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CONCEPTUAL AND STRUCTURAL DESIGN OF ADAPTIVE MEMBRANE STRUCTURES WITH SPOKED WHEEL PRINCIPLE – FOLDING TO THE PERIMETER

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Motoi Masubuchi

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Dissertationsschrift von Motoi Masubuchi

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der Technischen Universität Berlin

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ABSTRACT

Functionally-adaptive structures are increasingly being demanded by infrastructure owners, who need to utilize space for multiple purposes, optimally. Convertible roofs fall under this category, for example, an event space with a retractable roof could be used for sports games in an open condition and for music concerts in the closed condition.

To date, several membrane retractable roofs combined with a spoked-wheel structure have been designed and constructed. The advantage of this combination is that the light weight and flexibility of the membrane allows it to be moved and positioned easily, while the spoked wheel structure -similar in construction to a bicycle wheel- provides a lightweight support system for the membrane. Thus large areas can be covered with a relatively small amount of material. Furthermore, since their profiles are small, large transparency in the overall appearance can be obtained.

Most of the membrane retractable roofs with spoked-wheel structure store the folded membrane in the center, when the roof is open. A bundle of folded membrane remains in the center of the roof, which is not favorable, for instance, for broadcasting; the bundle casts a shadow in the playing field. There are also aesthetic considerations in leaving this membrane at the centre. However, if the textile membrane can be folded to the perimeter of the roof, these problems would be solved. There will be no shadows on the field and moreover this creates a free opening. This is the basic motivation of the current research.

Any proposed solution has to deal with two aspects: first, there is a geometrical issue, and second, a structural question concerning the prestressing of the membrane. The geometrical issue presents an inconsistency between the required shape of the membrane and the radial cable. Amongst several approaches to overcome these problems, two practical geometrical solutions have been developed.

In the first approach, the membrane strips are shaped so that the radial cables are aligned straight in space. Generally, the structural behavior of the membrane is related to its geometry. Therefore, the main challenge in this approach is how to obtain the doubly curved structural form of the membrane that can also satisfy the condition of the foldability. The proposed solution here is to change the boundary condition of the membrane to an intermediate state between prestressed and non-prestressed. This geometrical alternation could be achieved by the vertical movement of the entire compression ring. This 'raised compression ring' method is developed and discussed as the 'case study A'. In addition to the structural analysis, the feasibility of this method was checked through the physical model that the author built in the laboratory of TU-Berlin in Germany.

For the second approach, the radial cables are curved, thus rectangular membrane strips can be used. The main challenge of this approach is how to introduce the prestressing force uniformly in the textile membrane. The solution is to lift the cable girders along with the textile membrane. One advantage of this mechanism is that a minor shift of the anchor point of the upper cable efficiently causes a major lift of the whole structure. The kinematic behavior of the cable girders was revealed through an exhaustive parameter study. Then, these analytical results were transferred to the prestressing system of a retractable membrane roof.

KURZFASSUNG

Räume, die sich an die jeweiligen Bedürfnisse anpassen können, (Mehrzweck- bzw. funktional adaptive Konstruktionen) werden von Bauherren immer mehr gefordert, da sie eine optimale Nutzung unter veränderlichen Randbedingungen ermöglichen. Eine Antwort darauf sind wandelbare Strukturen, so wie ein wandelbares Dach, das eine Nutzungsvielfalt von z.B. großen Hallen zulässt: je nach den Anforderungen können Sportveranstaltungen oder Konzerte stattfinden, es sind Openair- bzw. Inhouseveranstaltung möglich.

Bisher wurden mehrere wandelbare Membrandächer kombiniert mit einer Speichenrad-Konstruktion entworfen und gebaut. Der Vorteil dieser Kombination ist klar: zum einen hat eine Membran ein geringes Gewicht und ist daher leicht zu bewegen. Zum anderen ist die Membran sehr flexibel und kann gefaltet werden. Das Prinzip eines Speichenrads, wie es beispielsweise für Fahrräder verwendet wird, ist zugleich ein sehr effizientes Konstruktionssystem, da es hauptsächlich aus Zugelementen besteht und ebenfalls ein geringes Gewicht aufweist. So können große Spannweiten mit einer geringen Menge an Material erreicht und aufgrund der geringen Abmessungen der Tragprofile kann zugleich eine große Transparenz erzielt werden.

Die meisten beweglichen Membrandächer mit einer Speichenrad-Konstruktion falten sich bei der Öffnung des Dachs zur Mitte hin auf. Folglich hängt dann die zusammengefaltete Membran in der Dachmitte und wirft einen Schatten auf das Spielfeld. Dieses ist für Fernsehübertragungen sehr nachteilig. Außerdem beeinträchtigt das über dem Spielfeld hängende Membranbündel den freien Blick in den Himmel und somit das ästhetische Erscheinungsbild. Eine Faltung der Membran in die entgegengesetzte Richtung, also zum Dachrand hin, würde diese Probleme lösen: es käme zu keinem Schattenwurf der Membran auf das Spielfeld und eine freie Öffnung über dem Spielfeld wäre erreicht! Dies ist die grundlegende Motivation dieser Arbeit.

Eine mögliche Lösung für ein wandelbares Membrandach mit Faltung zum Dachrand muss sich mit zwei Aspekten befassen: zum einen mit der geometrischen Umsetzung, zum anderen mit der Aufbringung der Vorspannung der Membran. Die geometrische Problemstellung beruht auf der Inkonsistenz zwischen der erforderlichen Form der Membran und den gerade verlaufenden radialen Seilen des Speichenrades. Unter den verschiedenen Ansätzen, die zur Lösung aufgezeigt wurden, sind zwei praktische und mögliche Lösungen weiter entwickelt worden.

Für den ersten Ansatz werden die Membranstreifen so geformt, dass die radialen Seile gerade verlaufen können. Im Allgemeinen ist das Tragverhalten einer Membran durch ihre Geometrie bedingt. Daher ist bei diesem Ansatz die größte Herausforderung, die Membran in eine doppelt-gekrümmte Form zu überführen und gleichzeitig die Faltbarkeit zu gewährleisten. Die vorgeschlagene Lösung verändert die Randbedingung der Membran im nicht vorgespannten und im vorgespannten Zustand. Die geometrische Veränderung kann durch die vertikale Bewegung des gesamten Druckrings durchgeführt werden. Diese Methode wird 'bewegliche Druckring-Methode' genannt und in 'Fallstudie A' eingehend analysiert und diskutiert. Dabei wurde neben der strukturellen Analyse auch die Umsetzung dieser Methode anhand eines physikalischen Modells überprüft, das der Autor im Labor der TU-Berlin in Deutschland gebaut hat.

Beim zweiten Lösungsansatz dienen Seilbinder dazu, die radialen Seile zu krümmen, so dass zwischen den Radialseilen rechteckige Membranstreifen verwendet werden können. Bei diesem Ansatz stellt die gleichmäßige Aufbringung der Membranvaspannung die größte Herausforderung dar. Durch das Anheben der Seilbinder, die die textile Membran 'mitziehen', kann die Vorspannung erzielt werden. Dieser Mechanismus nutzt den Vorteil, dass eine kleine, nach außen gerichtete, Verschiebung der Ankerpunkte der oberen Seile des Seilbinders eine große Verformung der gesamten Struktur nach oben verursacht. Das kinematische Verhalten der Seilbinder wurde in einer umfassenden Parameterstudie untersucht, die analytischen Ergebnisse auf das bewegliche Membrandach übertragen und so ein neuartiges Prinzip zur Vorspannung umgesetzt.

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LIST OF SYMBOLS

a	Width of a membrane strip
a_m	Width of a membrane strip with the position m
A	Name of a point / Area
A_i	Combination of reduction factors
A_{res}	Safety factor
c	Circumference / Compression ring
C	Compression Force
C_e	Exposure coefficient
C_t	Thermal coefficient
C_{pe}	External pressure coefficient for wind pressure acting on the external surfaces
C_{pi}	External pressure coefficient for wind pressure acting on the internal surfaces
C_{ALT}	Altitude factor
C_{DIR}	Direction factor
C_{TEM}	Reduction factor for temporary or provisional structures
D	Compression force
E_i	Cable girder's elevation
EA	Cables stiffness
f	Function
f_d	Allowable stress
f_{tk}	Tensile strength
f_u	Sag of the upper cable
h	Height
i	Iteration number
K	Stiffness matrix
K_M	Material stiffness matrix
K_G	Geometric stiffness matrix
L	Name of edge line / Length / Electrical power to move a roof [kW]
m	Position at a membrane strip
n	Number of radial cables / Raising-factor
p	Force
PX	Reaction force in x-direction [kN]
PY	Reaction force in y-direction [kN]
Q	Weight [t]
q_{ref}	Reference wind pressure
r	Radius
R_d	Design resistance
s	Snow Load
S	Tension force
s_k	Characteristic snow load on the ground
S_k	Characteristic load effects
T	Tension ring / Tension Force
U	Deformation

v	Vertical force
V	Running velocity [m/min] / Prestressing force
V_u	Prestressing force in a upper cable
W	Travel resistance [kgf/t]
w_e	Wind pressure acting on the external surfaces
w_i	Wind pressure acting on the internal surfaces
xx	Warp direction of a membrane
yy	Weft direction of a membrane

Greek Letters

α	Inclination angle of a membrane strip
Γ	Safety factor
Δ	Input parameter
η	Mechanical efficiency
θ	Twisted angle of a membrane strip
μ_i	Snow load shape coefficient
v_{ref}	Reference wind velocity [m/s]
$v_{ref,0}$	Basic value of reference wind velocity [m/s]
ρ	Air density [kg / m^3]
γ_f	Load-factor
γ_M	Material safety coefficient

Others

ASCE	American Society of Civil Engineers
ASD	Allowable (permissible) stress design
BC	Before Christ
B.C.	Boundary Condition
ETFE	Ethylene Tetrafluoroethylene
FE	Finite Element
GFRP	Glass fiber-reinforced polymer
IASS	International Association for Shell and Spatial Structures
LC	Load case
PC	Polycarbonate
PES	Polyester
PET	Polyethylene Terephthalate
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
SLS	Serviceability limit State
THV	Tetrahydrocannabivarin
ULS	Ultimate limit State
UV	Ultraviolet
WCSE	World Congress on Space Enclosure