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TORSION AS A DESIGN DRIVER IN BENDING-ACTIVE TENSILE STRUCTURES
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Engineers and architects are pushing the limits in search for innovation. New undertakings lead to attempts to transcend and renegotiate current knowledge about technical solutions. These challenges have led to modern lightweight architecture, whose roots lead back to ancient tent structures, and questions conventional solutions. Bending-active tensile structures introduce a new integrative solution into the lightweight architecture world. Their engineering and architectural potential results from their structural complexity and unexplored design space.

Hybrid structures still remain mainly on an educational and academic level. Although these structures have a promising future ahead for their very efficient material usage, only a hand full examples have been built the last decade. Compared to traditional systems, the necessary form-finding process involves an increased level of complexity on different levels: simulation, analysis, fabrication, and construction.

This master thesis analyses and demonstrates the structural and architectural potentials of torsion and plate elements for bending-active tensile structures. The advantages of plate structures are investigated in conjunction with the geometric stiffening and pre-stressing effect of tensile elements, and the effective control of geometry by torsion. The results are employed as design drivers influencing the material's structural and geometric behaviour in order to develop a highly efficient system. By incorporating an assembly-based approach the relation between the bending-active and membrane elements is. With a focus on the structural advantages the project explores the resulting design potentials for the development of performative, complex and adaptive architectural articulations.

The workflow of the research is divided into four main steps: (1) the integration of torsion into plate bending-active structures; (2) the investigation of the geometrical stiffening effect; (3) including a membrane and analysing the possible advantage of pre-stressing the membrane through torsion; (4) the in-depth research of existing bending-active tensile structures and their assembly process and the performance system.
The first phase of the research starts from a structural point of view looking into the geometrical stiffening effect through torsion in non-warping free cross-sections. This preliminary research covers the content of the concept and investigate through several case studies, among other questions, how torsion is generated, what torsion means in structures with large deformations, what the influence of warping torsion is, how geometrical stiffening can be achieved, as well as how the stiffening effect can be influenced in its reciprocal relation up to a maximum benefit. This investigation is executed with finite element method software, by physical modelling, and through analytical analysis. The validation method for defining the geometrical stiffening effect is the comparison of the Dynamic Eigenmode, stress distribution, and the load displacement curve.

The first conclusion that can be drawn from this first research step is that both physical and digital testing conform the geometrical stress stiffening effect. They show a decreased deflection under vertical loading while twisting in the plate is increased, and the stress distribution shows, as expected, high tensile stresses at the outer fibres of the cross-section and a reduced compression stress in the centre. The physical and digital tests are validating these findings but have a different scale and material definition.

A bending-active system with torsion is not occurring in one plane but is extend into the third dimension through out-of-plane bending. When the system starts bending out-of-plane, the resistance to a vertical load greatly decreases. Tests show that when the geometry is pushed back in plane with the same amount of twisting in the plate, the deflection under vertical loading is reduced to a minimal deformation. Twisting is directly related to the geometrical stiffness, but global stability and boundary conditions have to be taken into account.

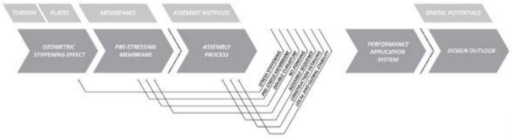
The scaling of bending-active structure is not linear. The out-of-plane bending of large models simulated in Sofistik is much more noticeable than in the small physical models. Gravity plays an important role in scaling, which will be taken into account for further research.
In a second step the membrane is added to the system. When considering the design process of membranes it is important to have double anticlastic curvature, no wrinkles, pre-stress and no ponding. It would be an added value for the use of plates and torsion if there are more than one benefit, i.e. geometrical stiffening by torsion, between these two aspects. Now that the membrane is added to the structural system, it can serve as an additional advantage in conjunction with torsion.

Introducing geometrical stiffening effect by torsion generates a spatial bending of the plate. When the plate is twisted to a certain degree, it starts to bend out-of-plane. A translational displacement of the plate is achieved by rotating the supports. This displacement can then be used to pre-stress the membrane. Case studies show an advantage of twisting the supports in order to generate the needed translational displacement for pre-stressing the membrane. At the same time this method ensures the global stability that the system requires. An additional advantage that occurs in this composition is that the membrane pulls along the width of the strips, i.e. the strong area moment of inertia axis. The results of the Softistik calculations show that the maximum pre-stress that can be generated with this method is less than the required pre-stresses for a small membrane of 200N/m. Normal scaled membrane structures mostly require a pre-stress of 1 to 5 kN/m.
The conclusion here is that using only torsion to pre-stress the membrane in a plate hybrid structure isn’t sufficient for real outdoor applications.

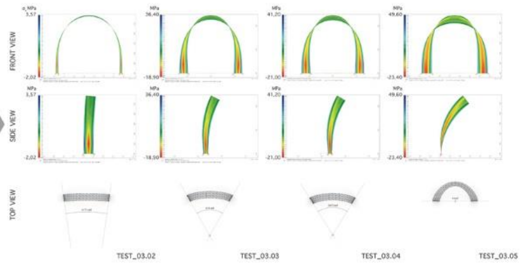
The next step in the workflow is the in depth research of existing bending-active tensile structures and their assembly process. A step is taken back to analyse the assembly sequence and pre-stress strategy in current bending-active tensile structures. With this information a new assembly strategy will be defined for the use of plates.
The conclusion here is pre-stressing a low strain membrane biaxial in a bending-active tensile structure isn’t trivial. The use of pockets that are mostly used in current structures isn’t a possibility with plate structures due to the high friction and spatial bending of the plates. The chosen assembly sequence is based on the sequence of bending-active tensile structures without a cutting pattern and high pre-stress forces, but completed with a post-process to pre-stress the membrane.

The results of these three preliminary phases are combined and used as a filtering method for developing a system that works within these boundaries. In the course of the following phases different case studies are developed and analysed. Their different structural articulations is the result of a parallel input of architectural and structural requirements that emphasises the inseparability of these two fields.

The main focus of the architectural potential is not on a particular case study but on the general concept of using plate structures in bending-active tensile structures. The architectural advantage becomes obvious in comparison to the use of circular profiles. The bending elements are now not only a supporting element anymore but become part of the architectural quality and appearance.
The research finds the limits to which points torsion can be employed to pre-stress membranes in a plate hybrid. It defines the influences on different levels together with the advantages and disadvantages of using plates instead of circular cross sections.



TORSION
PLATES
MEMBRANES
ASSEMBLY METHODS
SPATIAL POTENTIALS
GEOMETRIC STIFFENING EFFECT
PRE-STRESSING MEMBRANE
ASSEMBLY PROCESS
STRESS STIFFENING
PRE-STRESS MEMBRANE
DOUBLE CURVATURE
NO PONDING
ASSEMBLY SEQUENCE
CONSTRUCTION DETAILING
LOCAL AND GLOBAL STABILITY
PERFORMANCE APPLICATION SYSTEM
DESIGN OUTLOOK



FRONT VIEW
SIDE VIEW
TOP VIEW
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MPa
3,57
-2,02
36,40
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-21,00
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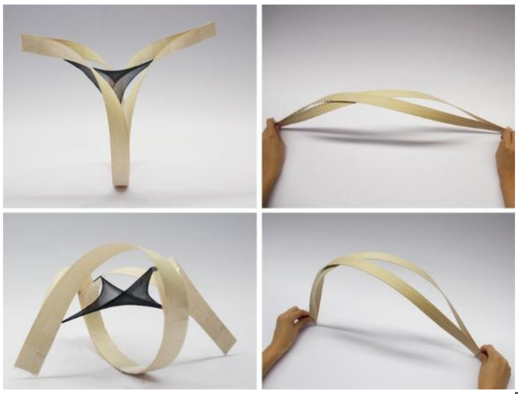
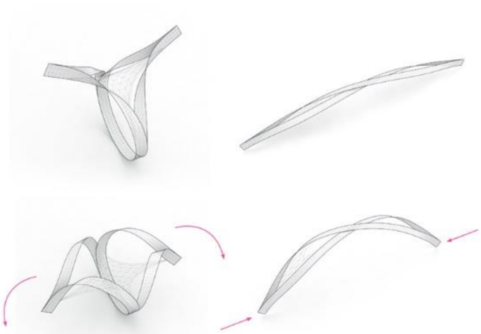
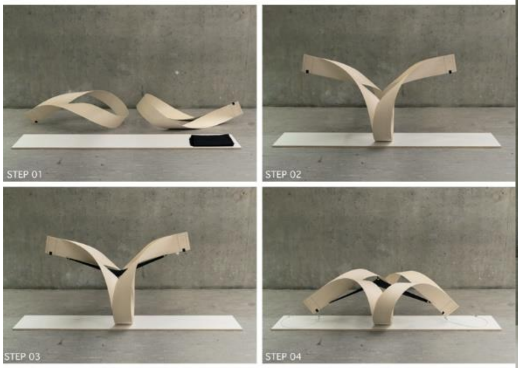
-23,40
TEST_03.02
TEST_03.03
TEST_03.04
TEST_03.05







STEP 01
STEP 02
STEP 03
STEP 04