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PRODUCING OPTIMIZED STRUCTURES WITH INFLATABLES STRUCTURAL MEMBRANES 2013

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Summary. In this paper we describe the research of the best combination of construction, material and typology for structures with bending moments constructed with fabric formwork. The results are inflated three dimensional (open cell) structures rigidized and structurally optimized. The structure is 40% lighter as conventional beams of the same material and was realized and tested in prototypes and full scale models.

1 INTRODUCTION

A novel method for reducing the amount of material used for structural components in a building is the use of structural optimization in the design process. Structural optimization integrates structure and form in a way similar to natural or biological optimization. Weight reductions of structural members cascade through the structural system of a building decreasing design loads on other structural members leading to an additional reduction in material use [1]. Currently, there are no efficient production methods which are suited for producing the organic shapes distinctive for structurally optimized elements and contemporary architecture mainly focuses on zeroclastic, multi faced bodies [3].The best results thus far have been achieved with fabric formworks. These mechanically pre-stressed membranes transfer loads solely by linear tension, reducing the volume of the necessary formwork up to 1/300. Subsequently, transportation, storage, landfill and thus embodied energy is also reduced [3].

Despite the achievements, the method can be complicated since often a large quantity of additional falsework is needed [4]. In a highly industrialized manufacturing process this would not be an issue, since the formwork and additional falsework can be reused many times. However, the custom and unique nature of shapes resulting from a structural optimization analysis call for a more flexible formwork system. In that case the formwork of the three-dimensional structure consists entirely of inflatables and is therefore completely based on form-active principles.

2 METHODOLOGICAL APPROACH

This paper discusses the preliminary findings of an ongoing multidisciplinary research into the possibilities of using inflatable membranes as formwork which can be rigidized to produce structurally optimized section active structure systems. The research consisted of an experimental study and in depth literature reviews into the state of the art of structural optimization, inflatable structures and rigidizable materials. The formfinding process initiated with the topological optimization of the four section active systems defined in a theoretical framework by Engel [7]. Its objective was to derive a case on which the proposed production method is based, by identifying the general morphological features of the optimized section active structures. Thorough empirical case studies were performed using solidThinking Inspire 9.0 [8] to determine which optimized structure reflected the most of the general morphological features. Subsequently, shape and size optimization was performed using the ParaGen method to complete the formfinding process [9].

3 STRUCTURAL OPTIMIZATION

Structural optimization is a technique to minimize the material use to a given loading. Research to structural optimization has a long history and is studied intensively.

Structural optimization begins with the earlier work of Galilei, (Fig. 1.) Later on, Bernouilli, Lagrange, Navier sought for the `best' shapes for structural elements to satisfy strength requirements [11]. In the 1960, Lucien Schmidt's seminal paper introduced structural optimization [12, 13].

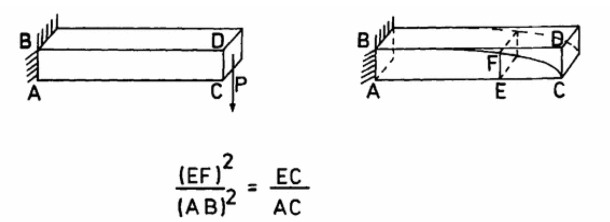

Fig. 1. Galilei Beam, equal strength [11]

Optimal structures –in an architectural context- can be generated by appling an optimization process, this process is already well known method in the car industry, mechanical engineering and aeronautical engineering [14]. Preconditions for the optimization process are; i) the boundaries, ii) load case, iii) material conditions. Using this conditions, the optimization process, generates an optimal structure, based on maximum strength and minimal amount of material.

The optima forma is comparable to the optimization process of mechanical engineering . Rozvany [14] described how to optimize structures in different load cases.

According to Rozvany it is possible to optimize a structure by three types of optimization: i) size, ii) shape and iii) topological [14]. They address different aspects of structural design problem, e.g. the goal may be find the optimal thickness distribution of a linearly elastic plate or the optimal member areas in a truss structure. The aim of shape optimization is to find the optimum shape of its domain. Topology optimization aims at finding the optimal layout of a structure within a specific domain. Structural optimization seeks to achieve the best performance for a structure while satisfying various constraints such as a given amount of material [15].

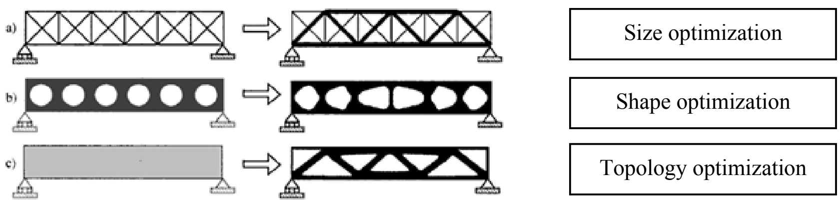

Fig. 2. Optimization process [15]

To perform a structural optimization 3 variables are required;

i) Objective function; a function used to classify designs: for every possible design, f, returns a number which indicates the goodness of the design [17].
ii) Design variable: a function or vector that describes the design, and which can be changed during optimization [17].
iii) State variable: represents the response of the structure [17].

$$(\mathrm{so}) = \begin{cases} \text{minimize } f(x,y) \text{ with respect to } x \text{ and } y \\ \text{subject to } \begin{cases} \text{behavioral constraints on } y \\ \text{design constraints on } x \\ \text{equilibrium constraint.} \end{cases} \end{cases}$$

Fig. 3. The Structural optimization process [17].

There are several well-established techniques for the generation of solid-void optimal topologies such as solid isotropic material with penalization (SIMP) method and evolutionary structural optimization (ESO) and its later version bi-directional ESO (BESO) methods [16]

In this research we used the SIMP method. the SIMP method is numerical FE-based topology optimization method. It stands for Solid Isotropic Microstructure with penalization. The basic idea was proposed by Bendsoe [15].

Common to these well-known topology optimization techniques is that they produce organic looking shapes that cannot usually be cast using conventional techniques. There is a gap between structurally optimized forms, and those developed intuitively by fabric casting, can be bridged (flexible membrane)

Producing organic shapes in concrete (outcome of optimization) has been a challenge problem since complex freeform buildings became a major trend in contemporary architecture

Optimal structures can be widely used in architecture, developing new production techniques are necessary. This results in more efficient (smarter) and sustainable buildings.

Optimal structures require non-orthogonal geometries. Fabric formwork should not be seen as replacement for conventional orthogonal planar formwork but as a disruptive technology that offers a new paradigm with a clearly emerging parametric requirements for form, process, precision and complexity [27].

Producing optimal structures is possible with flexible moulding; fabric formwork.

Fabric formwork can be used to create durable, visually appealing, optimized concrete structures. Fabric formwork provides a means by which architects and engineers can create low-carbon concrete structures to facilitate a sustainable future in concrete construction.

Examples structural optimization in practice.

Example 1; A cantilever with a concentrated load at its free end. The cantilever structure having an inner hollow with two plate-like parts which have two holes on them.

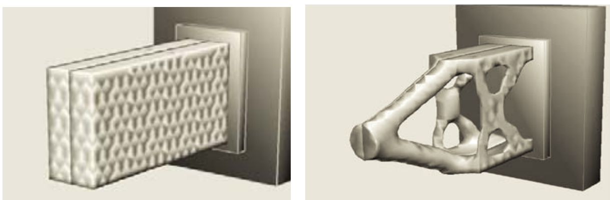

Fig. 4. Optimization of cantilever with ESO [26].

Example 2; An optimized beam produced with fabric formwork using two rigid panels sandwiched, see figure 5. This method with 'pinch points' makes it possible to produce concrete trusses in relatively easy ways [18].

Fig. 5. Production of beam [3]

Fig. 6. Optimized beam with fabric formwork [3]

4 PARAGEN METHODOLOGY

To find a suitable geometry for the beam, a method was chosen which combines parametric form generation with multi-objective shape optimization. The method used was ParaGen, a genetic algorithm (GA) based program developed at the University of Michigan.

ParaGen uses commercial software on a cluster of PCs connected through a web interface to a server that maintains a solutions database from which new solutions are bred. The optimization cycle shown in (Fig. 7) is divided into two parts: the server side and the client side.

On the client side there are basically two steps: 1. parametric form generation and 2. performance evaluation (in this case structural). For Step 1. Generative Components (GC by Bentley Systems) was used as the parametric modeler. To generate a new solution, the GC transaction file reads in a set of variables from an Excel file (the child solution) which was bred by the GA on the server and passed through the web interface to the client PC. Once the new child form is generated in GC, the geometry is passed to the analysis program through a DXF file.

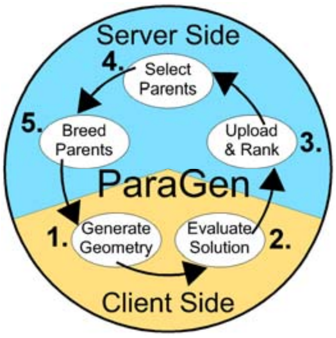

Fig. 7. The ParaGen cycle

In this case a structural analysis was performed using STAAD.Pro [29] to find internal forces, deflections and modal stiffness, and to determine the size of the elements.

In addition to these performance values, descriptive images were also generated in both STAAD.Pro and GC. These include the base geometry, deflected shape, axial force diagrams, depiction of the member sizes, and a rotatable, 3D VRML image. These images were also available later to aid in choosing which solutions to physically model.

For reasons of expedience, the model was initially generated in GC using straight rather than curved elements. In STAAD.Pro the model was designed using steel pipes in order to make relative comparisons of how the geometry affected the structural performance. Once a geometry was selected in ParaGen, additional detailed investigations were made using the curved geometry and concrete sections (see Section 8.).

In Step 3. all of the parametric variables along with the accompanying performance values and images are uploaded through the web interface to the SQL database on the server. The images are given id names which allow them to be linked to a specific solution in the database. Because the database contains only performance and variable values, it can be quite large and still be searched very effectively using standard database search and filter techniques. For this reason there is no need to limit the number of retained solutions to some predetermined population size as is normally the practice in GAs.

Step 4. is comprised of the GA parent selection. The population from which the selection of parents is made is composed on the fly by using SQL filters to create a limited population out of the entire database of solutions. The SQL filters can be very simple sorts to produce a set of solutions. For example the top 40 solutions sorted by least weight. Or they can be more complex limit sets, for example, the top 40 solutions where modal frequency is > 20Hz and weight is < 160 kg then sorted by least deflection. After creating a population set a parent solution is selected at random from the population. Actually this operation is performed twice, once for each parent, and a different filter can be used for each of the two populations. This filter method gives different results from simple objective weighting since particular areas of the solution space can be defined. Once two parents have been selected, the last step in the ParaGen cycle is the breeding of the parents to obtain a new child solution. In Step 5. the CHC breeding algorithm developed by Eshelman and Schaffer [19] is used for crossover of the genetic variables. Only one child is produced and passed through the web interface back to the waiting client PC where the cycle begins again.

The cycle is initialized by generating some number of random solutions. At some point with a sufficient number of solutions in the database, the populations can begin to be developed using the SQL sorts and filters. As the run progresses these population sorts and filters can also be tuned or altered to better search specific areas of the solution space. Finally, with a sufficiently developed database of solutions, interactive searches can be performed to explore and compare solutions. Figure 8 shows a selection set made by setting the filters at modal frequency > 30Hz and weight < 147 kg and sorting by least deflection.

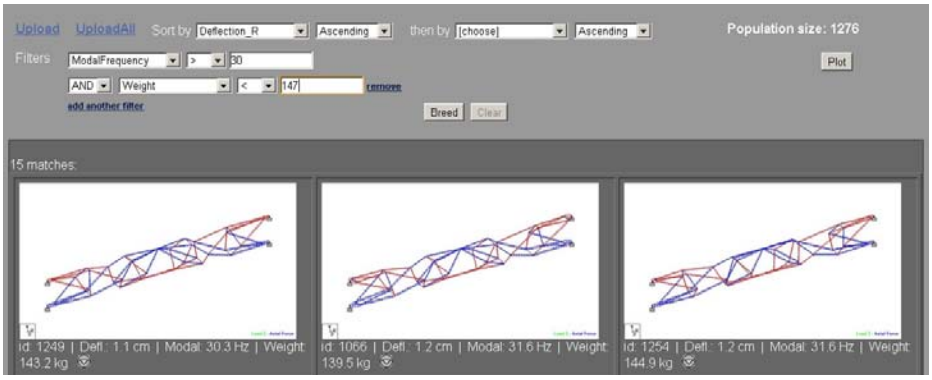

Fig. 8. Selection of solutions

Also multiple objectives can be compared and plotted to perform a Pareto investigation. Plots of two objectives as least weight and highest modal frequency can be shown. A mouse over of the data points will reveal the data values, and clicking on the points will display a small image of the solution. Using these techniques allows the designer not only to simply find the best performing solution, but to actually explore the solution space and perhaps better formulate some aspects of the problem.

5 INSPIRE CASE STUDIES

The first step of the form finding process included the topological optimization of section active structure systems [7]. The optimization of these structure systems was assumed to lead to the largest reduction in material, since form-, vector- and surface active systems can already be considered as lightweight structures. Empirical case studies are performed on the four section active structure systems;

- beam structures
- frame structures
- beam grid systems
- slab structures

The goal of these case studies was to reveal the morphological features of the four separate section active structure systems and the morphological features of topologically optimized section active structure systems in general. Ultimately, the structure that reflects the most of these general morphological features served as a case for the development of the production method. It has to be noted that beam grid systems were not elaborated, since it can easily be shown that an optimized beam grid is equal to a collection of optimized beam structures.

Empirical case studies were performed using solidThinking Inspire 9.0 [8]. The density method is the main solving strategy used in Inspire, which uses Altair OptiStruct [31] and HyperMesh [31] in the background. During optimization, the material density is the only design variable and is allowed to vary continuously between 0 and 1. The relation between the stiffness and the density of the material is assumed to be linear. Fictitious values of intermediate density are penalized using the power law representation of elastic properties to make the result behave more like an ISE topology [14]. For validation purposes, topological optimization on the section active structures was also performed using Topostruct [28], which uses the homogenization method as a solver.

Case studies were carried out using a morphological overview describing all the different constraints that can be applied on a given design space in Inspire 9.0, and the possible or characteristic values they can assume. Varying one parameter at a time, an empirical case study is performed revealing the influence of the individual constraints on the outcome of a topological optimization. The initial geometries were sized using rules of thumb which apply for the Dutch construction industry. The entity exerting the load on the design space was assumed to have its own stiffness. Therefore, material was allowed to be removed throughout the design space. (Fig. 9) displays a characteristic result of topology optimization on a one-bay beam, constrained by fixed supports and a centre point load of 5 kN. The mass target was set on 20% and the material used was standardized C20/25 concrete. Manufacturing constraints such as symmetry, draw direction and thickness control were not used since the manufacturing method has yet to be developed. Also, no frequency targets were specified since Inspire 9.0 always maximizes stiffness and thus natural frequency.

Fig. 9. Characteristic result of an optimized one-bay beam

The type of supports used, i.e. the degrees of freedom and location, have the most influence on the resulting morphology of topologically optimized section active structure systems. Less material is needed where the moment tends to zero, reducing the area of the cross section locally. In the case of frame structures the type of support has less influence, especially when the height to length ratio is equal to or larger than 1/10. With these larger spans, an optimal design space would allow the structure to form an arch at the inner side. With larger spans, larger moments occur which need to be transported via the corners of the frame towards the supports, leading to larger cross sections near the corners. In this context, the type of support has little influence on the moment distribution in the horizontal part of the frame. It has to be noted that fixed support generally lead to more clear and stable topologies than rolled and pinned supports.

Point loads lead to denser member distributions than distributed loads, except in the case of slab structures. With respect to beam and frame structures, forces caused by a point load will be transferred by two diagonal members towards the bottom flange. These members, as well as most other members in optimized structures, connect at an angle of about 45 degrees since forces also disperse at this angle. When incrementally increasing the number of point loads, the resulting morphology will move towards the morphology of an optimized structure constrained by a distributed load, meaning that the middle diagonal members move further apart.

The slenderness and height to width ratios were also studied to gain insight in the behavior of the optimization routine when the proportions of the design space change. The separate structure systems that were studied are mathematically speaking closely related. When increasing the width of a beam structure while maintaining a constant height, the geometry will move towards a slab structure. When increasing the height of a slab structure while keeping the width constant the result will be similar to an optimized frame structure. For the intermediate height to width ratios in between the three structure systems no general morphological features were found. Increasing the slenderness, i.e. height to length ratio, of beam and frame structures does not result in new topology. The result of its one-bay counterpart merely gets stretched. However, there are certain limits where further increase of the slenderness will lead to unclear topologies. These limits are mainly determined by the type of supports and type of load that is used. In addition, making a beam or frame structure continuous also does not result in new topology. Here, the result of its one bay counterpart gets copied. The same generalization can be made regarding slabs with high widths.

Mass targets, material choice and the value of the load(s) used have little influence on the resulting topology of an optimized structure, but influence component attributes that mostly deal with size and shape optimization. (Fig. 10) shows two optimized elements with an identical design space and constraints, with a mass target of 20% on the left and 40% on the right.

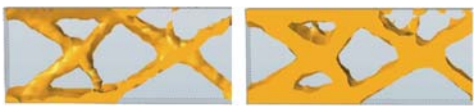

Fig. 10. Influence of alternative mass targets

The relation between structure and form, i.e. the structural morphology, of these optimized elements is very strong. The resulting topology and morphology of an optimization routine is determined by the force distribution through the design space and the different constraints and performance requirements that act on that specific design space. The morphology of an optimized one-bay beam can be recognized in every optimized section active structure system. Many morphological features that apply for an optimized beam structure therefore also apply for frame structures, beam grid systems and slab structures. The production method that is proposed in this paper will therefore be based on an optimized beam structure. The final structure derived of SolidThinking Inspire is a hollow circular beam that conforms to the funicular shapes of inflatable structures, (Fig. 11).

Fig. 11. Optimized circular beam structure

6 PARAGEN RESULTS

The optimized three dimensional beam was used as a basis for the development of the parametric model, which in turn forms the basis for the ParaGen method. The model consisted of 46 nodes, of which 42 were parametric. The nodes were bound to the surface of a hypothetical tube, limiting the number of free variables to 2; the elevation in the x-direction (x) and the angle (α). Compared with a model using 3 free variables, this lead to better output with respect to the proposed production method, and also reduced the necessary computational capacity. In addition, due to computational limitations the model was schematized using linear instead of curved members. The FEA model used a center point load of 50 kN, fixed supports, continuous members with fixed moment connections and the material properties of ASTM A-36 steel. Pipe profiles were used with selected diameter and wall thicknesses resulting from the structural analysis.

With this set up a total population of 1276 individual solutions were created algorithmically and stored in the SQL database. ParaGen optimized for two different fitness functions, i.e. minimal weight and highest modal frequency (stiffness). With the plot function a scatter diagram was created to find the most promising solutions which performed well for both objectives (Fig. 12).

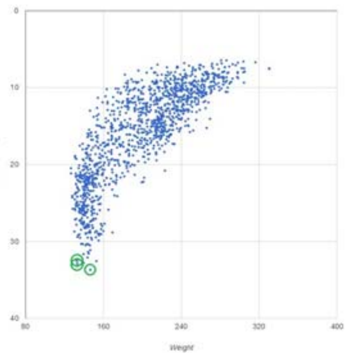

Fig. 12. Scatter diagram for weight vs. stiffness

The three most promising solutions were analyzed according to their morphology and the proposed production method. Solution 1269 was assessed to be the best solution, since it deviated the least form its curved counterpart.

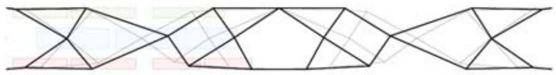

Fig. 13. Solution 1269 with the original parametric model and domain in the background
Fig. 14. 3D image of the prototype of solution 1269

The solution 1269 is also realized with 3D software to indicate the final result of the prototype.

7 RIGIDIZING INFLATABLES

To reduce expenses the models we have made and tested are rigidized with polypropylene fibre concrete. Finally the inflatable core will be rigidized with polymer composites in strings at the outer surface. The rigidization mechanisms with polymer composites developed over the last 50 years, including advanced mechanisms for use in space engineering, is impressive. In 2002 Pronk realized a curved concentric arch consisting of a synthetic matrix of fabrics around an inflatable cured by injecting a thermoset resin [20]. By varying the thickness, direction, structure and material of the fibers a range of E-moduli can be obtained. In the 2002 beam a change in layer composition was introduced in order to be able to produce the arch with the stiffness determined. The use of fibres with the E-module of 210 GPa (210.000 N/mm2, comparable to steel) was used, but turned out not to be sufficient. By adjusting the E-module from 210 GPa to 60 GPa a new stiffness was found (EIy = 5.14 • 1012 Nmm2). This led to the use of carbon fibers at the top and the bottom of the beam section and glass fibers in the other parts. (see Fig. 15).

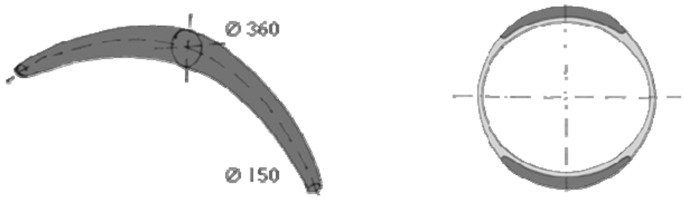

Fig. 15. Curved concentric arch

The form of the membrane is influenced by the curvature and demands to realize slender sections at the ends of the arch. The optimization of this beam was achieved by:

- a combination of different materials within the sections;
- a compensated curvature of the beam before comprehensive loading; and
- variable moments of inertia (Iy) at different sections.

In the 2002 project an inflatable mould has been used to realize this beam. The mould was rigidized with a polymer composite by vacuum infusion. The material properties and production methods of polymer composite match the arch requirements. The advantages of polymer composite are amongst others: rigid and light-weight construction possibilities, fatigue resistance, chemical and corrosion resistance, freedom in design and form and the possibility to integrate parts. Disadvantages are the relatively high cost prices of material, mould, production (labour) and engineering. In the case of complex shapes, for example a conical arch, approximately 50% of the production costs consist of moulding. By using an inflatable mould the moulding costs can be reduced considerably.

A rigidizable inflatable structure can be described as a structure that is flexible when inflated and becomes rigid after exposure to an external influence. After rigidizing it is not necessary to maintain the overpressure. There are several ways to rigidize and new techniques are being researched. They can be divided into three categories: thermosetting composite systems, thermoplastic composite systems and aluminum/polymer laminate system. In the following experiments we focused our research to form optimization. Budget wise we have realized the models with cement bound composites.

8 SCALE MODELS

As a first step in the development of the production method, several different geometries derived using ParaGen were fabricated on a scale of 1:5. The solutions used were the following and represent the criteria which are leading in this research;

- Id:1269 Highest specific stiffness
- Id: 799 Low specific stiffness
- Id: 1249 Lowest deflection
- Id:1259: Highest stiffness

The models were tested using a 5-point bending test to determine the influence of curved members versus linear members. For example, id 1269 has a lower theoretical modal frequency than id 1259. However, id 1259 deviates more from its curved model which is disadvantageous with respect to its stiffness.

8.1 Manufacturing method

The manufacturing method was developed in a way to control the different parameters as much as possible. In this way, the only difference between the models is the geometry. Every geometry was manufactured three times to give significant results. The models were cast in 2 weeks, casting one model per day, and were tested using a 5-point bending test in sets of 3 after 13,14 or 15 days. Also, standardized mortar bars were made with every cast to test inconsistencies in the concrete composition [24]. The low viscosity concrete mixture was as follows;

Table 1: Concrete composition for 10 liters

Material	Amount [Kg]
CEM I 52.5 R	9.5
Limestone flour	3

Glenium 27 con.20%	0.45
Water	2.66
Polypropylene fiber(12mm)	0.114
Sand 0.125 – 0.25	2.144
Sand 0.25 – 0.5	3.369
Sand 0.5 - 1	0.612

The production technique used for the fabrication of the scale models was based on a method described by Dominicus [25] for producing concrete bone structures. The moulds for the concrete beams were constructed of multiple layers of PVC piping. Initially, clamps which represent the inverse of the beam were sawn out of standard PVC pipes with a diameter of 160 mm. Two layers of these clamps were mounted to a PVC pipe of 1.4 meters long. Then, two layers of high tenacity Lycra fabric were pulled over the PVC, followed by a third and final layer of clamps. The mould was then mounted in a steel bracket keeping it in place during the cast, and allowing the model to rotate about its axis to prevent sagging of the uncured concrete. Treaded rod was mounted into the top and bottom ends of the model, allowing every model to be fixed identically in the bending test. Since the model was pinned at the top and bottom of each side, the two form a force couple.

8.2 Results

All the scale models were tested in a 100 kN pressure bench et the van Musschenbroek laboratory at the TU/e campus. The weight of the beams varied between 23 and 33 kg due to member size fluctuations in the moulds. However, the distribution of the material within the model influenced the outcome more than the weight. The results of the mortar bars showed no significant variations with respect to the material density and yield strength. However, the flexural strength of the concrete mixture for id: 1249 was 27% less than the mixture for the other geometries due to the use of a different plasticizer (Glenium 51 con. 35%).

Fig. 15. Mould and falsework for the concrete scale models
Fig. 16. Concrete scale model ID: 1269

ID: 1269 failed in all the beams in the tension zone which runs helically around the beam. This is natural given the properties of concrete, and means that are no clear weak parts in the geometry. In every geometry, the members always fail near the nodes. The structural analysis performed in GSA and Staad PRO showed that stresses are the highest near the nodes due to the fixed moment connections, which explains the crack pattern of the scale models. ID: 1259, and to a lesser extent id: 1249, showed a concentrated crack pattern near the cross members at the supports. The morphology of the members prevents the formation of a stable cross locally, causing the node to fail due to buckling and not because the yield limit of the material is reached. Therefore, large angles between members should be avoided to prevent the nodes from local buckling, and the member length in transverse direction should be minimized.

To determine the stiffness of the four different geometries, the linear elastic region of every beam was determined using trendlines. In this region, according to Hooke's law, the deformation ε is proportional to the force F. All the beams showed this linear behavior until a first crack occurred, which caused the deformation-force diagram to behave unpredictably due to the use of polypropylene fibers. Figure 17 shows the average linear elastic region of the four geometries, where the angle α is used as a measure for the stiffness. This confirms that ID: 1259 indeed has a disadvantageous geometry with respect to curved members, since it was initially optimized for straight linear members. Now, ID:1269, which is also the case for the remainder of the research, has the highest stiffness. It has to be noted that ID:799, which had the lowest theoretical stiffness, is the second stiffest geometry according to these results. This might be due to the theoretical optimization with steel and linear members, while the scale models have curved members and are produced with concrete.

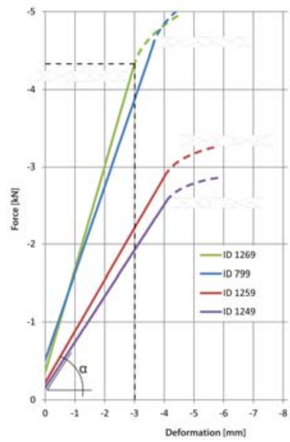

Fig. 17. Average linear elastic regions of the tested geometries

9 CONCLUSION

The aim of this research was to develop and refine new production techniques for producing optimal structures. Optimal structures can be described as a structure with a minimal material use and maximal strength and characterized as an open cell and complex structure. In this research we use different techniques to generate optimal structures, Solidthinking Inspire has been used for topological optimization and ParaGen is used for size and shape optimization. A gap was noticed in this research between the production and generating of optimized stuructures. Traditional framework cannot be used to produce these kind of structure, because of the high amount of material (formwork) and the necessary labour hours. Fabric formwork can provide an alternative. Current traditional fabric formwork is combined with additional (wooden) falsework. In this research we described a process of producing optimal structures without additional falsework by applying rigidizing inflatables. The scale models, we produced with fabric formwork and concrete, showed us, a smooth surface and a high accuracy to the digital models. The scale models are tested with structural analysis programs (Staad PRO and GSA) and physical tests (pressure bench). The digital geometry with the highest stiffness from the structural analysis program, indicates similar results in the physical tests. The combination of structural optimization and production method with rigidized inflatables is promising. Applications of rigidized inflatables are found in contemporary architecture such as emergency relief and military purposes.More research to validate and optimize the production technique is necessary.

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