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LIGHT CONCRETE STRUCTURES

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ABSTRACT

Reinforced concrete (RC) structures are mainly limited to elementary geometries with cubic shapes. The design is often dominated by simple formworks and not with respect to the principle stresses. Thereby, non-necessary material is used resulting in supplementary stresses which must be carried by additional reinforcement. Thus, concrete structures bear a great potential of weight reduction, since the material poses the feasibility of free shaping.

Topology optimization, already used in many engineering fields, is a useful tool for the designing engineer. It helps to design global structures as well as to identify and dimension reinforcement patterns and stiffeners following the flow of stresses. Advanced steered optimization methods integrate material or structural characteristics of the optimized structures. Thereby, the membrane stiffness of shells can be strengthened within the form-finding process or multi-material approaches integrate compressive (concrete) and tensile (steel) behavior within the design of RC structures. These pose the potential to save material costs while ensuring required load-bearing capacity and structural stiffness. In the contribution structural concepts are derived and then transferred to test specimens to show the feasibility. In experimental investigations the load bearing capacity and structural stiffness with weight reduction of approx. 85 % could be demonstrated.

Keywords: Topology optimization; multi-material approach; hybrid structure; steering; UHPFRC

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1. INTRODUCTION

Concrete structures are associated with heavy weight, simple cubic forms and solid cross-sections. They are primarily loaded by their self-weight. Most of the used material is statically not necessary. For example, in tensile zones concrete is only used as a cover to avoid corrosion and secure durability. However, concrete poses the ability of free shaping. Normal strength concrete and simple formworks can be sufficient when inherently robust designs are preferred. But, the use of high-performance concrete and non-corrosive reinforcements offer a wide range of building opportunities. By means of topology optimization [1,2] concrete structures can be designed following the flow of stresses with only the required material, hence with reduced material amounts.

2. TOPOLOGY OPTIMIZATION

Topology optimization varies the distribution of material (by means of a pseudo-density) within a pre-defined design space aiming for stiffness maximization (or compliance minimization, respectively) of the structure subject to a volume constraint [3,4]. For structural engineering, especially for reinforced concrete structures, it can be used as a tool for:

- Global form-finding of structures like shells, arches and truss structures (e. g. [5])
- Design of cross-sections as solid, hollow core or with stiffeners (e.g. [6])
- Local form-finding of reinforcement pattern with sizing (e. g. [7])

The optimization offers the possibility of steering the procedure and thus the computational results by means of penalization. The SIMP (Solid Isotropic Microstructures with Penalization) approach, which is the basis of most topology optimization methods, steers the distribution of material within the design space. Thereby, the material distribution can be controlled to generate a “1-0-design”, which means the design space should only consist of elements with full material (“1”) or no material (“0”). Otherwise, a graded distribution with intermediate densities would result which might not be suitable to identify structures that are appropriate for real executions.

Advanced steering methods integrate specific characteristics of the material or the manufacturing process. Some examples (with particular regard to RC structures) are:

- Prefer compression for structures made predominantly from concrete and penalize tensile areas, and vice versa for a predominantly steel use [8]
- Consider the characteristic material-specific properties of materials, hence penalize concrete in tension-dominated domains, and vice versa, steel in compression-dominated structural members [5]
- Preferring of membrane stiffness while penalizing bending and shear stiffness for shell structures
- Steering of reinforcement patterns to avoid special types of reinforcement (e. g. shear) for less installation efforts [7,9]

This leads to light concrete structures with a direct load transfer and most often an enhanced aesthetic appearance. Nevertheless, most engineering structures are unique. Here, modularization of optimized structures and lean manufacturing methods (already established in mechanical engineering) [10] can be conferred to structural engineering offering serial production of single components for a more simple and effective production.

3. EXAMPLES

3.1. Shells for solar parabolic trough collectors

Parabolic trough collectors focus the incident solar radiation onto line-like absorbers to heat up a heat fluid. In a downstream power block, electricity is gained. Due to high demands on accuracy of the solar concentration, a sufficient stiffness of the shell structures have to be ensured. In recent research projects between the TU Kaiserslautern, Ruhr University Bochum and other industrial as well as research partners slender shell designs have been development, optimized and built [6,11-13] as an alternative to conventional steel framework collectors [14,15].

For further cost savings by means of material reduction, modified approaches for topology optimization have been developed. These ensure robustness by means of the integration of different load cases and, therefore, the expansion of the objective to a weighted sum of the compliance due to the varying load situations [6,16]. Another method is to directly steer the separate stiffness components. For example, shell designs can be generated which prefer membrane stiffness and (numerically) avoid bending and shear stiffnesses. Fig. 1 compares the standard topology approach for a shell (left) with the separated stiffness components of the modified one.

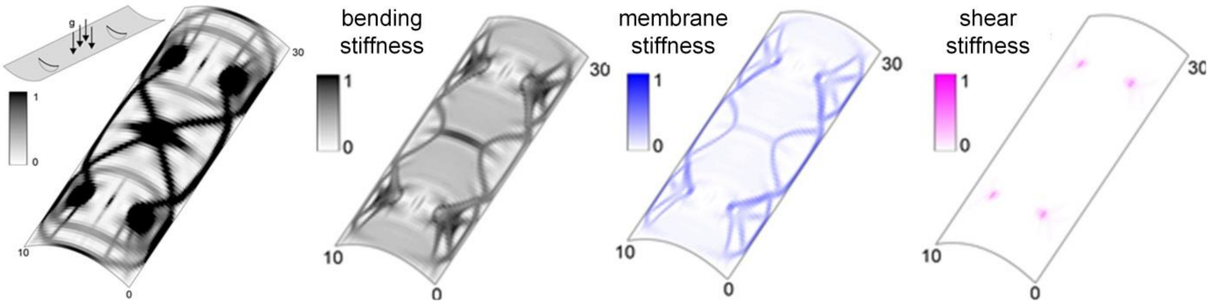

Fig. 1. Density distribution of a shell from standard topology optimization (left) and modified approach with separated stiffness components (right)

3.2. Multi-material tension/compression design

In combination of the 3-phase SIMP approach [2], now including two materials (and void space) with a heuristic enhancement of tension- or compression-only material [5], it is possible to generate structures optimized for RC or hybrids. Thereby, the material specific characteristics of concrete (compression-only) and steel (tension-only) are integrated into the topology optimization process. With the benchmark of a conventional RC beam with a rectangular cross-section in a 4-point bending test, a topological optimized truss structure is derived (Fig. 2). It can be separated into mainly compression struts (blue) and tensile ties (grey), which are transformed into a hybrid truss structure made from ultra-high performance steel fiber reinforced concrete (UHPFRC) for the struts and uncovered structural steel type S355 for the ties. As a result, the RC beam's weight is reduced by approx. 85 %. The aim is to maintain the load bearing capacity as well as the structural stiffness of the RC beam, what could be verified in tests [17].

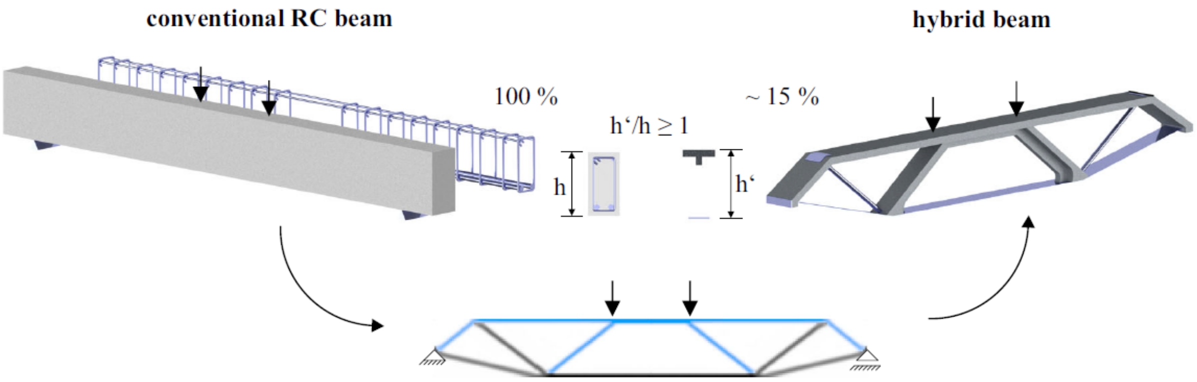

Fig. 2. Transformation of a conventionally reinforced concrete beam to a weight-optimized hybrid concrete-steel beam by means of topology optimization [5]

It could be shown that the majority of the self-weight can be avoided, but there is still a need for further research with respect to demands in robustness, a sufficient safety concept for slender structures and a precise manufacturing.

4. OUTLOOK

Topology optimization has shown the potential for the design of light-weight RC structures. Though they are significantly material-efficient, they often cannot be built economically by means of conventional manufacturing methods. Due to their uniqueness, modularization seems to be an appropriate method for a new manufacturing concept of these structures. Therefore, in the framework of the priority program SPP2187 “Adaptive modularized constructions made in a flux” (www.rub.de/SPP2187) methods for the modularization of structures into similar components made from high-performance materials are investigated. Thereby, the gap between optimized designs and appropriate serial manufacturing methods with enhanced safety concepts will be closed.

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