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"2 Landscapes" – interaction of 2 gridshells based on a modified Stewart – Gough - principle

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Abstract

This paper describes a novel timber gridshell design method and building technique by means of the realized pavilion "2Landscapes", which uses a modified Stewart - Gough - principle to interconnect two gridshells to a closed, extremely lightweight structural and architectural system. With the realization of the pavilion "2Landscapes" we put the issue of gridshells and bending-active structures in a completely new and innovative context by offering new approaches in formfinding, assembly, spatial qualities and possibly kinetic properties of gridshells, replacing the traditional determination of boundary conditions by sets of modified Stewart - Gough – principle configurations.

Keywords: Timber structure, Gridshell, Stewart – Gough principle, Form finding, Structural analysis, Dynamic relaxation, Kinetic

1. Context.

Since the development and erection of the pioneering construction of the Mannheim Multihalle by Frei Otto and his team at IL, Stuttgart, the construction of gridshells belongs to the supreme disciplines in the field of extreme lightweight structures (Happold [1]).

In general gridshells can be defined as a structural typology that is derived from the more general shell archetype. While shells are structural systems characterised by a doubly curved surface, gridshells are defined as structures "with the shape and strength of a double-curvature shell, but made of a grid instead of a solid surface" (Douthe [2]). Such structures can and have been constructed out of a variety of materials, including aluminium, steel, timber and more recently glass-fibre composites.

In addition, there is a further distinction to be made between certain types of gridshells, based on the forming method employed, in conjunction with the type of material used. On the one hand, there are gridshells that feature discrete grid members that are individually connected at the nodes. Examples of these include the British Museum Great Court Roof in London, UK (made from steel) or the Pods Sports Complex domes in Scunthorpe, UK (made from timber). These structures are piecewise assembled by connecting all the members together, usually using a temporary supporting system.

On the other hand, the second type of gridshells, exemplified here by the 2Landscapes pavilion, are termed elastically bent gridshells and they feature continuous grid members that span the whole of the structure and overlap each other at the nodes. Such systems rely on the relatively low bending and torsional stiffness of the small sections of material (e.g. timber) that allow a flat grid of straight elements (or laths) to be deformed into a doubly curved shape. This technique can lead to extremely lightweight structures, best exemplified by the pioneering Mannheim Multihalle (Happold [1]). The design methods and construction of such timber gridshells are detailed also in Harris et al [3] and Naicu et al [4]. Due to the nature of the assembly process, timber gridshells can be constructed using various numbers of layers (one layer is defined as two sets of laths arranged in two directions). The Mannheim Multihalle, for example, used a double-layered system with four sets of laths in two directions while the 2Landscapes pavilion used a single-layered system.

2. Form finding "2Landscapes".

The form-finding in elastically bent, lattice shell structures is mostly done in physical and digital hanging-models and/or their numerical simulation. Therefore, the shape and structure of gridshells can be generated in a self-organized process and they are determined by defining boundary conditions like linear or point-like elements within the gridshell and especially at the edges, respectively outline, of the gridshell. The formfinding for the presented pavilion was done in physical models, up to a scale of 1:5 (Fig.1, Fig.2) and is based on research on irregular positioning of linear elements in space (Schaur, Filz et al. [5]). With the realization of the pavilion "2Landscapes" we put the issue of gridshells and bending-active structures in a completely new and innovative context, which are mainly characterized by following aspects.

2.1. Modified Stewart – Gough – Principle.

The 2Landscapes pavilion has shown that by combining the timber gridshell technique with the Stewart – Gough principle, it has been possible to develop an innovation for both aspects, and to create new architectural and structural possibilities. The interaction of 2 gridshells is based on a modified Stewart – Gough – principle, which is simultaneously used for bidirectional load transfer and generation of form.

The "original" Stewart-Gough platform can be described as a parallel, six degree-of-freedom mechanism, which we know e.g. from flight simulators. In normal use, such a platform is composed of two parallel rigid planes interconnected by six telescopic legs forming isosceles triangles cut at vertices. All six points of the upper plane are connected with six points of the lower plane by spherical joints. Assuming the bottom plane is restrained, with the use of mentioned telescopic legs - commonly hydraulic jacks - such an arrangement allows full translational and rotational motion of the top plane based only on modifications done by the six actuators. This behaviour is commonly used in various types of vehicle simulators (Stewart [6]). The length of all legs set constant for any feasible, spatial position of the two planes, the configuration forms a stiff structure and has no movability in general (Husty and Karger [7]).
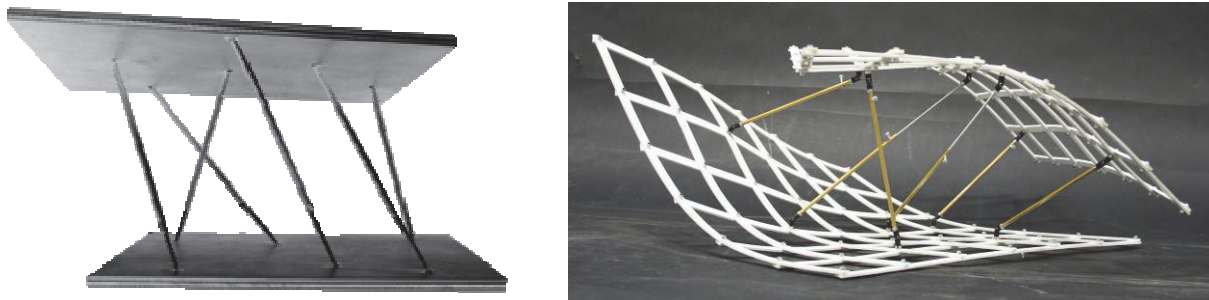

Figure 1: Stewart-Gough principle not forming isosceles triangles in scaled model with minimum amount of six interconnecting elements between rigid planes (left, researchmodel Schaur, koge) and between elastic grids deformed due to different length of struts (right).

The innovation here is achieved by modifying the conventional arrangement of the Stewart – Gough platform by replacing the rigid top and bottom planes with the elastically deformable timber grids, thereby increasing the total freedom of the system (Fig.1). Simultaneously the six compression and/or tension elements interconnecting the two timber grids are not forming isosceles triangles but are skew-whiff arranged. This causes translational and rotational motion of the system in most cases until it reaches a spatial configuration, which is blocked by geometrical constraints. Constellations with more than six interconnecting elements cause configurations with less total freedom of the system, whereas no stable configuration can be achieved by constellations with less than six interconnecting elements.

2.2. Replacing the traditional Determination of Boundary Conditions of Gridshells.

Due to angular displacement of the initial square lattice grid and its elastic bending properties it is possible to control the shape and curvature of the gridshell within the set of possible modified Stewart – Gough – constellations.

This offers a new method in formfinding by replacing the traditional determination of boundary conditions of gridshells, which are usually supported along the boundaries, or feature "free" edges, which have to be framed respectively need closing-off members. In the case of "2Landscapes", however, the requirement of the Stewart –

Gough platform makes it necessary to have part of the bottom grid as a ground support while also having the top grid supported on six pin joints within the grid itself, while all its edges are left free without closing-off members.

In contrast to traditional gridshell structures the lattice structures of "2Landscapes" are geometrically and structurally locked by distributor plates, which are part of the modified Stewart – Gough – members. Therefore bracing the gridshell with a third layer, which usually has to be installed in the 3D-state, is obsolete. This property can have huge impact in terms of timesaving in the erection process, or the cost of more complicated nodal connectors involving more than 4 members.

Simultaneously these distributor plates ensure the transfer of the axial tension or compression in the skew members into the plane of the gridshell, and remove potentially high point loads directly applied to the grid. Additionally, the length constraint of the six Stewart-Gough members ensures that certain naturally occurring deformations in an un-braced gridshell are reduced.

2.3. Kinetic Aspects and Effects.

Tests on physical models have also shown the option to construct a kinetic system, if one or more of the modified Stewart – Gough – members is designed to be telescopic (Fig.2). This partly replicates the original intent of the mechanism, that of a kinetic simulator, but it brings its potential use into the realm of the built environment. So the aluminium panels, which adapt their opening to the angular displacement of the lattice grid and its surface curvature, could be opened and closed as the whole structure can be moved and "frozen" in different states. In the context of "2Landscapes" these properties were not used in terms of a kinetic overall structure but for the assembly and erection process.
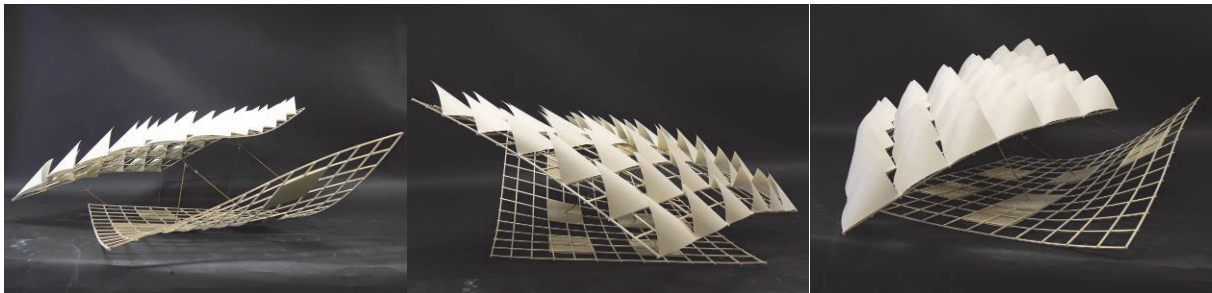

Figure 2: Kinetic scaled physical model with elastically deformed grids, respectively different surface curvature, due to different length of struts and cables.

Square, 0.5mm thin aluminium panels were mounted on of the initial square lattice grid (Fig.3). The displacement from square grid to an angle of 105°, which was fixed by the distributor plates described above, was used as a trigger for transforming these aluminium panels from plane into stable 3D-caps as a kind of bending active substructure. The magnitude of the panel`s opening refers to the curvature of the top gridshell.
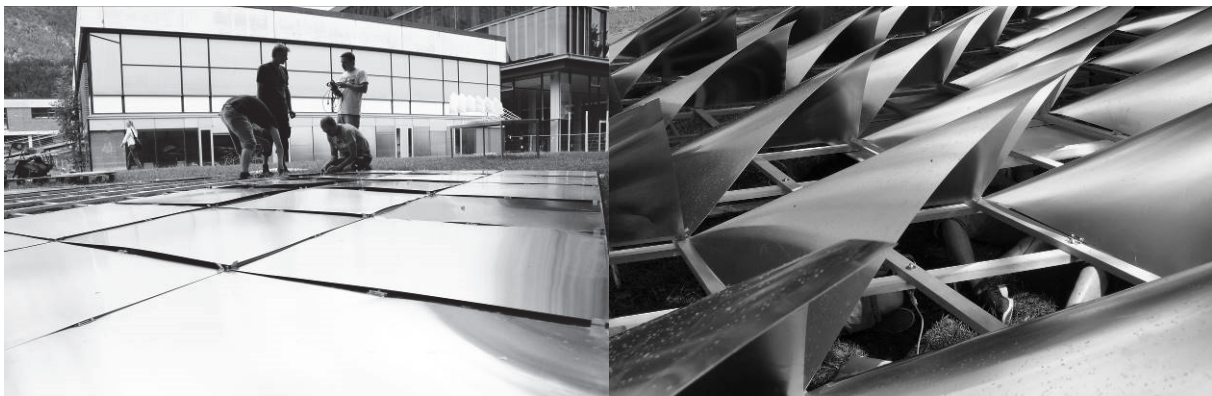

Figure 3: Square, 0.5mm thin aluminium panels mounted on of the initial square lattice grid (left) and transformation from plane into stable 3d caps by angular displacement of lattice grid (right)

3. Material Characteristics.

The timber sections used were 42 x 22mm rectangular profiles made from Rosewood respectively Tulipwood (Fig4). Our first intention was to use local Austrian wood. But at the time of realization wood in appropriate dimensions – minimum length of 5m - and knot-free quality was not available. Since the used species is not listed in the CITES Appendices or on the IUCN Red List of Threatened Species ethical concerns were dispelled. In general use wood has many desirable characteristics and is suitable for a wide variety of important uses from structural wood to furniture. The sapwood is creamy white and may be streaked, with the heartwood varying from pale yellowish brown to olive green. The green colour in the heartwood will tend to darken on exposure to UV light and turn brown. The wood has a medium to fine texture and is straight grained. The AHEC publication "Structural design in American" hardwoods rates the used wood as medium to high density wood with high bending (140-217 N/mm2), shock resistance, stiffness and compression values (Lawrence and Ross [8]).

The major influence of material properties on the final shape of the pavilion manifests itself mainly on the bending stiffness of the laths, and hence the bending stiffness of the gridshell itself. However, as the general shape is dictated more by the position of the six connector elements, the bending stiffness of the laths will only heavily influence how much the two grids deform, working together with the tension in the cables. By choosing appropriate materials and section sizes one can create more or less stiff configurations.

Figure 4: Timber sections, rectangular profiles 42 x 22mm

4. Assembly.

In particular "2Landscapes" connects two 5,20x5,20m gridshells, assembled from extremely thin wooden laths, on two hinged struts and four cables only to a closed, extremely lightweight structural and architectural system. At the same time these elements are responsible for the spatial curvature and therefore load-bearing capacity of the two architectural landscapes as described in Section 5 "Structural Behaviour".

Two equal lattice grids were assembled from timber laths with a dimension between the axes of 40cm (Fig.5, left). The connections between two laths were realized by 6mm bolts and washers to guarantee angular displacement (Fig.5, right). Having mounted square aluminium panels on of the top lattice grid first, both lattice grids – still in plane – were displaced from 90° to 105°. This angle was locked by mentioned distributor plates. Since the connection detail was executed as full swivel the two struts could be connected to the lattice grids which were placed with about 1m distance on top of each other (Fig.6, left). By the means of lashing straps the lattice grids were brought into their predefined position (Fig.6, right). These lashing straps were replaced by 4 cables, each starting from a distributor plate and branching out to four nodes on the top grid (Fig.7-9).
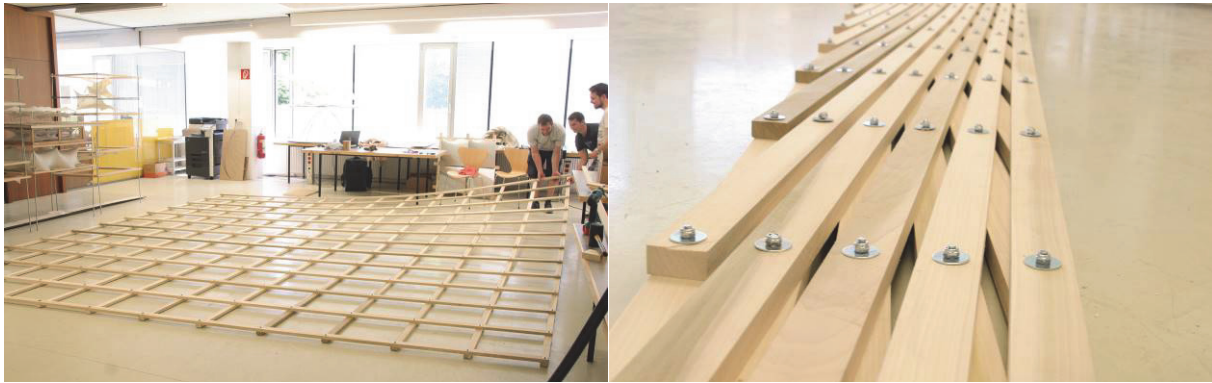
Figure 5: Square lattice grid with a dimension between the axes of 40cm (left) connected by 6mm bolts and washers to guarantee angular displacement (right).

Figure 6: Two struts connected to both lattice grids by full swivel - connection detail (left) and lattice grids were brought into their predefined position by the means of lashing straps (right)

Figure 7: Replacing lashing straps by 4 cables, each starting from a distributor plate and branching out to four nodes on the top grid.
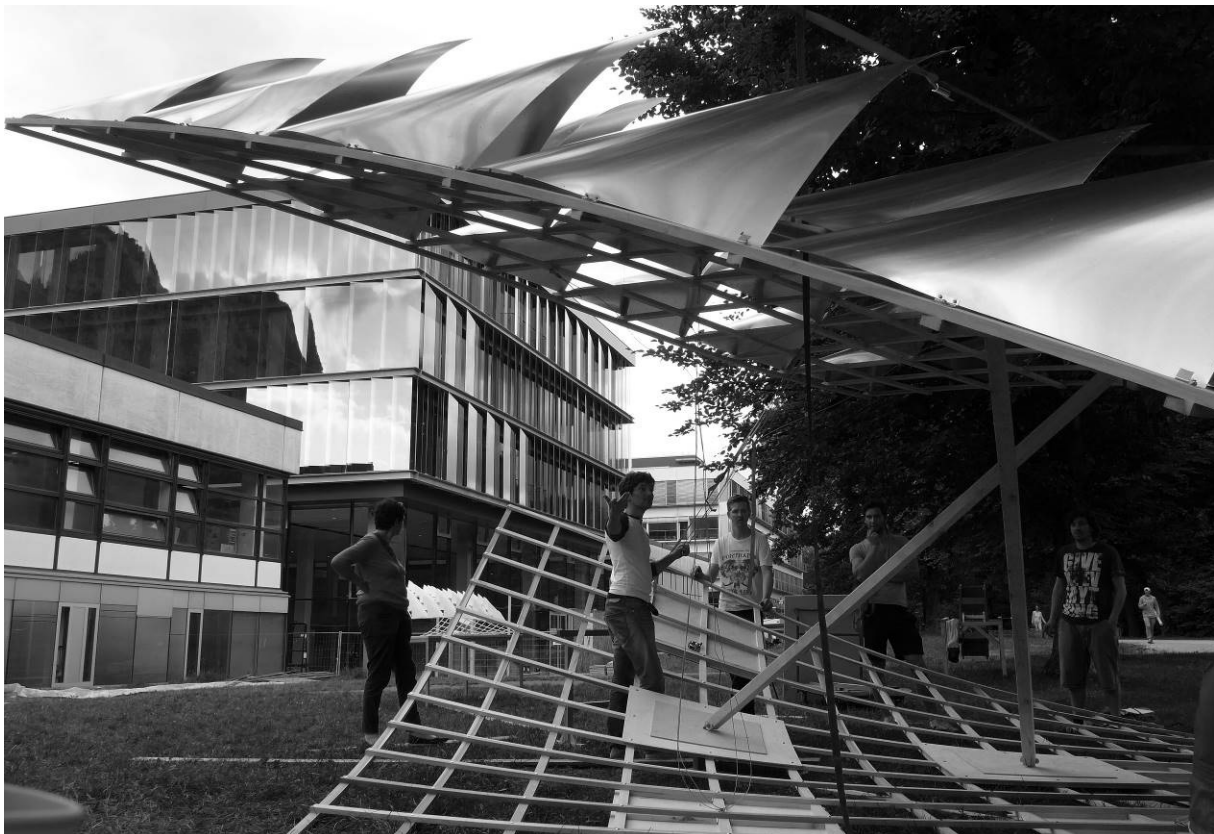
Figure 8: 2Landscapes - Finished Structure

Figure 9: 2Landscapes - Finished structure

5. Structural Behaviour.

From a structural point of view, the two gridshells here do not function as in conventional structures by carrying compressive loads through the curved shape down to the supports, nor do they function as a hanging net. Instead, the upper grid is loading the two compressive struts, which are then unloaded onto the bottom grid, with both ends of the struts being pinned. At the same time, the equilibrium of the shape is maintained by the four cables connecting the two grids which serve both as further shape modifiers, and as a way to restrain the relative movement of the top and bottom layers (Fig.9).

In order for the flat grids to be deformed into curved shapes it is required to allow rotational freedom at the nodes, thus making possible a scissoring motion around each node. However, once the desired shape is obtained, a restraint has to be introduced within the plane of the gridshell so as to lock the shape of the structure. This can be done by means of diagonal cable ties, diagonal rigid struts, adding a stiff membrane covering or fully fixing the nodes. The 2Landscapes structure achieves this by the following methods:

- Bottom grid – by partly restraining the grid on the ground once the desired form was obtained
- Top grid – by adding another layer of actively bent elements in the form of aluminium panels
- Both grids – through the action of the distributor plates

The square aluminium panels were fixed on the top grid at three corners only (Fig.9). As a consequence, when the upper layer was deformed the relative rotation of the nodes induced an upward bending of the panels. This can be effectively viewed as the bending resistance of the panels contributing to the in-plane shear stiffness of the grid. By using different materials or configurations of panels one can imagine achieving various degrees of in-plane stiffness which can correspond to different desired characteristics. In the case of 2Landscapes, the aluminium panels contributed to the overall aesthetic of the structure as well as a shading device.

6. Simulation

The form finding of the 2Landscapes pavilion was done entirely using physical models (see Section 2). Once the pavilion was finalized, it was 3D-scanned and a point cloud of the two grids was obtained (Fig.10, left). This raised the question of whether or not it was possible to simulate the outcome in a digital environment (Fig.10, right), and to compare it with the realized structure.
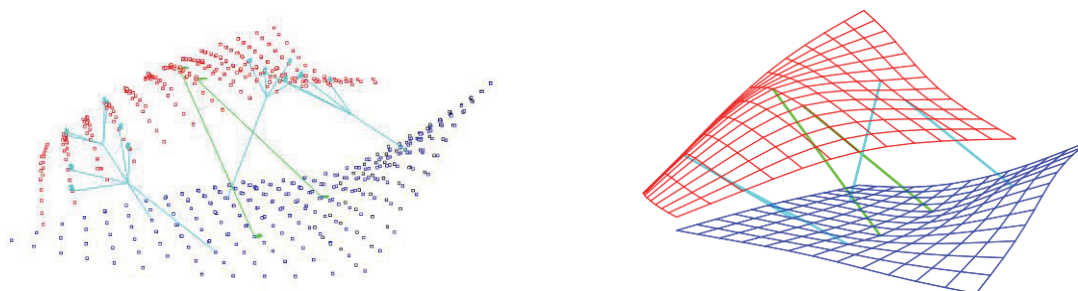

Figure 10: 3D scan of finished structure – point cloud of nodes (left, koge) and numerical simulation (right, Naicu, D.).

The form finding simulation was done using Kangaroo Live Physics (used together with Rhino3D and Grasshopper), which is a computational tool developed by Daniel Piker based on the Dynamic Relaxation technique (Senatore and Piker [6]). As the entire system is very complex with various types of elements working together, the simulation was separated into two major components. Firstly, the combined effect of the two grids and the six connectors was simulated as Component 1. Secondly, Component 2 involved modelling the curvature of the panels on the top layer and was achieved subsequently, on the shape determined by Component 1. This separation was necessary due to the computational resources required. The machine used featured an Intel® Core™ i3 CPU @ 3.07GHz, but given enough resources, the whole system will be able to be integrated into one simulation cycle.

7. Conclusion and Perspective.

The "2Landscapes" pavilion is a unique showcase of the merger of two techniques, that of a freely moving kinetic system and that of an elastic timber gridshell. By combining them in this architectural prototype, new avenues of design and exploration are opened. This paper aims to describe the design and construction of the pavilion, and to highlight its architectural and structural properties.

Above mentioned kinetic aspects of modified Steward Gough principle were not fully used in the context of the "2Landscapes" pavilion, but offer manifold capabilities for ongoing research. One of them is the panel`s opening, which is directly linked to the surface curvature, a phenomenon, which might also lead to other potential implementations in architecture.

Acknowledgement

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