Analysis Tool for Grid Shells Using the Dynamic Relaxation Method

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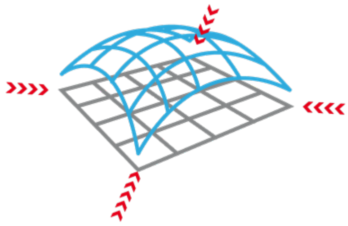
1 Introduction

The research project "Analysis Tool for Grid Shells Using the Dynamic Relaxation Method" was divided into two parts. The first part included the development of a formfinding tool for grid shells using an algorithm, that allows further structural analysis. In order to validate the numerical simulations, a grid shell prototype (using a geometry calculated by the software tool) was developed and constructed in the second part of the research project.

1.1 Grid shells, erection methods, connectors, materials

As described by Burkhardt et al. [1], a grid shell is a spacially curved framework of rods and rigid joints. The rod elements form a planar grid with rectangular meshes and constant spaces between the nodes. Due to the development of the prototype, grid shells had been analyzed, which can be deployed out of a flat grid into a threedimensional structure. The focus was to detect the main principles of erecting such structures. Furthermore the research concentrated on the application of materials and the use of connector types.

There are two procedures that are commonly used for the erection of grid shells. On the one hand, grid structures can be pushed upwards. This method was used in order to lift both of the two wooden grids of the Mannheim Hall using hoists [3]. On the other hand, flat grids can be deformed by lowering from a scaffold. The application of this method benefits from the selfweight of the grid - the structure can be transformed into its final threedimensional shape according to the lowering process. This method had been used during the erection process of the Downland grid shell in Sussex [4]. As both methods require a huge amount of material, one focus of this research project was to demonstrate the feasability of erecting grid shells kinematically by just translating their supports laterally (Image 1.1 and Image 1.2).



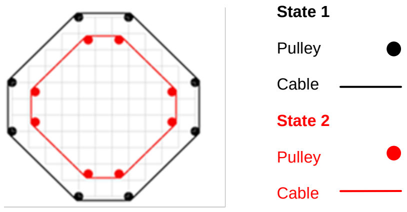


Image 1.1: Pictogram: kinematic erection of a grid shell due to support translation (left Image)

Image 1.2: Pictogram: shortening a cable, mounted to a grid structure using pulleys (right image)

1.2 The dynamic relaxation method

The dynamic relaxation (DR) method is a vector based method that can be used in order to describe the static behaviour of non linear structures. It was described by A. S. Day in 1965 in order to compute tidal flows [5]. Based on Day´s definition, the DR method had been expanded to calculate tensile structures, cable nets, hanging roofs and grid shells [6]. M. R. Barnes describes the DR method as follows: "the basis of the method is to trace step-by-step for small time increments, delta t, the motion of each node of a structure until, due to artificial damping, the structure comes to rest in static equilibrium." The flow chart illustrates the operating mode of the algorithm (Image 1.3) in a simplified manner.

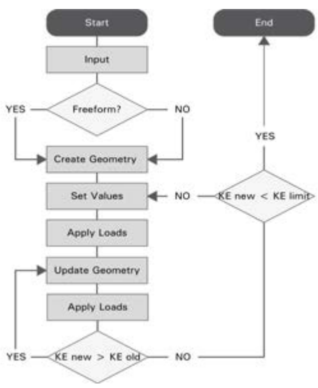


Image 1.3: Flow chart illustrating a simplified principle of the DR-algorithm [6, 7]

1.3 Implementing and developing the software tool

The DR-algorithm was implemented in RhinoScript, a programming language based on Visual Basic Scripting. The RhinoScript compiler runs as an add-on to Rhinoceros (Rhino), a versatile 3D-modelling-program. The software tool was developed for the creation of synclastic (Image 1.4) and anticlastic shell geometries. Thus the user is enabled to design, to develop, and to analyze grid shell geometries within one tool.

The operation of the tool is described within the following five steps:

- Creation of a base geometry (creation of a surface by the user);
- Parameter input (mesh size, diameter of the rods, Young's modulus);
- Optional modification of the system / approval (selection of the supports, adding point loads to the system);
- Computing / optimizing the geometry by the DR-algorithm;
- Post process (data export).

The grid shell geometry (Image 1.5) has been calculated to provide an exemplary base for the validation process of the tool.

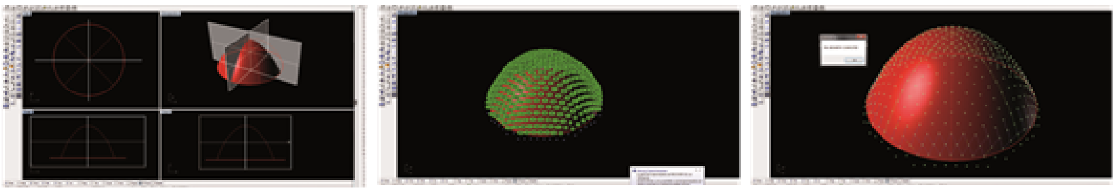


Image 1.4: Operating the tool: creation of a user-defined surface, grid development and start of the DR-algorithm, finalizing the equilibrium geometry

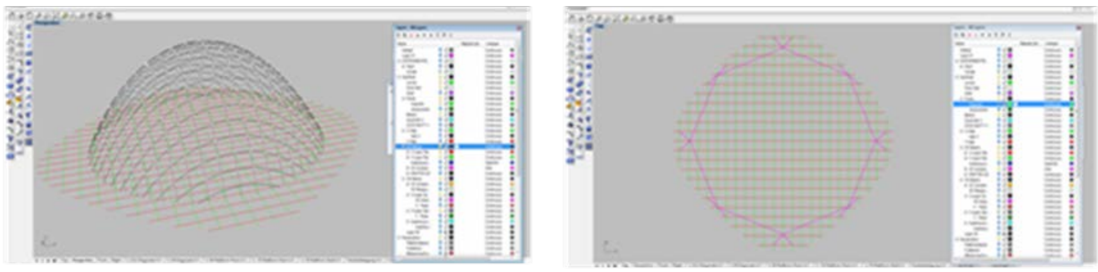


Image 1.5: Post process: flattening of the surface taking into account the real length of the rods

1.4 Design and erection of the mock-up

Two physical grid shells had been designed and realized: one small-sized mock-up (surface area approximately 25 m²) and one full-sized prototype (surface area approximately 150 m²).

The aim of building the mock-up (Image 1.6) was to demonstrate the feasability of the erection process. According to this, the dynamic behaviour of the structure could be explored while moving the supports towards their final position. Possible risks, that might occur transferring this erection method to the prototype, could be estimated.

Image 1.6: Sequence of the erection process for the mock-up

1.5 Design, development and erection of the prototype

The development of the prototype included additional material tests. As the applicability of the rods and its connectors had to be assessed, three point bending tests (rods) and tensile tests (connectors) had been conducted.

As the potential of composite materials had to be demonstrated, slender ComBAR elements (diameter 13.5 mm) - concrete reinforcement bars made of glasfiber reinforced plastics (GFRP) - were chosen. These rods were mounted to a flat grid (mesh size: 650 mm) using customized swivel couplers.

For the purpose of erecting the structure, a steel cable was arranged in a circle and closed by a grip hoist. In a further step, the cable was transformed into an octagon, that was defined by eight pulleys. Those pulleys were connected to sixteen system nodes within the range of the supports. Shortening the cable by operating the hoist enabled a translocation of the pin-ended supports of the rods. According to this procedure, a threedimensional transformation of the initially flat grid could be generated. After fastening the supports to a system of two circular rings made of ComBAR elements, the gridshell turned into a state of static equilibrium. The height of the structure was 4.65 m, spanning over a distance of 11.10 m. This kinematic erection process (Image 1.7) had been accomplished within less than two hours.

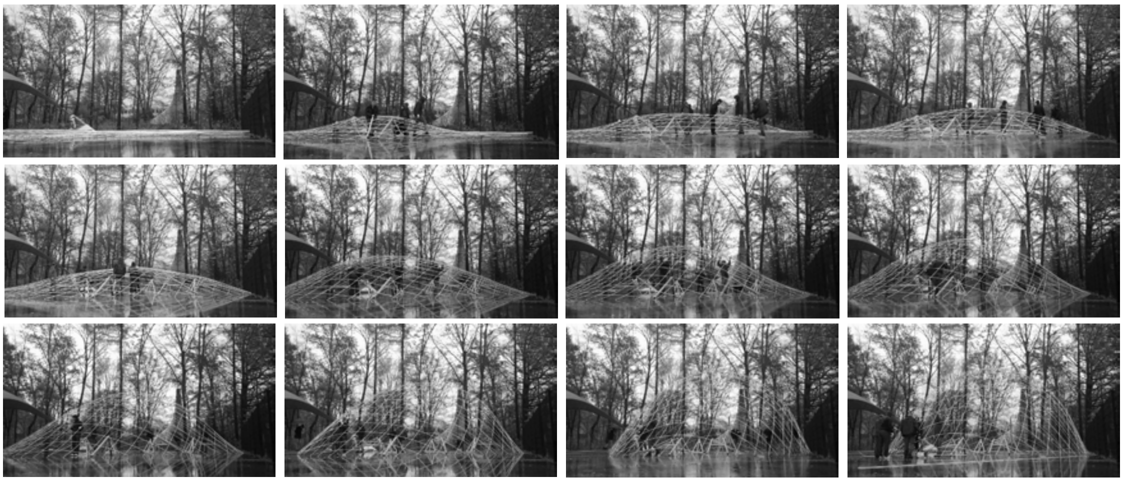


Image 1.7: Sequence of the kinematic erection process of the grid shell prototype (top left to bottom right)

1.6 Empirical validation of the tool: laserscanning

In a further step, a 3D-laserscanner enabled the measurement of the prototype. This empiric approach allowed a validation of the tool, as the scanner converted the physical environment of the construction site into a digital 3D-model.

The reduction of the number of reference points (system nodes: 377, reference points: 17) simplified the comparsion of the two models (Table 1.1). The average deviation between those points was 195 mm, which is approximately 1.9 % (deviation relating to the maximum span).

Node	Ø	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Distance (mm)	**195**	288	136	182	133	304	225	216	164	253	90	218	102	241	241	220	100	203

Table 1.1: Validation by laserscanning: deviation between the reference nodes

1.7 Numerical validation of the tool: simulation in ANSYS

The numerical grid shell geometry created by the tool was additionally modeled and analyzed using the simulation software ANSYS. The deviances between the reference nodes (both of the two numerical models) were insignificant small. The average deviation was 17 mm (Table 1.2), which is approximately 0.15 % (deviation relating to the maximum span).

Node	Ø	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Distance (mm)	**17**	22	20	27	20	22	20	27	20	4	24	4	24	4	24	4	24	1

Table 1.2: Validation by Simulating in ANSYS: Deviation between the reference nodes

1.8 Summary and Perspective

Summary: The DR-algorithm was implemented successfully in RhinoScript. The software tool is easy to operate and enables the user to design, to plan, to build and to analyze grid shell geometries.

The tool could be validated successfully - both empirically and numerically. As expected, the comparison of the different validation principles demonstrates, that physical prototyping features higher tolerances within geometries than numerical ones do.

Various material tests - both as bending and tensile tests - allowed a safe construction and erection of the grid shell prototype.

The feasability of erecting grid shells kinematically by translating the supports had been proved, so that a material-saving erection method could be introduced.

Perspective: A further development of the DR-tool could be to integrate the use of tensile structures. Then the interaction between bending elements (grid shell) and tensile elements (cables) could be simulated and as a result, the advantages of the kinematic erection process could be transferred to more complex geometries.

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