Parametric Modelling and Structural Optimisation Framework for Early Design Exploration of Tall Buildings

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Abstract

The increasing complexity of modern tall buildings has raised the importance of close collaboration between architectural and engineering disciplines in the design. However, the first major task in conventional building design is to establish the preliminary shape and architectural appearance, considering the functionality and architectural aesthetics. The structural system is then developed for providing the skeleton of the building, taking account of the safety and stability of the structure. The structural aspect is commonly not considered in the architectural planning stage, while the influence of the architectural design to the structural performance is often overlooked. Therefore, this paper presents a parametric modelling-based optimisation framework for the synthesized architectural-structural design exploration of high-rise buildings at early stages. The proposed framework embeds the parametric modelling technique in the optimisation process. First, the architectural envelop of the building is parametrised by defining the shape variables, which represent the geometric entities, to provide a numerical representation for shape variations. Provided the pre-defined building shape, the design variables for topological arrangement of the building structure is defined by identifying the topological variables. By varying the shape and topology variables, the structural performance of design candidates with different architectural and structural attributes can be evaluated, and the fittest design options can provide recommendations in the preliminary design process and guide the final design scheme decision. A case study demonstrates how the proposed platform can be applied as a decision-support system in the early building design stage and shows the influence of changes in building shape and structural topology to the structural efficiency.

Keywords: Architectural design, High-rise buildings, Optimality criteria, Parametric modelling, Structural optimisation

1. Introduction

Modern tall buildings have become taller and more complex thanks to the advance in construction technology. The increasing complexity of modern architecture has created challenges and difficulties in the design process and has raised the importance of close collaboration between the architectural and engineering disciplines. However, these two disciplines are usually separated in conventional design process and lack interactive coordination in the early design phases. The architects firstly establish the preliminary building shape and layout for satisfying the functional requirements and adding aesthetic value. The structural engineers then develop the structural system for providing the skeleton of the building, considering the safety and the stability of the structure. Commonly, structural considerations are ignored in the architectural planning stage and the influence of the building shape to the structural performance is often overlooked. It is possible that the architects invent the building envelop which is structurally inefficient or even infeasible to be built (Macdonald, 2018). In such cases, the architects and engineers have to work collaboratively and come up with a feasible design, while maintaining the functionality, aesthetics and the structural integrity of the building. In order to facilitate the architectural-structural collaboration, a synthesised design framework is needed for modern tall building design.

Many researchers have proposed design frameworks with the use of parametric modelling for providing solutions to the architectural and structural design synthesis. Park, Elnimeiri, Sharpe and Krawczyk (2004) proposed an interactive design process framework, taking client's requirements, architectural and structural design criteria into consideration. On top of the framework, this study also provided a geometry generation and exploration method, which allows the architects to create unique and distinctive building shapes in a systematic manner and facilitates the generation of the structural model from the architectural model. Another study also presented a framework based on geometric modelling, the hierarchical process model and the integrated architectural-structural representation model for facilitating interactive collaborations (Mora, Bédard, & Rivard, 2008). A synthesised performance-based design approach was proposed for early form design of tall buildings, with the integration the architectural parametric modelling tool and structural analysis tool. (Almusharaf & Elnimeiri, 2010; Elnimeiri & Almusharaf, 2010). The integration of the tools enables structural performance evaluations in the architectural design stage, which in turn can assist the architects to improve the design of the building. Some researchers and practitioners focused on practical applications of the architectural and structural synergy. Holzer, Hough and Burry (2007; 2007) studied interconnectivity of building design software across the two disciplines and developed customised tools for the collaborative process and interdisciplinary decision support. Another stream of researches focused more on the design optimisation on top of the architectural-structural synthesis. Dominik, Jiwu, Mik and Mark (2005) developed a combined approach for architectural form design, using parametric design and evolutionary optimisation techniques, in order to identify appropriate building forms with efficient structural systems. Other researches applied structural topology optimisation techniques for achieving structural efficiency optimality, while maintaining the aesthetics and functionality of the building (Beghini, Beghini, Katz, Baker, & Paulino, 2014; Kingman, Tsavdaridis, & Toropov, 2014; Kingman, Tsavdaridis, & Toropov, 2015). The possibilities of integrating automatic computational techniques of topology optimisation were also investigated for enhancing the computer aided design process (Kazakis, Kanellopoulos, Sotiropoulos, & Lagaros, 2017).

Although some successes in the synergy between architectural and structural design have been demonstrated in the previous studies, the combined influences of the building shape and structural topology arrangement to the structural efficiency were not fully explored. Without a robust hybridised structural topology and member sizing optimisation technique, an accurate structural efficiency assessment could not be conducted comprehensively. Therefore, this paper aims to develop a parametric modelling and structural optimisation framework for providing a more robust structural performance assessment at the early stages of the synthesised architectural-structural design exploration of high-rise buildings. On the other hand, the recent advancement in parametric designing and building modelling tools fosters the development of holistic multidisciplinary design approaches. This study attempts to leverage the state-of-the-art parametric modelling tools for promoting a better architectural-structural synthesis. In this parametric optimisation framework, the architectural form of the building is parametrically represented by defining the shape variables and mathematical functions for generating the geometric entities. The design variables for topological arrangement of the structure are then defined by identifying the topological variables of the structural system. The use of numerical variables and mathematical functions can provide an efficient manner for varying the architectural form and the structural topology of the building. Design candidates with different architectural and structural attributes can be generated by the varying of the shape and topology variables. Another advantage of using parametric representation is the ease of architectural and structural model generation. The parametric variables and functions enable that the models can be generated programmatically, facilitating the structural performance evaluation process for providing design recommendations. This work presents a parametric geometric representation of tall buildings for providing a more generalised model generation method and incorporates a robust structural optimisation technique for more accurate performance evaluation in the early design process.

2. Methodology

2.1. Parametric Optimisation Framework

This section presents the parametric structural optimisation framework for identifying desirable architectural form design with an efficient structural system in the early stages. As shown in *Figure 1*, the purposed framework begins with the design inputs, which there are three main types of inputs: site environment, design regulations and design preference. The framework takes the site condition into account in order to exclude infeasible design candidates in the design process and ensure the validity of the solutions. For example, the development of the building must not exceed the site boundary, and the building height must adhere to the height restriction of the region. With the provided design input, the process proceeds to the architectural form design. First, the shape design parameters, which define the form of the building, are identified by the architects, based on the site condition and designer preferences. The base plan shape and the vertical form of the building are then generated according to the shape parameters. The details of the shape parameters are explained in section 2.2. With the defined geometric information, the architectural model is generated in the building modelling software with parametric design tools. The structural engineers then identify the possible type of structural system and the corresponding structural topology parameters. The details of the structural topology parameters are explained in section 2.3. The structural system of the building is then established accordingly, and the structural analysis model is generated for performance evaluation, followed by structural topology and member sizing optimisation. The building shape can also be altered for improving the structural efficiency in the iterative design process, and the structural design would adapt to the new building form. The influences of the building shape and the topology arrangement to the structural performance is analysed throughout the process, which provide guidance to the architects and engineers for improving the design. After several architectural and structural design cycles, the design team identifies the final design scheme, including the building shape, structural system and preliminary structural member sizes, as the output of this framework.

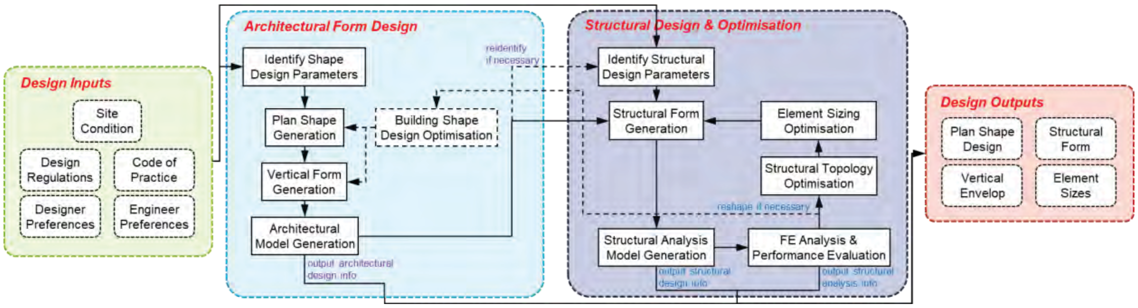
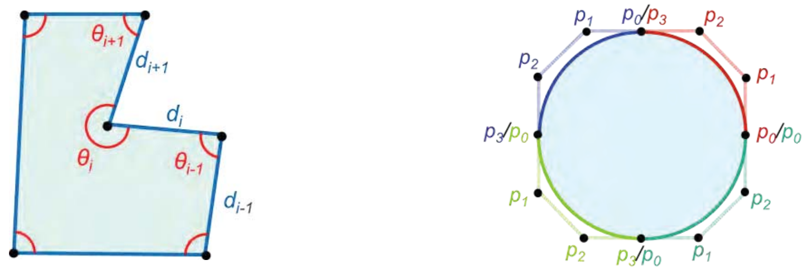


Figure 1: Proposed parametric structural optimisation framework

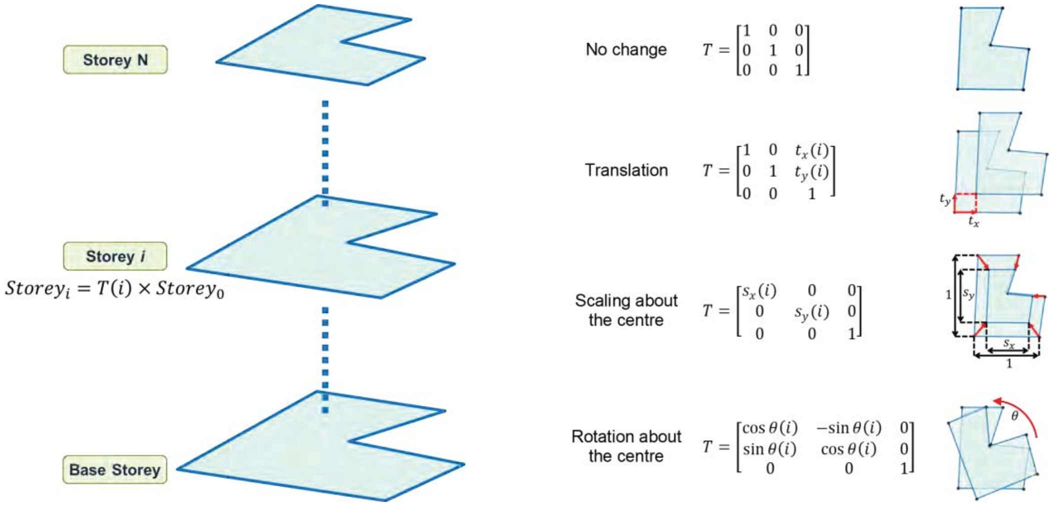
2.2. Building Shape Parameterisation

The concept of parameterising the building shape is to represent the geometry information of the building by using a set of variables and mathematical functions and provide a simple and generic method for generating complex and irregular building forms. The parametric representation of building shapes can be divided into two main components, the horizontal and vertical component. The horizontal component represents the base floor plan shape of a building; and the vertical component means the vertical envelop of a building. The base floor plan shape is defined by the architects using the parametric representation of geometry. For the plan shape with straight edges, like the "L-shape" floor plan in *Figure 2(a)*, the outline of the shape can be represented as a set of edge lengths and the angles between the edges as the parameters. *Figure 2(b)* shows another example of a circular base plan shape with curved edges, which the outline of the shape is represented by a collection of Bezier curves, and the shape parameters are the controlling points of the curves. Not only limited to the parameterisation methods shown in *Figure 2*, other representations can also be applicable, as long as the building plan shape can be depicted by the parameters.



(a) Representation for straight lines　*(b) Representation for curves using Bezier curves*

Figure 2: Parametric representation for base plan shapes of buildings



(a) Vertical relationship representation　*(b) Vertical transformation operations*

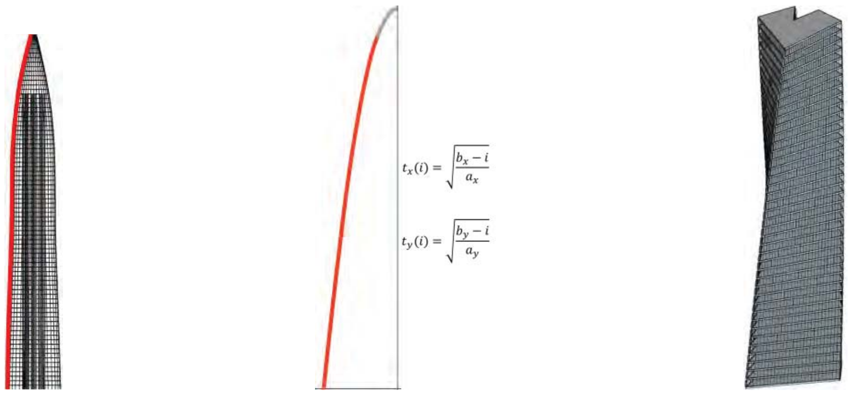
Figure 3: Parametric representation for vertical envelop of buildings

With the parameters for the base plan shape, the vertical form and the overall envelop of the building are then parametrically defined by a set of mathematical functions. The geometry of the plan shapes of the levels above the base level are represented by the transformation function with reference to the base plan shape (as shown in *Figure 3*). The "no change" transformation with the identity matrix can represent the prismatic building with constant floor plan shapes along the building height, like the original world trade centre in New York. The inclined shapes of the world-famous twin skyscrapers, the Gate of Europe, in Madrid can be represented by the translation function. The scaling transformation can generate the setback of the plan shape commonly found in tall buildings, which the floor plans getting smaller along the building height. The twist towers, Cayan Tower in Dubai and Turning Torso in Malmö can also be modelled by using rotation transformation to resemble the twisting effects of these distinctive shapes. Moreover, the different transformations of the building shape can be used combinedly, providing flexibility and more variations for modelling the vertical form of the building.

The usage of the transformation functions can provide a simple representation for the envelop of high-rise buildings. Regardless of the height of the building, number of the parameters or design variables for the vertical shape of the building is maintained in a small size, resulting in a scalable design problem. However, for buildings with discontinuity in the plan shape along the building height, like the

Bank of China Tower in Hong Kong, the vertical shapes cannot be simply represented by the continuous transformation functions. Multiple sets of the shape parameters are required for separate parts of the buildings. The benefit of parameterisation is less significant in such cases.

As shown in *Figure 4(a)*, the building with a nose-cone vertical form has the floor plan shrinking in size along the building height. This nonlinear shrinkage of building plan can be represented by the scaling transformation function, where the scaling ratio is also a function with respect to the storey number or height. *Figure 4(b)* shows an example of the square root function for the scaling ratio in x and y directions. a_x, a_y, b_x and b_y are the parameters of the functions defined by the designers. The parameters can be adjusted according to the architects' preference to control shape of the building envelop. The functions are not only limited to be quadratic; other functions, like trigonometric, exponential, reciprocal or polynomial functions, can also be applied. Similarly, the rotating angle θ of rotation transformation is a mathematical function in terms of the storey level as well. An example of a building with a linear rotation of the floor plans, with an increasing rotating angle θ of $2°$ for every storey, is shown in *Figure 4(c)*.



(a)Vertical variation of the building envelop *(b) Function of the scaling factor w.r.t the storey level* *(c) Building model of the rotational transformation*

Figure 4: Parametric function for representing the vertical variation (i.e. scaling and rotation) of the plan shape

2.3. Structural Topology Parameterisation

After having defined building shape, the structural engineers identify the best suitable structural systems (e.g. outrigger-braced, tubular system). Each structural system has a particular set of topology parameters. For instance, an outrigger-braced structure with three locations of outrigger trusses (as shown in *Figure 5(a)*) has a set of three variables representing the storey levels of the trusses and a set of variables indicating the column spacing of the perimeter frame. *Figure* 5*(b)* and *(c)* shows two examples of the variations of the structural topology variables for an outrigger-braced structure. The design in *Figure 5(b)* has a wider column grid spacing, and the design in *Figure 5(c)*) places the bottom outrigger truss at a much lower level. The structural model is then generated by parametric modelling tools according to the defined topology parameters for the structural performance evaluation.

(a) Original design
(b) Design variation in column grid spacing
(c) Design variation in outrigger truss level

Figure 5: Illustrations of variations of the structural topology variables

2.4. Member Sizing Optimisation

To conduct an accurate structural performance evaluation for the design candidates, varying from the shape of the building and the topology arrangement of structural elements, structural member sizing optimisation is applied in the structural design of each individual candidates. A robust optimality criteria method (C.-M. Chan, Grierson, & Sherbourne, 1995; C. M. Chan, 2001) is adopted for minimising the total amount of structural materials required in the building while satisfying member strength requirements and the lateral drift limits under wind loads. The design with the given building shape and structural topology, expressed in terms of the shape and topology variables, is transferred to structural analysis model for structural performance evaluation and member sizing optimisation. Following the sizing optimisation, the structural material demand for the design candidate is quantified and structural efficiency comparison between different designs is carried afterwards.

3. Result and Discussion

This section presents an illustrative example of applying the propose framework. Two buildings with peculiar forms in China, the China Resources Headquarters and the CITIC Tower (aka China Zun) are as the reference buildings in the study, as shown in *Figure 6*.

(a) (b)

Figure 6: Reference buildings: (a) China Resources Headquarters, (b) China Zun

3.1. Building Shape Design

With the insights about building shapes from the two reference buildings, 6 different building form were generated as the demonstrative examples, as shown as *Figure 7*. They are all 400 m tall and having around 240,000 m^2 of the total floor area for providing the same level of functionality and serviceability. The first 3 designs, *(a)-(c)*, with the circular plan shapes are mimicking the China Resource Headquarters, and another 3 designs, *(d)-(f)*, are resembling the round square plan shape of the China Zun. The illustrative example not only makes reference to the plan shapes, the vertical forms of the two special buildings are also taken into consideration, such as the convex, "bullet-like" shape is adopted in design *(a)* and *(d)*, and design *(c)* and *(f)* replicate the concave, "vase-like" shape. In addition, two buildings with linear vertical outline were modelled for a more comprehensive analysis of the influence of building shapes to the structural efficiency. To conduct the structural performance analysis, the structural models for the 6 shapes are generated, and the structural systems are fitted within the building envelops accordingly. In this illustrative example, the tubular structural system is used for all the shapes, since this system can adaptively fit for the irregular geometry of the buildings. Only the elements contributing to the lateral stability systems are designed because the ability of resisting wind loads is a critical criterion for tall building design.

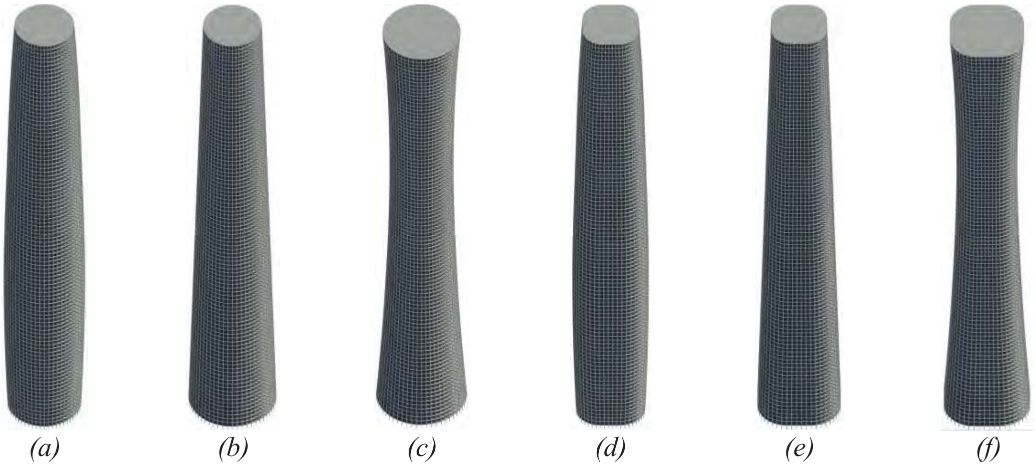


Figure 7: Variations of the building shapes: circular plan shape with (a) convex outline, (b) linear outline, (c) concave outline and rounded square plan shape with (d) convex outline, (e) linear outline, (f) concave outline

The lateral stability systems for all the building shapes were design according to the same code of practice and under the same loading conditions. The member sizes were optimised for achieving the minimum structural material cost while the top deflections of the buildings are controlled within the limits. *Figure 8* shows the optimised material cost for each design candidate, and the vertical axis represents the structural material cost required in the lateral stability system, i.e. the total material cost of the perimeter steel frame and the interior concrete core wall. The design *(b)* with a circular plan shape and a linear vertical outline is the most cost-effective design while satisfying the same structural requirements and functional demands. Comparing to the buildings with other vertical outline, this design has a vertical shape with the floor plans decreasing in size along the building height, whereas the convex and concave shapes have larger building widths in the middle or the upper part of the buildings. This feature can significantly reduce the wind load on the building due to the smaller frontal projected area, and thus less structural materials are required for maintaining the allowable amount of lateral deflection when withstanding the overturning moment. This similar observation can also be found in the rounded-square buildings (i.e. design *(d)*-*(f)*). Even though design *(b)* and *(e)* also have the linear vertical profile, the former has slightly better structural efficiency, due to the more aerodynamically streamlined circular shape resulting in a smaller amount of wind loads than the rounded square building. In this example, only the code-stipulated wind loads were used in the analysis, computational fluid dynamic analysis tools or wind tunnel testing data can be used for a more accurate and sophisticated structural performance assessment, especially for the buildings with irregular shapes.

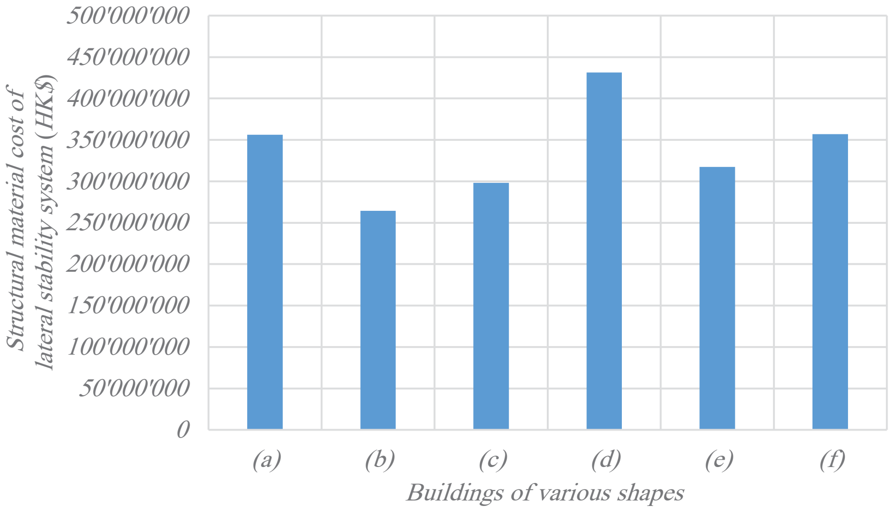
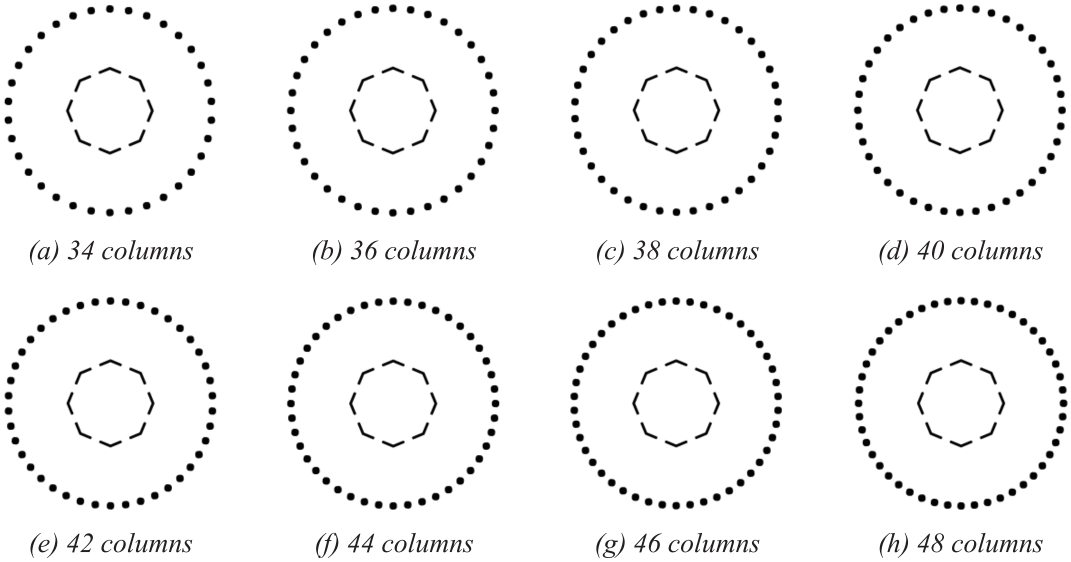


Figure 8: Optimised structural material cost for the different building shapes

3.2. Structural Topology Design

The building shape design candidate with the best structural efficiency (i.e. design *(b)*) is adopted and the design process then proceeds to the structural topology design. In this illustrative example, the tubular structural system is used in this circular building. The structural system consists of a core wall part and a perimeter frame of beams and closely spaced columns. The number of perimeter columns is the only topology variable in this example. 8 cases of different number of columns were investigated, as shown in *Figure 9,* ranging from 34 columns to 48 columns. The average column spacing is about 3-6 meters, which is within the optimal range of column spacing for the tubular system, and the columns are separated reasonably wide enough for practical reasons and constructability concerns.



(a) 34 columns *(b) 36 columns* *(c) 38 columns* *(d) 40 columns*

(e) 42 columns *(f) 44 columns* *(g) 46 columns* *(h) 48 columns*

Figure 9: Variations of the structural topology variable (i.e. no. of perimeter columns) for the example building

The member sizing optimisation process was then undertaken for the 8 design candidates with different numbers of perimeter columns. The optimised structural material consumptions for each individual building are shown in *Figure 10*. The structural material weight of the vertical axis in the figure represents the total weight of the construction material required in the lateral stability system and includes the material of the perimeter steel frame and the interior concrete core wall. It shows the trend that the buildings with closer perimeter column spacing require less structural materials for achieving the same structural performance. The design with 48 columns can save about 16% of structural materials, comparing to the design with 34 columns. Because of the working principle of a tubular structural system in this circular building, the closely spacing column can reduce the shear lag effects of the perimeter beams, which in turn that the beams can be more efficient for carrying loads between the columns. Therefore, the tubular structures with closely spaced perimeter columns can achieve better structural efficiency. In this case, the design with 46 or 48 columns is much preferable and suggested. This part of the example can demonstrate how the proposed framework provides recommendations and suggestion for assisting the structural engineers.

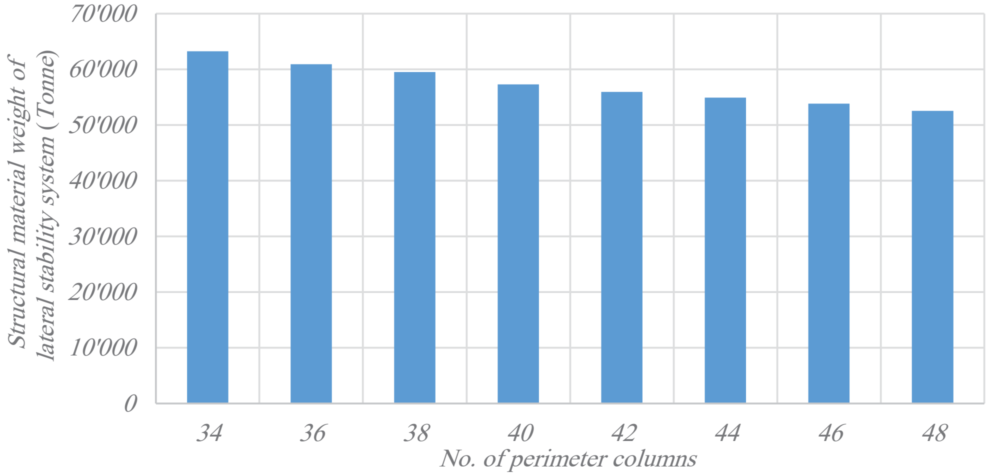


Figure 10: Optimised structural material consumptions for the design candidates with different numbers of perimeter columns

Despite the fact that the design candidates with more columns are preferable from the structural engineering point of view, these design solutions may not be practically and aesthetically desirable for the clients and architects. The closely placed columns would create blockage for sunlight penetrating the indoor environment, which reducing the natural daylight for the building. The design may also affect the aesthetic value of the building, for instance, the densely spaced columns may create an unattractive interior environment. This kind of conflicts requires collaboration of architects and engineers and interactions throughout the design process.

4. Conclusion and Future Work

This paper presented a parametric design and structural optimisation framework for early design stages of tall buildings. On top of the synergy between architectural and structural discipline, this work introduced a numerical representation method for building shape generation and incorporated a robust structural optimisation technique to accurately evaluate each design candidates. A case study demonstrated how the proposed framework was applied in the early design stage of a tall building which can provide recommendations for architects to improve the design and guide engineers to come up with an efficient structural system design. Even though the work of this paper focused on the early building design phase, the proposed framework can be further extended to later part of the design and provide a base platform for detailed design, for example rebar and steel connection design. These would provide a more holistic tall building design platform for the early to detailed design phases and for system-level to component-level design.

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