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Potential of structural multi-objective optimization of reinforced concrete slabs in the context of sustainable development

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Abstract

Reducing material usage and ensuring adequate performance and safety of bearing structures became fundamental aspects of modern engineering design and optimization. Reinforced concrete slabs in multi-storey buildings transfer vertical floor loads and horizontal shear loads to other bearing elements, such as walls, columns, or beams. They provide stability and contribute to overall structural integrity. Especially in large structures with a repeating floor plan over several storeys, material consumption in reinforced concrete slabs can add up quickly. Structural optimization aimed at reducing material usage can provide significant benefits in terms of sustainability and conservation of resources. This paper presents a recommendation for a framework of structural multi-objective optimization (MOO) of storey slabs made of reinforced concrete and highlights the need for efficient use of resources, especially in the context of sustainable development. A case study of the suggested structural MOO-framework is carried out on an existing concrete slab of a large residential building using "*C-SLOP"* (*C*oncrete *SL*ab *OP*timizer), a tool developed for this purpose. Using the case study results as a basis, input parameters for the optimization process were calibrated in order to obtain more realistic results, to consider the structural aspects from the execution phase and to find an optimized design solution. The paper highlights the importance of multi-objective structural optimization of simple common bearing parts, such as reinforced concrete slabs, in early stages of structural design and emphasizes the potential for material savings in the construction industry.

Keywords: parametric modelling, structural multi-objective optimization, reinforced concrete slabs

1. Introduction

Concrete is well known as the most used material in construction industry due to its durability and strength, however its consumption is responsible at least for 8.6% of all anthropogenic CO_2 emissions [1, 2]. Despite its popularity, there is a significant lack of parametrical structural optimization of common bearing parts and elements during the civil engineering planning process [3]. Even though such parametric optimization and decision support (POD) model framework has proven to be very effective to identify potential savings in terms of the economic and environmental resource efficiency of structural objects and buildings at a very early design stage [4] by generating solutions with an aid of multi-objective optimization (MOO) process and investigating them on quantified findings, while still ensuring the strength and safety of the structure [5].

This paper presents a novel pipeline of implementation of structural MOO process into the daily based task of structural engineering, such as design of reinforced concrete storey slabs with repeating floor plan. For this occasion, a tool called *C-SLOP* (*C*oncrete *SL*ab *OP*timizer) has been developed within this research. This paper aims to present the framework of the above-mentioned tool and to emphasize the potential for material savings in the construction industry, especially of common bearing parts and elements. As test case, an already built up real reinforced concrete slab of a large residential building will be examined with *C-SLOP*. In order to find an optimized design solution and to consider the structural aspects from the execution phase, the results of the examined case study were compared with the real results. The examination of deviation between both cases helped to calibrate input parameters for the MOO process and get more realistic results.

2. Framework

The computational framework of *C-SLOP* finds itself within the CAD-Software *Rhinoceros3D* [6]. Its visual programming language *Grasshopper3D* [6] allows the creation of complex parametric algorithms and power them with generative evolutionary solvers, e.g. Octopus [7], which was used within *C-SLOP*´s framework described in following chapters. The finite element analysis (FEA) is performed with an aid of Grasshopper´s plugin *Karamba3D* [8].

2.1. Structural FE model and analysis

The structural model is represented by the 2D finite element (FE), located parallel to the cartesian XY-plane, whereby the height (Z-coordinate) can be chosen freely by the user. Within the slab geometry, the slab openings can also be defined (e.g., lift shaft, infrastructure shaft etc.). Fig. 1(a). exemplarily depicts a slab geometry with opening and line support definition in *C-SLOP*. The walls are represented by line support definition along the wall-slab connection. The line support definition includes free degree of freedom (DOF) for rotation around local x-axis and translation perpendicular to wall-slab connection line (local y-axis). The translation along global Z-axis and along local x-axis of the connection is rigid. Fig. 1(b) depicts the described line support connection at the reference FE surface of the slab.

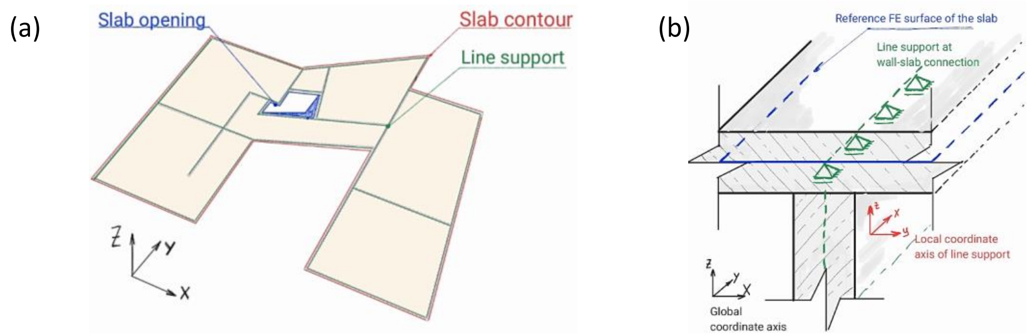

Fig. 1. (a) Slab geometry with openings and line supports; (b) wall-slab connection.

Within the process of the structural analysis of reinforced concrete slabs, it´s significant to consider the load distribution along the whole slab´s geometry. Thus, the slab is normally separated into individual sections, so called *fields*. This separation allows to apply different loads and their combination independently on every slab field. As also envisaged by the standards and codes, it´s mandatory to consider all possible (advantageous and disadvantageous) load combinations scenarios in structural analysis due to their effects on the structural performance. Thus, some loads can act in different directions and partially cancel other loads (advantageous). Disadvantageous loads act accordingly in the same direction and produce grater level of stress and deflection. Building codes and standards, such as Eurocode, address this problem with so called safety factors $\gamma_{G,dis}$, $\gamma_{G,adv}$ for permanent and $\gamma_{Q,dis}$, $\gamma_{Q,adv}$ for variable loads. Fig. 2(a) depicts a possible contribution of the field in a slab. The application of different load combination scenarios for this exemplary field distribution is shown in Fig. 2(b).

Structural analysis is performed for all possible load combinations in ultimate and serviceability limit states (ULS & SLS). The long-term deflection of the slab, which includes the effects of creep and dwindle of concrete, is calculated in SLS quasi-permanent.

As a part of structural analysis, the required amount of steel reinforcement per layer and direction is calculated with the *Karamba3D´s* component "*Optimize Reinforcement"* [9], based on the sandwich model approach of Marti [10, 11]. However, this approach doesn´t cover the amount of needed overlap, edge, and connection reinforcement.

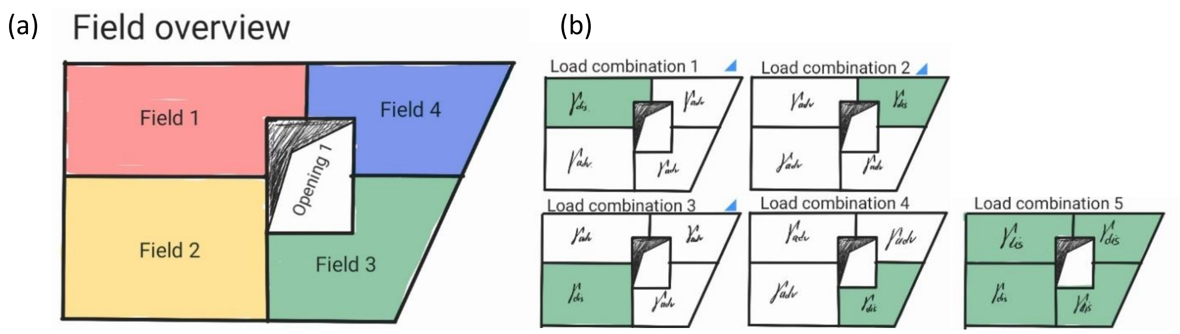

Fig. 2. (a) Slab field overview; (b) Different load combinations on slab fields.

2.2. Optimization

As mentioned before, the novel approach of MOO is used within the described framework. Variable inputs in *C-SLOP* are listed in Table 1.

Table 1. Input parameter of the test case

Name	Description
Variables:	
Concrete sort	C20/25, C25/30, C30/37, C35/45, C40/50, C50/60
Slab thickness	18cm, 19cm, 20cm, 21cm, 22cm, 23cm, …, 60cm
1st bottom main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
2nd bottom main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
1st upper main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
2nd upper main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
Goals:	
Minimization of used concrete mass	Reduction of environmental and cost impact
Minimization of used steel reinforcement mass ($A_{s,total}$ in Fig. 3)	Reduction of environmental and cost impact
Deterioration of concrete sort	Reduction of environmental and cost impact
Maximization of the step of rebars in the main grid	Minimization of time effort in reinforcing process

* Only standard-complaint reinforcement grids are considered. It means, that only main grids with provided amount of reinforcement $A_{s,prov,main}$ greater than the minimal required amount of reinforcement $A_{s,req,min}$ acc. to Eurocode 2 [12, 13] are used as variables in MOO-process. This approach allows to consider all possible variants of structure, where the usage of heavier main grid could lead to smaller usage of additional reinforcement $A_{s,req,add}$ and overall used steel reinforcement material $A_{s,total} = A_{s,prov,main} + A_{s,req,add} + A_{s,constr}$. Constructive reinforcement $A_{s,constr}$ describes edge, lap joints and connection reinforcement. Fig. 3 depicts other above-mentioned definitions of steel reinforcement amount (exemplary on two-fielded slab strip spanned in one direction).

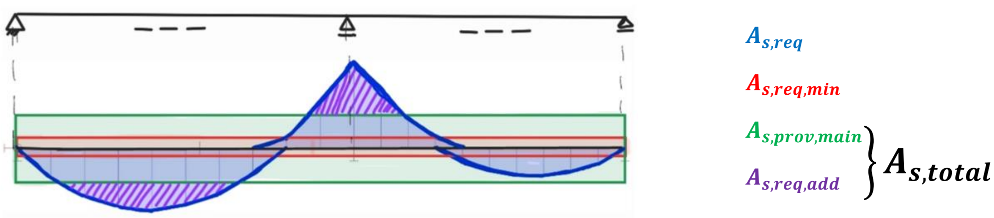

Fig. 3. Definition of the steel reinforcement amounts.

The SLS-criteria in characteristic (initial deflection) and quasi-permanent (long-term deflection) according to Eurocode 2 take role as constraints during the MOO-process.

3. Test case

As already mentioned before, the test case study is applied to already built-up residential project. It contains a concrete floor slab with 10 repeating storeys. The dimensions of the structural FE-model are depicted in Fig. 4.

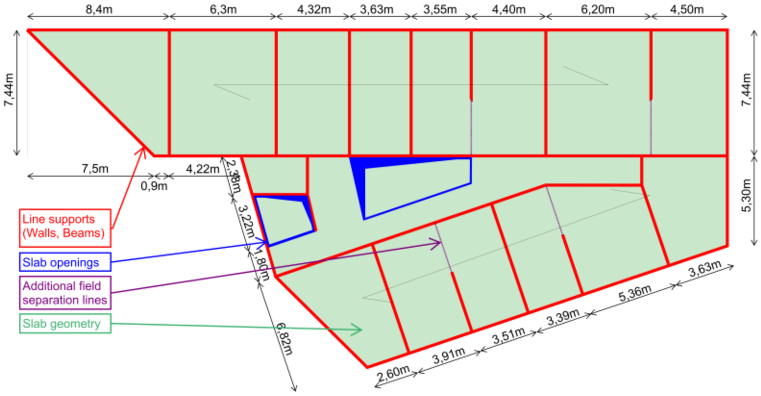

Fig. 4. Dimensions of the structural FE-model of the test case slab geometry

Generative structural multi-objective optimization took place with the input data and load definition listed in Table 2. The local axis of the reinforcement direction is aligned in such way, that the shortest span length of the field represents the direction of the 1st rebar layer. The 2nd rebar layer is located crosswise.

Table 2. Input parameter of the test case

Name	Description
Variables:	
Range of applied concrete sort	C25/30, C30/37, C35/45, C40/50, C45/55, C50/60
Range of applied slab thickness	18cm, 19cm, 20cm, 21cm, 22cm, 23cm, …, 40cm
Range of applied amount of reinforcement steel as the main grid $A_{s,prov,main}$	Minimal standard acceptable main grid, …, Ø20/15
Constant values:	
Steel sort of the reinforcement	B550B acc. To Eurocode 2 [14, 15]
Loads:	
Self-weight	Self-weight of the structure is calculated automatically within the FE-Analysis of Karamba3D
Dead load	Areal load 2,50 kN/m², permanent loads
Payloads	Areal load 3,00 kN/m², variable loads
FE-mesh resolution	~0,25 meter
MOO-parameters:	
Elitism	0.500
Mutation probability	0.200
Crossover rate	0.800
Population size	100
Maximal generations	20

4. Results

Due to competing properties of possible optimal solutions, no overall optimal variant of the structure can be found. Therefore, the so called pareto front is examined and compared. Pareto solution of the test case are listed in Table 3 and depicted in Fig. 5 with the dependence on concrete sort (*CS*), slab thickness $h\ [cm]$, 1st upper rebar layer (*1+*), 2nd upper rebar layer (*2+*), 2nd button rebar layer (*2-*) and 1st button rebar layer (*1-*).

Table 3. Input parameter of the test case

CS_h_*1+_2+_2-_1-*	Needed concrete mass [kg] and [% from the lowest]		Needed steel mass [kg] and [% from the lowest]	
C25/30_18_*Ø8/23_Ø8/23_Ø8/23_Ø8/23*	225587	100%	4115	100%
C25/30_18_*Ø8/23_Ø8/23_Ø8/22_Ø8/23*	225587	100%	4149	101%
C25/30_18_*Ø10/25_Ø8/23_Ø8/23_Ø8/23*	225587	100%	4520	110%
C25/30_18_*Ø10/25_Ø8/23_Ø10/25_Ø8/23*	225587	100%	4880	119%
C45/55_18_*Ø12/24_Ø12/25_Ø10/25_Ø10/25*	225587	100%	7229	176%
C45/55_18_*Ø12/24_Ø12/23_Ø10/25_Ø10/25*	225587	100%	7438	181%
C35/45_19_*Ø10/25_Ø10/23_Ø10/24_Ø10/25*	238120	106%	5936	144%
C30/37_19_*Ø10/25_Ø14/25_Ø14/22_Ø12/25*	238120	106%	9494	231%
C30/37_21_*Ø10/25_Ø10/23_Ø10/24_Ø10/25*	263185	117%	5925	144%
C25/30_24_*Ø10/24_Ø10/25_Ø10/25_Ø10/25*	300783	133%	5789	141%

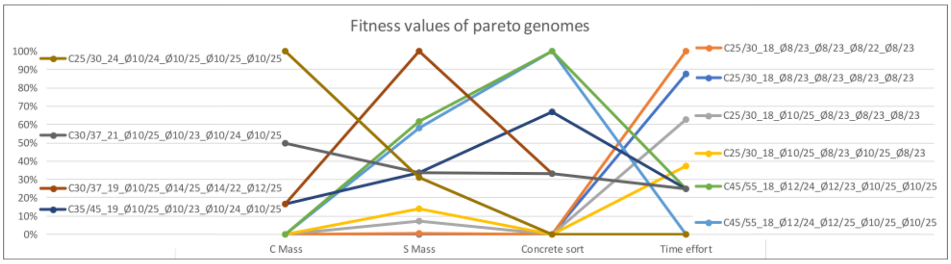

Fig. 5. Fitness values of pareto genomes

Due to small differences in the rebar step (from 22cm to 25cm) and accumulating time effort, one can neglect this objective. Based on this accusation, one variant may be chosen as optimal and be used for further analysis – the slab with C25/30 concrete sort and 18 [cm] slab thickness. This variant is compared to the existing slab which is build out of C25/30 concrete sort with 20 [cm] thickness. For more realistic comparison of overall used mass of reinforcement steel, reinforcement plans of the *C25/30_18* slab are created with the consideration of *edge, overlap, and connection reinforcement*. This variant is called *C25/30_18_realistic* in the further comparison which is listed in Table 4.

Table 4. Comparison of the already built-up slab *C25/30_20*, optimal solution of C-SLOP *C25/30_18* and practical variant of the optimum *C25/30_18_realistic*.

Name	Concrete volume [m³]	Mass of used reinforcement steel [kg]	Degree of reinforcement [kg/m³]
Built-up *C25/30_20*	109,3	6630	60,7
Optimum of the test case *C25/30_18*	98,37	4115	41,8
Realistically designed *C25/30_18_realisitc*	98,37	6627	67,4

5. Conclusion

The primary objective of the research presented in this paper is to introduce a novel methodology for the optimization of reinforced concrete slabs using the developed tool *C-SLOP* (*C*oncrete *SL*ab *OP*timizer). The tool is aided by parametric modelling, structural finite element analysis and multi-objective optimization. To prove its functionality, a test case was conducted on an already built-up concrete slab with repeating floor plans. The results of the optimization process were analyzed and lead to following conclusions:

- Comparing the thickness of existing and optimized slab, one may have reduced it from 20 cm to 18 cm without higher reinforcement effort (see also Table 4). Such reduction in thickness of the slab could have led to significant lower environmental and price impacts due to material saving, considering the repeating geometry of the slab over 10 storeys of the building (almost 11 m³ concrete per slab and 110 m³ in total).

- However, the calculated needed amount of reinforce steel is significantly lower than the realistically imitated structurally designed model of the same slab with 18 cm thickness. This discrepancy occurs due to the lacking functionality (consideration of overlap, edge, and connection reinforcement) of used framework for the calculation of the needed rebar amount. Therefore, the actual amount of steel required for the optimized slab geometry is 61% higher than the calculated one (6627 kg to 4115 kg).
- The case study has estimated that the difference in the rebar step between all pareto optimal solutions is not significant for this exact slab geometry (see also Fig. 4).

Summarized, the *C-SLOP* tool could potentially lead to substantial material savings and lower environmental impact providing several possible solutions and establishing the range for decision making support. However, further research is needed to improve tool´s functionality regarding more precise output for amount of reinforced steel. Occasionally, the computational framework of *C-SLOP* may be included in common structural FE software and become an everyday habit in the design process.

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