Reflection on graduation

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Process

The goal of my graduation research was to find a solution for the missing link in analytical shell calculations and model the total analytical calculations in a tool for others to be used. This research is on the edges of the known mechanical theories, so I frequently hit side tracks and wrong methods, making the process definitely non-linear.

During the process a lot of theories were tested and tried. Some of them where so far off track that they are not documented in this thesis to keep the description short and clear. Because a lot of theory is already known in the field of structural mechanics, it was simple to verify intermediate results during the research with hand calculations or calculations in different software suites. This prevented the research from running too far off track at any point.

At some points, when new directions where found, that where not directly related to the main goal, it is tempting to do more research in that field. This happened for example with the area relations in the force polygon and the line of thrust. At the end, this research also paid off, so overall no big side tracks delayed the research of the main goal.

The initial goal of the research was to find the distribution in normal and bending forces in shell structures. Because researching new theories can take a lot of time, and one never knows when a good solution is found, a research like this can take much more time than expected. Half way it became clear that there is so much to find and learn in arches and beam structures, that the goal was adjusted to cover only these structures and not make the step to shells and vaults. Recommendations are made on how to continue this line of research in shells.

Calculation method and tool

The developed method holds a quick manner to find the distribution of normal forces and bending moments in arches and curved beam structures. The method is incorporated in the calculation component, so these results are discussed simultaneously. In order of the chapters, all (sub) conclusions and other findings are stated;

- Using the line of thrust and the complementary normal energy, the correct equilibrium solution for arches without bending moments and a hinged support can be found. The line of thrust returning the least complementary normal energy gives the right equilibrium. This only holds for structures in projected loads.

- Constructions with a known (simple) mathematical description, hinged supports, a projected load and the supports on one horizontal line, can be analysed using an Excel calculation sheet to find the construction with the least total complementary energy. This can be done by relating the normal forces in the line of thrust to the normal forces and bending moments in the construction. By trying lines of thrust with different heights, the construction with the least complementary energy can be found.

- For calculating structures with their own weight, the formula for catenary structures is used. This can only be done if the length of the catenary is equal to the length of the structure. The support reactions of a catenary structure change when the length of the catenary changes. So trying different heights will not return the structure with the least energy. There is no other mathematical description to find the line of thrust, so a step to a more graphical approach is made.

- The first graphical approach modelled in Grasshopper returns values close to the calculations made in GSA. In this calculation the own weight of the structure is used. Due to rounding errors and the discretization of the structure small deviations between the GSA calculations and the Grasshopper calculations are found. An extra calculation step is introduced to make the component also applicable to asymmetrical structures. The method still only works for hinged supports and supports on one horizontal line.

- The area under the line of thrust seems to be equal to the area under the construction. Applying this idea in the component gives the opportunity to calculate structures where the supports are not on a horizontal line. For this both the vertical and horizontal supports are variables to test different lines of thrust. Not all lines of thrust generated present an equilibrium solution.

- Using the closing line in the calculation method eliminates all the solutions that do not present equilibrium. With his extra information the calculation works with one variable. Searching for equal areas presents more accurate results than searching for the minimum energy. This is caused by the different calculations steps in the script.

- The script gives visual feedback that can be used in the beginning of the design process to give easy to understand feedback on the relation between the forces in the structure and the shape of the structure.

- The script gives numerical output to check if the stresses in the structure become too high, and shows the support reactions, bending moments and normal forces in the structure.

- The script is modelled in a clear manner, so others interested in this theory can use the script and develop the script further.

Context

So the goal of solving the analytical shell calculations is not reached, but a good recommendation on how to continue can be given.

- Finding the exact mathematical method to find the equilibrium that returns least complementary energy is still a big challenge. If this method is found, the process of analysing arches and beams can be linearized and a script running with mathematical calculations is faster than a script using graphical analytics. Downside here is the chance that a black box is created around the calculation.

- Increasing the flexibility of the component to make it applicable on more structures and load cases is a good direction for expansion. For example the possibility to calculate point loads on the structure, or loads in different directions. This addition is a pure scripting challenge, but the results should be validated. The method of calculating and using graphic statics should be valid in more complex load cases as well.
  Another example is the addition of more support cases, like clamped supports. In this case the line of thrust does not start and end in the support points, so more lines are possible. How to solve this and find the leas energy is a calculation challenge. No direct leads on how to solve this problem are found.
  Yet another addition can be a component where you can select section for the beam and select certain materials, so the user does not have to script this manually.

- Adding deformation calculations to the component improves the use for designing purposes. Especially when the script is linearized, the component can be implemented in a generative algorithm component enabling structures and beams to be optimized for bending moments, normal forces, deflections or stresses.

- To apply the method on vaults and shells, some things should be taken into consideration. First important step is that, just like beams and arches, a valid discretization needs to be generated. This force network, representing the structure, needs to be transformed in to a thrust network as described by P. Block. After that the different parameters defining the height of the thrust network need to be defined, and their influences on how they change the shape of the thrust network. The forces in the different bars can be related in a similar fashion as in the beams and arches. Important to take in consideration is the fact that in shells, one can find hoop forces. How these forces can be included in the calculations needs its own research.