Received: 23 September 2022 | Revised: 5 December 2022 | Accepted: 31 December 2022

DOI: 10.1002/eng2.12632

RESEARCH ARTICLE

Engineering Reports Open Access WILEY

CAD-integrated parametric modular construction design

Tobias Teschemacher[1,2] | **Kai-Uwe Bletzinger**[1]

[1]Chair of Structural Analysis, Technical University of Munich, Munich, Bavaria, Germany

[2]School of Engineering, The University of Queensland, St Lucia, Queensland, Australia

Correspondence
Tobias Teschemacher, Chair of Structural Analysis, Technical University of Munich, Munich, Bavaria, Germany.
Email: tobias.teschemacher@tum.de

Funding information
Deutsche Forschungsgemeinschaft, Grant/Award Numbers: BL306/34-1, SPP 2187

Abstract

This publication presents a novel CAD-integrated avenue for structural analyses of modular constructions, by applying the isogeometric analysis. The approach relies on trimming of segments from an original geometry and allows accordingly to introduce kinematics at the interfaces and to assess the connections of the parametrically defined modules. The proposed research is presented along some exemplary structures.

KEYWORDS

construction stages, isogeometric analysis, module construction, parametric design

1 | INTRODUCTION

Modular building, referring to off-site prefabricated construction modules, has arisen as a significant field within civil engineering as it comes along with superiority. Among others, some advantages are: faster on-site construction with an improved scheduling, better quality, reduced amount of recourses and waste,[1-3] and thusly mostly more economical.[4] On the other end, modular construction is mostly tied to the availability of segments and the limitations of inter-module connections. An accurate structural analysis is therefore required to gain an understanding of the possibilities with respective modules.

For modular construction mostly two design avenues are applied: bottom-up and top-down.[5,6] While bottom-up is using available segments to build up an entire structure or building, top-down is mostly referring to the split of the structure in smaller modules. Those may be repetitive or unique.[7,8] The latter avenue typically allows more variety in shapes, however, needs more involved production, which often demands methods such as 3D printing.[9-11]

The structural assessments of prefabrication structures shall cover the overall strength. From this point the estimation of contact forces between segments may be processed. Additionally, the simulation of possible construction stages to avoid failure and minimize necessities of casts is an important criteria within the design process. Even though, bottom-up or top-down would interfere with the feasible solutions, the structural analyses processes may be similar.

Simultaneously to the advents of prefabrication in construction, the usage of building information modeling (BIM) has emerged significantly.[12,13] BIM appears to be tailored for modular construction as most of the apparent tools can deal efficiently with repeating objects or segments, which enables a fast, but sophisticated design and planning of modular buildings. The definition and specific extensions of BIM yet varies broadly, however, generically it stands for the unification of processes with the aid of digital tools. Within this scope BIM shall cover the design towards the geometrical expression, which results in models known from computer-aided design (CAD).

Within the design, involving standard procedures or BIM, parametric design has grown into a powerful methodology as it allows a repetitive but parameter-dependent design. In architecture, those parameters can mostly be the dimensions of various extensions but frequently it is also applied to the number of repetitive objects within a large framework. In modular building design, apart from the overall dimensions, the introduced parameters may represent the chosen patterns coming from available segments or different constraints, such as limitations of transport. A famous parametric design tool is *Grasshopper*,[14] a plugin known from Reference 15. The result of the application of the graphical parameter-based programming within *Grasshopper* is primarily a CAD model. This model shall constitute the basis for the structural analyses.

The isogeometric analysis (IGA),[16] is a finite element method that makes direct use of the CAD provided shape descriptions. Thus, it shapes perfectly within the application in the parametric CAD design environment. The plugin *Cocodrilo*[17,18] has been developed to specifically enable the simulation of IGA within *Grasshopper*.

To emerge facilities for a structural assessment of modular construction a novel digital methodology, which covers the possibilities of parametric design along the usage of IGA is presented within this publication. This enables to introduce kinematics between the continuously described modules. Furthermore, the parametric environment allows the advanced coupling of various approaches.

2 | PARAMETRIC CAD-INTEGRATED ANALYSIS OF MODULAR STRUCTURES

Within this section shall be proposed a novel avenue which enables a segmented analysis of structures, which are directly derived from the CAD-provided geometry description.

2.1 | B-Rep CAD model

Boundary representation (B-Rep) is probably the most famous approach in expressing geometrical shapes within CAD. It described the objects by its spatial delineations, called boundaries. This means solids are described by their outlining surfaces. Those have each wise a shape which itself is bounded by a finite set of curves. Curves do have a form and starting and end points. This approach allows to efficiently describe complex geometries. However, up-to-date it limits the analysis to 2D-based structures, such as shells[19-21] or membranes.[22] Therefore, in this scope only shell structures shall be considered for the simulation.

2.2 | Isogeometric analysis (IGA)

IGA has been introduced in 2005 by Hughes et al.[16] with the goal to bridge the gap between CAD and numerical simulation by applying non uniform rational B-splines (NURBS) within the finite element description. Since then the method has experienced a massive development. Initially, the numerical approach was relying on the natural shape descriptions of NURBS. Hence, Breitenberger et al.[23] has enhanced the method by the application of trimmed multipatches to cope with a larger spectrum of CAD models (see Section 2.1). Within Reference 24 are introduced required interfaces from CAD to various numerical solvers.

2.3 | Structural segmentation within IGA

Consequently, the geometrical description shall be obtained from CAD, as described within Figure 1. From this description is trimmed a set of modules with either a structured or an unstructured pattern. The trimming curves (C_{module}) need to be mapped onto the surface description[*]. Those obtained trimmed surfaces are considering duplicated control points (exemplary presented in blue within Figure 1) from the original shape to avoid an influencing geometry description. Thus, the resulting domains are independent and the control point deflections, which are generally non-local would not affect the neighboring segments.

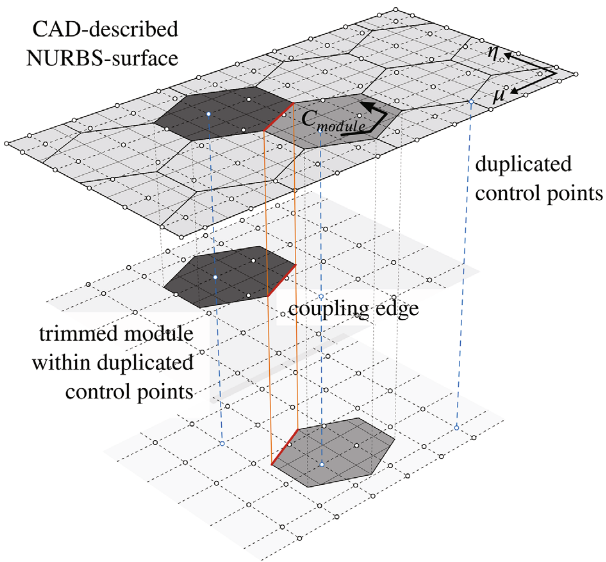

FIGURE 1 Exemplary segment selection with corresponding interfaces.

Those independent surfaces are being coupled at their intersecting edge. This requires the introduction of weak formulations such as the penalty-approach.[23-25] Alternatives would be the Lagrange multiplier method,[24,26] the Nitsche method[26] or Mortar methods.[27,28] Within this research, the focus is kept on the penalty approach even though it is dependent upon a user chosen penalty factor and introduces a model error in the solution. Within the coupling, the physical properties of the segment interfaces should be considered. Accordingly, either displacements are coupled, or eventually moments if it is considered as a clamped connection. Also a direction dependent support may be possible, like a support which is only active within compressive direction.[29] Furthermore, a damage formulation such as cracking at the interface would be imaginable for future application.

The described duplication of domains ensures that additional kinematics may be introduced within the structure. Thusly, eventual kinematic and therefore failing systems introduced through non-beneficial coupling interfaces may be detected by the simulation.

2.4 | Modular parametric design path

The proposed modular design process shall be structured as following:

(i) Design is CAD specific. The employed parameters may be geometrical extensions, however, no structural properties.
   a. Pre-structural analysis may be performed. This is advantageous to check the overall performance of the chosen structural shapes. Simulations on the entire system are generally computationally cheaper and may have less complexity, which allows a better validation of the solution.
   b. Shape optimization may be performed on the structure to gain a better structural performance. This could be done at any stage with varying outcomes.

(ii) Consequently, the selection of the patterning is performed. This is selected upon availability of design criteria.
   a. Structured patterns do generally imply the bottom-up procedure, as here, the pattern may be selected upon available modules. This does not imply if the chosen geometry is irregular, which would be the case for most form found shapes.
   b. Unstructured or free form patterns are habitually a sign for top-down design approaches. Here, kinematic criteria or fabrication limits may be taken into consideration.

(iii) The merge between geometrical shapes and selected pattern, applied with the operations from Section 2.3. This shall be the stage for further structural assessments. It shall be noted that if the original design is not regular or distorted,

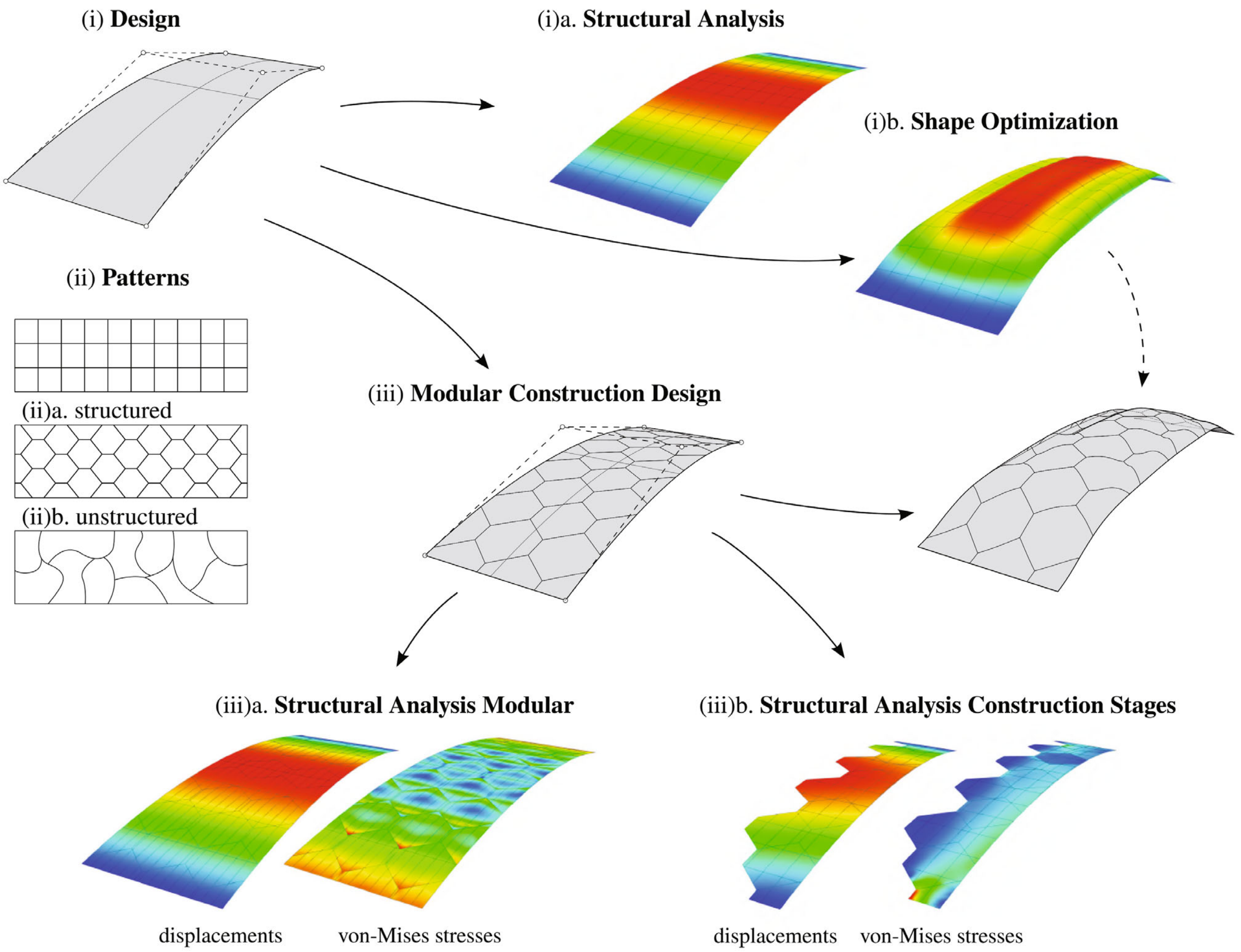

FIGURE 2 Modular construction design path.

as in the case of the shape optimized structure, then even regular modules would result in modules with special shape. This would be contradictory to the bottom-up procedure.

a. Simulation on the modules.
b. Separate assembly of a certain amount of modules. The importance of this simulation is to estimate the load carrying behavior and the maximum expected stresses and moments.

Within Figure 3 is displayed an eventual setup of the described design path within *Grasshopper* and *Cocodrilo*.[17,18] It shows the respective blocks and numbering from Figure 2 and their relation within the analyses.

3 | EXAMPLES

In this section shall be presented two examples. One is examining the numerical features of the additional kinematics which are enhanced between the patches (see Section 3.1). The second example is showing the matureness of this CAD-integrated approach within a staged analysis (see Section 3.2). Therefore, this problem contains one initial form finding and then a modularized structural analysis.

3.1 | Bending beam

Within the primal example a simply supported bending beam under constant load shall be examined. Once within a continuous domain and second in a patterned setup. The problem description can be found within Figure 4. If a structured

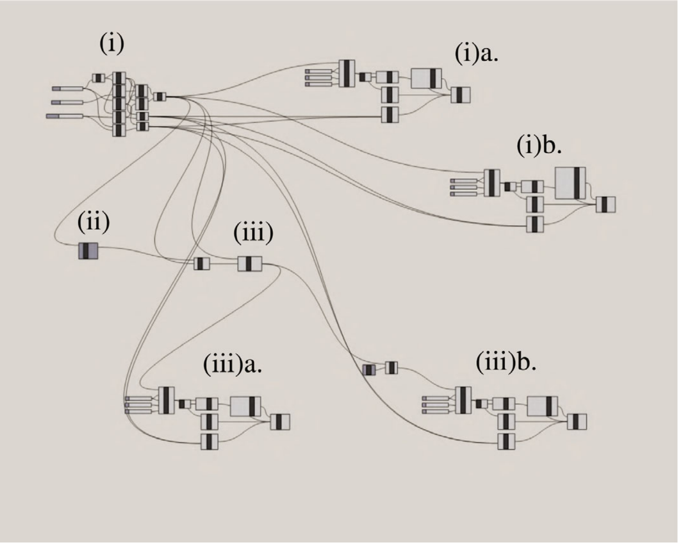

FIGURE 3 *Grasshopper* framework for the simulation of various stages in the design process.

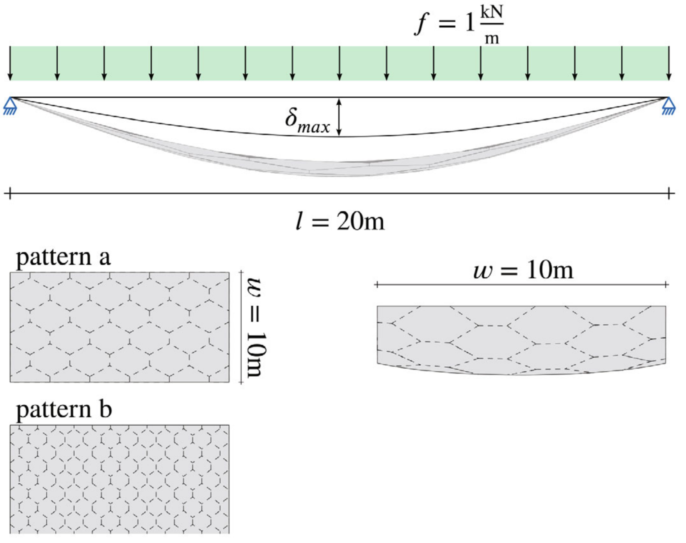

FIGURE 4 Bending beam problem.

patterning would be applied, the system would not be solvable, as it would be under-constraint and would contain an open kinematic system. Therefore, the example is studied with hexagonal modules.

The maximal deflection at the middle of the beam is being defined as:

$$\delta_{\max} = \frac{5 \cdot f \cdot l^4}{384 \cdot \mathrm{E\,I}} = \frac{5 \cdot 10 \frac{\text{kN m}}{\text{m}} \cdot (20\ \text{m})^4}{384 \cdot 30 \times 10^6 \frac{\text{kN}}{\text{m}^2} \frac{10\ \ \text{m} \cdot (1\ \ \text{m})^3}{12}} = 8.333 \times 10^{-4}\ \ \text{m}\ . \tag{1}$$

The continuous analysis contains the same deflection as the expected result, while the analysis with the patterned problem is containing significant larger deflections. The maximum displacement in the modularized system with pattern a is 2.1235×10^{-3} m. This is more than twice as the deflections from the original system. That proves that the additional kinematics between the modules do have an impact on the results. Within Figure 4 are displayed the deflections with a scaling of 2×10^3. In Figure 5 are presented the result plots of the respective displacements within the beam. Two

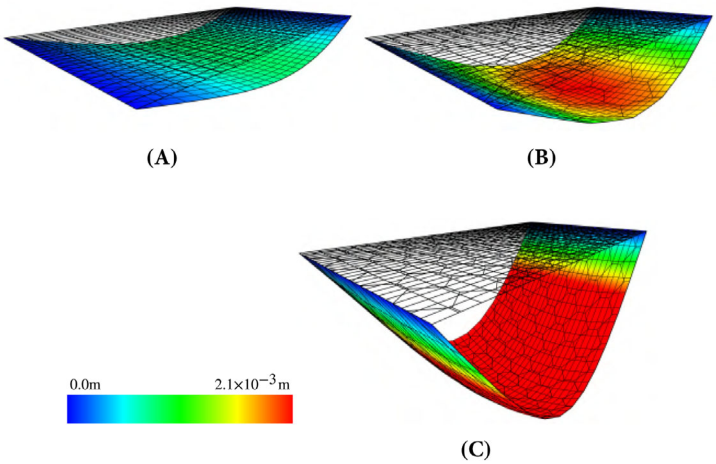

FIGURE 5 Deflections of bending beam problem. (A) Continuous; (B) pattern a; (C) pattern b

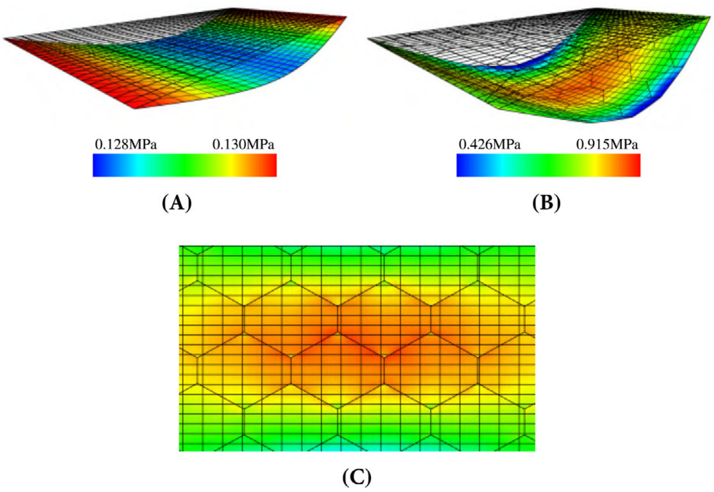

FIGURE 6 Stresses within the bending beam problem. (A) Continuous; (B) patterned; (C) patterned zoom

aspects are important to be observed for this problem. Once the deflections are significantly higher. Second, the problem is not purely 1D as it gains an additional dimension in the deflections throughout the width with the highest deformations being in the center of the beam. Considering pattern b with 113 modules, an even larger deflection of the entire problem can be observed (see Figure 5C). The maximal deflections in this structure are 5.1259×10^{-3} m, being more than 2 times the deflections from pattern a. This is the outcome of the many additional discontinuities in G^1 within the system.

Additionally, the internal stresses shall be examined. In the continuous system, those are obviously considerably constant throughout the structure. However, within the patterned beam, those are generally larger, specifically in the center of the beam. Furthermore, within Figure 6C is presented a zoomed section from the middle of the beam. One can see that the stresses at the corners of each module become significantly higher than in the remaining domains. This is expected as the additionally allowed kinematics at the edges would result in over-constraints and therefore interact with the connected modules. That clearly denotes that such patterned analysis is essential to correctly design module structures. Specifically, while considering non-linearities in materials, as apparent with concrete, those high stresses may result in damage of the modules.

The exact quantities shall not be studied within this scope. This example has been presented to show the capabilities of the proposed numerical approach for modular design.

3.2 | Staged analysis

This example is primarily referring to the advantages of the staged analysis with the proposed design process. Thereby, initially, structural optimization is being processed. This could be a more advanced problem, however, to indicate the approach a plane geometry is applied (see Figure 7A). Here, all corners are used as supports and a constant load is applied on the body. The outcome of this form-finding step is presented within Figure 7B. This shape shall consequently be considered the basis for a modularization. As the shape of the shell structure is curved, eventual patterning can be applied in a structured and aligned manner. Therefore, only a regular grid is used within this example (see Figure 7C). Also, diverse patterns would be applicable.

This modularized system is consequently used with a continuous surface load. All edges are employed as supports. The outcomes of this simulation are presented within Figure 7D–F. The displacements from Figure 7D indicate that

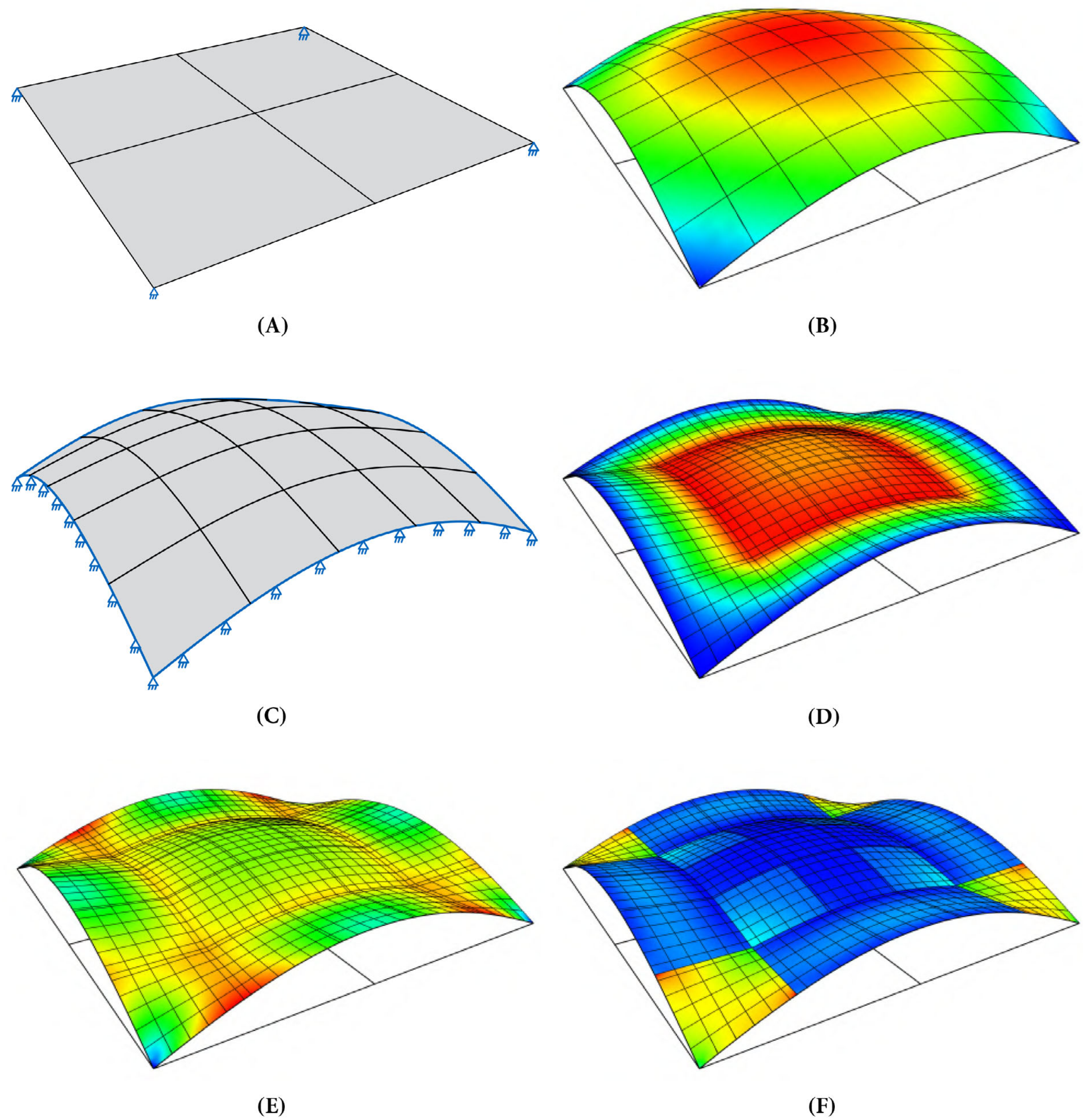

FIGURE 7 Stresses within the bending beam problem. (A) Initial shape; (B) form found shape; (C) module system; (D) displacements with scaling of 2×10^3; (E) Von Mises stresses; (F) moments

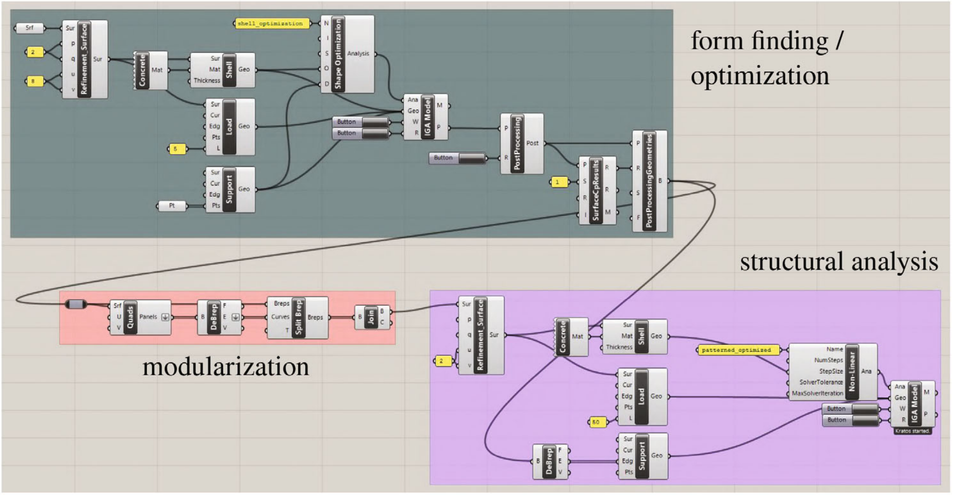

FIGURE 8 *Grasshopper* script of the staged analysis by using *Cocodrilo*.[17,18]

the system is sort of separated into two subsystems. The outer ring of modules and the inner part. While the inner part moves almost rigidly, the outer ring deflects and bends significantly. This mode of deflection is only possible due to the introduced kinematics at the interfaces between the employed modules. Second, the stresses within the structure shall be examined (see Figure 7E). It can be noted that at the interfaces between the outer ring and the middle structure the stresses increase. The severest stresses are at the edges of the problem between the first and the second module, respectively at each corner. This is something that would be unexpected within a continuous system. Therefore, it indicates clearly that a modularized analysis is inevitable to estimate contact forces to ensure connectors would resist the apparent loads. Ultimately, the internal moments shall be investigated. Primarily, it shows moments vary largely between the modules. Furthermore, due to the moment jumps it can be indicated that the moments are not transferred at the module interfaces. This is happening due to the additional kinematics. It shows that within most of the panels little moments are expected. However, for the corner modules, the moments are significantly higher. This information can be exploited to inform the construction of the respective modules and maybe apply thicker cross-sections at the corner patches to resist bending. The inner segments could be constructed with less material to contain a more sustainable design.

The correspondingly employed *Grasshopper* script is presented within Figure 8. It illustrates the three main stages: form finding/optimization, modularization, and structural analysis. All three stages are interconnected. Therefore, dependencies are used to update eventual shapes if previous steps would be exchanged or updated. Hereby, various objectives in the optimization or numerous patterns may be exchanged easily. Respective analyses would reconstruct themselves consistently.

4 | CONCLUSIONS AND OUTLOOK

Within this publication has been proposed a generic numerical avenue for structural assessments for segmented structures. The algorithm can generically cope with either bottom-up or top-down procedures. As it is relying on IGA, the procedure are fully CAD integrated and thusly predesignated for the application within BIM. Another advantage in the usage of IGA is its direct applicability within parametric design environments, such as *Grasshopper*. The proposed procedures may allow users a fast and generic design, whereby eventual changes and updates would update themselves within the proceeding steps.

Within Section 3 are presented some use cases of the proposed approach. One example (see Section 3.1) focuses on the comparison between original continuous systems and modular structures. It shows that the discontinuity can be applied successfully, while denoting dissimilarities in the results. The second showcase (see Section 3.2) presents the possibilities within the parametric CAD-integrated process. Thereby, a form finding is combined with a patterning of the structure and subsequent analysis. All instances may be exchanged to study various options.

As an outlook shall be proposed to investigate methodologies to optimize the location of the separations between modules (as e.g., References 30-32), such that contact forces may be minimized and building procedures facilitated. One possible avenue therefore may be the usage of agent-based modeling.[33] Furthermore, the presented investigations have been delimited to thin-walled structures, however, this may not be appropriate for many types of modules. Immediate future research shall cover the application of solid approaches for modularized structures within the CAD-integrated framework (see e.g., Reference 34 for a solid analysis within CAD).

AUTHOR CONTRIBUTIONS

Tobias Teschemacher: conceptualization (lead); formal analysis (lead); software (lead); writing – original draft (lead). **Kai-Uwe Bletzinger:** conceptualization (supporting); funding acquisition (lead); methodology (supporting); supervision (lead); writing – review and editing (supporting).

ACKNOWLEDGMENTS

The authors gratefully acknowledge support from the *Deutsche Forschungsgemeinschaft* (DFG) as part of the SPP 2187 with the project “Der digitale Baukasten – Simulationsbasierte Modelle und Methoden für den Entwurf mo-dularer Tragsysteme aus Beton” and the project “Eine Methode zur effizienten Simulation grosser Mauerwerksscheiben unter exzentrischer und/oder zyklischer biaxialer Beanspruchung auf Grundlagewirklichkeitsnaher Kleinkörperversuche” (BL306/34-1). Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/eng2.12632.

DATA AVAILABILITY STATEMENT

The datasets used and/or analyzed during the current study is available from the corresponding author on request. The analyses have been processed with *Kratos Multiphysics*.[35] The pre- and post-processing have been operated with *Cocodrilo*.[18]

ENDNOTE

* If the module boundaries are described within a 2-dimensional parameter space it needs to be ensured that the parameter space of the geometry does not contain any distortions, as otherwise, all segments would have different sizes.

ORCID

Tobias Teschemacher https://orcid.org/0000-0002-4525-1271

REFERENCES

1. Lawson RM, Ogden RG, Bergin R. Application of modular construction in high-rise buildings. *J Archit Eng*. 2012;18(2):148-154. doi:10.1061/(ASCE)AE.1943-5568.0000057
2. Hong J, Shen GQ, Feng Y, tWS L, Mao C. Greenhouse gas emissions during the construction phase of a building: a case study in China. *J Clean Prod*. 2015;103:249-259. doi:10.1016/j.jclepro.2014.11.023
3. Lacey AW, Chen W, Hao H, Bi K. Structural response of modular buildings—an overview. *J Build Eng*. 2018;16:45-56. doi:10.1016/j.jobe.2017.12.008
4. Lopez D, Froese TM. Analysis of costs and benefits of panelized and modular prefabricated homes. *Proc Eng*. 2016;145:1291-1297. doi:10.1016/j.proeng.2016.04.166
5. Mark P, Lanza G, Lordick D, et al. Industrializing precast productions. *Civ Eng Des*. 2021;3(3):87-98. doi:10.1002/cend.202100019
6. Kudsk A, Grønvold B, Olsen M, Hvam L, Thuesen C. Stepwise modularization in the construction industry using a bottom-up approach. *Open Constr Build Technol J*. 2013;7:99-107. doi:10.2174/1874836801307010099
7. Stieler D, Schwinn T, Menges A. Automatisierte Bauteilzerlegung für Betonfertigteile aus additiv hergestellten Schalungen. *Beton- und Stahlbetonbau*. 2022;117:324-332. doi:10.1002/best.202200006
8. Stieler D, Schwinn T, Menges A. Additive formwork in precast construction—agent-based methods for fabrication-aware modularization of concrete building elements. Proceedings of the 27th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2022; 2022:81–90.

9. Gericke O, Kovaleva D, Sobek W. Fabrication of concrete parts using a frozen sand formwork. Proceedings of IASS Annual Symposia; 2016:1–10.
10. Lowke D, Vandenberg A, Pierre A, Thomas A, Kloft H, Hack N. Injection 3D concrete printing in a carrier liquid—underlying physics and applications to lightweight space frame structures. *Cem Concr Compos*. 2021;124:104169. doi:10.1016/j.cemconcomp.2021.104169
11. Kloft H, Gehlen C, Dörfler K, et al. TRR 277: additive Fertigung im Bauwesen. *Bautechnik*. 2021;98(3):222-231. doi:10.1002/bate.202000113
12. Crotty R. *The Impact of Building Information Modelling*. Routledge; 2011.
13. Borrmann A, König M, Koch C, et al. *Building Information Modeling: Technologische Grundlagen Und Industrielle Praxis*. Springer Vieweg; 2015.
14. Grasshopper. https://www.grasshopper3d.com
15. Rhinoceros. https://www.rhino3d.com
16. Hughes TJR, Cottrell JA, Bazilevs Y. Isogeometric analysis: CAD, finite elements, NURBS, exact geometry and mesh refinement. *Comput Methods Appl Mech Eng*. 2005;194(39-41):4135-4195. doi:10.1016/j.cma.2004.10.008
17. Teschemacher T, Bauer AM, Aristio R, Meßmer M, Wüchner R, Bletzinger KU. Concepts of data collection for the CAD-integrated isogeometric analysis. *Eng Comput*. 2022;38:5675-5693. doi:10.1007/s00366-022-01732-4
18. Teschemacher T, Bauer AM, Aristio R, Messmer M, Wüchner R, Bletzinger KU. Cocodrilo. https://github.com/CocodriloCAD/Cocodrilo
19. Kiendl J, Bletzinger KU, Linhard J, Wüchner R. Isogeometric shell analysis with Kirchhoff–Love elements. *Comput Methods Appl Mech Eng*. 2009;198(49–52):3902-3914. doi:10.1016/j.cma.2009.08.013
20. Oesterle B, Ramm E, Bischoff M. A shear deformable, rotation-free isogeometric shell formulation. *Comput Methods Appl Mech Eng*. 2016;307:235-255. doi:10.1016/j.cma.2016.04.015
21. Müller A, Bischoff M. A consistent finite element formulation of the geometrically non-linear Reissner-Mindlin Shell model. *Arch Comput Methods Eng*. 2022;29:3387-3434. doi:10.1007/s11831-021-09702-7
22. Philipp B, Breitenberger M, D'Auria I, Wüchner R, Bletzinger KU. Integrated design and analysis of structural membranes using the isogeometric B-rep analysis. *Comput Methods Appl Mech Eng*. 2016;303:312-340. doi:10.1016/j.cma.2016.02.003
23. Breitenberger M, Apostolatos A, Philipp B, Wüchner R, Bletzinger KU. Analysis in computer aided design: nonlinear isogeometric B-rep analysis of shell structures. *Comput Methods Appl Mech Eng*. 2015;284(284):401-457. doi:10.1016/j.cma.2014.09.033
24. Teschemacher T, Bauer AM, Oberbichler T, et al. Realization of CAD-integrated shell simulation based on isogeometric B-rep analysis. *Adv Model Simul Eng Sci*. 2018;5(1):1-54. doi:10.1186/s40323-018-0109-4
25. Pasch T, Leidinger LF, Apostolatos A, Wüchner R, Bletzinger KU, Duddeck F. A priori penalty factor determination for (trimmed) NURBS-based shells with Dirichlet and coupling constraints in isogeometric analysis. *Comput Methods Appl Mech Eng*. 2021;377:113688. doi:10.1016/j.cma.2021.113688
26. Apostolatos A, Schmidt R, Wüchner R, Bletzinger KU. A Nitsche-type formulation and comparison of the most common domain decomposition methods in isogeometric analysis. *Int J Numer Methods Eng*. 2014;97(7):473-504. doi:10.1002/nme.4568
27. Brivadis E, Buffa A, Wohlmuth B, Wunderlich L. Isogeometric mortar methods. *Comput Methods Appl Mech Eng*. 2015;284:292-319. doi:10.1016/j.cma.2014.09.012
28. Wilson P, Teschemacher T, Bucher P, Wüchner R. Non-conforming FEM-FEM coupling approaches and their application to dynamic structural analysis. *Eng Struct*. 2021;241:112342. doi:10.1016/j.engstruct.2021.112342
29. Chandra B, Singer V, Teschemacher T, Wüchner R, Larese A. Nonconforming Dirichlet boundary conditions in implicit material point method by means of penalty augmentation. *Acta Geotech*. 2021;16:2315-2335. doi:10.1007/s11440-020-01123-3
30. Groenewolt A, Schwinn T, Nguyen L, Menges A. An interactive agent-based framework for materialization-informed architectural design. *Swarm Intell*. 2018;12:155-186. doi:10.1007/s11721-017-0151-8
31. Oval R, Rippmann M, Mesnil R, Van Mele T, Baverel O, Block P. Feature-based topology finding of patterns for shell structures. *Autom Constr*. 2019;103:185-201. doi:10.1016/j.autcon.2019.02.008
32. Frey AM, Stindt J, Lanza G, Mark P. Geometrische Bewertung und Optimierung der Modulanordnung in Tragwerken – Ein Beitrag zur adaptiven Fertigung im Bauwesen. *Bautechnik*. 2021;98(9):662-670. doi:10.1002/bate.202100027
33. Stieler D, Schwinn T, Leder S, Maierhofer M, Kannenberg F, Menges A. Agent-based modeling and simulation in architecture. *Autom Constr*. 2022;141:104426. doi:10.1016/j.autcon.2022.104426
34. Messmer M, Teschemacher T, Leidinger L, Wüchner R, Bletzinger KU. Efficient CAD-integrated isogeometric analysis of trimmed solids. *Comput Methods Appl Mech Eng*. 2022;400:115584.
35. KratosMultiphysics. https://github.com/KratosMultiphysics

How to cite this article: Teschemacher T, Bletzinger K-U. CAD-integrated parametric modular construction design. *Engineering Reports*. 2023;5(8):e12632. doi: 10.1002/eng2.12632