SIMULTANEOUS EFFECT OF FORM MODIFICATIONS AND TOPOLOGY OF THE BRACING SYSTEM ON THE STRUCTURAL PERFORMANCE OF TIMBER HIGH RISE BUILDING

Introducing an innovative approach using parametric design

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Abstract. Topology optimization is a tool that minimizes the material consumption in a structure, while at the same time provides us design alternatives integrating architectural and structural engineering concepts. However, topology optimization is a structural engineering subject and its known methods are required professional knowledge of engineering to be used. In this article, the mutual effect of form modifications and topology of the bracing system in a 9-story timber exoskeleton high-rise building regarding the governing wind load and seismic load is examined. What differentiates this study from former ones and in fact its main purpose is introducing an innovative approach towards structural topology optimization using parametric design. In this innovative approach, the possibility of moving for each central node of bracing systems in defined ranges independently and the possibility of the existence or absence of each bracing member is provided. This parametric model will enable architects to optimize the topology of the structural elements which are part of their architectural design by themselves. The CMA-ES-algorithm-based optimization is done to minimize both “total mass of structure per unit area” and “the horizontal displacement of the top floor”. For modeling, optimizing cross-sections and structural analysis, Grasshopper and its plug-in called Karamba are utilized.

Keywords. Topology optimization; Form finding; Parametric design; Timber tall buildings; Exoskeleton structures.

1. Introduction

Environmental advantages, building performance, and speed of timber construction on one hand, and the need for high rise building caused by the growing population and lack of land, on the other hand, rationalize the increasing attention towards timber high rise buildings all around the world. ‘‘In recent

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years, the wood industry has developed new engineered timber products such as glue-laminated wood, laminated veneer lumber (LVL), and cross-laminated timber (CLT). These products were developed to increase the strength of the structural members, provide a more precise and consistent product, and to provide more effective use of natural resources‘’ (Hein and Baldassarra,2015, p.5). ‘’Between 2008 and 2016, the height of modern buildings using engineered timber increased from the nine-story Stadthaus building in London to TallWood at Brock Commons building in Vancouver‘’ (Foster, Ramage and Reynolds, 2017, p.28). Because of the fact that structural behavior is most influenced by the geometric form, the highest potential for structural efficiency and a balance of design goals occurs when determinative decisions are made in conceptual design. In field of form modification of high-rise buildings, some studies have been done. In the study of Moon (2011) parametric structural models are used to investigate the impacts of variation of important geometric configurations of complex-shaped tall buildings utilizing diagrid system, such as the rate of twisting and angle of tilting. In the paper of Ardekani et al. (2019) the effects of form parameters including tapering and changing plan shape as two commonly used modifications on the structural efficiency of tall buildings are investigated by generating a parametric platform. Mirniazmandan et al. (2018) focuses on studying the effect of both geometric modification of tall building and the angle of diagrid structure to improve the efficiency of tall buildings. In research of Alaghmandan et al. (2014) a design method of tall buildings considering integrated architectural and structural strategies, and reducing the along wind effect is presented to achieve the minimum weight of the structure as one of the main parameters of the efficiency. ‘’Researchers have previously developed many computational optimization tools for design optimization, in which the goal is to reduce the cost or material usage in a structure while satisfying specific design criteria. Among these tools, there are the cases of size optimization, shape optimization, genetic algorithms, topology optimization, and others‘’ (Beghini, 2013,p.18). ‘’Topology optimization has been recognized as one of the most effective tools for least-weight and performance design. It has undergone a remarkable development in both academic research and industrial applications. Various approaches have been proposed, such as density-based methods, evolutionary procedures, and level set methods‘’ (Xia, 2016, pp.4-8). In regards to topology optimization, several different studies have been done over the years. The research of Baldock (2007) has focused on structural topology optimization of steel building frameworks and has investigated three distinct methods. Symmetry constraints, rules for element removal and addition, and also some aesthetic requirements are considered in this study. Paper of Baldock and Shea (2006) presents a genetic programming method for the topology optimization of steel bracing systems that aims to create optimal design solutions. Liang (2007) utilizes the performance-based optimization (PBO) technique to investigate the effects of continuum design domains on the layouts and performance of multistory steel bracing systems under lateral loads. In this system, underused finite elements are gradually removed to obtain optimal bracing systems. Former the other similar study was done by Liang, Xie and Steven (2000). In the study of Mijar, et al. (1998) a continuum structural topology optimization formulation is presented for the concept design optimization of structural bracing under lateral-wind and seismic loading. In research of Balling, Briggs and Gillman (2006) simultaneous optimization of size, shape, and topology of skeletal structures, including trusses and frames is done through a genetic algorithm that is presented. Considering the fact that this is a well-documented field of research So what is the need for a new study? Firstly, ‘’the spatial arrangement of material, often known in the literature as the layout problem, is of key importance for the design and usability of many engineering products. Specifically, in building design, the manner in which material is distributed is significant for engineers to develop a lateral bracing system or create a conceptual design for structural members. While topology optimization is a very powerful tool for design, often the resulting topologies produced consist of complex geometries and poor material layouts which are of limited value to real-world problems due to expense and ease of manufacturing‘’ (Stromberg et al., 2010, p.165). So considering a manufacturing constraint on the size of members in a study will make the result more valuable. Of course, this issue has been paid attention to in some of the former studies but still, there is potential for more progress. Secondly, topology optimization is a specialized field of civil engineering so its known methods are required the knowledge of engineering and are not easy to understand by architects. The purpose of this study is to introduce an innovative methodology and in fact, a parametric model that enables architects to do the structural topology optimization of their design by themselves. Needless to say, these elements are parts of architecture too. In other words, they will affect the structure and architecture at the same time. So, using this approach allows the architect to choose from a wide range of architectural options resulted from the optimization process and also makes them sure that their choice is structurally efficient too. Or, it will enable them to design their desired structure in the parametric model and check it structurally. Moreover, in this study, the effect of form modification and topology of bracing systems is examined simultaneously and in a timber exoskeleton structure, unlike most of the former works that choose steel or concrete as their main material. These new considerations can bring novel interesting results.

2. Methods

2.1. FORM MODIFICATION

To find the general form of the building, the diameters of the two ellipses, which were created as the initial top plan and initial base plan to form the initial total volume, were considered as variables in the optimization process. In fact, by changing these diameters, different forms of tall buildings can be achieved. (Figure.1) In this research, the range of changes of each diameter is defined between 24 to 40 meters, as a result of which we will have 81 different forms. This range of change is determined according to the importance of effective daylighting for spaces. So that considering the defined fixed central core in the structure with a diameter of 16 meters, the lease span will be between 4 to 12 meters. ‘’Leasing depth or lease span is the distance of the usable area between the exterior wall and the fixed interior element, such as the core or the multi-tenant corridor.‘’(Sev and Ozgen, 2009, p.75) The maximum lease span varies from region to region but some countries have determined it. For example, in Germany, the maximum leasing depth cannot be more than 8.0 meters, but in Japan it is typically 18.0 meters. In the United states buildings with a lease span of 17.0 meters can be found (Sev and Ozgen, 2009).

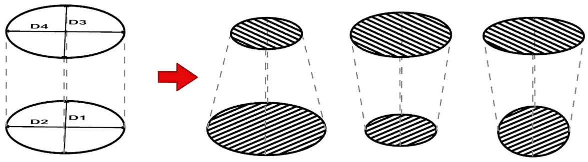


Figure 1. General form modifications of the building with changes in the diameters of the base ellipses.

What is defined as the main top plan and main base plan in this study, is the polygons inscribed in the described ellipses. In the parametric model (modeled in Grasshopper), a situation is provided that allows the formation of any polygon (from triangle to circle) in the base ellipses. So that it is even possible to define the top plan and base plan differently. (Figure 2) But, in this study, to simplify the model and to examine the effect of optimization variables on the results as accurately as possible, the top plan and base plan were both considered as 30-sided (close to a circle). However, as described, it is possible to examine more complex forms in future studies.

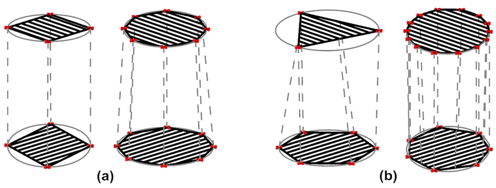


Figure 2. Some forms that their formation is possible in the parametric model. The similarity in top plan and base plan (a), The difference in top plan and base plan (b).

In the parametric model, it is possible to change the number of columns in certain ranges, in fact, it is possible to consider this number as a variable in the optimization process. But for this study, according to the mentioned reasons, the fixed number of 30 columns located at the vertices of the polygon is defined. Also, for braced frames, a fixed height of 3 floors (equivalent to 12 meters) is considered.The procedure to study the topology of these bracing members is shown in Figure 3. As shown in Figure 3, the possibility of moving for each central node of bracing systems is provided in defined ranges independently. Moreover, the possibility of the existence or absence of each bracing member is provided. So, there are 32 different modes of formation for each frame “independently”. All these modifications are done randomly and based on seed in the grasshopper plugin. Some possible modes of formation of exoskeleton structure on the façade are shown in Figure 4.

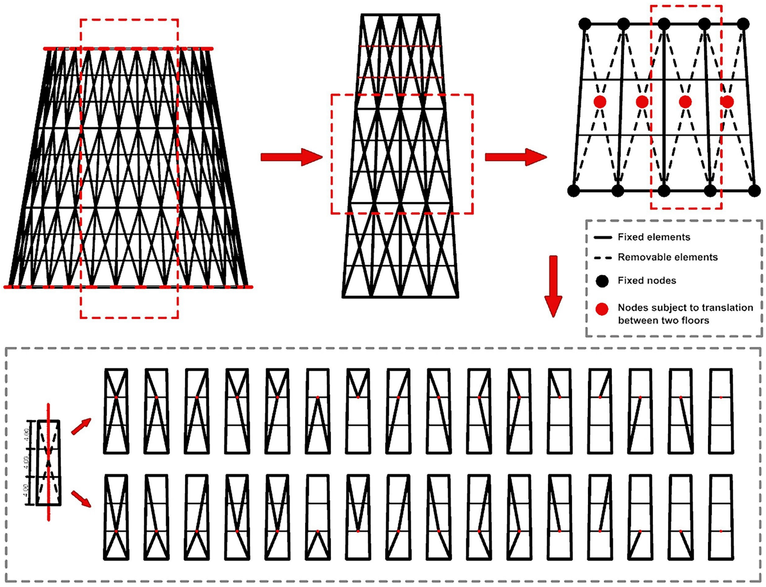


Figure 3. The procedure to study the topology of the bracing members.

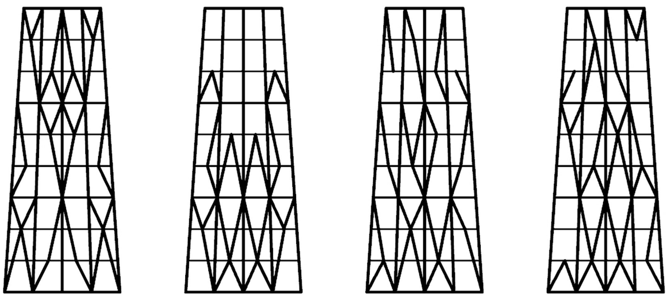


Figure 4. Some possible topologies of bracing members.

After modeling the members of the exterior structure parametrically, other structural members were also modeled to transform the model into a stable integrated structure. In this research, the considered structure includes 1- Central core (fixed position and fixed diameter), 2- Radial beams (fixed number, variable and parametric length), 3- Peripheral beams (fixed number, variable and parametric length), 4- Exoskeleton structure (fixed number, variable and parametric length for columns- variable and parametric number and length for bracing members).

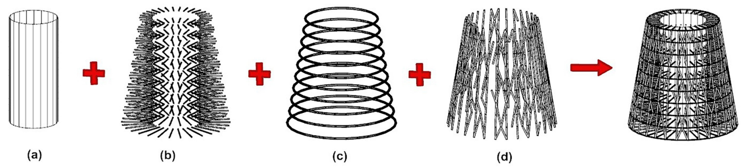


Figure 5. Considered structure in this study: Central core(a), Radial beams (b), Peripheral beams (c), Exoskeleton structure (d).

2.2. FINITE ELEMENT MODEL OF STRUCTURE

To convert modeled members into the structure and to analyze the final structure, the Karamba plugin (FE method) is utilized. ‘’Finite Element Method (FEM) is a computational technique used to obtain approximate solutions of boundary value problems in engineering (Bialkowski and Kepcyznska-Walczak, 2015, p.2).‘’ The loads considered for structural analysis in this study are:1-gravity load, 2-totally live load and dead load on each floor (8kn/m2 on each floor), 3-wind load, 4-seismic loadThe calculation of wind load and seismic load is done based on CBC (Canada’s building code), Iran National Building Regulations provisions, and Iranian Seismic Code 2800.

2.3. STRUCTURAL ANALYSIS AND OPTIMIZATION

After the formation of integrated structure and applying horizontal and vertical loads, in the initial step for structural analysis, optimized cross-section tool of Karamba is used to limit the maximum displacement -based on (AISC)- to (H/500=0.072, H= the total height of the building) by changing Cross-section dimensions of structural members (peripheral and radial beams and also exoskeleton structure) in defined ranges. Table 1 reports details about building elements. When cross-sections are chosen, and structural analysis is completed, some structural information such as maximum displacement and mass are extractable. In fact, these steps (includes 1- formation of structural members based on variables, 2- formation of integrated structure, 3- optimization of cross-sections, 4- analysis of structure, 5- extraction of structural information) repeat during the optimization process. One example of structural analysis in Karamba under defined horizontal and vertical loads is shown in Figure 6. In this study, the objective of the optimization is minimizing both “total mass of structure per unit area” and “the horizontal displacement of the top floor”. To do this optimization a CMAES-algorithm-based optimizer called Opossum is implemented. ‘’Covariance Matrix Adaptation Evolution Strategy (CMA-ES) developed by Nikolaus Hansen is an evolutionary algorithm for difficult non-linear non-convex black-box optimization problems in continuous domains. The CMA-ES is considered as state-of-the-art in evolutionary computation and has been adopted as one of the standard tools for continuous optimization in many research labs and industrial environments around the world that is proved to converge at optimal solution in very few generations, thus, decreasing the time complexity ‘’ (Gagganapalli, 2015,p.13).

Table 1. building elements details.

Building elements	Cross section	Fixed dimensions	Variable dimensions	Material
Core	Shell const	Diameter: 16m Thickness: 15cm	-	Wood material E:1050[kN/cm2] G12:360[kN/cm2] G3:360[kN/cm2] gamma:6[kN/m3] alphaT:5.0E-6[1/C°] fy:1.3[kN/cm2]
Radial beams	Solid rectangle	-	Cross section height:10-100cm Cross section Width:10-100cm Length: Around 4-12m	
Peripheral beams	Solid rectangle	-	Cross section Height:10-100cm Cross section Width:10-100cm Length: Around 2.5-4m	
Columns	Solid rectangle	Length: Around 4m (each floor)	Cross section Height:15-95cm Cross section Width:15-95cm	
Bracings	Solid rectangle	-	Cross section Height:15-95cm Cross section Width:15-95cm Length: Around 4-4.5m	
Slabs	Shell const	Thickness: 15cm	Diameters: 24-40m	

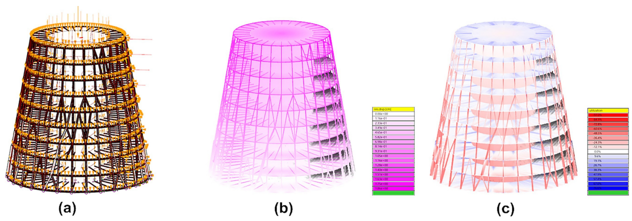


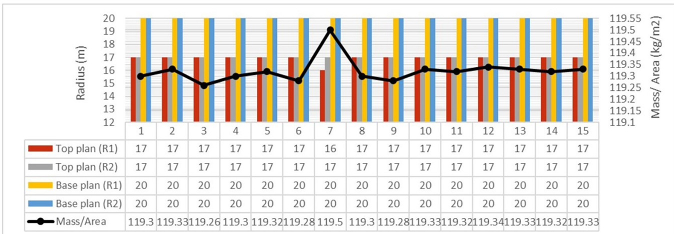
Figure 6. One example of the structure under defined horizontal and vertical loads (a), Displacement in structural members after structural analysis (b), Utilization in structural members after structural analysis (c).

3. Results and discussion

During the optimization process, about 39,000 different alternatives were investigated. Form modification results and information about maximum displacement and mass/area of the first 15 optimal results are shown in Figures 7 and 8. As shown in the graphs, the most appropriate form according to the objectives set for optimization is the top plan with radiuses of 17 and the base plan with radiuses of 20. Figure 9 shows the results of topology optimization in the first 3 optimal alternatives. In this figure, the different sides of each optimized result are displayed according to their position relative to the wind. It should be noted here that the parametric model described is under development and it is expected that a more complete and flawless version of it be presented in future studies. In such a way that more regular results can be reached and stronger conclusions can be made. Also, if this study is done on a building with a higher height, the effect of wind force on the formation of the topology of bracing members on different sides will be more visible. But as mentioned before, the main purpose of this research is not to achieve the most optimal answer, but to introduce a simple and easy-to-use platform that enables the architect to study the topology of the structure and the form modification in a building. This is even more important when the considered structure is an exterior structure. Because in exoskeleton structures, the facade of the building and the structure are practically the same and no boundary can be drawn between them. Using this parametric model, the architect is able to create a favorable form as well as an architecturally desirable pattern with the structural members and evaluate its structural performance. An example of patterns that can be created with this model and their structural performance is shown in Figure 10. As it is clear, these structures, while meeting the architectural needs, are structurally acceptable.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Top plan (R1)	17	17	17	17	17	17	16	17	17	17	17	17	17	17	17
Top plan (R2)	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
Base plan (R1)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Base plan (R2)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Max displacement	2.62	2.63	2.7	2.66	2.64	2.68	2.47	2.68	2.69	2.65	2.66	2.65	2.66	2.67	2.66

Figure 7. The radius of the top plan and base plan vs. max displacement.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Top plan (R1)	17	17	17	17	17	17	16	17	17	17	17	17	17	17	17
Top plan (R2)	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
Base plan (R1)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Base plan (R2)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Mass/Area	119.3	119.33	119.26	119.3	119.32	119.28	119.5	119.3	119.28	119.33	119.32	119.34	119.33	119.32	119.33

Figure 8. The radius of the top plan and base plan vs. Mass/Area.

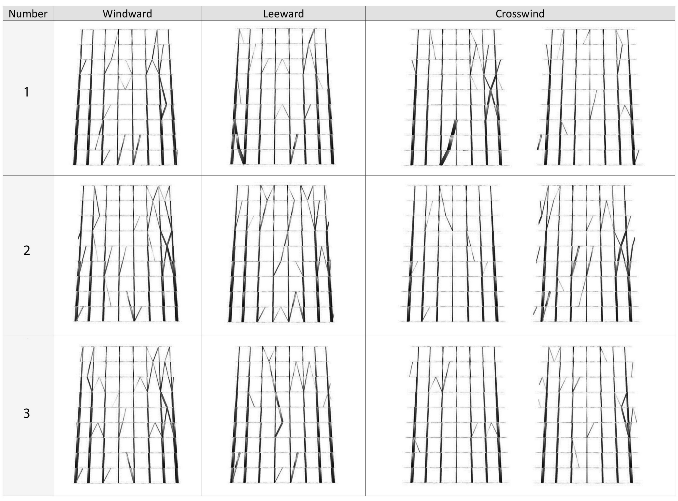


Figure 9. Results of topology optimization in the first 3 optimal alternatives.

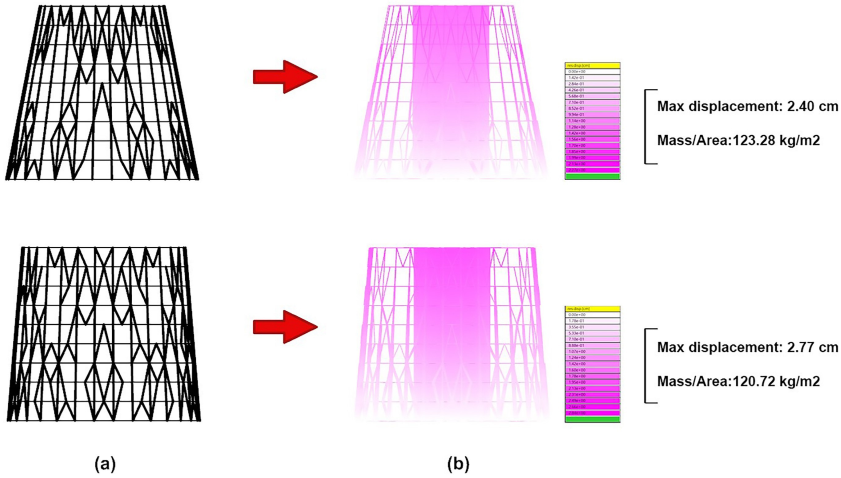


Figure 10. Some patterns that can be created by the architect in the parametric model (a), Displacement in structural members after structural analysis (b).

4. Conclusion

The study was done to propose an innovative method that makes form-finding and also modifying the topology of the bracing system in a timber exoskeleton structure possible. In this innovative approach, unlike the past works, some bracing elements are defined, and the possibility of relocating and even eliminating them is provided. In fact, the central nodes of these elements are able to move in defined ranges to find their best location according to the objectives of the optimization or desires of the architect. Of course, it should be noted that this study does not seek to downplay the role of the structural engineer or eliminate it, because this is certainly not possible, and naturally the design of an optimal building is the result of the interaction between the architect and structural engineer. The purpose of this study is to empower the architect as much as possible to propose designs consistent with engineering principles. This method opens up new perspectives on the role of computational design and parametric design in the future of architecture.The methodology although helpful has some limitations. Making the locating of nodes independently which has increased the number of variables, on one hand, dependence on randomness, and seed, on the other hand, Extends optimization time. This will be more obvious when the topology of a higher tall building is going to be investigated. It is expected that the more developed parametric model in the futures studies provides us more specific results. Considering some constraints like symmetry constraint that decreases the number of variables is a suggestion.

References

Alaghmandan, M., Elnimeiri, M., Carlson, A. and Krawczyk, R.: 2014, Optimizing the Form of Tall Buildings to Achieve Minimum Structural Weight by Considering along Wind Effect, *Proceedings of the Symposium on Simulation for Architecture & Urban Design*.

Ardekani, A.R., Dabbaghchian, I., Alaghmandan, M., Golabchi, M., Hosseini, S.M. and Mirghaderi, S.R.: 2019, Parametric design of diagrid tall buildings regarding structural efficiency, *Architectural Science Review*, **63**, 87-102.

Baldock, R.: 2007, *Structural optimization in building design practice: case-studies in topology optimization of bracing systems*, Ph.D. Thesis, Cambridge University.

Baldock, R. and Shea, K. 2006, Structural Topology Optimization of Braced Steel Frameworks Using Genetic Programming, *in* I.F.C. Smith (ed.), *Intelligent computing in engineering and architecture : revised selected papers*, Springer, Heidelberg, 54-61.

Balling, R.J., Briggs, R.R. and Gillman, K.: 2006, Multiple Optimum Size/Shape/Topology Designs for Skeletal Structures Using a Genetic Algorithm, *Structural engineering*, **132**(7), 1158-1165.

Beghini, L.L.: 2013, *Building science through topology optimization*, Ph.D. Thesis, University of Illinois at Urbana-Champaign.

Bialkowski, S. and Kepcyznska-Walczak, A.: 2015, Engineering Tools Applied in Architecture – Challenges of Topology Optimization Implementation, *eCAADe 2015*, Vienna, 261-268.

Foster, R., Ramage, M. and Reynolds, T.: 2017, Rethinking CTBUH height criteria in the context of tall timber, *CTBUH journal*, 28-33.

Gagganapalli, S.R.: 2015, *Implementation of And Evaluation of CMA-ES Algorithm*, Master's Thesis, North Dakota University.

Hein, C. and Baldassarra, C.: 2015, Debating tall: Tall timber in 10 years?, *CTBUH journal*, 5.

Liang, Q.Q.: 2007, Effects of continuum design do-mains on optimal bracing systems for multistory steel building frameworks, *5th Australasian Congress on Applied Mechanics*, Brisbane.

Liang, Q.Q., Xie, Y.M. and Steven, G.P.: 2000, Optimal Topology Design of Bracing Systems for Multistory Steel Frames, *Structural engineering*, **124**(7), 823-829.

Mijar, A.R., Swan, C.C., Arosa, J.S. and Kosaka, I.: 1998, Continuum topology optimization for concept de-sign of frame bracing systems, *Structural engineering*, **124**(5), 541-550.

Mirniazmandan, S.A., Alaghmandan, M., Barazande, F. and Rahimianzarif, E.: 2018, Mutual effect of geometric modifications and diagrid structure on structural optimization of tall buildings, *Architectural science review*, **61**, 371-383.

Moon, K.S.: 2011, Diagrid Structures for Complex-Shaped Tall Buildings, *Procedia Engineering*, **14**, 1343–1350.

Sev, A. and Ozgen, A.: 2009, Space Efficiency In High-Rise Office Buildings, *METU Journal of the Faculty of Architecture*, **26**, 69-89.

Stromberg, L.L., Beghini, A., Baker, W.F. and Paulino, G.H.: 2010, Application of layout and topology optimization using pattern gradation for the conceptual design of buildings, *Structural and Multidisciplinary Optimization*, **43**, 165-180.

Xia, L.: 2016, *Multiscale Structural Topology Optimization*, ISTE Press & Elsevier.