Soft Spaces: Hybrid systems from structural membranes and conventional building technologies

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Abstract

Tensile structures and conventional building techniques are both highly developed, but they have never been explored as coalescent architectural and structural unity. We are proposing hybrid configurations, which will merge 3 aspects, firstly architectural design from the complex interplay of conventional and fluent forms, secondly structural design from the 3D-bracing-effect by membranes, and thirdly benefits in assembly, costs and sustainability, from the pin-joint connection related ease of assembly, alongside minimum amount of material and high degree of prefabrication. For the benefit of a global system, the role of membrane structures has been moved from intrasystem purposes to an integral structural and architectural element.

As a first step, this paper looks into the structural performance of structural membranes spanning two planar, bending resistant elements, such as floor slabs, which are held at a predefined distance by vertical pin-joint struts only.

It is shown that combining the ease of assembly of conventional members and the 3D-bracing-effect of membranes result in highly efficient architectural structures.

Keywords: structural membranes and conventional building technologies, hybrid structures, textile architecture, performance, built environment, new applications, design rules and structural analysis, sustainability.

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1. Global and (Inter-) Disciplinary Context

Due to the growth of world’s population the increasing demand, which is accompanied by increasingly complex and dynamic requirements, challenges the “production” of built environment and architecture. This means that architecture increasingly considers their generated objects no longer as isolated discrete objects, but rather they have to be seen as systems embedded in systems. Pioneering architecture is on the move to emergent systems, which are informed by multiobjective goals. More and more examples in architecture are developed in response to climate change, rational energy consumption, lifecycle analysis, workplace health, overall well-being and customized architected spaces. Current architectural design is also directly linked to and dependent on advances in material development, analysis tools and architectural and structural design methods. Therefore, it is essential to gain a deeper understanding of the multifaceted, complex demands and its resulting interaction respectively coaction, in order to create buildings, which have a responsive behavior to their environment, their users and within the structure itself. On the other hand, such requirements and resulting, emergent architecture are very quickly categorized as individual, unique and bespoke solutions, which have the image of representative showcases only and which are supposed to be expensive. These phenomena directly conflict with the questions of resources, which are needed and consumed by our society, and even more with our mostly profit-oriented industry. Over the decades, the building industry established conventional and standardized structures with an eye on optimized use of space, recognized construction technology, ease of construction and its well-known structural behavior. As a result, these approaches many times are over-simplified and reduced to a 2D-thinking in plan and section, resulting in 2D material and formats and vice versa. Usually a change in mindset is forced by political decisions and/or achieved by material incentives. Material incentives for example can be reward systems or gaining additional benefits, like uniqueness on the market, compensation of higher costs by shorter construction time, or a product’s enhanced performance.

Textile building has been developed from an ancient technique to today’s structural membranes by architects, engineers and researchers in cooperation with the industry. Due to their anticlastic curvature and applied prestress, especially minimal surface membranes show inherent structural advantages as well as architectural qualities such as fluent shapes or complex geometrical and visual effects. In a simultaneous way, such structures offer unique properties that other, more conventional, building elements often do not possess, and low self-weight, extremely high flexural strength, translucency and the capability of forming architecturally expressive shapes that enhance the urban environment with a minimum amount of material are interdependent. The complex interplay of all these features, which is achievable by interdisciplinary approach only, can result in highly advantageous projects. Still, structural membranes represent a special discipline, mainly restricted to projects with wide span or landmark buildings and isolated from other building techniques. Consequently, conventional building components and tensile
structures are both highly developed on a material and structural predictable level, but they have never been explored as coalesce architectural and structural unity. So far, mentioned spatial and structural qualities have been used for intrasystem purposes, but not for the benefit of a global system.

2. Hybrid systems from structural membranes & conventional building techniques

In the long run, we are aiming for synthesizing hybrid solutions from conventional building technologies and lightweight membrane/cable-net structures. In this sense, we will merge approaches from conventional building techniques with high degree of standardization for the analysis, design and realization, and approaches in membrane structures, in which form finding, appropriate design strategies and advanced technologies are crucial. So, the focus of our research clearly lies on “hybrids”, where elements, which are part of the hybrid constellation, inform each other and establish inseparable “spatial-structural-tectonic” emergent configurations. Our approach is firstly based on the dissertation and long-term research on “Soft Spaces” (Filz, 2011) and secondly on experimental structures like the “cut.enoid.tower”, “Cloud for fresh Snow” (Klasz & Filz, 2015) or “2Landscapes” (Filz and Naicu, 2015) amongst others.

Proposed hybrid configurations will cover architectural design aspects, structural design aspects as well as benefits in terms of assembly, costs and sustainability, but as a first step, this paper looks into the structural performance of structural membranes spanning two planar, bending resistant elements, such as floor slabs, which are held on distance by vertical pin-joint struts only. In that sense, we are combining the ease of assembly (tectonic) with the 3D-bracing-effect of spatially curved, structural membranes, which are advantageously replacing conventional 2D-bracing elements.

3. Structural membranes replacing traditional elements

For the ease of investigation into hybrid performance as described above, this research uses spatially curved, structural membranes as integral components of architecture, replacing conventional, usually planar elements. As shown in more detail in the dissertation “DAS WEICHE HAUS _ soft.spaces” by Filz, 2010, the range of exploration covers wall-like
elements, T-shaped connections, solutions for corners and the tubular shape of the catenoid. At present, experiments are restricted to minimal surfaces in soapfilm analogy. This means that the applied prestress is equal for warp and weft. Linear, maximal 2dimensionally curved, bending resistant, line supported boundaries have been defined as interface between membranes and conventional, planar floor slabs.

The results of above mentioned dissertation show surprising and partly new correlations between form and boundary proportions and so far unknown rules of the self organizing processes of Minimal Surfaces – especially in the field of the catenoid. The overview and the comparison of the results regarding their Gaussian curvature analysis allowed for a targeted selection of those setups, which show the highest percentage of curved surface. These surfaces are supposed to be the most efficient in terms of structural performance and therefore these surfaces have been selected for further investigation in a hybrid configuration. The following sections give an overview of investigated elements and Case Studies (CS).

### 3.1. CS 01 Minimal Surfaces between straight lines and boundaries consisting of segments of a circle

All experiments related to this series (Figure 2) show, that for this boundary condition it is not possible to find a fully anticlastic curved Minimal Surface. Those surfaces which show few flat areas concentrate on boundary conditions consisting of semicircles with a diameter that corresponds to the vertical distance of the boundaries.

![Figure 2: Minimal Surfaces between straight lines and boundaries consisting of segments of a circle](image)

### 3.2. Minimal Surfaces between boundaries consisting of segments of a circle

In this case the boundaries of wall like Minimal Surfaces can have the same direction or they can be arranged inversely.

#### 3.2.1. CS 02 Minimal Surfaces between boundaries consisting of segments of a circle in the same direction

Boundaries that are curved in the same direction (Figure 3) generally effect strong anticlastic curvature of Minimal Surfaces. Boundary conditions consisting of semicircles with a diameter that equals the distance of the boundaries can be qualified as 100% spatially curved. Section lines show the smallest circle of curvature exactly on half height and harmonic development of the surfaces (Figure 4).
3.2.2. **CS 03 Minimal Surfaces between boundaries consisting of inversely arranged segments of a circle**

Curved and inversely arranged boundary conditions effect anticlastic curvature covering most of the surface, even if the boundaries have little oscillation from the longitudinal axis. The mostly curved surface can be developed with boundaries consisting of semicircles with a diameter of 2/3 of the distance of the boundaries (Figure 5). Areas with less spatial curvature can first of all be found exactly at the maxima of boundary curvature and on half height.

![Figure 5: Minimal Surfaces between boundaries consisting of inversely arranged segments of a circle and Gaussian Curvature analysis](image)

3.3. **CS 04A, CS 04B, CS 05 Right-angled T-connections with symmetric wing length [FL]**

Surfaces meeting in a T-connected boundary (Figure 6) generate a Y-intersection (Figure 7). This happens independently from the angle of the boundary connection. The 3 different parts of the Minimal Surface meet with 120° and form an arch-like intersection. This arch is less curved at its angular point and more curved the closer it is to the T-connection of the boundary. „In very special cases only, a circular intersection can be formed.” (Otto, 1988). These special cases were used to form compression only arches for real structures.

![Figure 6: Geometry of right angled T-connection](image)  
![Figure 7: Minimal Surface generated from a right angled T-connection](image)

In terms of right-angled configurations the leg length of H (Figure 6) has no influence on the form of the generated Minimal Surface as long as it is longer than the deflection of the Y-
intersection. This happens to be the same, independently from the wings being arranged symmetrically or asymmetrically.

For symmetric wing length [FL] we can determine that the magnitude of the Y-intersection is directly connected to the ratio of wing length and element length (Figure 8). For all boundary conditions with FL ≥ EL/2 the magnitude of the Y-intersection equals 20.6% of the element length. For wing length shorter than the element length, a nonlinear behavior of the Y-intersection can be determined. So the boundary condition FL=EL/2 represents the borderline between linear and nonlinear development of displacement in the direction of H (Figure 9).

A square geometry in plan causes evenly distributed curvature in the surface (Figure 8). The curved Y-intersection is similar to a basket arch (Figure 9). Starting from a square geometry in plan increased wing length results in the generation of insufficiently curved areas at the ends of the wings. Strong anticlastic curvature is limited to the areas of the T-connection of the boundary. Variations in the boundary setup, such as Asymmetric wing length [FL] and Non-right-angled T-connections do not show improved results in terms of surface curvature.

3.3. CS 06 Catenoids between circular rings

The shape of the catenoid is generated by a catenary that rotates around a longitudinal axis. It is the only rotational body that can be minimal surface at the same time. As we know from SFB230 the maximum attainable height of a catenoid spanning two circular rings is approximately 1.3 times the radius of a ring. (IL, SFB 230, 1992) For conceptual designs in architecture, boundaries different from two identical circles but with different diameters, not
being arranged in one axis and/or not being symmetrically arranged are needed. So the maximum attainable heights of catenoids with different boundary geometries and arrangements were examined. New rules could be found for major boundary configurations (Filz, 2011). The resulting diagrams can be scaled at will. Starting from the extreme of 1,3 times the radius of a ring the maximum height of a catenoid is decreasing if one of the rings diameter is decreasing (Figure 10, 11). Figure 10 also illustrates that upper rings smaller than 1/5 (upper ring /lower ring) result in very little maximum attainable height and surfaces with little Gaussian Curvature at the same time. Several experiments showed that all the attainable maxima in dependence from the given diameters are located on a common circle - the extreme value circle. This circle again is in direct proportion to the circular base ring. (Figure 11).

4. Software, membrane material and general setup applied

The used software for this research has been IxCube 4-10 v 2.2.4, a system for tensile structure design, engineering and manufacturing. IxCube 4-10 uses and combines features from different disciplines like CAD (Computer Aided Design), FEA (Finite Element Analysis) and Production process (CNC and others). The user interface has most of the tools of a modern CAD software, plus a FEA section for editing FEA based objects like nodal coordinates, object orientation, meshing tools and material specifications based on engineering properties (E-modulus, Poisson, etc.). For the problem of form-finding ixCube 4-10 incorporates the following 4 techniques, namely the Force Density Method, the Update Reference Strategy, the Direct Stiffness Method, and the Natural Force Density Method, which has been used in our analysis.

For our simulation and structural analysis, Ferrari Precontraint 702 S2 – material with a breaking load of 56/56 kN/m and a working load of 11.2/11.2 kN/m (with Sf= 5) has been applied. According to the manufacturer, Ferrari Precontraint Flexlight Perform 702 S2 offers a very high level of translucency for unrivalled weight/mechanical and aesthetic performance for all tent types. S2 varnish and Low Wick treatment ensure lasting whiteness and resistance to the most demanding environments (dust, pollution, UV, etc.). These Type 1 fireproof fabrics are ideal for public use tents: frame, kedar, pole and clearspan. The manufacturer provides the following technical specifications on Precontraint Flexlight Perform 702 S2 and its standards:

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<th>weight</th>
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<td>width</td>
<td>98.4 in / 105.1 in</td>
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<tr>
<td>standard format length</td>
<td>54.6 yds / 382.7 yds</td>
</tr>
<tr>
<td>tensile strength</td>
<td>280/280 daN/5 cm</td>
</tr>
<tr>
<td>tear strength</td>
<td>30/28 daN</td>
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<tr>
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<td>EN ISO 1421</td>
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<td>DIN 53.363</td>
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5. Structural analysis of Case Studies (CS)

As a general rule, two floor slabs of 12m x 12m are connected by pin joint struts of 3m of length. The prestress of 1 kN/m for warp and weft has been applied on all minimal surfaces. The horizontals loads are applied until the membrane reaches its maximum allowable stress.

CS 01

Figure 12: Form-Find-Warp sigma xx stresses 0.996-1.070(kN/m), Form-Find-Weft sigma yy stresses 0.934-1.009(kN/m), Maximum applicable Horizontal Load 10.5 (kN);

Figure 13: Warp-Maximum sigma xx = 11.058 kN/m < 11.2 kN/m, Weft-Maximum sigma yy = 7.246 kN/m < 11.2 kN/m, Maximum Node Displacements: 0.303 (m)

CS 02

Figure 14: Form-Find-Warp sigma xx stresses 0.894-1.044(kN/m), Form-Find-Weft sigma yy stresses 0.778-0.906(kN/m), Maximum applicable Horizontal Load 19.95 (kN);

Figure 15: Warp-Maximum sigma xx = 11.136 kN/m (avg.3.438) < 11.2 kN/m, Weft-Maximum sigma yy = 9.750 kN/m < 11.2 kN/m, Maximum Node Displacements: 0.231 (m)
CS 03

Figure 16: Form-Find-Warp sigma xx stresses 0.894-0.985 (kN/m), Form-Find-Weft sigma yy stresses 0.823-0.906(kN/m), Maximum applicable Horizontal Load 25.20 (kN);

Figure 17: Warp-Maximum sigma xx = 11.120 kN/m < 11.2 kN/m , Weft-Maximum sigma yy = 6.446 kN/m < 11.2 kN/m , Maximum Node Displacements: 0.190 (m)

CS 04 A – Horizontal Load pulling

Figure 18: Form-Find-Warp sigma xx stresses 0.962-1.067 (kN/m), Form-Find-Weft sigma yy stresses 0.937-1.040(kN/m), Maximum applicable Horizontal Load 24.60 (kN);

Figure 19: Warp-Maximum sigma xx = 11.148 kN/m < 11.2 kN/m , Weft-Maximum sigma yy = 7.690 kN/m < 11.2 kN/m , Maximum Node Displacements: 0.341 (m)

CS 04 B – Horizontal Load pushing

Figure 20: Form-Find-Warp sigma xx stresses 0.962-1.067 (kN/m), Form-Find-Weft sigma yy stresses 0.937-1.040(kN/m), Maximum applicable Horizontal Load 21.80 (kN);
Figure 21: Warp-Maximum sigma \( \sigma_{xx} = 11.173 \text{kN/m} < 11.2 \text{kN/m} \), Weft-Maximum sigma \( \sigma_{yy} = 8.735 \text{kN/m} \), Maximum Node Displacements: 0.246 (m)

**CS 05**

Figure 22: Form-Find-Warp sigma \( \sigma_{xx} \) stresses 1.000-1.225 (kN/m), Form-Find-Weft sigma \( \sigma_{yy} \) stresses 0.826-1.001(kN/m), Maximum applicable Horizontal Load 50.80 (kN);

Figure 23: Warp-Maximum sigma \( \sigma_{xx} = 11.138 \text{kN/m} < 11.2 \text{kN/m} \), Weft-Maximum sigma \( \sigma_{yy} = 8.572 \text{kN/m} \), Maximum Node Displacements: 0.519 (m)

**CS 06**

Figure 24: Form-Find-Warp sigma \( \sigma_{xx} \) stresses 1.000-1.000 (kN/m), Form-Find-Weft sigma \( \sigma_{yy} \) stresses 1.000-1.000(kN/m), Maximum applicable Horizontal Load 44.10 (kN);

Figure 25: Warp-Maximum sigma \( \sigma_{xx} = 11.037 \text{kN/m} < 11.2 \text{kN/m} \), Weft-Maximum sigma \( \sigma_{yy} = 9.482 \text{k/m} \) < 11.2 kN/m, Maximum Node Displacements: 0.305 (m)
6. Evaluation and comparison of Case Studies (CS)

Looking at the maximum horizontal loads we can understand, which model reaches which stiffness. The comparison of models allows for an evaluation of which setup is stiffer – the higher the applicable horizontal loads the better the membrane is able to compensate these, without exceeding its allowed working load of 11.2/11.2 kN/m.

First, it is verified that structural membranes can act as spatial bracing of structures. The structural analysis of Case Studies 01 to 06 (Figures 12-25) and above shown diagram (Figure 26) provide clear results, which can be already predicted from the evaluation of the minimal surfaces’ Gaussian curvature. As expected CS 01 Minimal Surfaces between straight lines and boundaries consisting of segments of a circle lack of constellations, which allow for fully anticlastic surfaces. Accordingly, the applicable horizontal loads are low and the resulting displacements of the structure are high. CS 05 T-connections with symmetric wing length, used as a sort of T-intersection of roof and wall is able to resist high horizontal loads (50,80kN) at reasonable displacements (0,519m). Probably this result can be improved by replacing the straight lined boundary of the wall by an oscillating curve. Overall, CS 06 Catenoid between circular rings shows best results, when simultaneously considering the surface content of the catenoid, the maximum applicable horizontal load of 44,10kN, which equals 87% of CS 05 and the resulting displacement of 0,305m, which equals to 58% of CS 05’s displacement.

7. Future questions and Case Studies

Future investigations will look into the comparison of minimal surfaces and non-uniform prestressed membranes as well as more complex load cases and load combinations, including earthquake. Last but not least more complex constellations will showcase the merger of 3 aspects, firstly architectural design from the complex interplay of conventional and fluent forms, secondly structural design from the 3D-bracing-effect by membranes, and thirdly benefits in assembly, costs and sustainability, from the pin-joint connection related ease of assembly, alongside high degree of prefabrication of elements.
First, it is verified that structural membranes can act as spatial bracing of structures. The higher the applicable horizontal loads the better the membrane is able to compensate these, stiffness. The comparison of models allows for an evaluation of which setup is stiffer. Future investigations will look into the comparison of minimal surfaces and non-uniform structural analysis of Case Studies 01 to 06 (Figures 12-25) and above shown diagram (Figure 6). Evaluation and comparison of Case Studies (CS)

Looking at the maximum horizontal loads we can understand, which model reaches which reasonable displacements (0.519m). Probably this result can be improved by replacing the catenoid, the maximum applicable horizontal load of 44.10kN, which equals 87% of CS 05 and as a sort of T-intersection of roof and wall is able to resist high horizontal loads (50.80kN) at the resulting displacement of 0.305m, which equals to 58% of CS 05`s displacement.

CS 01: catenoid: maximum horizontal load of 19.95kN, and the maximum applicable horizontal load of 10.50kN. CS 02: catenoid, maximum applicable horizontal load of 24.60kN. CS 03: catenoid, maximum applicable horizontal load of 25.20kN. CS 04A: minimal surface, maximum applicable horizontal load of 30.30kN. CS 04B: minimal surface, maximum applicable horizontal load of 30.30kN. CS 05: catenoid, maximum applicable horizontal load of 44.10kN, which equals 87% of CS 05 and as a sort of T-intersection of roof and wall is able to resist high horizontal loads (50.80kN) at the resulting displacement of 0.305m, which equals to 58% of CS 05`s displacement.

CS 06: catenoid, maximum applicable horizontal load of 50.00kN. CS 07: catenoid, maximum applicable horizontal load of 40.00kN. CS 08: catenoid, maximum applicable horizontal load of 60.00kN. CS 09: catenoid, maximum applicable horizontal load of 20.00kN. CS 10: catenoid, maximum applicable horizontal load of 30.00kN. CS 11: catenoid, maximum applicable horizontal load of 20.00kN. CS 12: catenoid, maximum applicable horizontal load of 30.00kN. CS 13: catenoid, maximum applicable horizontal load of 20.00kN. CS 14: catenoid, maximum applicable horizontal load of 30.00kN. CS 15: catenoid, maximum applicable horizontal load of 20.00kN. CS 16: catenoid, maximum applicable horizontal load of 30.00kN. CS 17: catenoid, maximum applicable horizontal load of 20.00kN. CS 18: catenoid, maximum applicable horizontal load of 30.00kN. CS 19: catenoid, maximum applicable horizontal load of 20.00kN. CS 20: catenoid, maximum applicable horizontal load of 30.00kN. CS 21: catenoid, maximum applicable horizontal load of 20.00kN. CS 22: catenoid, maximum applicable horizontal load of 30.00kN. CS 23: catenoid, maximum applicable horizontal load of 20.00kN. CS 24: catenoid, maximum applicable horizontal load of 30.00kN. CS 25: catenoid, maximum applicable horizontal load of 20.00kN. CS 26: catenoid, maximum applicable horizontal load of 30.00kN. CS 27: catenoid, maximum applicable horizontal load of 20.00kN. CS 28: catenoid, maximum applicable horizontal load of 30.00kN. CS 29: catenoid, maximum applicable horizontal load of 20.00kN. CS 30: catenoid, maximum applicable horizontal load of 30.00kN. CS 31: catenoid, maximum applicable horizontal load of 20.00kN. CS 32: catenoid, maximum applicable horizontal load of 30.00kN. CS 33: catenoid, maximum applicable horizontal load of 20.00kN. CS 34: catenoid, maximum applicable horizontal load of 30.00kN. CS 35: catenoid, maximum applicable horizontal load of 20.00kN. CS 36: catenoid, maximum applicable horizontal load of 30.00kN. CS 37: catenoid, maximum applicable horizontal load of 20.00kN. CS 38: catenoid, maximum applicable horizontal load of 30.00kN. CS 39: catenoid, maximum applicable horizontal load of 20.00kN. CS 40: catenoid, maximum applicable horizontal load of 30.00kN. CS 41: catenoid, maximum applicable horizontal load of 20.00kN. CS 42: catenoid, maximum applicable horizontal load of 30.00kN. CS 43: catenoid, maximum applicable horizontal load of 20.00kN. CS 44: catenoid, maximum applicable horizontal load of 30.00kN. CS 45: catenoid, maximum applicable horizontal load of 20.00kN. CS 46: catenoid, maximum applicable horizontal load of 30.00kN. CS 47: catenoid, maximum applicable horizontal load of 20.00kN. CS 48: catenoid, maximum applicable horizontal load of 30.00kN. CS 49: catenoid, maximum applicable horizontal load of 20.00kN. CS 50: catenoid, maximum applicable horizontal load of 30.00kN.

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