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Structural pattern’s granularity variation to optimize a vertical structure Eunike Kristi Julistionoa,*

aDepartment of Architecture, Petra Christian University, Siwalankerto 121-131, Surabaya 60236, **Indonesia Abstract** 4

The increasing demand of vertical buildings has encouraged the development of vertical structure optimization. Most optimization has focused on size optimization. However, shape/form optimization and pattern/topology optimization are believed to have more impact not only towards structural efficiency, but also to the aesthetic of the building. Modifying structural pattern on the vertical building’s perimeter has great potential to improve the structural performance, not only to satisfy the efficiency criteria, but also to fulfil functional and aesthetic consideration. Thus, previous research has been performed to optimize the performance of the vertical structure by applying different patterns of the perimeter structure. Result showed that among three non-routine patterns applied and orthogonal pattern as the benchmark, triangular pattern is the optimum in terms of efficiency, economy, expressiveness, and environmental sustainability. This paper examines the effect of granularity variation of triangular pattern employed on the perimeter of vertical buildings to optimize the structural performance. In here, granularity of the pattern is taken as the key structural feature to be manipulated in increasing further the efficiency of the structure.

Medium and high-rise buildings are taken as **the** case studies **to** examine **the** 6

performance of each pattern under two loading conditions - vertical and horizontal loads. For each case, triangular pattern in three different degrees of granularity are modelled using CAD modelling and optimized with structural design and optimization software. Results from different granularities applied are then compared, and analyzed to decide the effect of the structural pattern’s granularity variation towards the efficiency of the structure.

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Triangular pattern; granularity; structural optimization; efficiency *

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2017.04.232 1. Introduction Nowadays, there is an increasing demand of vertical building structures, especially in big cities and the central business districts. The reasons are the increasing number of population due to globalization or migration from sub- urban to urban area and land scarcity in urban area. Other reason is the concept of sustainable living in a mixed-used building. Driven by the awareness to minimize resources and energy for sustainable development, vertical mixed- used building where people can live, work, eat, and even have entertainment all in a single building is considered beneficial to achieve efficiency in energy and resources, especially in reducing the transportation energy [1]. Demand of vertical buildings has been followed by development of vertical structure optimization. Considering that buildings are responsible for around

40% of the world's energy, and even 50-80% in 11

metropolitan areas, it is essential to aim on an efficient building structure [2]. In fact, more than four decades of research to optimize vertical structures has resulted a broad range of computational optimization methods, which are shape/form optimization, pattern/topology optimization and size optimization. Most research has focused on size optimization which is an effort to achieve structural efficiency by optimizing the size/dimension of structural components. In here, geometry and topology of the structure are unchanged

in the optimization process, and therefore **the** dimension **of structural** components is **the** 12

only key feature to be optimized. However, realizing that geometry and topology of the structure are actually more potential to increase the structural efficiency, some research has focused on modifying the structural form and pattern. The structural form is the 2D or 3D geometry of the structure, while the structural pattern is the topology or connectivity and arrangement of structural members. Modifying the structural pattern of a vertical building to optimize its structural efficiency has several benefit. Variation of structural pattern on the perimeter of vertical buildings has given certain aesthetics towards a ubiquitous and monotone prismatic form, especially considering that limitation of site and functional consideration usually does not allow much modification of the vertical building's form. This becomes the reason for the emerging of prismatic vertical building with distinct perimeter patterns, such as COR Building in Miami [3] and Hearst Tower in New York [4]. Various structural patterns used in the vertical buildings has driven a question regarding which pattern is the optimum pattern for medium and high-rise buildings. Thus, previous research has been performed to find the optimum pattern for the vertical buildings [5]. In that research, orthogonal pattern has been compared with three non-routine patterns - triangular, hexagonal, and diamond; as the structural pattern employed on perimeter of vertical buildings. For two different loading conditions - vertical loads for medium-rise case and lateral loads for high-rise case; each pattern is applied on the perimeter of a prismatic structure. Then, the results are compared in terms of efficiency, economy, expressiveness, and environmental sustainability (4Es). The research concludes that triangular pattern is the optimum pattern for resisting both vertical and horizontal loads. Conclusion of the previous research [5] supports the recent development of diagrid structural system [4]. Over the last 10 years, more vertical buildings (from medium-rise height to the tall and even super tall structures) have used diagrid system as their structural system, due to the structural efficiency and the versatility of diagrid [6]. This fact has proven that triangular pattern is the optimum pattern for vertical buildings. Some research has observed different geometries of diagrid resulted from different modules of diagrid and angles of diagonal members [7]. However, some questions remain and can be investigated further, such as the effect of the changes on pattern granularity towards the structural performance. Does denser granularity give more structural efficiency? Considering bigger size of triangles results less stiffness and then requires bigger size of the members. This paper examines the influence of changing the structural pattern's granularity towards the efficiency of the structure. Since this research is the continuation of the previous research, thus the triangular pattern as the optimum pattern decided in the previous research [5] is taken as the pattern to be observed. For two cases observed - the medium and high-rise structures; triangular pattern in three distinct granularities are applied on the perimeter of the structures. Then, the optimized structures resulted are compared in term of their structural efficiency, to examine the influence of changing the pattern granularity towards the structural performance, and decide the optimum granularity. 2. Structural pattern optimization 2.1. Structural pattern Structural pattern can be defined as a certain arrangement of structural components which has impact on the appearance of the structure as well as structural behavior and construction complexity. Structural components here can be columns and beams, or structural members in trusses or skeleton structure, or bearing walls/shear walls in wall structure. Structural pattern can be seen on the building elevation directing the arrangement of columns and beams or other structural members, on a building plan showing the arrangement of columns or other vertical members, or on three-dimensional image of the surface structure [5]. Structural pattern optimization is a structural optimization process aiming in increasing pattern. Effort to modify structural patterns in order to increase the structural performance has been found throughout development of structural system. However, recently there has been more application of various structural patterns in vertical structures, due to the prospect of structural patterns to increase the structural performance and driven by the development of computer technology. There are three objects of optimization in the development of structural optimization; form/geometry, topology, and size/dimension. Structural pattern is a structural feature which includes information regarding all three. A structural pattern has geometry description, granularity and connectivity of the components, and also dimensions of the members, to be considered in its modification. Therefore, in investigating the structural pattern, there is a need to take into account the influence of structural pattern's geometry and granularity. 2.2. Similar research There are only few research trying to optimize structural pattern on the perimeter of the vertical buildings. Most optimization related to the vertical building structure with diagonal bracing still focuses on size optimization [8]. A method to design and optimize the pattern of diagonal bracings in vertical buildings utilizing an evolutionary process has been introduced by researchers from George Mason University in Investor 2001 software [9]. In this program, a stable structure with a certain arrangement of diagonal bracings is taken as an input, and then it is optimized through an evolutionary process until an efficient pattern is resulted. Besides, optimization of diagonal bracings in high-rise structures has also been carried out using modified pattern search which did not only focus on size optimization, but also tried to find an efficient pattern of diagonal bracings through an evolutionary process by eliminating non beneficial bracing members [10]. Pattern gradation of braced frame structure has also been performed using topology optimization [11]. In above research, structural pattern optimization is automatically performed by utilizing computer as a design partner, executed using structural analysis and optimization software whether through an evolutionary process or a random search. In this research, the optimization process focuses on the granularity modification of initial structural pattern. However, considering a limited resource (structural optimization software which is still based on size optimization), varying the structural pattern's granularity is carried out manually through CAD modelling. 2.3. Previous research Previous research has been performed with the objective to find the optimum structural pattern for the perimeter of vertical buildings, compared to the routine orthogonal pattern [5]. Research was started by looking for the possible non-routine patterns from natural structures and recent building structures. Three non-routine patterns - triangular, diamond, and hexagonal, were chosen, modelled and optimized. Then, the optimized structures produced from the three patterns were then compared, and the optimum solution was decided in terms of efficiency, economy, expressiveness, and environmental sustainability (4Es). Result showed that triangular pattern is the optimum pattern for both medium and high-rise cases. Founding of the previous research that triangular pattern is the optimum pattern has confirmed the efficiency of diagrid structure. Diagrid is a perimeter structure with triangular pattern which is vastly used in various scale of vertical buildings. It is very adaptable in structuring any structural building forms and spans [4]. Diagrid system is known for its structural efficiency. Compared to conventional exterior braced frame structures, diagrid eliminates all vertical columns, since the diagonal members can also carry the gravity loads. Compared to conventional tubular structure with rigid frame, diagrid is more efficient since it works with axial forces, and thus minimizing the shear deformation of the framed tube system [7]. Looking at applications of diagrid structure, there are various sizes of triangular pattern employed on the buildings. Some use small modules of diagrid, such as Capital Gate in Abu Dhabi [4], while others use medium and large modules of diagrid, such as

Hearst Tower in New York [4] and The Bow Tower in

Calgary [12]. Different size of triangular patterns produces different granularity of structural pattern used. Thus, this paper tries to examine which granularity is more optimal for improving the structural performance. 3. Structural optimization problems and methodology 3.1. Design requirements As in the previous research [5], two cases are observed in this research - medium and high-rise case, to examine structural efficiency towards vertical loads and lateral loads respectively: ? Medium-rise case observed has a building height of 80m (20 stories high), with a slenderness ratio of 2:1 ? High-rise case has a building height of 240m (60 stories high), with a slenderness ratio of 6:1 The above ratio is determined based on the definition and ratio of medium and high-rise structures [13]. Three behavioral requirements - stability, stiffness, and strength, are considered to obtained a feasible design solution. Here, the usual limits on stresses and deflections are applied as constraints. The vertical deflection is limited to less than (span/250) mm and the lateral sway is limited under (height/300) mm [13]. Two design loads are considered during the research, for medium and high-rise cases respectively. To simplify the process, the same design loads (based on Australian Standard) used in previous research [5] is applied: ? The vertical imposed loads recommended in AS1170.1:2002, which is a uniform distributed load of 3kPa for office building, is used in medium-rise case. ? Whereas for high-rise case, the wind pressures on windward wall are calculated based on AS1170.2:2002, with assumption that the site is located in Sydney urban terrain with no shielding from the surroundings. Thus, the wind loads applied in the structures are varied from 0.432kPa on the ground, increasing to 1.037kPa on the peak of the building (240m high above ground). 3.2. Structural features Prismatic form with square plan is chosen as the form of the structure to be observed, with the plan dimensions of 40m x 40m. 4m is set as the floor-to-floor height to produce the desired building height and slenderness ratio, as mentioned in Section 3.1. Since the pattern to be applied in the perimeter structure observed is triangular pattern, thus some adjustments of building corners are allowed, such as indentation and inclined faces. For both medium and high-rise cases, three different granularities of triangular pattern are applied to the perimeter structure and compared. In here, the triangular pattern from previous research [5] is taken as the benchmark, and then scaled into 50% and 25%. ? Alternative 1 (the benchmark) uses triangular pattern with 4-story triangles, similar to the pattern used by The Hearst Tower in New York [4]. ? Alternative 2 uses triangular pattern with 2-story triangles, as the pattern used by Swiss Re Tower in London [4] and Tornado Tower in Doha [14]. ? Alternative 3 uses triangular pattern with 1-story triangles, as the pattern used by Mode Gakuen Cocoon Tower in Tokyo [15] and Capital Gate in Abu Dhabi [4]. The three granularities observed can be seen in Fig. 1. All three patterns use the same geometry of triangular pattern with a diagrid angle of 67□, which considered as an optimal range of diagrid angle for tall buildings [7]. In computer modelling, structural analysis and optimization, all joints are set to be rigid, and all supports are set to be fixed. The perimeter structure is the only structural element modelled and analyzed, with assumption that perimeter structure and a 16m wide central core are two sub-systems which work together in resisting both vertical and lateral loads [16]. Assuming that the central core resists 50% of the vertical loads and 40% of the lateral loads, the loads used in modelling, analysis and optimization of the perimeter structure alternatives can be reduced. Floor beams at each story are not included in the model, except if the floor beams are parts of the triangular pattern observed. However, the stiffness of the diagonal members due to the bracing of the floor beams is taken into consideration. The structural material used in the research is grade 350 steel to minimize the size of the members. Circular Hollow Section steel library is used in discrete size optimization. Fig. 1. Three different granularities of triangular pattern compared in the research. 3.3. Decision criteria In previous research [5], two types of criteria were used in finding the optimum structural pattern for vertical building.

The first one is efficiency criterion, while the second is multi

-criteria of efficiency, economy, expressiveness, and environmental sustainability 9

(4Es). The limitation of using multi-criteria is the fact that most structural optimization software/tool still operates based on single criterion of efficiency. Thus, other criteria should be defined manually. Since the purpose of this research

is to examine the effect of variation **on structural** 8

pattern's granularity towards the performance of vertical structure, efficiency is chosen as the main decision criterion to be considered, both for medium and high-rise cases. The reason behind is because in this research, optimization process is carried out using Multiframe4D which works with single criterion of efficiency. Besides, since the geometry of the pattern is fixed, which is triangular pattern, aesthetic/expressiveness of the alternatives are considered to be quite similar. Whereas, the indicator of environmental sustainability criterion is also efficiency, showing minimum amount of resource usage. Meanwhile, the economy criterion is still considered by grouping of structural members, but it is not a decisive factor. Structural efficiency indicates the percentage of the strength of the material in each structural component uses to resist structural loads. Efficiency is the ratio of the load carried by a structure to its total weight (strength to weight ratio). An efficient structure is a structure which has maximum strength with minimum weight [17]. Therefore, using efficiency as decision criteria, means alternatives observed are compared in term of the material weight used to withstand the same loads. In this research, the indicator of efficiency is the total mass of each structure resulted through optimization process. Thus, in evaluating structural performance of patterns with different granularities, the total mass of each design using certain granularity becomes the indicator to be compared. 3.4. Research methodology To examine distinct pattern granularities, triangular pattern used in the previous research [5] is used as the benchmark, and then compared to the same triangular pattern with different degree of granularities. For each granularity observed, 3D model of the perimeter structure is created using CAD modelling. After that, the 3D wireframe model is imported into Multiframe4D software, to be assembled into a complete structure. Then, the initial structure is analyzed and optimized with discrete size optimization, until the most efficient structure is obtained. Two computational processes are involved in this research, as shown in Fig. 2. Fig. 2. Two computational methods involved in this research. ? CAD modelling using AutoCAD software AutoCAD is utilized to create 3D wireframe models of perimeter structure with different granularities. ? Discrete size optimization with Multiframe4D software Multiframe4D is used to produce a feasible and optimum structure from each imported AutoCAD wireframe model, through repeated cycle of linear analysis, code checking, and changing of member sizes. Each structural design solution is optimized with discrete size optimization method by changing of member sizes provided in discrete section library until the minimum weight of the structure is achieved. For each optimization cycle, the linear analysis is used to define member forces, deflection, and efficiency expressed as a percentage of member capacity used in the design, towards a predefined user code (Fig. 3). User code is set as a requirement to design all structural members to satisfy the limit of axial forces, bending, and combined stresses, while ignoring the slenderness limit. Automatic design feature and manual modification are used to vary the member sizes with an objective to achieve an overall efficiency closest to 100%. 4. Results 4.1. Medium-rise case To examine the performance of the structural patterns towards vertical loads, three distinct granularities of triangular pattern are applied on the perimeter of medium-rise structures. The vertical impose loads are calculated as a uniform distributed loads of 3kPA, by taking into account that perimeter frame is working together with the central core in resisting the loads. By assuming that only half of the loads go to perimeter frame, the area of loads supported by perimeter structure is shown in Fig. 4.a. These loads are applied on each joints of the triangular pattern (Fig. 4.b), and being considered in the structural analysis and optimization process. For economic consideration, the structural members are grouped every 4 stories. Fig. 3. The predefined user code used in optimization with Multiframe4D. Fig. 4. (a) The area of vertical imposed loads supported by the perimeter structure; (b) Point loads applied on the medium-rise model. The optimum perimeter structures with three distinct granularities for medium-rise case and comparison of the alternatives' attributes are shown in Fig. 5 and Table 1. Table 1. Attributes of medium-rise case structures. Alternative 1 Alternative 2 Alternative 3 with 4-story triangles with 2-story triangles with 1-story triangles Total mass 107767.37 kg 191258.52 kg 185520.74 kg Average efficiency 68.56% 61.97% 59.21% Number of joints 72 264 1008 Number of members 180 720 2880 Fig. 5. 3D models of medium-rise case structures (alternative 1, 2, 3 from left to right). Result shows that in term of structural efficiency, Alternative 1 has the least weight (with the total mass almost half the total mass of Alternative 2 or 3), which means it is the most efficient pattern. Further examination shows that the average efficiency of the structures (average of members' strength used in resisting loads) is decreasing from Alternative 1 to Alternative 2, and to Alternative 3. This is possibly caused by more members in Alternative 2 and 3, since it is impossible to use 100% strength of each member in the structure. In term of construction economy, grouping of member sizes are applied every 4 stories, thus the smaller the triangular pattern (denser granularity) means more member sizes are rounded to the biggest size every 4 stories. This may cause Alternative 1 to have highest average efficiency, while Alternative 3 has lowest average efficiency. However, the difference is not significant, meaning even if Alternative 2 and 3 are optimized further to reach average efficiency similar to Alternative 1, total mass of both alternatives will still be higher than Alternative 1. Hence, it is concluded that to resist vertical loads, triangular pattern with biggest granularity (Alternative 1) is the optimum. Looking at the small difference between total mass and average efficiency of members from Alternative 2 and 3, it is considered that in denser granularities (pattern with smaller size of triangles), the changing of structural pattern's granularity does not have significant impact to the performance of structural pattern. However, considering large amount of joints and members in Alternative 3, Alternative 2 is still considered to be a better solution in term of economy of the construction. 4.2. High-rise case To investigate the performance of triangular pattern towards lateral loads, the wind pressures on windward walls are considered as the lateral loads, and calculated based on Australian Standard. Considering that the perimeter structure is working together with the central core in resisting lateral loads, it is assumed that only 60% of the loads are taken by perimeter structure, while 40% of the loads are resisted by the central core. Assuming the role of floor diaphragm to distribute loads into two sidewalls, in the modelling process, the lateral loads are applied as point loads on joints of the sidewalls (Fig. 6). Here, the member sizes are grouped every 12 stories for economic consideration. The optimum perimeter structures with three distinct granularities for high-rise case and comparison of the alternatives' attributes

are shown in Fig. 7 **and Table 2. Table 2**

shows that in term of efficiency criterion, Alternative 2 has the least weight, even with the least average efficiency of members. This means that if Alternative 2 is optimized further to reach the same efficiency as Alternative 1, it is possible that Alternative 2 has less weight. Thus, it is concluded that Alternative 2 is the optimum pattern. Further observation shows that the total mass and average efficiency of Alternative 2 and 3 are quite similar, showing that in resisting lateral loads, triangular pattern with smaller granularities have better performance. However, unlike in medium-rise case, where the most efficient alternative has almost half the weight of other alternatives, in high-rise case, the total mass of three alternatives are not significantly different. The total mass of Alternative 2 with the least weight, compared to Alternative 1 with the highest weight, only differs by 7%. Fig. 6. Point loads applied on the three high-rise models observed (alternative 1, 2, 3 from left to right). Fig. 7. 3D models of high-rise case structures (alternative 1, 2, 3 from left to right). Table 2. Attributes of high-rise case structures. Alternative 1 Alternative 2 Alternative 3 with 4-story triangles with 2-story triangles with 1-story triangles Total mass 891209.83 kg 825433.54 kg 829838.03 kg Average efficiency 75.28% 66.01% 66.84% Number of joints 192 744 2928 Number of members 540 2160 8640 5. Discussion This research is performed to examine the influence of granularity variation of structural pattern on the perimeter of vertical structure, towards its structural performance. Several founding from the research are below: ? In resisting vertical loads (medium-rise case), triangular pattern with largest granularity (pattern with 4-story triangles) is the optimum. Perimeter structure modelled with this pattern has the least weight, with total mass around 55-60% of two other alternatives. ? In resisting lateral loads (high-rise case), triangular pattern with medium granularity (pattern with 2-story triangles) is the optimum. However, the weight is not significantly reduced, showing that for resisting lateral loads, changing of structural pattern's granularity has minor impact towards efficiency of the structure. ? Average efficiency of the members tends to decrease in denser granularity (pattern consisting smaller triangles), since structure with smaller granularity has larger amount of members. Thus, more members mean more rounding up of member sizes has been performed due to economic consideration (grouping members every 4 or 12 stories). Overall, this research confirms that greater granularity is more efficient for resisting vertical loads. 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