RESEARCH

KINEMATIC FORM-ACTIVE STRUCTURES FOR ARCHITECTURAL APPLICATIONS

Design, Analysis and Experimental Verification

Due to their low self-weight and their inherently high flexibility, lightweight technical textiles offer great possibilities for the integration in kinematic structures. Furthermore, new interesting typologies combine the use of mechanically prestressed membranes with the lightweight principles of active bending. Integrating these principles in a transformable design creates challenging perspectives, exploring the great variability in possible geometries and expressive shapes. Unfortunately, until now, there is still a lot of research to be covered on the material properties of technical textiles, their structural behaviour during deformation and the use of available design tools. Also for the design and analysis of textile hybrids many research is still ongoing and, furthermore, the interaction between the bending elements and the membrane complicates the integration of the kinematic aspect. Up to the present, the inability to keep the fabric properly pretensioned in all deployment stages within the structure's limitations obstructs the use of fabric structures for kinematic applications (like e.g. as an adaptable façade shading system as presented in Fig. 1).

The challenge of this research was to obtain (two) transformable systems for kinematic applications in which the membrane prestress is controlled throughout all the folding states of the structure. The aim was thus to keep both the membrane and the supporting structure stable in the different phases of the deployment. Through the analysis of case studies, the main research question is aimed to be answered: «Can the integration of technical textiles in kine(ma)tically deployable structures result in an efficient transformable lightweight structure, remaining tensioned in all configurations of the application range?»

This article is based on the research presented in the doctoral thesis [1] and describes the design, analysis and experimental verification of two selected case studies in order to prove the feasibility of designing kinematic form-active structures and confirming both the possibilities and the remaining challenges. More detailed results can be obtained by consulting the thesis manuscript and in the journal papers [2] [3], where the results of case study 1 are discussed thoroughly. The results of case study 2 will be presented in two other journal papers.

Two representative case studies

The first case study consists of a membrane that is tensioned in a transformable frame. Opening and closing the frame results in unfolding and folding the membrane. As the deployment is established through the rotation of rigid hinged angulated beam elements (i.e. a rigid body motion), this case is classified under 'rigid hinged boundary kinematics' (Fig. 2 - left). The second case study investigated in this research consists of a (quasi-) self-supporting structure with a flexible membrane that is tensioned in a bending-active ring element and will be referred to as 'bending-active boundary kinematics' (i.e. elastic kinetics). By applying a certain prestress on the membrane, the originally flat structure pops up to a three-dimensional shape. This form-found geometry is then used as a starting position of the kinetic deployment (Fig. 2 - right).

To be able to provide a clear answer to the main research question, also a number of important sub questions is aimed to be answered:

How will we simulate these KFAS? *To what extent can an analysis tool used for the analysis of tensile surface structures be used to model different configurations of the kinematic form-active structures (KFAS)?*

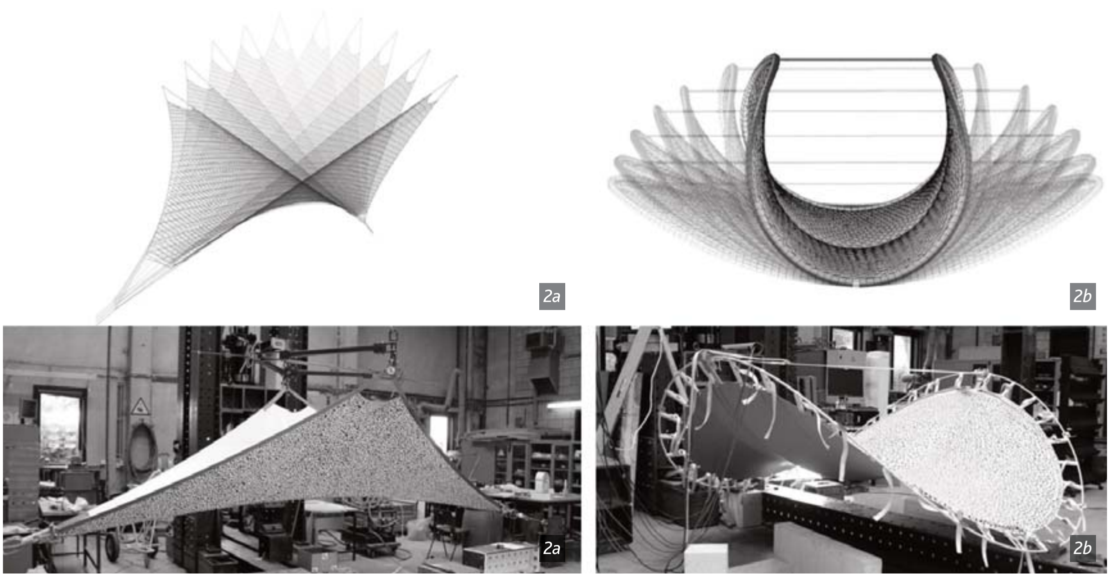
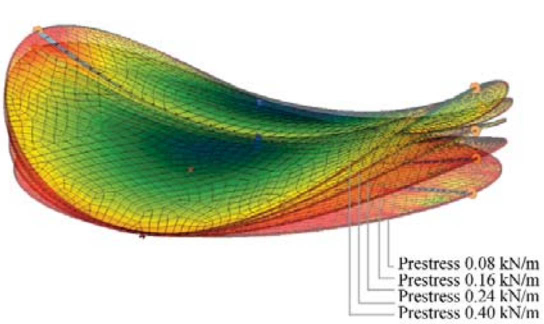


Figure 1. Conceptual visualisation of a kinetic facade system integrating a mechanically stressed membrane.
Figure 2. Numerical and experimental models of: (left) Case study 1 – rigid hinged boundary kinematics; (right) Case study 2 – bending-active boundary kinematics.



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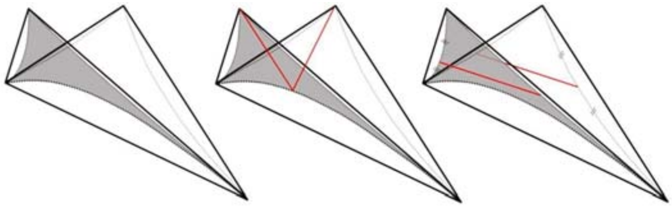

	Area (m²)	Height (mm)	Width (mm)
10°	2.91	1346.1	2833.9
30°	2.92	1347.0	2831.7
50°	2.91	1350.5	2822.5
70°	2.91	1364.2	2803.3
90°	2.90	1397.4	2763.3

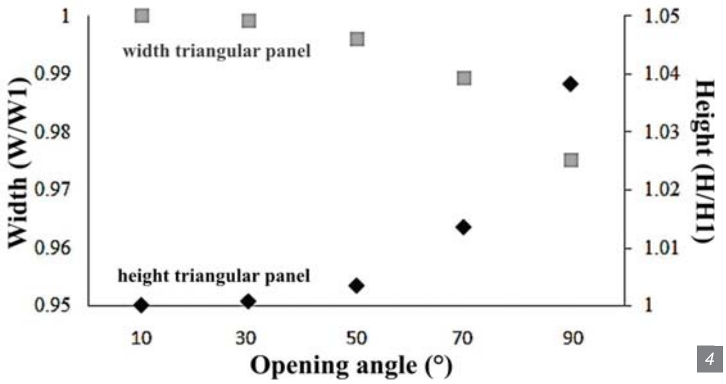

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Figure 3. Case study 2 - The applied prestress determines the three dimensional shape of the pringle-shaped textile hybrid.

Figure 4. Case study 1 - The geometry changes throughout the deployment: increase in height (H/H1) and decrease in width (W/W1) with increasing opening angle.

The thesis discusses how a simple linear elastic numerical model can serve as a valuable design tool both for the form-finding and for the simulation of the kinematic deployment.

The first case study is modelled in Easy© [4], where the membrane surface is approximated by a cable net. The Easy software is specifically developed for the design and analysis of membrane structures and uses a linear elastic material model, integrating the shear stiffness and the effect of crimp interchange. In the second case study, bending-active elements are integrated in the kinematic membrane structure. As Easy cannot cope properly with those bending elements, new options are explored. Therefore, the Finite Element software Sofistik© [5] is used to model the textile hybrid, where the membrane is simulated as a continuous surface. Also here a linear elastic material model is implemented. Both software programs allow implementing a geometrically nonlinear calculation and have an integrated cutting pattern generation tool.

Even to model the simple linear elastic material behaviour a correct determination of the material properties is of major importance. The kinematic aspect of the membrane structures adds an extra dimension. For the PVC-coated polyester membrane (case study 1) both a standard MSAJ biaxial test was performed and a tailored biaxial test that mimics the behaviour of the kinematic deployment of the KFAS (where the biaxial load profile is based on the stresses in the large-scale numerical model). The observed difference confirmed the importance of a project oriented biaxial load protocol and thus the importance to approximate the material behaviour as close as possible. For the PU-coated fabric (case study 2), the limits of the biaxial bench at the Vrije Universiteit Brussel unfortunately didn't allow a project oriented biaxial test (due to the high deformations and the low applied loads) and thus only a standard biaxial test was carried out.

The form-finding under the applied prestress occurs in Easy through the force density method, whereas Sofistik uses the reduced stiffness method for the form-finding of the membrane. The high deformations of the bending-active boundary elements complicate the numerical modelling and therefore a slightly adapted form-finding process is adopted compared to traditional membrane structures. In this second case study, the geometry changes significantly with increasing prestress (Fig. 3).

The kinematic deployments of the structures are modelled as an analysis under external loading that is applied on the form-found geometry. Both software packages allow an iterative calculation process, whereby the relative deformations, forces and strain variations can easily be compared for different opening phases.

In order to verify the accuracy of the numerical models, experimental investigations serve as a validation of the simulation process. The experiments showed that the results derived from the numerical model give a good approximation of the experimentally obtained results and confirm thus that the simple linear elastic material models allow a good prediction of the actual behaviour of the membrane structure. More information on the experimental investigation is given further in this research article.

However, an important point of concern is that the linear elastic model does not take into account the large initial and permanent deformations of both the membrane and the polyester belts. It is confirmed that a correct derivation of the compensation factor is of major importance, as deviations in the used cutting patterns influence both the form-finding geometry and the behaviour during the kinematic deployment.

How do we design KFA? *...to keep the membrane tensioned in all its phases of the considered transformation. In other words, which design parameters and values can improve the overall structural response in various configurations?*

This research proves that an exhaustive preliminary numerical study is essential to enhance the overall structural behaviour of the membrane structure in all stages of its transformation (within the application range), keeping the membrane properly tensioned and avoiding excessive stress concentrations. As the design and analysis of KFAS is quite new, these parameter studies clarified some important steps that need to be integrated in the design process.

For both case studies a parameter study was performed to derive a set of conceptual design considerations for the kinematic prestressed fabric structure. The specified parameters to be verified in the design process were (i) the boundary configuration in which form-finding was conducted (i.e. the reference state), (ii) the prestress levels and ratios, (iii) the control of the deployment and (iv) the used material parameters and dimensions of the elements. Note that for the case study with integrated bending-active elements (i) and (ii) are directly related, due to the high interaction between the boundary and the membrane.

Compared to the design of traditional membrane structures, the choices of the above mentioned parameters do not only depend on the structural behaviour under external loading, but also on the behaviour of the kinematic deployment.

For example, the geometry of the membrane in case study 1 changes when folding and unfolding the structure (Fig. 4). This results in varying strains and stresses of the membrane material. It thus needs to be verified that the membrane remains tensioned in the different phases of the deployment.

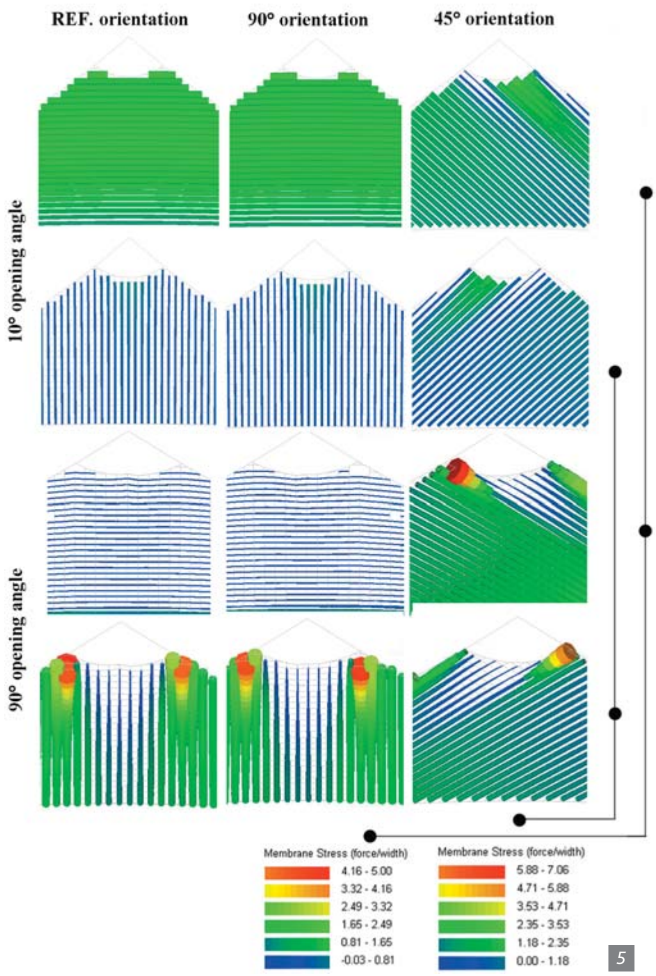
The influence of each of the selected parameters is investigated by varying every parameter separately. Both the form-finding state and the kinematically deformed configurations are studied in order to quantify the effect. Therefore, the stresses in the membrane in both warp and weft direction are compared, in order to select the conditions where the prestress is preserved the best in all the phases of the deployment. Other criteria for choosing a certain design parameter are for example the ease of prestressing the membrane and kinematically deploying the structure. As an illustration, the membrane stresses in warp and weft direction of case study 1 are presented in Figure 5, comparing different fibre orientations. More detailed findings on both case studies can be found in the thesis manuscript.

The analysis of this parameter study confirms that for kinematic form-active structures a whole series of possible combinations has to be investigated because one needs to take into account different phases of the structure's application range. The process of designing KFAS is thus clearly an iterative process, which underlines the advantages of using simple linear elastic numerical models. The available basic material models allow to change and adapt material properties, structural choices and geometrical data easily and quickly. For this type of preliminary design studies they prove to be an interesting tool.

Can this behaviour be confirmed by experimental validation? *Does the experimental data validate the numerical simulation, i.e. can we use this simplified simulation tool for the preliminary design of KFAS?*

The described parameter study leads to a 'final' design for each of the case studies, i.e. with an improved structural behaviour. For each case study a large-scale experimental set-up is then constructed and tested. The rigid hinged membrane structure has dimensions of ~6m by 1.5m, whereas the pringle-shaped textile hybrid has a diameter of ~3.2m. Displacements of the overall structure, strains in the membrane (in both warp and weft directions) and forces in the boundary elements are experimentally measured and compared to the results obtained from the numerical analyses.
Initially, the overall structural behaviour and measurements of the experiment show the same tendencies as the numerically predicted ones, however, the actual values of forces and strains showed some deviations. After further investigation of the experimental models, it became clear that those deviations occurred due to the application of inaccurate compensation factors. In case study 1, the large (elastic + permanent) deformation of the belts was not taken properly into account, whereas for case study 2, the membrane was overcompensated due to the impossibility to perform a project oriented biaxial test (as the limitations of the biaxial bench were reached). A re-calculation of the numerical model with adapted cutting patterns (membrane) or lengths (belts) confirmed the importance of using the right compensation factor, as these adapted numerical models showed an improved correspondence with the experimental results, both on the global level and on the level of actual strain values, displacements, forces etc. Figure 6 compares the strains measured with Digital Image Correlation [7] to the numerical strains from Easy.

The experimental investigation not only confirms the reliability of the numerical design models, but also involves a better understanding and some practical insights in the behaviour of the transformable membrane structures.



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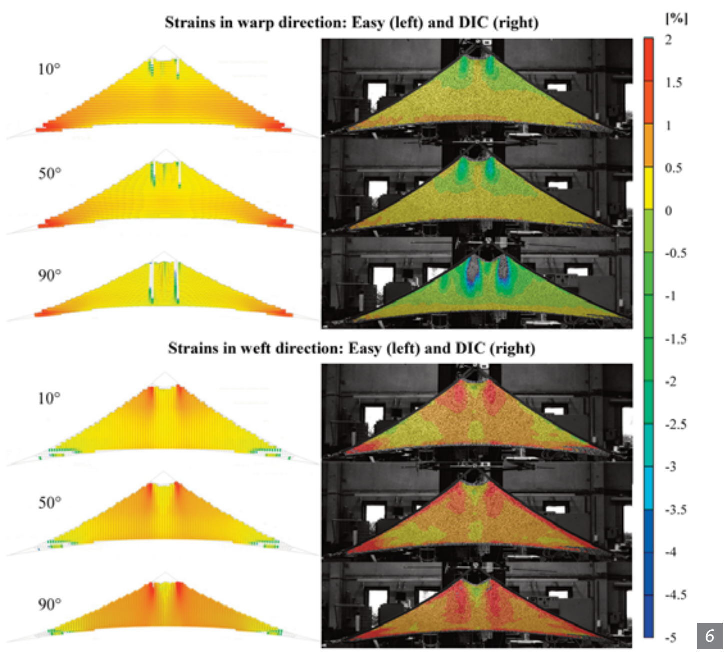

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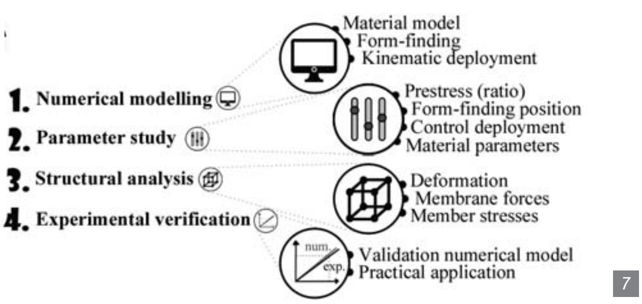

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Figure 5. Case study 1 - Membrane stresses (kN/m) in warp and weft direction oriented following the reference, rotated 90° and rotated 45°. The results in 10° and 90° opening angle are shown, starting from a form-finding at 50° with a prestress of 1 kN/m in warp and weft direction.
Figure 6. Case study 1 - Comparing the experimental strain fields (measured with Digital Image Correlation) to the numerical results (derived from Easy) in both warp and weft direction.
Figure 7. Different steps in the "Design, Analysis and Experimental Verification of Kinematic Form-Active Structures (KFAS)".

Compared to traditional building components, the high membrane flexibility implies that every small (construction) detail can have a great influence on the actual behaviour.
This integrated analysis confirms the feasibility of creating kinematic form-active structures and the suitability of the used simplified numerical models to design those structures. The different steps of the analysis comprise generating an appropriate numerical model, performing a parameter study, carrying out a structural analysis and validating the numerical models by means of an experimental analysis (scheme shown in Fig. 7). This combination of numerical and experimental analyses definitely contributed to the overall understanding.
Although every type of structure will have its unique solution and this research thus not provides an overall design guide, this study provides an overview of some interesting insights and some important parameters to consider during the design of kinematic form-active structures. In what follows, some general conclusions are formulated that can be used for further investigation.

General guidelines

Case Study 1 showed some great opportunities of kinematic form-active structures for the integration in different applications: from transformable roof cover to kinematic façade shading… Some general thoughts can be summarised in order to extend the use to other geometries and sizes of transformable membrane structures. For now, this generalisation is restricted to membrane structures where the deployment results in a limited variation of the overall geometry, i.e. a variation in length of the principal axes of the membrane of ~0 to 5%.
Based on a study of geometrical variations, it can be concluded that increasing the prestress in the direction where the length decreases (the most), results in a more homogeneous stress distribution throughout the deployment. Depending on the amount of length variation, the prestress ratio between warp and weft direction can vary (e.g. opting for 1 kN/m in warp direction and 1.2 kN/m in weft direction, instead of 1 and 2 kN/m). If the change in lengths is too high, one could implement additional compression or bending elements, like is the case in the Soft House [6].
Also the choice of the form-finding position could be related to the variation in lengths during the deployment. One could select the opening angle that provides a compromise between the reduction in length in the one direction and the increase in length in the other direction (Fig. 4), in order to find the middle ground between stress increase and decrease when opening and/or closing the membrane.
In transformable membrane structures, the force-controlled connections could help to keep the membrane tensioned in the different phases of the deployment and avoid stress concentrations. In the Soft House, for example, a relatively simple system is designed to control the tension, using bending-active plate elements. Another way to obtain more homogeneously distributed stresses throughout the deployment is to align the 45° direction along highest loading directions, which provides more flexibility. In future investigations, one could use an uncoated mesh instead of the used PVC-coated polyester membrane (e.g. for façade shading).

Case Study 2 brought the design and the kinematic deployment to a next level. Not only the large deformations of the membrane material were important, but also the flexibility of the integrated bending-active elements played a crucial role in the design and experimental investigation of the kinematic textile hybrid. The important interaction between the prestressed membrane and the bending-active boundary elements complicated both the selection of the parameters and the interpretation of the results. Nevertheless, generalising some findings could extend the use of textile hybrids for transformable architectural solutions to other geometrical shapes and sizes.
A first step is to estimate the configuration and the zone with the highest beam curvature, which could occur either in the form-found position or in one of the transformation phases. Based on this curvature (and the selected material properties of the beam elements), the section can be chosen depending on the resulting initial stress. Next, the prestress in the membrane can be increased (i) until the intended geometrical shape is obtained or (ii) until the prestress value exceeds the acceptable range for the selected beam section. Combining different bending-active beam sections allows further increasing the prestress, as this increases the overall structural stiffness. Finally, the zones or directions where the highest loss of tension occurs can be reinforced with one or more internal elements.
Adding internal beam elements, on the one hand, contributes to the maintenance of lengths of the membrane but, on the other hand, also provides additional structural stiffness. Future research could investigate whether one has to add additional internal elements (in this case e.g. running from one lower point to the other lower point) to also preserve the length in this direction or whether other configurations of internal elements could provide better results. The latter leads us to the opportunities of using a knitted membrane material that allows integrating different materials and knitting types in order to (locally) change the membrane stiffness.

To conclude, it can be stated that although this study indicates the great potential of kinematic form-active (hybrid) structures, it only forms the first step towards an even more varied use of textiles in architecture. Thanks to the combination of the numerical analyses and the experimental investigations new interesting insights are revealed in the structural behaviour of both the case studies.

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