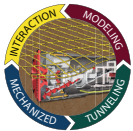


Mario J. Smarslik

# Optimization-based design of structural concrete using hybrid reinforcements



SFB 837  
Interaction Modeling in  
Mechanized Tunneling

Schriftenreihe des Instituts für  
Konstruktiven Ingenieurbau, Heft 2020-01

**RUHR  
UNIVERSITÄT  
BOCHUM**

**RUB**

# **Optimization-based design of structural concrete using hybrid reinforcements**

by

**Dipl.-Ing. Mario J. Smarslik**

**Dissertation**

for the degree

**Doctor of Engineering (Dr.-Ing.)**

**Faculty of Civil and Environmental Engineering  
Ruhr-Universität Bochum**

Bochum, August 2019



Schriftenreihe des Instituts für Konstruktiven Ingenieurbau

Herausgeber:  
Geschäftsführender Direktor des  
Instituts für Konstruktiven Ingenieurbau  
Ruhr-Universität Bochum

Heft 2020-1

**Mario J. Smarslik**

**Optimization-based design of structural concrete  
using hybrid reinforcements**

Shaker Verlag  
Düren 2020

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Bochum, Univ., Diss., 2019

Copyright Shaker Verlag 2020

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-7257-0

ISSN 1614-4384

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: [www.shaker.de](http://www.shaker.de) • e-mail: [info@shaker.de](mailto:info@shaker.de)

For my loved ones.



---

# Abstract

---

Optimization methods are applied to a variety of problems in engineering disciplines. In structural engineering, however, most constructions have a unique character, and optimization hence remains only sparingly used. In addition to other approaches, topology optimization carries excellent potential for the application to structural engineering problems. By providing information on where to place or remove material within a prescribed design domain, topology optimization can assist engineers at different levels of the design process. The more practice-oriented works in this field either focus on generating qualitative design suggestions, which still require manual post-processing, or resort to simplified calculation models, which inadequately describe the behavior of reinforced concrete.

The main objective of this thesis is to make topology optimization more readily available for practical application in structural engineering and to fully integrate it into the design process in order to provide reliable, qualitatively and quantitatively ready-to-use reinforced concrete (*RC*) concepts. To achieve this goal, this thesis is divided into two main parts.

The first part focuses on the development of a topology optimization approach tailored to *RC* design. This approach is based on combined truss–continuum topology optimization (*TCTO*), which couples continuum- and truss elements in a single analysis model. Trusses are associated with steel, whereas continua represent the concrete matrix by employing a bilinear material model and hence offer an appropriate representation of *RC*. A new *Optimality Criteria*-based solution strategy is deduced to improve the usability of *TCTO*. By employing this new solution strategy, a numerical study is able to identify the application limits of the most relevant input parameters, which serve as the basis of practical recommendations for generating accurate optimization results that follow engineering theory. Building upon these results, *TCTO* is further advanced to facilitate the consideration of steel fiber- and hybrid steel fiber–rebar reinforcements as well as robust multi-load optimization by including exclusive load case combinations.

The second part of the thesis is devoted to the practical application and experimental validation of the newly devised quantitative optimization methodology at the example of segmental lining longitudinal joints. The experimental analyses comprise four individual series, which focus on the enhancement of the joint by employing various reinforcement- and material concepts: low-deformation, welded rebar cages; steel fibers with and without modification of their orientation; hybrid steel fiber–rebar configurations;



and hybrid material schemes that combine standard materials and localized, high-performance steel fiber-reinforced concrete additions in sensitive areas. The results provide several insights into both the load-bearing behavior of concrete elements under partial area strip loading as well as segmental lining longitudinal joints, which are transferred into practical design recommendations.

---

# Acknowledgements

---

This thesis presents the main result of my research work conducted in the scope of the German Research Foundation (DFG) funded Collaborative Research Center SFB 837 "Interaction Modeling in Mechanized Tunneling" at the Institute of Concrete Structures of the Ruhr-Universität Bochum during the years 2015 to 2019.

First of all, I would like to express my gratitude to Prof. Dr.-Ing. habil. Peter Mark for providing me with the opportunity to work at his institute and for his continuous guidance, encouragement, and support. Thank you to Univ.-Prof. Dr.-Ing. Rolf Breitenbücher for our always enriching cooperation within the SFB and for being my second referee. And thanks to Prof. Dr.-Ing. Martin Radenberg for chairing the examination committee.

Thank you to all of my colleagues at the Institute of Concrete Structures and the SFB for a great work environment and teamwork. A special mention goes out to Georgios, Sylvia, Gisela, and Alex for their technical and organizational support in completing this thesis. I especially want to thank my officemate and friend Dr.-Ing. Markus Obel for all the fruitful technical discussions, his positive influence, and the fun time we shared.

Lastly, I would like to thank my loved ones. My mom and dad for doing everything in their power to provide me with the right tool-set for life and for making me the person I am today. My brother, Patrick, for being a great man who I can always count on. My daughter Enie, for showing me what's more to life. And above all, I thank my soon-to-be wife, Irma. For sharing all the ups and downs, for always having my back, for being a loving mother and a great partner in life. I couldn't have done it without you.

Essen Katernberg, February 2020

Mario J. Smarslik

Date of submission: August 22<sup>nd</sup>, 2019

Date of oral examination: December 18<sup>th</sup>, 2019

Referees: Prof. Dr.-Ing. habil. Peter Mark, Ruhr-Universität Bochum  
Univ.-Prof. Dr.-Ing. Rolf Breitenbücher, Ruhr-Universität Bochum  
Prof. Dr.-Ing. Martin Radenberg, Ruhr-Universität Bochum



---

# Contents

---

<b>Abstract</b>	<b>iii</b>
<b>Acknowledgements</b>	<b>v</b>
<b>Contents</b>	<b>vii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background and motivation . . . . .	1
1.2 Research objectives . . . . .	2
1.3 Thesis structure and overview . . . . .	3
<b>2 Design aspects of segmental linings</b>	<b>7</b>
2.1 General introduction to mechanized tunneling . . . . .	8
2.1.1 Loading conditions and calculation models . . . . .	11
2.1.2 Design guidelines . . . . .	13
2.2 Longitudinal joint design . . . . .	14
2.3 Partial area loading . . . . .	17
2.3.1 Compressive yield strength . . . . .	21
2.3.2 Splitting forces . . . . .	25
2.4 Steel fiber-reinforced concrete . . . . .	28
2.4.1 Mechanical properties . . . . .	29
2.4.2 Design guidelines . . . . .	33
2.4.3 Classification . . . . .	34
2.4.4 SFRC under partial area loading . . . . .	38
2.5 Hybrid reinforcement approaches for segmental linings . . . . .	39
<b>3 Selected principles of structural optimization</b>	<b>41</b>
3.1 Structural optimization approaches . . . . .	42
3.2 Optimization model - general optimization terminology and definition . . . . .	44

3.3	Problem classification and solution strategies . . . . .	45
3.3.1	Optimality Criteria . . . . .	47
3.3.2	Penalty function methods . . . . .	47
3.3.3	Approximation methods . . . . .	47
3.3.4	Direct methods . . . . .	48
3.4	Sensitivity analysis . . . . .	49
3.5	Analysis model . . . . .	49
3.5.1	Fundamentals of linear-elastic continua . . . . .	49
3.5.2	Finite Element Method . . . . .	51
<b>4</b>	<b>Basics of topology optimization</b> . . . . .	<b>57</b>
4.1	Truss topology optimization . . . . .	59
4.1.1	Basic problem formulations and application considerations . . . . .	61
4.2	Continuum topology optimization . . . . .	63
4.2.1	Basic problem formulations . . . . .	64
4.2.2	Numerical issues and mitigation strategies . . . . .	66
4.2.3	Application considerations . . . . .	71
4.3	Combined truss-continuum topology optimization . . . . .	72
4.3.1	Basic problem formulation . . . . .	74
4.3.2	Bilinear constitutive model . . . . .	75
4.3.3	Solution strategies and application considerations . . . . .	77
4.4	Topology optimization in practical design . . . . .	79
4.4.1	Stress-dependent material properties . . . . .	79
4.4.2	Practical reinforced concrete design . . . . .	80
4.4.3	Conceptual architecture . . . . .	82
<b>5</b>	<b>Development of an optimization-based design approach</b> . . . . .	<b>83</b>
5.1	Lagrange-based <i>Optimality Criteria</i> for <i>TCTO</i> . . . . .	84
5.2	Algorithm verification and efficiency evaluation . . . . .	86
5.3	Qualitative assessment of optimized material layouts . . . . .	91
5.3.1	Initial stiffness relation and volume restriction . . . . .	91
5.3.2	Connectivity . . . . .	95
5.3.3	Penalization . . . . .	97
5.4	Quantitative reinforcement design . . . . .	99
5.4.1	Theoretical validation and assessment of truss axial forces . . . . .	99
5.4.2	Truss-continuum stiffness ratio adjustment . . . . .	101
5.4.3	Volume constraint separation . . . . .	103
5.4.4	Practical recommendations . . . . .	103
5.4.5	Truss layout simplification . . . . .	105
5.4.6	Steel fiber- and hybrid reinforcements . . . . .	109

5.5 Modified multi-load optimization . . . . . 112

**6 Experimental investigation of hybrid longitudinal joint designs 119**

6.1 Materials . . . . . 121

6.1.1 Concrete . . . . . 121

6.1.2 Reinforcement . . . . . 123

6.2 General test-setup and instrumentation . . . . . 125

6.3 Experimental programs and results . . . . . 128

6.3.1 Series 1: Welded rebar . . . . . 129

6.3.2 Series 2: Oriented steel fibers . . . . . 134

6.3.3 Series 3: Hybrid reinforcements . . . . . 142

6.3.4 Series 4: Localized high-performance materials . . . . . 151

6.4 General synopsis and practical design recommendations . . . . . 161

**7 Conclusions 165**

**Bibliography 169**

**A Optimization solution strategies 193**

**B Supplemental experimental data: materials 201**

**C Supplemental experimental data: specimens 207**