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Parametric Analysis of Tensegrity-Membrane-Structures

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Abstract

This research project deals with the parametric analysis of tensegrity-membrane-structures. Based on the 2011 designed temporarily pavilion in Noda (Japan), a reference model was created to mainly investigate the influence of single geometric parameters, such as *strut length*, *overlap length ratio* and *spacing*. At the beginning of this paper, a short overview is given about the pavilion structure in Noda and its geometrical characteristics. After that, a former study of this pavilion and its structural mechanism is discussed. With that knowledge, a parametric analysis was accomplished to find out the influence of single geometric parameters. Based on the results an exemplary geometric more optimized pavilion structure for the combination with textile membranes was worked out. The paper is finishing with an overview of the next steps for design and construction of a tensegrity-membrane-structure based on the shown structural behavior while using a standard textile membrane.

Keywords: tensegrity principle, textile membrane, tensegrity-membrane-structure

1. Introduction

Tensegrity-structures impress with the interplay of few compressed struts in a stabilizing sea of tensioned elements. These structures fascinate with their apparent lightness and their supposed ability to resist gravity. There are almost no limits in design flexibility and variety of forms of Tensegrity-structures. Because of the large deformation capacity any equilibrium figure can adjust, but this effect is among other things also responsible for the minor importance of these structures in the construction industry. (Meeß-Olsohn [6])

With the introduction of structurally effective textile membranes as stabilizing tension elements of Tensegrity structures, the possibility of further development and a revival of these structures in the construction industry arise. Previous studies have shown the potential quality and synergies of the combination of the Tensegrity principle with textile membranes. (Ratschke and Bögle [7]) First experimental Tensegrity-membrane structures have been implemented within the last fifteen years. They were usually designed for architectural expression and the structural behavior was focused on. A fascinating example of this experimental building is the "temporary Pavilion in Noda", which was realized in 2011 by students at the Tokyo University of Science, under supervision of Jun Sato and Kazuhiro Kojima. (Detail [1]) This Tensegrity-membrane-structure serves as a reference model for a detailed parametric study, which is used to find an optimized, membrane-oriented geometry that is suitable for a future practical implementation.

2. Temporary Pavilion in Noda

In 2011 the pavilion in Noda, Japan, was designed, planned and built by architecture students of the Tokyo University of Science, supervised by Kazuhiro Kojima and Jun Sato in collaboration with a membrane manufacturer. The structure consists of 131 aluminum tubes Ø 25 mm and a stretchable, meshed 0.7 mm thick Polyester mesh without coating. A room of 8 x 26 m is spanned, whereby the membrane works as a tension element and the aluminum tubes act as compression elements. Only due to the interaction of these elements, the final structure of the pavilion can arise. (Detail [1], Tu and Lin [8])

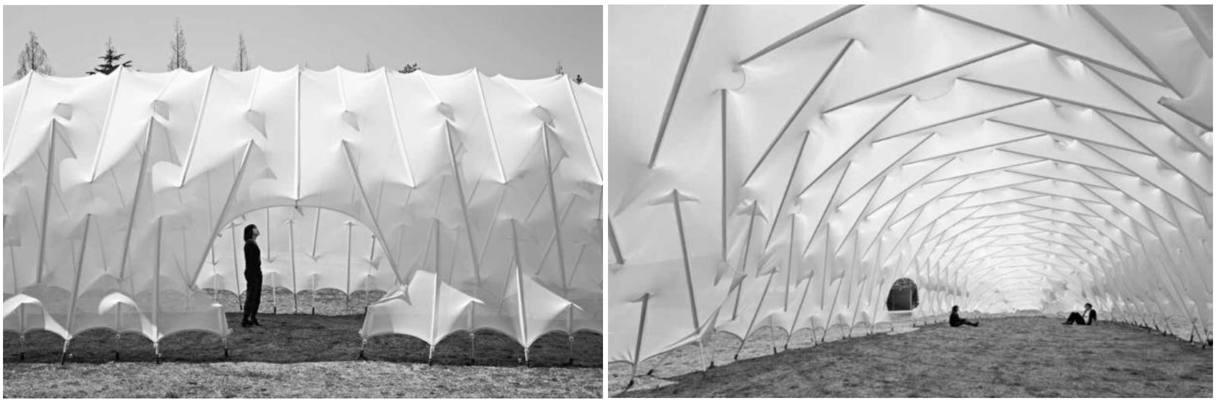


Figure 1: Pavilion Noda (Source: Temporärer Pavillon in Noda. In: Detail 2012-10. [Picture: Shinkenchiku-sha])

Similar to classical Tensegrity structures, deflecting forces between the ends of the compression struts and the tensioned membrane surface occur at the temporary pavilion in Noda. The struts are also working like local "compression islands" in a surface of tension. This characteristic of tensegrity is an essential design feature, which can be found again in the pavilion structures and shapes the typical structural behavior of these constructions. Therefore, these hybrid structures can be entirely understood as a further development of Tensegrity-structures. (Emmerich [2], Fuller [3])

From the structural point of view, the pavilion consists of two essential materials: the polyester fabric and the aluminum tubes, which is a classic separation in pure compression and pure tension elements (a minimum influence of bending moment is neglected here due to the relatively high bending stiffness of the compression elements). In closer consideration of the structure, three structural elements can be identified: 1st Compression stressed linear strut elements (green), 2nd the diagonal, tension stressed and weakly curved membrane areas as a connection of the strut-ends (red) and 3rd the, in direction of the strut axis trending, strongly curved membrane areas (blue). This fact can simply be expressed on the following image of the pavilion structure. The identification of these, especially in the membrane surface, differently behaving areas is used later in the analysis of the parameter study and is therefore of considerable significance.

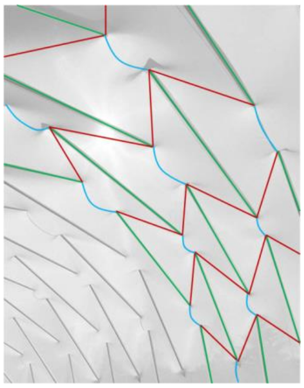


Figure 2: Identified structural elements: compression elements (red), diagonal tension elements (green), and straight tension elements (blue) [Nils Ratschke, 2017]

3. Parametric Analysis

The geometric parameters and their effects on the mechanical behavior of Tensegrity-membrane-structures were already investigated in 2015 by Tu and Lin as part of their master's thesis at the National Cheng Kung University in Taiwan. They also used the temporary pavilion in Noda as an example. Based on the Yoshimura-folding they described a geometrically simplified and linearized (like folding) reference object and specified its parameters and their dependencies. The state of pretension of the membrane surface in interaction with the compression elements was simulated as a motion in circular direction. Through appropriate assumptions and material values, a comparison between initial (without pretension) and final (prestressed) geometry was completed, thus obtaining a theoretical insight into the expected forces, respectively the influence of individual parameters on the mechanical behavior. (Tu and Lin [8])

To precisely comprehend the structural behavior of a membrane structure, a consideration of form-finding is generally inevitable. (Knippers [4]) Tu and Lin simulated the state of form-finding of the pavilion structure by moving the geometry along a circular orbit. However, the actual geometric change is not corresponding to a circle. Therefore, the circular orbit is no longer sufficiently accurate to characterize the structural behavior. In addition, the reference model is presented as a geometrically simplified linear cable model by Tu and Lin. As a result no precise statement about the biaxiale load bearing capacity of the membrane can be made. Nevertheless, Tu and Lin describe the geometrical parameters and their complex dependencies to each other detailed within their study. This knowledge is used for further development of the numerical model in this parametric study.

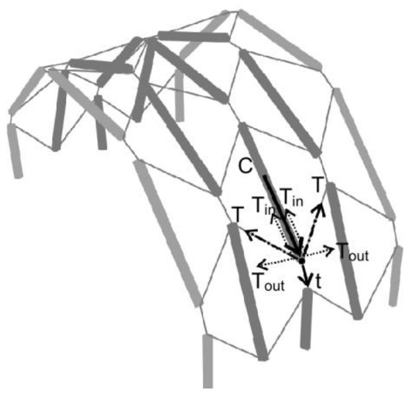


Figure 3: simplified force equilibrium model of pavilion structure [Tu and Lin, 2016]

Based on the parameters, identified by Tu and Lin, and their associated dependencies, a numerical reference model of the temporary Pavilion in Noda was created with Rhinoceros 3d and the PlugIn grasshopper. This made one significant change possible: instead of direct linear connections of strut elements, a uniform mesh with different orientations (orthogonal mesh 0 ° / diagonal mesh 45°) and corresponding mesh fineness (20 mm / 50 mm) was introduced to be able to simulate exactly the biaxial load bearing capacity of the membrane surfaces. The form-finding of the structure was performed with the PlugIn Kangaroo Physics, which is based on the dynamic relaxation method. The pavilion structure is simplified to five middle strut rows in order to reduce calculation times. For the structural mechanisms this simplification provides a sufficiently precise statement for the observed parameters. In addition, this approach requires a flexible horizontal support in the edges of the pavilion. The struts with ground contact are supported by translationally fixed joints. Also the contact between strut and membrane, due to the form-finding method is limited to a nodal connection; however, a sufficiently precise statement can be made due to the symmetry of the model.

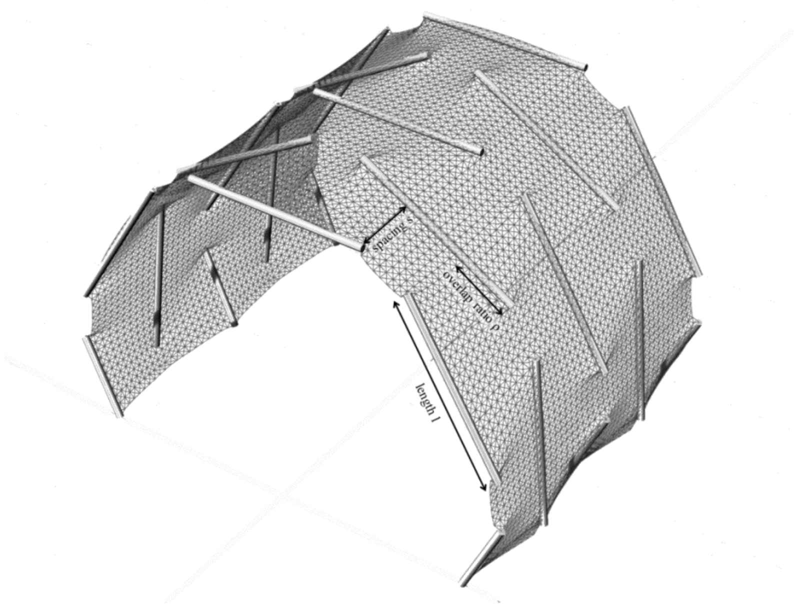


Figure 4: parametric model [Ratschke and Lindenberg, 2017]

Tu and Lin defined six geometric parameters that can be used to describe the structure of the Pavilion: 1st opening angle of the sector, 2nd strut number in the axial direction of the struts, 3rd number of strut lines, 4th the strut length, 5th overlap length factor of two neighboring struts and 6th spacing of two struts. All other parameters have been defined in dependency to the first six values and are considered identical in this study. (Tu and Lin [8])

For this parametric study only three parameters are changed. The parameter *strut length* (initial value l = 1.0 m), the parameter *overlap length factor* (initial value of ρ = 0.3) and the parameter *spacing* (initial value s = 0.5 m). Both the opening angle (Ω = 120°), as well as the number of struts in both directions (n = 4 and N = 5) are considerably changing the initial geometry of the pavilion. Therefore no sufficient comparability with other configurations can be made. For the appropriate parameters, fixed values were applied in the following investigation. Accordingly, the study focuses on the changes of proportion caused by the variation of the mentioned geometric parameters, taking into account the form-finding. With the representation of the membrane surface as a finely woven mesh, the effect of direction-dependent and material-specific properties on the load bearing capacity can be analyzed.

The compression stressed linear elements were set to be nearly rigid in the form-finding process. The membrane was set comparatively flexible. Due to the interaction between the struts and the membrane, low and high points occur in surface of the pavilion when starting the form-finding. Two recurring hypersurfaces, based on the involved high and low points can be defined in terms of the three previously identified structural elements (Figure 2). With that knowledge in mind, a statement of a membrane-oriented geometry of the pavilion can be obtained. These two hypersurfaces are ideal for describing the emerging influences on membrane-oriented characteristics of the surface by changing the parameters. The hypersurface I (blue) is located in the area of the strong curved connection of the struts; the hypar II (red) is located in the area of the diagonal connection of neighboring struts. Both previously identified structural elements define one of the principal directions of the two hypersurfaces.

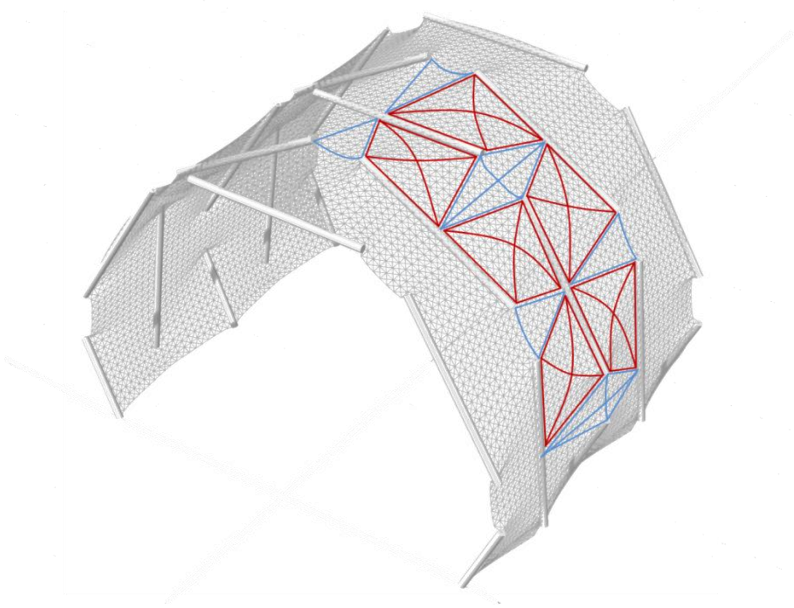


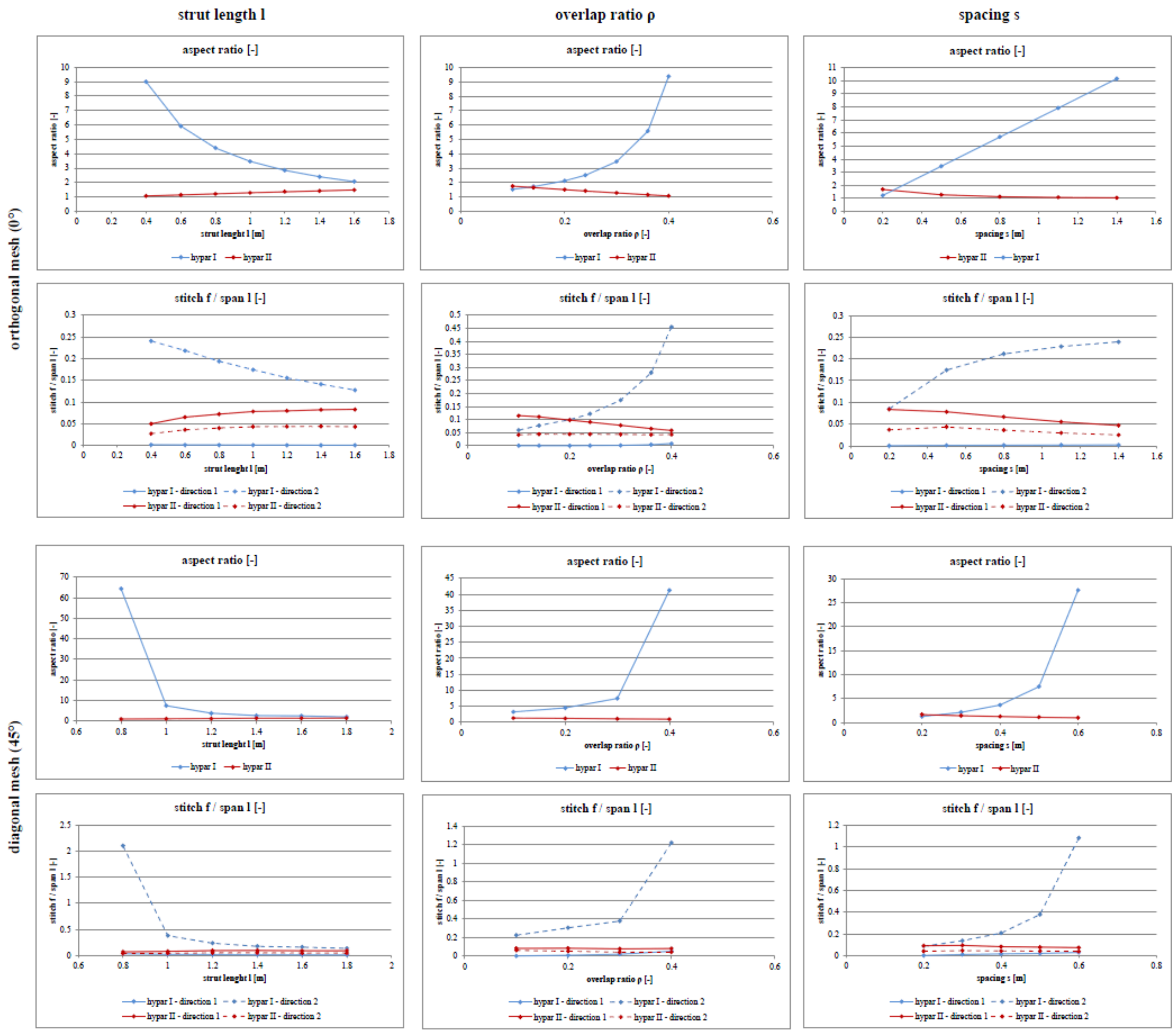
Figure 5: Identified recurring hypersurfaces: hypar I (blue) and hypar II (red) [Ratschke and Lindenberg, 2017]

To evaluate the impacts resulting from the parameter variation, the aspect ratio and the respective stitch-/span ratio of the principal directions of the two described hypersurfaces were investigated. The parameters *strut length*, *overlap length factor* and *spacing* were considered separately. In this step, all variations were carried out on the assumption of identical material properties. The aspect ratio gives information about the equality of the hypar I and hypar II in direct comparison to the whole pavilion surface. When the aspect ratios converge to a common low value, this can be judged positive for the geometric characteristics of the structure.

Four fundamental insights can be gained: First, the hypersurfaces behave oppositely as a result of *strut length* change in comparison to the *overlap length factor* and the *spacing*. The *strut length* must be increased to achieve an approximation of the aspect ratios of the two surfaces, whereas the *overlap length factor* and the *spacing* must be reduced. Secondly the *spacing* parameter causes only linear changes, while the other two parameters have exponential changes. Thirdly, it is to recognize on the basis of the aspect ratio, that hypersurface I shows high deformations, when a diagonal grid (45°) is used. And fourthly, it can be noted that the hypersurface I has much greater differences in its aspect ratio than the hypersurface II.

The evaluation of the stitch-/span ratios also allows a detailed statement about the geometrical shape of the principle directions of the respective surfaces. A consistent stitch-/span ratio within a hypersurface ensure that even a uniform load transfer can be achieved. Also, in particular the large differences in the stitch-/span ratio of the hypersurface I are significant. The hypersurface II, however, responds to all parameter variations only with small variations of stitch-/span ratios to each other. Thus, the hypersurface II is the much impervious constructive element of the pavilion structure. Regarding the orientation of the mesh, it can be noted that the stitch-/span ratios of the diagonal mesh (45 °) is much less favorably for the hypersurface I.

Table 1: Results of single parameter variation [Ratschke and Lindenberg, 2017]



Based on the knowledge already gained with different variants, a second step of the parametric study was made to obtain a load-bearing-optimized membrane structure. Since the diagonal mesh (45 °) had generally worse results for the hypersurface I, the study was limited here to an orthogonal orientated mesh (0 °). First, the *strut length* was set by fixing the desired height of the pavilion to roughly 3.0 m (the range is between l = 1.20 m to l = 1.80 m). Because the radius of the pavilion is influenced by the length of the struts, this parameter is ideal to build a desired global dimension. Then, a matching of *overlap length factor* (ρ = 0.1 to ρ = 0.28) and strut *spacing* (s = 0.48 m to s = 0.64 m) was done. In addition, the influence of direction-dependent stiffness of the membrane was used to make fine adjustments of the geometry (in a ratio of 2:1, 1:1 and 1:2).

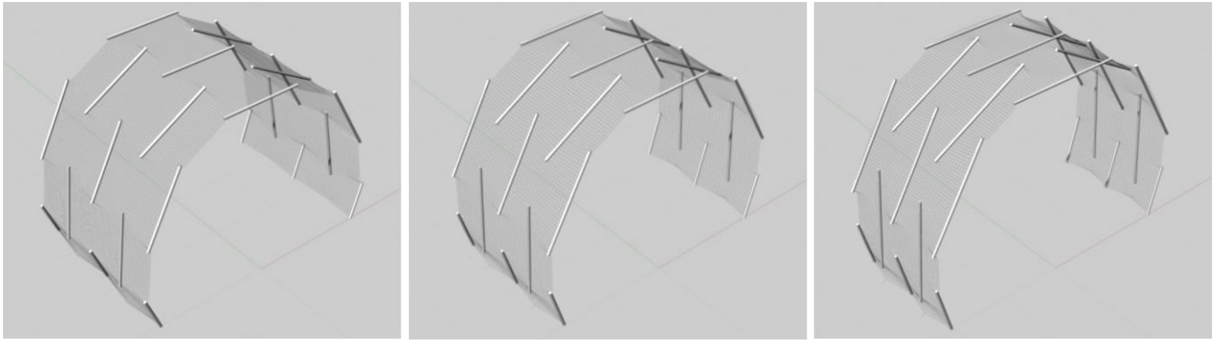
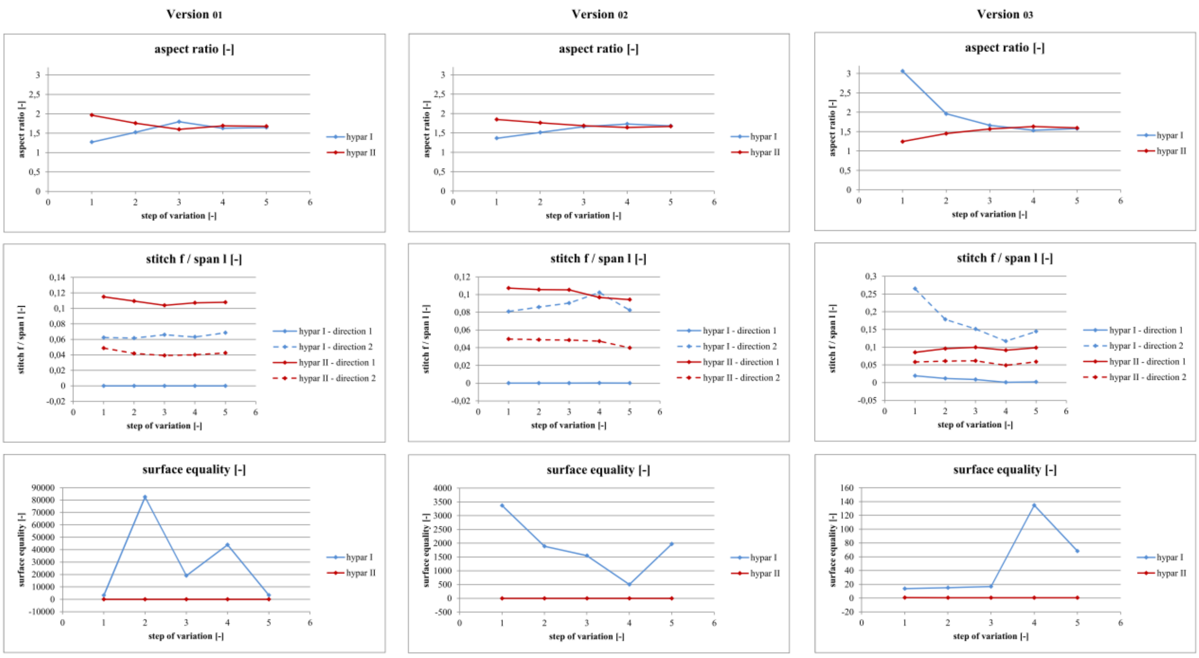


Figure 6: variation of geometry-optimized pavilion structures: Version 1 (left), version 2 (middle) and version 3 (right) [Ratschke and Lindenberg, 2017]

The alteration of parameters was carried out in several steps, in relevance to the comparison with the aspect ratios of the two hypersurfaces. The aim was to implement an identical aspect ratio, which has been achieved for all three variants. Relating to the first setting, the stitch-/span ratios of individual surface areas were analyzed to estimate if equality in the two hypersurfaces can be achieved. As shown, only very small stitches formed in one principal direction of hypersurface I, a second relationship, the surface equality ratio (consisting of the ratio of stitch-/span of both principal directions of the hypersurfaces to each other), was formed to more accurately assess. It can be recognized, that only with the parametric setting of the third variant at all, a stitch can be trained in the critical principal direction of hypersurface I. It can also be noted that an absolutely identical aspect ratio of both hypersurfaces does not cause the best area equality ratio.

Table 2: Results of multi-parameter variation [Ratschke and Lindenberg, 2017]



4. Conclusions

Summarizing, several conclusions can be drawn: firstly, it was, related to the previous investigations, confirmed that for these structures, due to their high deformation capacity, a corresponding form-finding is essential. Secondly, it was proven that geometrical parameters exert a significant influence on the structural behavior of the pavilion structure that is caused by the geometric stiffness compared to the elastic stiffness has much more influence on the load bearing capacity. This was also confirmed later, when changing the direction-depending stiffness of the membrane and a fine tuning of geometry could be carried out. Thirdly, the hypersurface I was identified as a particularly critical area. This area has a less membrane-optimized geometric form, which could be improved with this model only in small ranges, especially in the transverse direction. This is due to a high curvature which is used for the deviation of compression forces in the opposite direction on the one hand. And on the other hand, only a selective force transmission between strut and membrane is possible, caused by to the form-finding method used in this model (strut and membrane are decoupled over the length of the single strut element). Fourthly, the diagonal mesh leads to large surface deformations in hypersurface I, which could be verified by worse results in the corresponding diagrams. As a result, the diagonal grid could be excluded for the further studies.

4. Future Perspective

For the further development of this research project, the study has an essential relevance. The purpose is the implementation of the earlier discussed structural principle as a prototype, using a standardized common textile membrane. In advancement of the temporary Pavilion Noda, a full protection for the users (wind and water resistance) should be ensured. In addition, the principle should be made even more accessible by the implementation of the structure, using simple and available materials. A statement about the geometric boundary conditions can now be made with the parametric study.

Continuing to approach the target of implementation various important steps will be necessary. The parametric study so far only provides information about the geometrical specification by form-finding, using relative values of individual material stiffness. This has to be included more accurately, for example in an FE model. This demand makes accurate material values necessary. For the textile membrane these should be gathered in a biaxial test and implemented in the FE model. In addition, also the influence of a type of line supported membrane by the strut elements can be examined more precisely in a corresponding model. This will improve the geometric behavior of the hypersurface I according to the first results. Also, the assembly and in particular the application of pretension on the membrane surface is very important for realization. So, an appropriate concept has to be developed and transferred to the FE simulation.

References

[1] Detail: Temporärer Pavillon Noda. In: *Detail 2012-10*, p. 1086-1088

[2] Emmerich, D. G.: Emmerich on Self-Tensioning Structures. In: *International Journal of Space Structures Vol. 11 Nos. 1&2 1996*

[3] Fuller, R. B.: R. Buckminster Fuller on priority of Tensegrity: Excerpts from Fuller's Letter to Snelson. In: *International Journal of Space Structures Vol. 11 Nos. 1&2 1996*

[4] Knippers; et al: *Atlas Kunststoffe und Membranen*, Detail, München, 2010.

[5] Lindenberg, J.: *Tensegrity-Membran-Strukturen – Untersuchung der Interaktion linearer Stabelemente und strukturell wirksamer Membrane am Beispiel des Noda Pavillons.* Masterthesis, HafenCity Universität Hamburg, 2017, bisher unveröffentlicht.

[6] Meeß-Olsohn, L.: *Textegrity – Textiles and Tensegrity*, Dissertation, Universität Duisburg-Essen, 2004.

[7] Ratschke, N.; Bögle, A.: Analysis of the interaction between integrated linear compression elements in membranes. In: *Proceedings of the IASS Annual Symposium 2016*, Tokyo.

[8] Tu; Lin: Tensegric membrane structure with radiated struts. In: *Proceedings of the IASS Annual Symposium 2016*, Tokyo