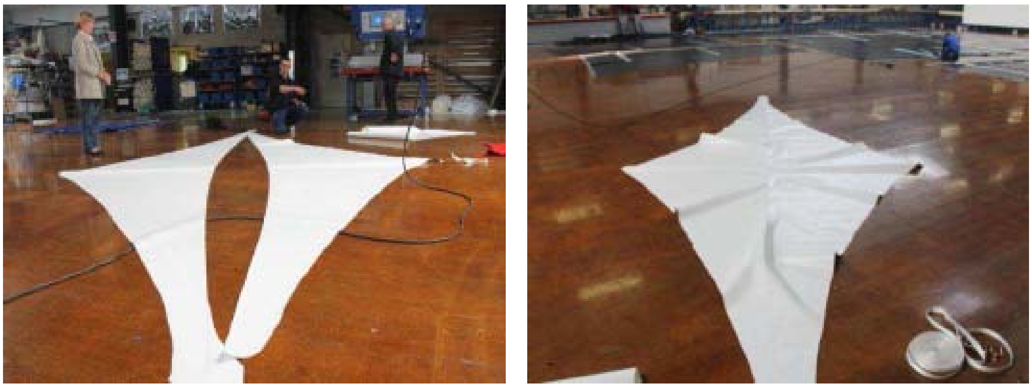

Figure 9. The single unit: a. membrane parts b. assembled

The membrane is placed in a foldable frame made from the elements used for the first experimental model: only the connection elements - where the membrane needs to be attached to - had to be adapted (Figure 10).

Figure 10. Modified connections: a. welded bars and an additional hole in the plate b. ring to attach the belts

3.3 Assembling and testing

The membrane and the frame have been assembled a first time (Figure 11.a. and b.) to check the folding and the possibility to introduce a pre-tension of 1kN/m in the membrane. The system could not be folded up to the angle of 20° due to the thickness of the shackle and the ratchets (Figure 11.b.) and the pre-tensioning was not performed.

After the connections have been simplified (Figure 12.a.), the membrane has again been attached in the frame. The lengths of the links connecting the membrane to the frame were set according to the prescribed values.

This time (un)folding was no problem, but the membrane seemed to be too large for the frame. It was not possible to tension the membrane uniformly in the different configurations (Figure 12.b.), although the frame as well as the membrane were made according to the designed geometry.

Figure 11. a. the base angle b. the apex angle

Figure 12. a. Simplified connection at the base angle b. membrane opened 90°

3.4 Further experimental tests

When fixing the membrane, the belts - connecting the membrane to the corner points of the frame - have to be adjusted to a specific length to obtain a ‘well tensioned’ equilibrium state without wrinkles. Also the valley belt should be tensioned correctly. The influence of shortening the belts or tensioning the valley line, depends on the real stiffness of the fabric and its reinforcements. The constant stiffness set in the numerical model implies a linear approximation.

To be able to understand the structural behaviour of the system the fabricated membrane is tested on its own. The membrane is folded (opening angle 0°) and attached at its corner points in a test rig (Figure 13).

During the tensioning process the anchorage points at the base remain fixed and the apex point moves upward. The geometry (circumscribed triangle, sag at the borderlines), the forces in the anchorage points and the biaxial strains in the membrane are measured in consecutive steps up to a ‘well tensioned’ state.

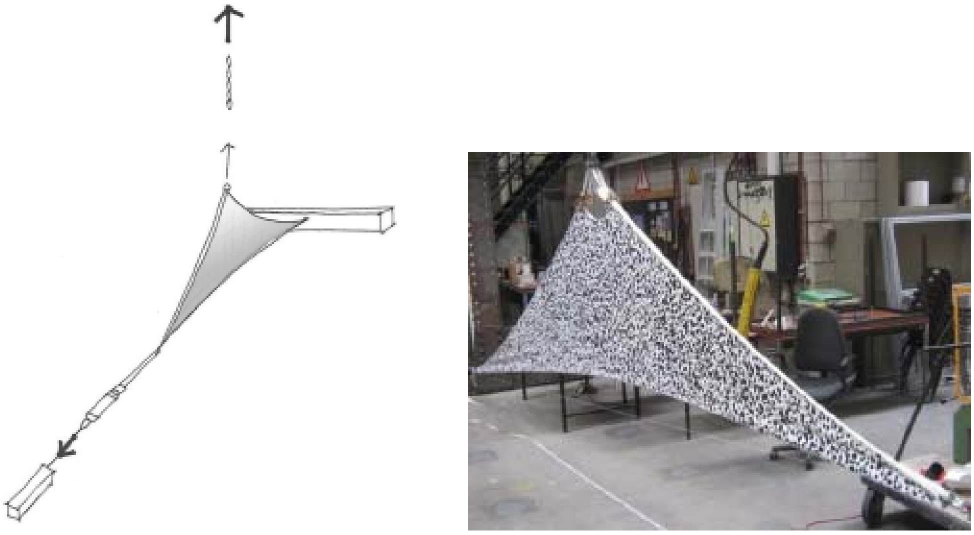

Figure 13. Experimental set-up: a. schematic b. membrane with pattern for the DIC-measurements

With the method of Digital Image Correlation for optic strain field measurements (DIC Vic3D) the process of increasing the tension can be observed in detail. The images have been numbered from 0 to 87.

Since the stiffness in the borders is discontinuous, a complex deformation pattern is obtained especially below the circular cut-out at the apex corner (Figure 14). Similar irregularities had been observed in the cable net model (for the forces).

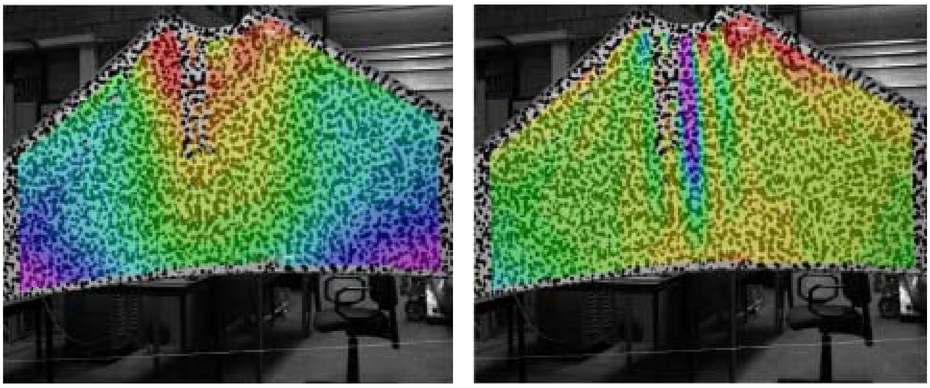

Figure 14. Strain field measurements a. in y- direction b. in x-direction (red: high, blue: low values)

The experimental results for the 'well tensioned' equilibrium state without wrinkles (reference number 87) will now be summarised. The width of the membrane is 5.54m, the force at the base corners 12.1kN and the sag for the valley belt 34,5cm. Hence, the tension in the membrane in the y-direction (vertical) can roughly be estimated to be 0.3kN/m in each membrane layer (considering equal forces for the valley and the two border belts).

When comparing the experimental results with the numerical simulations the following can be stated: (i) the numerical model gives a force value of 23kN in the valley belt which corresponds to a membrane stress of 1kN/m, the values are lower in the experiments, (ii) in the numerical model the membrane stresses are more uniformly spread over the surface and (iii) the lower tensions below the cut-out at the apex corner (clearly visible in Figure 14) were only obtained at higher opening angles in the numerical models.

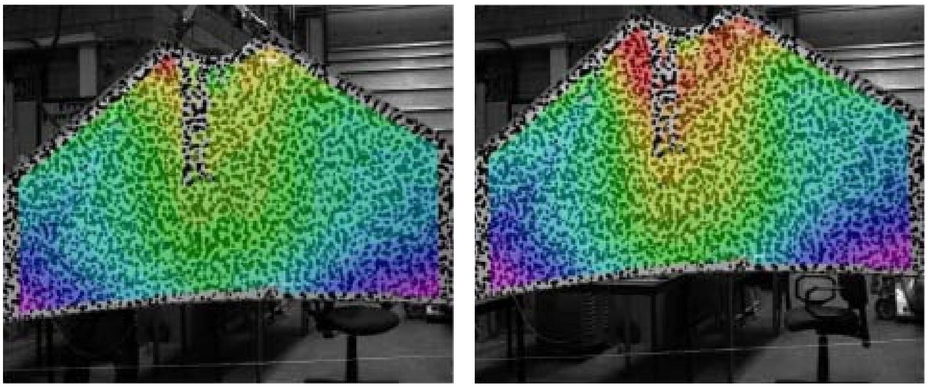

Figure 15. Strain field measurements in y- direction a. image 54 b. image 87 (red: high, blue: low values)

From the comparison between the image with reference number 54, for which the geometry corresponds to the numerical model, and the image with reference number 87, corresponding to the highest displacement of the apex corner, it can be seen that the circumscribed triangle highly deforms. The sag of the base line increases from 27.5cm to 34.5cm (Figure 15). Thus, the height of the circumscribed triangle for the ‘well tensioned’ state is greater than the height of the foldable frame. The stiffness of the membrane, especially in the weft-direction, has been overestimated.

This experiment is only a first step to further investigate the (un)folding procedure of the tensioned membrane.

4 CONCLUSIONS

Numerical simulations demonstrate the possibility to tension one and the same foldable membrane, tensioned in a foldable frame, into different configurations. The validity of these calculations, using a cable net as model for the membrane, has to be confirmed.

For this reason and to gain insight in the structural behaviour, the experimental stress-strain behaviour of a simple membrane unit tensioned in a system of foldable ‘kinked’ beams was investigated.

In a first set-up the membrane was fixed to a frame. Here it was not possible to obtain a wrinkle-free membrane since it was too difficult to introduce the high forces manually.

In the next set-up the membrane was fixed between two anchorage points and a hoisting crane. The upward displacement of the apex corner was used (without other adjustments) to pre-tension the membrane. The process was registered by digital images to measure the strain fields. The forces in the anchorage points and the sag of the valley line were read off in each step.

This simple test clearly shows: (i) that although designed to be light and low-tech, the high forces in the belts cannot be introduced manually, (ii) that even in the folded reference state the strain behaviour of the membrane, reinforced with belts, is complex, (iii) that high strains occur in the membrane, especially in the weft direction (iv) and that it is feasible to control the tension by moving the apex corner up or down. The folding will be studied in a similar way by rotating the membrane panels about the base line.

5 ACKNOWLEDGEMENT

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