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Optimum Structural Patterns for Vertical Buildings

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Abstract

This paper investigates the optimality of non-routine regular and irregular structural patterns of different degrees of granularity for vertical buildings. Two approaches, based on two different computational methods, are used. The first is based on non-routine regular patterns mostly found in nature and in recent building designs, and the second uses shape grammar for generating non-routine irregular patterns and the simulated annealing method to optimise the patterns. A multi-criteria decision making framework based on the Simple Additive Weighting method is used to evaluate the performances of the different regular patterns on the four decision criteria of efficiency, economy, expressiveness and environmental sustainability.

Keywords: structural patterns, multi-criteria, optimisation, simulated annealing, vertical buildings, perimeter structure.

1 Introduction

More than four decades of research in structural optimisation has provided a broad range of computational methods for optimising structural features such as shape, topology and member sizes. These include novel synthesis techniques such as Evolutionary Structural Optimisation (ESO), the generative structural shape annealing, and topology optimisation. Most research, however, has focussed on the single criterion of efficiency, which is usually defined as minimum weight, and is of main concern in certain engineering applications. Even where the optimisation problem was posed in terms of multi-criteria, the additional criteria were introduced only to optimise some aspects of structural behaviour. There has been very little research done in developing computational methods for optimising other criteria for the structure, particularly those which are relevant to building designs.

Nevertheless, a structure has other dimensions along which it influences building designs and can hence also be optimised. Billington identified the three dimensions of a structure as; scientific, symbolic and social [1]. While efficiency reflects the scientific dimension, the other two dimensions need to be addressed as well, in an integrated design of a building. The social dimension relates to the economy of construction; and the symbolic dimension to aesthetic perception. In addition, there is now a growing concern about the impact of building designs on the environment, and it is estimated that the structure accounts for more than 10% of energy usage and greenhouse gas emission over 50 years of a building's lifespan. Further, one-third of the material used and the waste generated are as a result of the structural system selected [2]. Hence, it is also important to consider environmental sustainability in the design of building structures.

Thus, in this paper, the integration of structural design within the overall building design process is posed as a multi-criteria optimisation problem, with efficiency, economy, expressiveness and environmental sustainability (4Es) as the decision criteria. As in most of the other multi-criteria problems, the values of the criteria are usually measured and expressed in different units, and there is the invariable trade-off between the different criteria during the decision making process, based on the decision maker's preferences. A multi-criteria decision making framework that can address these issues is hence also required, and a Simple Additive Weighting (SAW) method is used. In order to make the problem tractable, at this stage of research development, the investigation have been limited to vertical building structures and structural pattern as the high level feature that is manipulated to optimise the four decision criteria.

Vertical building structures have developed in response to the requirements arising from the continuing increase in world population and rapid urbanisation. In recent times, the demand for these structures has increased enormously, especially driven by environmental considerations. In a resource scarce era, expanding a building vertically to create a denser city is more energy efficient because the energy consumed for transferring electricity and transportation can be minimised, while the land used for building will be reduced and thus saving more green areas [3]. Therefore, this paper focuses on the optimum design of vertical structures.

In a vertical structure, structural pattern is one of structural features which can be manipulated to optimise performance in terms of multi-criteria. By arranging the structural members in a particular pattern, an efficient structure can be produced, whereas the economy of construction can be increased by grouping structural member dimensions according to their arrangement. Moreover, by employing an optimum pattern, member sizes can be minimised and thus opening areas can be maximised to ensure occupant comfort. In terms of expressiveness, the use of a certain pattern in a vertical building can produce a unique architectural expression, given that a monotonous rectilinear prismatic form is often adopted for economic and pragmatic reasons. For this reason, even though there has been very little research and implementation of non-routine structural patterns in vertical structures, the recent trend has been for more vertical buildings to employ non-routine structural patterns. The patterns explored in recent notable building designs have been mainly non-routine with some regular and the others irregular, and with varying degrees of granularity. The possibilities to create complex patterns using advanced computer technology available at present have given impetus to this trend.

This paper examines the optimality of non-routine regular and irregular structural patterns employed on the perimeter of vertical buildings in terms of the multiple criteria of efficiency, economy, expressiveness and environmental sustainability. In here, non-routine patterns are employed on the perimeter of vertical buildings to replace the usual orthogonal arrangement and create optimum structural designs.

Two cases are considered in examining the performance of structural patterns in two distinct height ranges and their corresponding dominant loading conditions - medium-rise case with vertical gravitational loads and the high-rise case with horizontal wind loads. For each case, two types of patterns were investigated - non-routine regular patterns obtained either from recent buildings or those available in nature, and non-routine irregular patterns generated by the computer.

Designs with regular patterns were optimised using a combination of CAD modelling and a technique based on simple resizing of elements based on local information provided by the analysis results, on both stresses and deflections, to select optimum members from a discrete sections library while keeping the pattern geometry and granularity fixed. Designs with irregular-patterns were synthesised by a shape grammar approach and optimised by the simulated annealing method. Both approaches use a multi-criteria decision making framework. The first evaluates the performance of the different regular patterns on the four decision criteria and then ranks the patterns by the Simple Additive Weighting method after the performance values have been normalised.

2 Structural Pattern and Optimisation

2.1 Developments in Structural Patterns

Structural pattern can be defined as an arrangement of structural components, including joints, which impacts on visual appearance, behaviour and construction complexity. It can be seen on the elevation and plan of a building, or on a three-dimensional surface structure.

Three structural features traditionally considered in previous structural optimisation research are shape, topology and member sizes. Shape represents the 2D and 3D form of the structure, and usually modified by varying the joint or node positions in skeletal structures; topology is the pattern of connectivity of structural elements; while size specifies cross-sectional dimensions of structural members. Structural pattern is a high level feature that includes information on geometry, granularity and member sizes, and hence can encapsulate all three structural features described above.

Structural patterns have existed throughout architectural history, whether it was purposely designed to optimise structural performance or subsequently introduced to distribute loads evenly among structural members following the design decision to use particular form and/or material. However, only in wide-span and surface structures has structural pattern been widely manipulated in the past and considered as a significant feature for designing an optimum structure. The structural pattern of the geodesic dome, lamella configuration of the Sports Palace by Pier Luigi Nervi and triangular pattern used in trusses and surface structures are some examples of it.

In vertical buildings, despite the use of a variety of bracing systems such as X, V and Z as patterns of bracing, the dominant shape used is still the rectangle or square forming an orthogonal pattern on the perimeter. It thus raises the crucial question; is the orthogonal pattern the most optimum? This pattern transfers loads in bending and compression, is prone to shear lag effects under lateral loads, uses the most complicated joints to construct and dismantle, tends to create a denser grid, which obstructs view, natural light and ventilation and hence detracts from occupants comfort. It does not align with the principles used by structures in nature, which have been shown to have attributes of 4Es. Thus, there is now a move to explore other patterns for vertical buildings.

Recently, with the development of computer technology there has been a major shift in the development of vertical buildings. In addition to the emergence of new and complex forms, there has also been a move towards the use of non-routine patterns. The 25 storey COR Building in Miami [4] and the 22 storey O-14 commercial tower in Dubai [5], which fall into the medium-rise category, both use circular pattern with identical or distinct granularity. On the other hand, the proposed 93 storey Transbay Transit Centre in San Francisco [6] and the 60 storey Torre Absolute in Ontario, Canada [7] were designed with more irregular patterns.

2.2 Developments in Structural Optimisation

Structural optimisation has widely developed from traditional empirical-based techniques into mathematical-based design methods that unify logic and aesthetics [8]. In fact, the key method of the future is a combination of computer modelling and mathematics. A number of recent methods were developed based on the principles of natural systems. Amazed at the complexity, durability and adaptability of natural creatures, scientists and designers continue to learn from nature and apply the knowledge gained in the creation of the built environment. These principles are translated into mathematical formulae and computational processes to generate complex and innovative forms or patterns.

The three main features of the structure - shape, topology and size - were the main focus of the structural optimisation methods. Some techniques focused mainly on optimising one of them;

- Form finding and optimisation which focus on shape or geometry of the structure is a design method to develop a structural form based on the self-organisation of a material system especially in response to external forces [9]. Recent computational methods are sensitivity analysis using the Finite Element Method (FEM) [8] and evolutionary form-finding method using evolutionary algorithm for automating repetition and creating adaptive qualities [10]. In both methods, minimum strain energy is taken as the single or main decision criterion. Even though, the form produced is an attractive free-form structure, the expressiveness is not a governing criterion; it is just a consequence of finding an efficient form. The optimisation process of sensitivity analysis with FEM is based on mathematical programming, while evolutionary form-finding method combines mathematics with natural process of evolution.

- Topology optimisation is a method that designs topology (connectivity of structural members) by distributing a given amount of material in a design domain according to load and support condition so that the stiffness of the structure can be maximised [11]. In here, a single criterion is defined as minimum compliance or maximum global stiffness.
- Size optimisation finds the optimal cross-sectional dimensions of the structural members while the geometry and topology of the structure are fixed. Most methods have relied on classical optimisation using differential calculus, mathematical programming methods and more recently evolutionary computing methods such as genetic algorithm. In discrete size optimisation, the sizes of structural members are chosen from a discrete sections library, while in continuous size optimisation, the sizes are optimised between the range of minimum and maximum sizes and the dimension precision defined formerly. Once more, efficiency is taken as the criterion for decision making.

Other methods manipulate a mixture of shape, topology and size or two of them to obtain an optimum structural design;

- ESO is a method to optimise a design by gradually removing inefficient elements from a structure, based on Von Mises stress of each element using finite element method as an analysis tool [12, 13]. In here, efficiency is indirectly taken as the main decision criterion, while the result can be an optimum structural form, topology, size or a mixture of them.
- Structural shape annealing - a combination of structural shape grammars and simulated annealing optimisation process - is implemented as a research computer program called eifForm [14, 15]. It is a generative design method based on natural analogy and logical basis which optimises designs by applying shape, size and topology transformation rules to an initial design using a stochastic optimisation approach with a search algorithm to check random changes by assessing the performance and then selecting the optimum. In here, all three features - shape, topology and size - can be manipulated, and the criteria of efficiency, economy, utility and aesthetics are optimised by combining them into a cost function that measures the global performance.

Although some of the above methods can be used to optimise the structural patterns, a specific method for optimising the bracing patterns of a vertical rectangular frame structure through an evolutionary process was only recently presented [16]. Discrete patterns of bracing and discrete sections were also used in the optimisation of rectangular tall steel frames [17]. In both these investigations weight of structure was only optimised.

In this paper, optimum structural designs, with regular and irregular patterns, for medium-rise and high-rise vertical buildings are considered. For both cases, a 3D structure on the perimeter of the building is assumed, rather than the plane frame structures considered in previous investigations. Two approaches are used for arriving at optimum structural patterns. The first uses discrete patterns that differ from the traditional rectangular ones and are based on either those available in nature and/or used in recent notable buildings, and optimises the sizes of structural members, selected from a library of discrete sections, by maximising the efficiency of individual members using the Multiframe4D software. The second approach uses structural shape annealing capability of the eifForm software, to initially generate irregular patterns for the 2D frame, optimised with the preset built-in decision criteria. This optimised solution is then assembled to form the 3D structure, which is then further optimised using the optimisation method outlined for the first approach.

3 The Structural Optimisation Problem

This section describes the structural optimisation problems posed and solved in this paper. It identifies the design requirements, the features of the structure that are fixed and those that are manipulated during the optimisation process, and the procedures for evaluating the performances of the solutions on the decision criteria. In all cases, steel structures for typical office buildings are assumed.

3.1 Design Requirements

3.1.1 Functional Requirements

In vertical structures, as the slenderness increases with height, the lateral loads begin to dominate the design. Schueller [18] defines 20-30 storeys buildings as having medium-rise structures, and the high-rise structures as those in buildings with height more than five times its minimum base dimension. In this latter case, lateral deformation becomes the major concern. Besides, above 60 storeys height, a perimeter structure is required to achieve maximum structural depth for resisting lateral loads. Thus, two cases have been considered;

- Case 1 : Medium-rise structure subject to vertical loads with building height of 80m (20 storeys high) and a slenderness ratio (Height : Width) of 2 : 1.
- Case 2 : High-rise structure subject to lateral loads with building height of 240m (60 storeys high) and a slenderness ratio (H : W) of 6 : 1.

3.1.2 Behavioural Requirements

The usual limits on stresses and deflections are applied as constraints. The vertical deflection is limited to less than span/250mm and the lateral sway is limited to under Y/300mm, where Y is the height of the building.

3.1.3 Design Loads

- For medium-rise case, the vertical imposed loads recommended in AS1170.1:2002 - uniform distributed load of 3kPa for offices.
- For high-rise case, the lateral wind loads based on AS1170.2:2002, with wind pressure only on the windward wall. It was assumed that the site is located in Sydney with an urban terrain and there is no shielding effect from neighbouring buildings. Hence, the wind pressure increases from 0.432kPa at ground level to 1.037kPa at 240m high.

3.2 Structural Features

3.2.1 Form

A prismatic form with square plan was used, as it is one of the most common shapes for vertical buildings. 40m was chosen as the base dimension to achieve the desired height to width ratio (Table 1).

Case	No of storeys	Floor-to-floor height	Building Height	Plan dimension	Ratio H : W
Medium-rise	20	4m	80m	40m x 40m	2 : 1
High-rise	60	4m	240m	40m x 40m	6 : 1

Table 1: Building dimensions for structural design.

To fit the non-routine patterns within the prismatic form, some treatment of the building corners, such as indentation and inclined faces, were allowed to accommodate the specific pattern. This can result in the reduction of the floor area at some levels; however, it is advantageous in improving the aerodynamics of the building and hence reducing the lateral loads.

3.2.2 Pattern

The two aspects of a pattern that can be varied within the optimisation process are the geometry and granularity. Three non-routine patterns from previous buildings - triangular, hexagonal and diamond - were selected in optimising the building perimeter structure, with the routine orthogonal pattern providing the benchmark for comparison. The irregular triangular patterns were generated and optimised by the structural shape annealing process with the eifForm software.

For the orthogonal pattern, each rectangle is selected one storey high to reflect the usual arrangement for framed tube structures. While, for non-routine patterns, a larger pattern size, similar to the patterns implemented in recent building projects, was investigated. In both the Hearst Headquarters and the St. Mary Axe, each of the triangular and diamond patterns are four storeys high, which is beneficial not only for minimising the structural weight, but also for creating larger openings that contribute to aesthetics, energy efficiency and occupant comfort. Thus, for each non-routine pattern, the height of the pattern was chosen as four storeys high.

3.2.3. Joints, supports and sub-systems

In computer modelling, all joints are set to be rigid and all supports are fixed. It was assumed that the perimeter structure and the central core are sub-systems that work together in resisting the loads. Since the intention was to optimise the patterns on the building perimeter, only perimeter structures were modelled, analysed and optimised. The central core was not included in the model, but its existence was considered in reducing the loads to be resisted by the perimeter structure. From a study of the ratio of central core width to building width in existing buildings, the central core was assumed to be 16m wide with a ratio of 2:5. It was assumed that the core resists 50% of the vertical loads and 40% of the lateral loads. Since the intention was to find an optimum pattern for the vertical structure, floor beams were considered as secondary members and were not included in the model, unless they were part of the pattern.

3.2.4. Member Sizes

In optimising the designs for regular patterns, the member sizes were selected from a library of member sections. For the medium-rise case, Universal Beam (UB) and Universal Column (UC) profiles were used for the orthogonal pattern, while Circular Hollow Sections (CHS) were used for non-routine patterns. For the high-rise case, Welded Beam (WB) and CHS were used for the orthogonal and other patterns respectively. For optimising designs with irregular patterns, continuous size optimisation was performed in eifForm, while discrete size optimisation in Multiframe4D was carried out for a customised CHS sections library created based on eifForm output file sections.

3.3 Decision Criteria

The designs based on the alternative regular and irregular patterns are first evaluated for their performance on the four decision criteria identified previously. The features of the design used in the evaluation of the criteria are described below. These features are treated as indicators/sub-criteria, and the values of these are then aggregated to get the overall performance on the particular criterion.

3.3.1 Efficiency

An efficient structure is defined as having the highest strength/maximum load-supporting capacity and the lowest weight [1]. Thus, structural efficiency can be defined as the ratio of the load carried by a structure to its total weight (strength to weight ratio). In this work, all designs were generated for the same loading conditions. Hence, total weight was used as the efficiency measure.

3.3.2 Economy

Economy is considered to be mainly a function of construction cost. It is also known as technological efficiency, which is the efficiency in the manufacture and construction of the structure. It can also be defined as cost per square metre or strength per unit cost. In the performance evaluation, the indicators for economy are:

- Minimum number of joints
- Minimum number of members.
- Minimum number of distinct lengths.
- Minimum number of distinct sections.

It is possible to improve the economy of the solution by grouping structural members to limit the number of distinct sections.

3.3.3 Expressiveness

Every structure, just like any other human creation, has an aesthetic value. To create an expressive structure, it should be correctly designed according to both its mechanical and spatial functions. Moreover, the structure should be exposed for it to enrich architecture [19].

To evaluate the expressiveness of each solution, some aesthetic indicators were required. Thus, innovation and complexity were chosen as the sub-criteria. The more original the pattern, the higher its innovation, whereas the more complex the pattern, the more expressive the design. The evaluations are thus in terms of linguistic values which need to be aggregated to obtain an overall performance value.

3.3.4 Environmental Sustainability

This criterion is based on the concept of sustainable development which is defined as "…development that meets the basic needs of the present…without compromising the ability of future generations to meet their own needs" [20]. Three main principles of sustainable design are low resource consumption, low environmental impact and maximum occupant comfort. Thus, the evaluation of environmental sustainability was performed based on:

- Minimum weight, to show low resource consumption.
- Maximum opening areas, to represent maximum occupant comfort and minimum operational energy usage. With larger opening, natural ventilation can be maximised, so that the use of air-conditioning can be reduced. There is, however, a need for a good interior layout and appropriate noise and dust shielding elements to balance large openings in vertical buildings. In here, total opening area of each solution was calculated using area inquiry tool from AutoCAD.
- Flexibility of joints, to signify low environmental impact by increasing the re-useable potential of structural members.

4 The Optimality of Non-routine Regular Patterns

4.1 The Synthesis Process

In optimising structural designs with non-routine regular patterns, two processes shown in Figure 1 were carried out; (i) generating a 3D model of design solutions with CAD software and (ii) assembling and then optimising each solution in Multiframe4D.

4.1.1. Generating 3D Models Using AutoCAD

3D modelling with AutoCAD was used to generate 3D model of each design. For each case, four initial models representing the four distinct patterns - orthogonal, triangular, hexagonal and diamond - were created and became the input for the next process - 3D skeletal structure modelling and size optimisation with Multiframe4D. However, when a solution fails to comply with the requirements (the solution failed even with the biggest section available in Multiframe4D sections library), CAD modelling was used again to change the geometry and granularity of the pattern and generate other alternative solutions. This cycle was repeated until a feasible and optimum solution for each pattern was achieved.

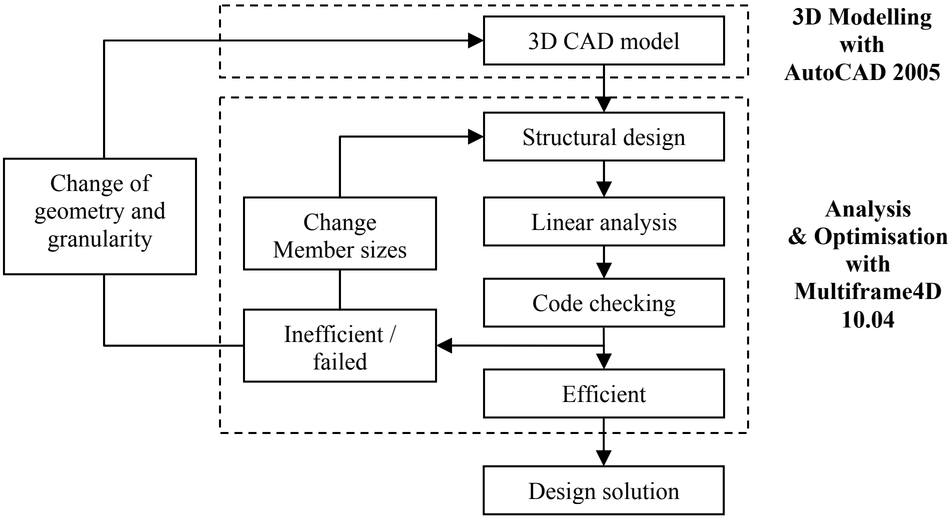

Figure 1: The synthesis process for designs with regular-patterns.

4.1.2. Assembling & Optimising Design Solutions Using Multiframe4D
Once the 3D model was created, it was imported into Multiframe4D to assemble a complete structure. The analyse/check/design cycle in Multiframe4D was used to optimise each solution. Structural designs were optimised by changing member sizes provided in the sections library till the minimum weight of structure is achieved.

Linear analysis was used to determine member forces and deflections for each of the solutions, and efficiencies for each member, expressed as a percentage of the member capacity used in the design, were then evaluated based on a predefined user code. For this research, the sizes of structural members were designed to satisfy the limit of axial force, bending and combined stresses set in Multiframe4D user code while the slenderness limit was ignored. Member sizes were adjusted both by automatic design feature of Multiframe4D based on local information provided in the previous efficiency check, and manually, when required. The objective is to achieve maximum strength with a minimum weight. Therefore an overall efficiency of 100% for each of the members is the best case scenario.

4.2 Design Results

4.2.1 Medium-rise Case
The optimum perimeter structures for medium-rise case, for the four distinct patterns considered, are shown in Figure 2, and details of the designs are in Table 2.

4.2.2 High-rise Case
The optimum designs for high-rise case, for the four distinct patterns considered, are shown in Figure 3, and details of the designs are in Table 3.

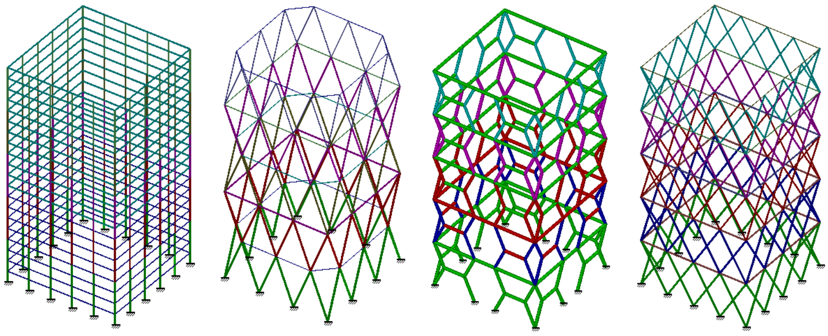

Figure 2: 3D models of medium-rise designs with regular patterns.

	Orthogonal	Triangular	Hexagonal	Diamond
Total mass (kg)	219,040	107,767.37	593,381.04	202,698.52
Member profiles	UB & UC	CHS	CHS	CHS
No. of joints	420	72	152	176
No. of members	800	180	260	400
No. of distinct lengths	2	3	3	2
No. of distinct sections	7	9	5	9
Opening area (m^2)	11,672.60	11,039.28	10,379.72	11,151.40

Table 2: Attributes of medium-rise designs with regular patterns.

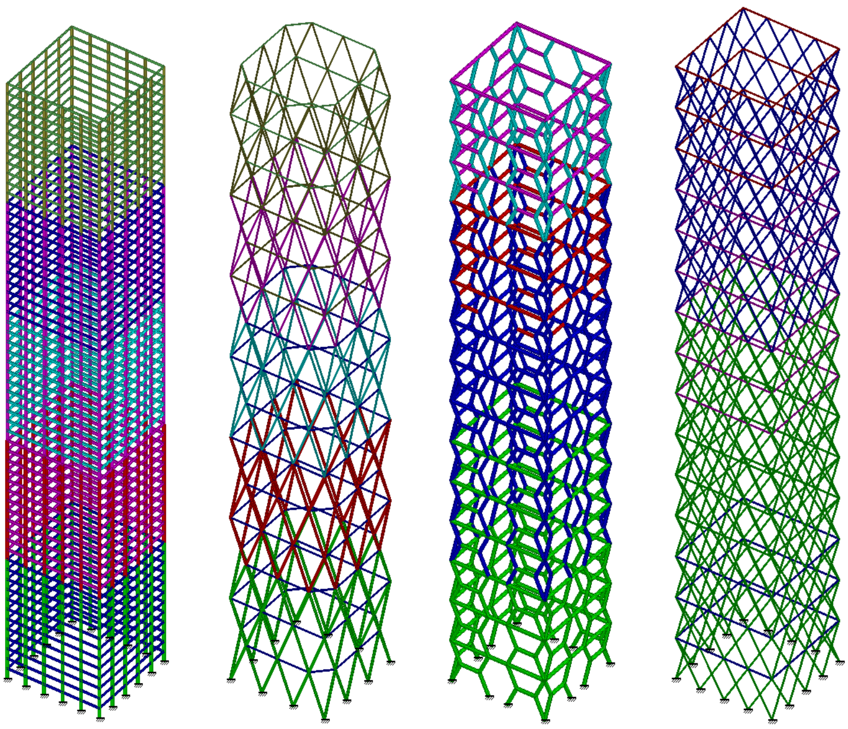

Figure 3: 3D models of high-rise designs with regular-patterns.

	Orthogonal	Triangular	Hexagonal	Diamond
Total mass (kg)	2,888,640	891,209.83	2,858,329.56	1,372,388.38
Member profiles	WB	CHS	CHS	CHS
No. of joints	1220	192	432	496
No. of members	2400	540	780	1200
No. of distinct lengths	2	3	3	2
No. of distinct sections	7	7	7	5
Opening area (m^2)	26,372.60	32,183.36	28,819.12	32,363.88

Table 3: Attributes of high-rise designs with regular-pattern.

4.3 Performance Evaluation

The overall performances of the solutions, in terms of multi-criteria, were evaluated by the Simple Additive Weighting (SAW) Method, by carrying out a compensatory multi-criteria analysis. It is a classical technique based on Multi-Attribute Utility Theory (MAUT) which permits trading-off between criteria and defining a utility function which expresses decision-maker satisfaction of the solution based on the relative weighting of the criteria [21]. In here, the performances of structural solutions on different criteria are defined on one common scale of measurement. Then, the scores are manipulated mathematically to compute the overall performance. Equation (1) shows that the overall score (V_i) for a solution (i) is estimated by multiplying the comparable normalised rating for each criterion by its importance weighting and then summing these results over all criteria.

$$V_i = \sum_{j=1}^{j=n} w_j \cdot r_{ij} \qquad (1)$$

where: w_j = weighting for criterion j
r_{ij} = rating for option i on criterion j

A 0-10 rating was used to represent the performance of the solutions on all the criteria. For quantitative criteria, the best performance was given a score 10, while others were rated with respect to the best value. On the other hand, for qualitative criteria, 0-10 rating was assigned for each solution. Two weighting values were used in the evaluations; presumption of equal weight (weighting A) and the preference of expressiveness and environmental sustainability over the other criteria (weighting B), to examine the role of decision maker's preferences in the assessment process.

4.3.1 Medium-rise Case

The performance evaluations for medium-rise design solutions with weightings A and B are shown in Table 4.

Based on both weightings, the triangular pattern is the optimum and the three non-routine patterns perform better than the orthogonal pattern. Different scores between two weightings indicate that the objective of the optimisation process can be adjusted based on the decision maker's preferences. Thus, by varying the weighting further, the ranking of the solutions can be changed.

Criteria		Weighting A (Equal weighting)					Weighting B (Preference on C3 and C4)				
		Weight	□	△	⬡	◇	Weight	□	△	⬡	◇
C1		0.25	4.92	10.00	1.82	5.32	0.08	4.92	10.00	1.82	5.32
C2	C2.1	0.0625	1.71	10.00	4.74	4.09	0.02	1.71	10.00	4.74	4.09
	C2.2	0.0625	2.25	10.00	6.92	4.50	0.02	2.25	10.00	6.92	4.50
	C2.3	0.0625	10.00	6.67	6.67	10.00	0.02	10.00	6.67	6.67	10.00
	C2.4	0.0625	7.14	5.56	10.00	10.00	0.02	7.14	5.56	10.00	10.00
C3	C3.1	0.125	2.00	6.00	9.00	8.00	0.21	2.00	6.00	9.00	8.00
	C3.2	0.125	2.00	5.00	8.00	7.00	0.21	2.00	5.00	8.00	7.00
C4	C4.1	0.083	4.92	10.00	1.82	5.32	0.14	4.92	10.00	1.82	5.32
	C4.2	0.083	10.00	9.46	8.89	9.55	0.14	10.00	9.46	8.89	9.55
	C4.3	0.083	2.00	10.00	6.00	8.00	0.14	2.00	10.00	6.00	8.00
Overall Score			**4.46**	**8.34**	**5.74**	**6.90**		**4.02**	**7.88**	**6.62**	**7.35**
Rank			**4th**	**1st**	**3rd**	**2nd**		**4th**	**1st**	**3rd**	**2nd**

Table 4: Performances of medium-rise solutions based on weightings A and B.

4.3.1 High-rise Case

Table 5 shows the performance evaluations for the high-rise solutions.

Criteria		Weighting A (Equal weighting)					Weighting B (Preference on C3 and C4)				
		Weight	□	△	⬡	◇	Weight	□	△	⬡	◇
C1		0.25	3.09	10.00	3.12	6.49	0.08	3.09	10.00	3.12	6.49
C2	C2.1	0.0625	1.57	10.00	4.44	3.87	0.02	1.57	10.00	4.44	3.87
	C2.2	0.0625	2.25	10.00	6.92	4.50	0.02	2.25	10.00	6.92	15.00
	C2.3	0.0625	10.00	6.67	6.67	10.00	0.02	10.00	6.67	6.67	10.00
	C2.4	0.0625	7.14	7.14	7.14	10.00	0.02	7.14	7.14	7.14	10.00
C3	C3.1	0.125	2.00	6.00	9.00	8.00	0.21	2.00	6.00	9.00	8.00
	C3.2	0.125	2.00	5.00	8.00	7.00	0.21	2.00	5.00	8.00	7.00
C4	C4.1	0.083	3.09	10.00	3.12	6.49	0.14	3.09	10.00	3.12	6.49
	C4.2	0.083	8.15	9.94	8.90	10.00	0.14	8.15	9.94	8.90	10.00
	C4.3	0.083	2.00	10.00	6.00	8.00	0.14	2.00	10.00	6.00	8.00
Overall Score			**3.68**	**8.48**	**5.98**	**7.31**		**3.36**	**7.98**	**6.85**	**7.88**
Rank			**4th**	**1st**	**3rd**	**2nd**		**4th**	**1st**	**3rd**	**2nd**

Table 5: Performances of high-rise solutions based on weightings A and B.

As in the result for the medium-rise case, the triangular pattern is again the optimum and has five best scores over the ten criteria and sub-criteria. The higher scores for solutions with non-routine patterns compared to the orthogonal pattern shows that these patterns are optimum especially for resisting lateral loads.

5 The Optimality of Non-routine Irregular Patterns

5.1 The Synthesis Process

Structural shape annealing, a generative design method, based on shape grammar and simulated annealing method of optimisation, and available in the eifForm software [15], was utilised to find an optimum irregular pattern. Since eifForm was created for designing free form surface structures [22], after experimenting, it appeared that the program could not be used to automatically modify a perimeter structural pattern of a 3D prismatic structure. Therefore, eifForm was employed to initially generate an optimum 2D structural pattern which was then assembled into a 3D structure using AutoCAD, and then optimised in Multiframe4D. Figure 4 shows the diagram of the synthesis process.

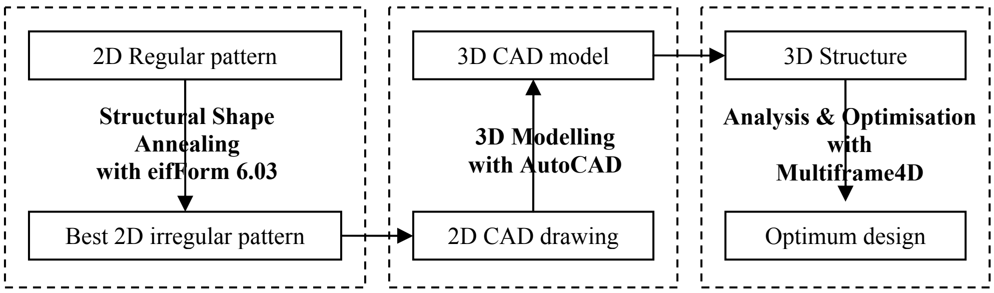

Figure 4: The synthesis of structural designs with of irregular-patterns.

5.1.1. 2D Pattern Generation

Structural shape annealing in eifForm includes a grammatical transformation of an initial design by randomly applying shape grammar rules and repeated structural analysis as well as performance evaluation to achieve the best possible design for the design constraints and objectives. The objectives that can be optimised by this program are efficiency, economy, utility and aesthetics [15]. The structural performance criteria and 2D geometric obstacles are implemented as soft constraints with cost penalties for their violations.

The eifForm program receives information regarding the initial design from an XML file. All of the settings; including activation of transformation rules, choice of structural analysis tool, objectives and constraints to be satisfied are defined in the input file by modifying the XML file in a text editor. At the end of the annealing process, eifForm produces XML and dxf output files, containing the best designs along with information regarding their performances. Figure 5 illustrates the structural shape annealing process in this research.

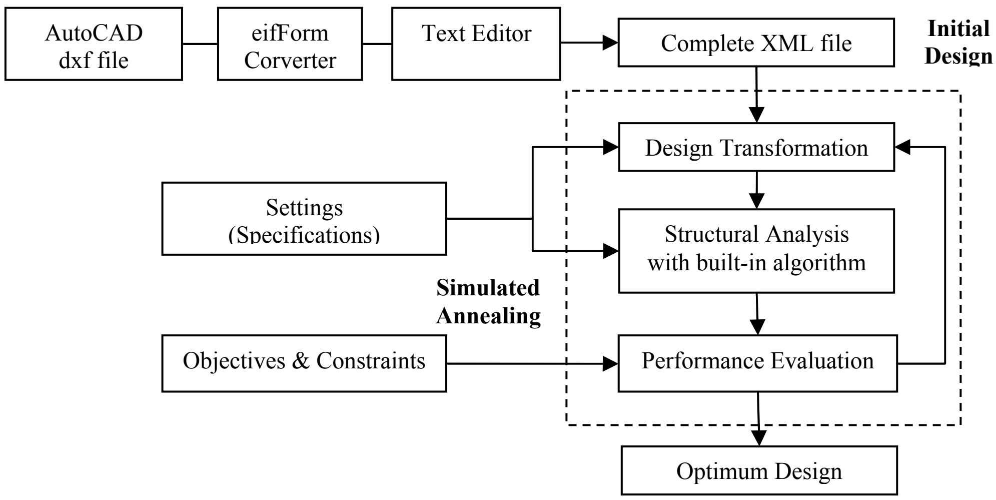

Figure 5: 2D pattern generation process with structural shape annealing.

All transformation rules - size, shape and topology - were activated in the shape annealing process to increase the chance of obtaining a design with an irregular-pattern. For size transformation, the sizes were chosen in the continuous range between minimum and maximum areas defined in the input file. For performance evaluation, the cost function, which represents the performance of the design generated, was evaluated based on the preset weighting. The cost function is the sum of objective and constraint cost. The three objectives of efficiency, identified with minimum mass; economy, shown with minimum class (grouping of members' sizes) and aesthetics, measured with aesthetic length and aesthetic golden ratio were selected with equal weighting, while the utility criterion was not activated as the boundary of the design is fixed. Meanwhile, stress and buckling constraints were activated with default weights in eifForm.

For the initial design, the same triangular pattern employed in designs with regular-patterns was used. There were two reasons for this: (i) eifForm only works with triangulated designs and (ii) the designs with regular-triangular patterns are optimum for both cases from previous performance analysis. The input file configures an initial design as 2D planar structure with four storeys high triangular patterns. The chamfered corners in previous solutions were ignored. Since the resulting design would act as one facade of a prismatic building and would be assembled into a 3D structure, the outer form of the design should not be changed. For this reason, 2D geometric obstacles were defined to provide a limited boundary for the design transformation. Moreover, while other points were allowed to move along with their imposed loads, all points on the two sides of the design and at the top were set so that they could not move during the annealing process.

For both cases - medium and high-rise cases, two annealing trials were performed with one run of full annealing cycle each and two others with two run of the full cycle. As a result, the six best alternative designs with variation on their performances were obtained, and then the best design was chosen.

5.1.2. 3D Modelling and Structural Optimisation

Figure 6 shows the synthesis process for the initial 3D structural design.

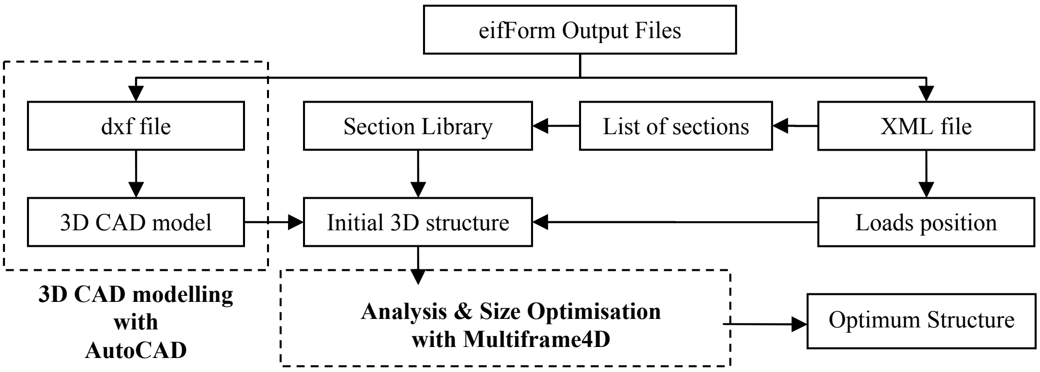

Figure 6: Synthesis process for 3D designs with irregular-patterns.

After the 2D optimum pattern for each case was obtained, the 3D model of the structural solution was assembled using AutoCAD. This 3D model was then analysed and optimised in Multiframe4D.

The tube members in eifForm have a different formula compared to the standard CHS in Multiframe4D, hence a specific CHS sections library was created for the optimisation process. Since continuous size optimisation was used in generating optimum 2D patterns, member diameters were rounded to discrete sections at 5cm intervals to reduce the variation and limit the number of sections to be created. For the medium-rise case, the loads moved along with the joints in the annealing process, so that the loads were no longer applied at floor levels. This was accepted for practical reasons considering that the total loads remained the same.

After the initial structure was completely defined, linear analysis was performed with Multiframe4D according to the specified code as for the previous designs. The efficiency was then checked and the structure was optimised using size optimisation by varying member sizes until a feasible and efficient solution was produced.

5.2 Design Results

The initial and optimum 2D design, along with the optimum 3D perimeter structure produced for medium and high-rise cases are shown in Figures 7 and 8 respectively.

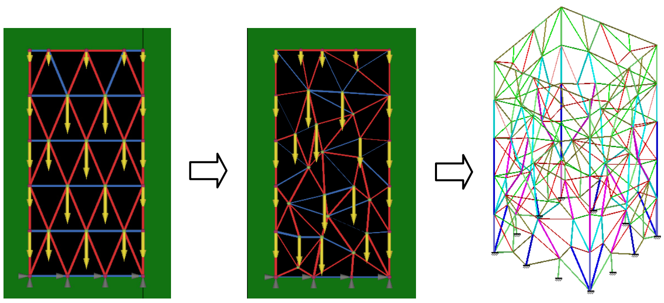

Figure 7: 2D initial design, 2D optimum design and 3D model of medium-rise design with irregular-pattern.

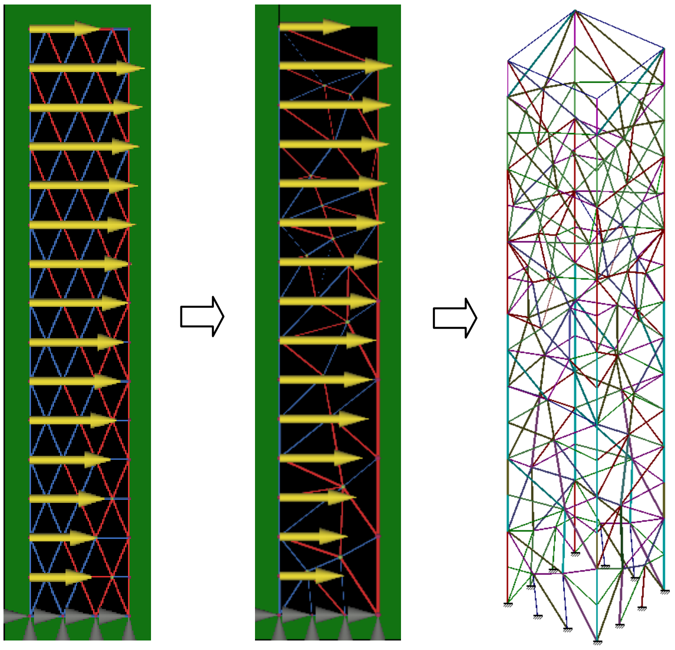

Figure 8: 2D initial design, 2D optimum design and 3D model of high-rise design with irregular-pattern.

5.3 Performance Evaluation

To evaluate the optimality of designs with irregular-triangular pattern, their performances were compared to the design with routine orthogonal pattern as the benchmark and non-routine regular-patterned designs. Since some performances are not comparable due to several reasons; such as the use of customised CHS profiles in the irregular-patterned designs, and also as multi-criteria optimisation was carried out during the structural shape annealing process, the SAW Method was not subsequently used. Thus, for each criterion, only comparison of performances between all solutions was performed.

5.3.1. Medium-rise Case

Table 6 presents a comparison of performances of medium-rise designs.

The irregular-patterned design is quite optimum in terms of economy, expressiveness and environmental sustainability. It has fewer joints and members compared to the benchmark. It is the most expressive one because the pattern was originally created using structural shape annealing and the appearance is the most complex due to the variation of member sizes, lengths and openings. In terms of efficiency, it is considered inefficient with the second heaviest weight, even though it is actually not comparable since there are different variables such as the limited number of profiles of CHS used. Besides, in the irregular-patterned designs, the bracing of the perimeter structure by the floor slabs was ignored, whereas it was accounted in the optimisation process of the regular-patterned designs by modifying the value of the effective length factor. It is relatively less sustainable due to its large weight, but since it is based on triangulation, the reusable potential of the structural member is the highest one. Besides, this solution has the largest opening area, because the customised CHS sections used have greater ratio between the diameter and the thickness according to the tube member formula in eifForm software, and thus have greater strength compared to the same diameter of default CHS sections.

		Benchmark	Regular-patterned Designs			Irregular-
Criteria	Sub-criteria	□	△	⬡	◇	patterned Design
Efficiency (C1)	Weight (kg)	219,040.00	107,767.37	593,381.04	202,698.52	507,171.01
	No. of joints	420	72	152	176	124
Economy (C2)	No. of members	800	180	260	400	332
	No. of sections	7	9	5	5	10
Expressiveness	Innovation	5 (least)	4	2	3	1 (most)
(C3)	Complexity	5 (least)	4	2	3	1 (most)
Environmental	Weight (kg)	219,040.00	107,767.37	593,381.04	202,698.52	507,171.01
Sustainability	Opening (m^2)	11,672.60	11,039.28	10,379.72	11,151.40	11,909.27
(C4)	Joint flexibility	4 (least)	1 (most)	3	2	1 (most)

Table 6: Comparison of performances of medium-rise designs.

5.3.2. High-rise Case

Table 7 presents a comparison of performances of high-rise designs.

		Benchmark	Regular-patterned Designs			Irregular-
Criteria	Sub-criteria	□	△	⬡	◇	patterned Design
C1	Weight (kg)	2,888,640.00	891,209.83	2,858,329.56	1,372,388.38	1,614,723.70
	No. of joints	1220	192	432	496	136
C2	No. of members	2400	540	780	1200	374
	No. of sections	7	7	7	5	12
C3	Innovation	5 (least)	4	2	3	1 (most)
	Complexity	5 (least)	4	2	3	1 (most)
	Weight (kg)	2,888,640.00	891,209.83	2,858,329.56	1,372,388.38	1,614,723.70
C4	Opening (m^2)	26,372.60	32,183.36	28,819.12	32,363.88	36,204.27
	Joint flexibility	4 (least)	1 (most)	3	2	1 (most)

Table 7: Comparison of performances of high-rise designs.

The high-rise design with the irregular pattern has a number of optimum features in terms of the 4Es. Its performance is much better than the medium-rise one. It has quite low weight, it is very economical, except for the number of distinct sections, which is the largest, possibly as a consequence of using continuous size optimisation in the annealing process, as well as having no grouping of structural members as in other solutions. It is very expressive and sustainable.

6 Discussion and Conclusion

The following conclusions can be drawn regarding the optimality of each of the patterns investigated, based on the comparisons of the performances:

- For both vertical and lateral loads, the performance of the orthogonal-patterned benchmark solution is the least optimum in terms of the 4Es.
- For both load cases, all solutions with non-routine regular patterns perform better than the benchmark in terms of the 4Es, even though for each criterion, some have lower scores compared to the benchmark pattern, such as the larger weight for the medium-rise case with the hexagonal pattern. The triangular-patterned solution is the optimum both in terms of the 4Es as well as for the weight criterion.
- The performance of the structural solution with the irregular-triangular pattern is higher than the benchmark solution on most of the criteria. In the medium-rise case, it is less efficient than most of the solutions, but it should be realised that this may be due to the bracing of the floor slabs being ignored, and the sections used to assemble the solution having greater strength intervals due to application of eifForm tube member formula and fewer choices in the sections library. In the high-rise case, the performance is considerably improved with good performances on all four criteria. Although, it is still lower than the regular triangular-patterned solution, it is a reasonably good solution and one of its benefits is its expressiveness and originality.

This paper demonstrates the potential of structural pattern as the high level feature to be manipulated for achieving optimum vertical building structures with respect to the four criteria, traditionally considered in building designs. Since non-routine patterns have better overall performance than the benchmark rectangular pattern, generating novel and innovative patterns that optimise the 4Es is a key challenge for designers of architectural structures. Besides, multi-criteria optimisation of structures should be encouraged and embraced due to its flexibility and reliability in producing novel structures.

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