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Effect of Perforation Area and Arrangement Pattern on Structural Behaviour of Nature Inspired Perforated Hollow Structure

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Abstract: The Cholla cactus skeleton has been the inspiration source for this study, in our effort to search for light and more structural effective structures. This woody skeleton of Cholla with oval shaped perforations arranged in spiral pattern is found strong enough to support the cactus self weight. This research has been carried out to investigate the effects of percentage of perforations and perforations arrangements on structural behaviour of cylindrical hollow section. A total of eleven models consisting of one cylindrical hollow section without perforation as the control model and ten simplified perforated cylindrical hollow sections have been constructed using a finite element method software. The perforated models have been assigned with 10 to 50 percent of perforations area by fixing the number of perforations to twenty and altering the perforation size to achieve the percentage variable. Computational analyses have been carried out for three loading conditions: compressive, flexural and torsional. Findings have shown that the increment in percentage of perforations produces higher stresses to the cylindrical hollow section. This has effects on the structural capacity of the cylindrical hollow section. Array arrangement of the perforations shows better structural performance in compression and flexural loading conditions while spiral arrangement exhibits better structural performance under torsional loading condition.

Key words: Light-weight structure · Biomimicry · Sustainability · Perforated hollow section · Cholla skeleton

INTRODUCTION

The responses of a structure (stress and deformation) under action of loads depend greatly on three major aspects regarding structural members such as arrangement, geometry of the cross section and material properties. A structural member is subjected to combination of actions like axial, flexural, shear and torsional forces resulted in different types of stresses. Geometry of the section must be chosen so that resultant stresses and deformations are minimized and at the same time, minimising its self weight without compromising safety of the structure.

Learn from Nature: In the era where sustainability of built environment has become the main concern, the use of light and more efficient structural members has become more important.

In the attempt of searching for innovative, sustainable and efficient structural system, nature has often been chosen as the source of inspiration - biomimicry. Better structures which can achieve more natural, integrated, efficient and healthy solutions together with high aesthetic value can be built or created benefited from biomimicry.

Biomimicry Can Be Defined in Several Ways Such As:

- Biomimicry is a new discipline that studies nature's best ideas and imitate them as answers to human problems [1].

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- Life has had millions of years to finely-tune mechanisms and structures that work better than current technologies, require less energy and produce no life-unfriendly waste. The emulation of this technology is the goal of biomimicry, the art of innovation inspired by nature [2].
- Biomimicry is a design discipline that seeks sustainable solutions by emulating nature's time-tested patterns and strategies [3].

As the natural world has had millions of years to improve, it makes sense for engineers to adopt the same concepts to create a more sustainable and energy efficient building. Structures inspired by sources from nature have found their ways into actual application; for instance, 'The Turning Torso', in Sweden inspired by twisting human body designed by architect Santiago Calatrava and 'Ludwig Erhard Haus Building' with its main steel arches supporting the tall atrium which was inspired by the skeleton of armadillo.

The Inspiration Source: Several cacti species grown in deserts within America and Mexico such as Cardon, Saguaro and Cholla exhibit some fantastic structural characteristics. Main stems of Cardon and Saguaro can achieve 12 to 20 meters tall supporting approximately 6 tonnes of body weight; Cholla too, can grow quite tall with its main stem cantilever far away from the plant center.

It is believed that the circular skeleton of inter-connected vascular bundle inside the succulent has contributed to these characteristics. Archeological evidence has shown that the ancient Indian used the cactus skeleton in their daily life [4]. Studies reported the capability of this cactus wood in providing flexural and axial capacity [5-9]. These studies however, were not interested on the effect of the openings on cacti skeletons' structural ability but more on the general geometrical contributions on the load carrying capabilities.

The skeleton of Cholla species as shown in Figure 1 has been chosen as the inspiration source in this study towards the invention of a light and more efficient perforated hollow section. The understanding of its biomechanical behaviour is essential in order to study the possible application of this idea in nature to structural engineering.

Inspired by the Cholla skeleton, a preliminary study on the effect of various perforation shapes on a hollow cylinder under compressive force has reported that elongated shape perforation with the longer edge oriented parallel to the longitudinal axis of the cylinder is most effective in resisting compressive force and elliptical shape perforations were recommended [10]. The study however, has yet to mimic the pattern and geometry as observed in Cholla skeleton.

Fig. 1: Inspiration source - Cholla Skeleton

A study carried out on effects on the load carrying characteristic due to variable perforation geometries and arrangement patterns has reported that load carrying capacity is significantly affected by the presence of perforations due to changes in the section properties [11]. Besides, the structural behaviour is found to be affected by layout pattern and shape of perforation. Circular and elliptical perforation in local square pattern has been reported to perform well in compression and flexural analysis. Circular perforation in local rhombus pattern however, better in torsional load case. There is however, no information about the effect of percentage of perforations and the application of spiral arrangement on the structural behaviour.

Perforated Structures to Date: One of the perforated structures found is a concrete pod mimicking the shape and geometries of an egg shell with randomly arranged circular perforations of various sizes fabricated by Japanese architect Kazuya Morita [12]. With only 15 mm thick, the pod as shown in Figure 2a is strong enough to support a grown man sitting on it.

Another bigger scale perforated structure is the O-14 Commercial Tower (Figure 2b) which has been built with the intentions of creating a unique column free building in Dubai. The building has a solar shade as part of the building shell [13]. This 22-storey building is sheathed in a 400 mm thick concrete shell with over 1,300 openings that creates a lace-like effect on the building's facade and formed an elegant perforated exterior shell.

Studies on Perforations: Apart from [10, 11], studies on the effect of openings or perforations on thin shell elements have shown that the perforations do cause decrement in the element's load carrying capability [15-19]. As an answer to this, numerous studies were carried out in searching for methods to strengthen the edges of perforations and increase the load carrying capacity of the structures [20-24].

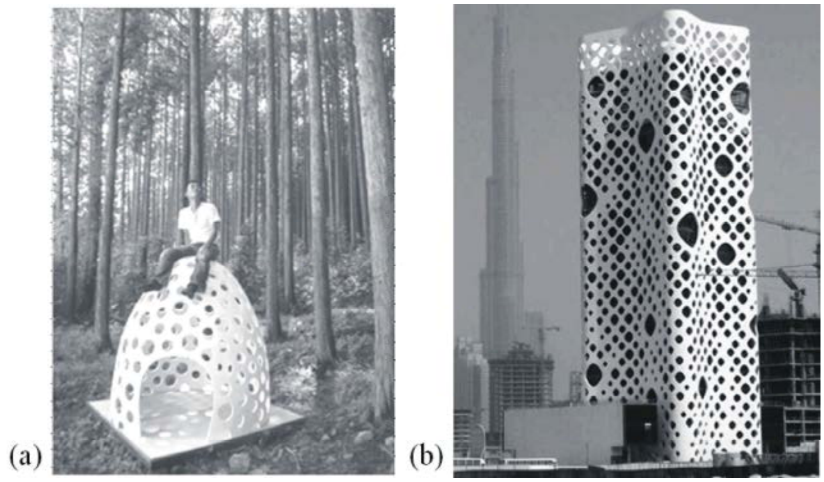

Fig. 2: a) Egg shape concrete pod [12]; b) The O-14 Tower [14]

Table 1: Criteria in the model naming method

Example of model's name: Model B: *AR*^{1} 1^2 : □25^3		
Node	Criterion	Example/ Unit
1	Global perforation arrangement	*SP* = spirally arranged, *AR* = arranged in array
2	Model number sequence (related to percentage)	1 ˜ 10%, 2 ˜ 20%, 3 ˜ 30%, 4 ˜ 40%, 5 ˜ 50%
3	Dimension of the perforation	mm

Table 2: The alphabetical representations and names of the 11 models

Model	A	B	C	D	E	F	G	H	I	J	K
Identification	Control	*AR* 1: □24.49	*AR* 2: □34	*AR* 3: □42.43	*AR* 4: □48.99	*AR* 5: □54.77	*SP* 1: □24.49	*SP* 2: □34	*SP* 3: □42.43	*SP* 4: □48.99	*SP* 5: □54.77

Study Objectives and Scope: Two objectives have been identified in this study. They are: i) to determine the effect of percentage of perforation on structural behaviour of perforated hollow section; and ii) to study the effect of perforation arrangement on structural behaviour of perforated hollow section.

This study investigates the effect of various perforation percentages of hollow structures. The selections of models are based on the changes in the opening size. Perforations arrangements being selected are in both array and spiral form. The shape of the perforations is limited to circular only. Only linear analysis has been conducted for three individual loading conditions: compressive, flexural and torsional.

Construction of Models: In this study, eleven cylindrical models have been generated. The hollow cylindrical models shared a general geometrical dimension of 600 mm in height (*H*), 200 mm in diameter (*D*) and 10 mm in wall thickness (*t*). All the models have been assigned with mild steel in accordance to BS 5400-3 and thin shell characteristic.

To produce different perforation percentages, there are two possible approaches: fix the number of perforation - altering the perforation size; fix the perforation size - changing the number of perforations. For this study, the former approach has been selected. The percentage of perforations has been fixed as approximately 10, 20, 30, 40 and 50 % of the total area of the cylindrical hollow section. Each perforated model consists of 4 rows of perforations and 5 numbers of perforations at each row. The size of the circular perforation has then being calculated based on the required percentage of perforation for each model.

A naming of the models has been properly worded to avoid difficulties in identifying the models as shown in Table 1. For the ease of discussion, the models were named as Models A to K (Table 2). Figure 3 gives a clear picture of the models designed. The analyses results have been compared among the perforated models and with the control model (Model A).

The models have been analysed under three loading conditions: compressive, flexural and torsional. Each load case has been assigned with different support conditions.

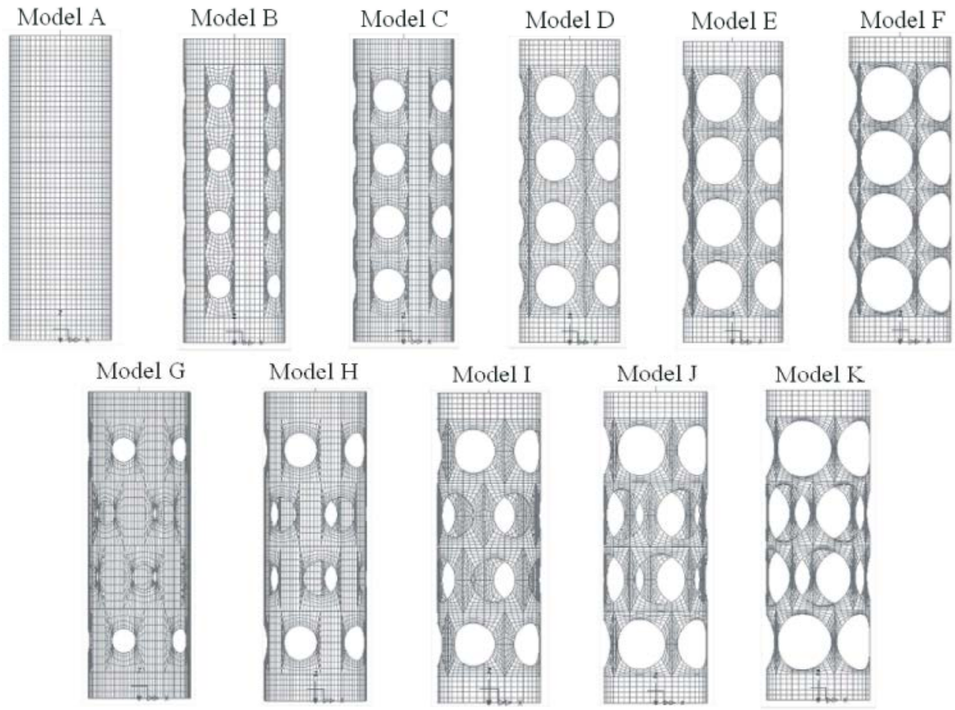

Fig. 3: Models designed in this study

For compressive case, top support is released along Z axis and bottom support is pinned; for flexural and torsional cases, top support is free and bottom support is pinned. Each loading condition has been applied with a load values which are sufficient to result obvious deformation to the models. To produce a uniform loading at the cylinder top, loadings have been applied as point load at the top of a 200 mm height circular thick beam which is connected to the top of the cylinders by rigid link. To provide good geometric fit to the curved surface, quadratic interpolation order surface mesh has been adopted. Higher mesh density has been assigned at regions surrounding the perforations.

RESULTS AND DISCUSSION

Only in-plane forces being examined in the result analysis (longitudinal force: N_z, tangential force N_t and in-plane shear force: N_{tz}). The in-plane stresses can be obtained by dividing the forces with the model thickness. The discussion is separated into each individual loading condition. Ratios between the forces values of the perforated models to the control model have been obtain for discussion (N_z/N_{z0}, N_t/N_{t0} and N_{tz}/N_{tz0} – where N_{z0}, N_{t0} and N_{tz0} are the in-plane forces for the control model). This provides in-sight view to the general trend of the forces of the perforated models in accordance to the percentage of perforations.

General finding has been drawn that presence of perforations has caused significant increase in internal forces of cylinder hollow section. This is due to the decrease of the effective local cross sectional properties at the level where the forces are measured.

It can be observed that most of the models under the three load conditions are experiencing consistent increment rate of forces for perforation percentage ranging from 10 until 30%. From 30 to 40%, high increment rates are observed. After 40%, the increment rate drastically increased.

Compressive Load Condition: Graphs for ratio of perforated models forces to control model versus percentage of perforation for the models under compressive load condition are shown in Figure 4.

Both array and spiral arranged models have almost identical forces ratios when the percentage of perforation is considered small (around 10%). Gaps gradually opened up between both patterns with the increase of perforation percentage. Spiral arranged models generally exhibits higher increment rate except for N_z where one can only notice very small difference in increment rate. This can be explain that although both

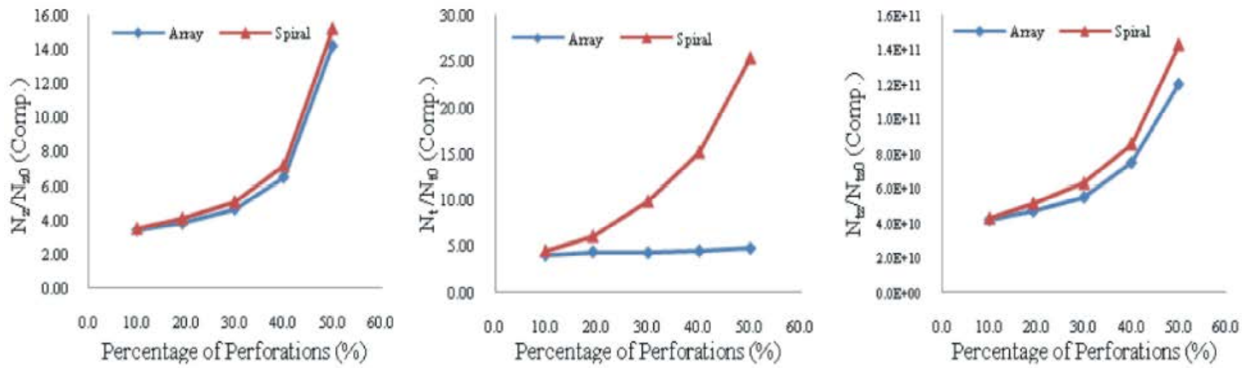

Fig. 4: Ratio of perforated models forces to control model vs. percentage of perforations for compressive load condition

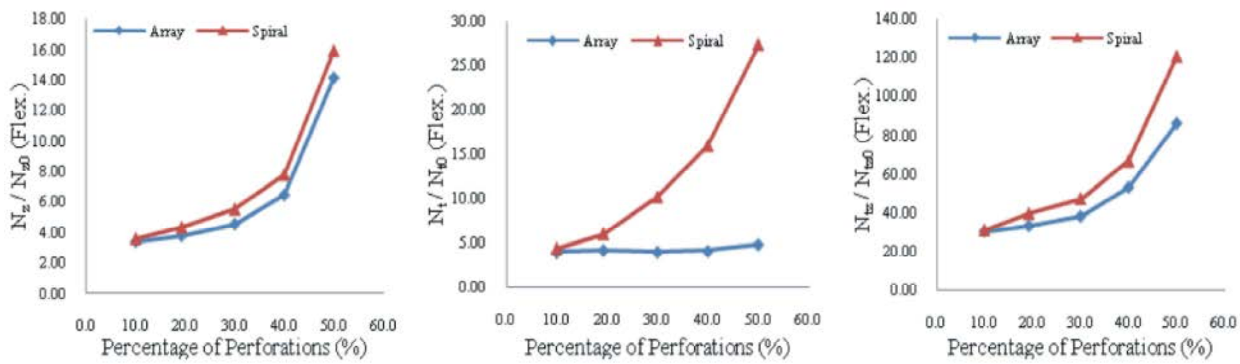

Fig. 5: Ratio of perforated models forces to control model vs. percentage of perforations for flexural load condition

arrangement patterns have the similar reduced local effective cross sectional area that caused the increase in the internal forces, the forces in the spiral arranged models requires to go through additional load diversion due to extra disruption in smoothness of load path.

The increment in the perforation percentage seems like not affecting the tangential force in the array arranged models as these models only experiencing minimal increment for forces ratios in the tangential axis. However, the spiral arranged models experienced increment in the tangential force with the increase of perforation percentage. This again can be explained base on the diversion of force. Tangential force is considered very small in the case of longitudinal load for control model. When the load path is being disrupted by openings, the diversion of force will create force in tangential direction. When the compressive load is moving downwards from the top of the cylinder, the force is forced to be diverted by the circular opening. For array arranged models, the diverted force has been channelled to several paths between the sides of the openings. After the top most row of openings, minimal or no further diversion occurred, hence the increment in tangential force has been noticed as minimal. Different story has been noticed in spiral arranged models where diversion of force happened at every row of openings. In another words, tangential force has been created at every row of openings. With the increase of accumulated tangential force and the decrease in the vertical gap between the rows of openings, the spiral arranged models experienced high increment rate in tangential force.

For tangential force, N_t. Stress concentration for array arranged models and spiral arranged models are observed to be concentrated at the gap between rows of holes.

Flexural Load Condition: Discussion for forces of the models subjected to flexural load condition can be referred to graphs shown in Figure 5.

Like the compressive load condition, spiral arranged models also exhibit high increment rate for the three forces. Almost similar trends as the compressive case can be noticed for flexural case, hence similar explanation as the compressive load condition can be adopted here.

The only observation that is different from the compressive case is that the gaps between the ratios of forces are big for the flexural load condition. The direction of flexural load acting on the cylinder is like two sets of

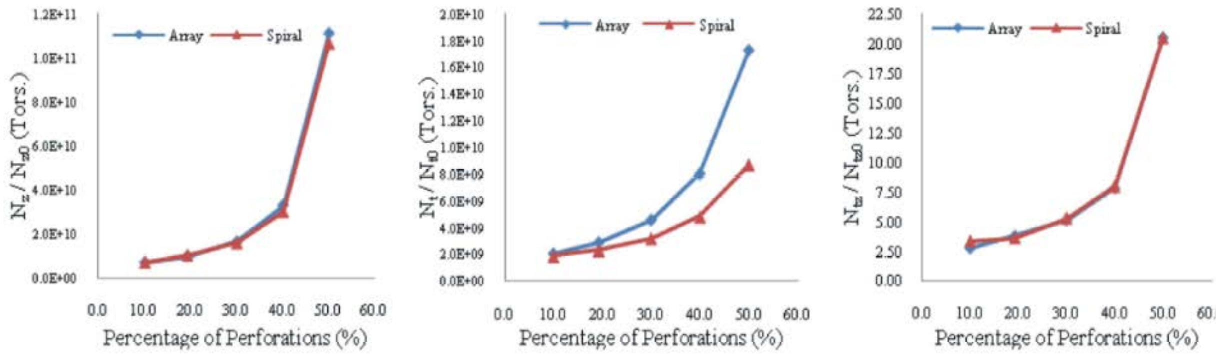

Fig. 6: Ratio of perforated models forces to control model vs. percentage of perforations for torsional load condition

longitudinal loads (couple) with similar magnitude but different direction. At the boundary between these two sets of longitudinal loads, the coupling action has created a transition zone where the force changes direction. The spiral arrangement of the perforations again has caused disruption to the process of changing direction if compare to models with array arranged openings. This might be able to explain the big gap between the array line and spiral line in the graphs.

Torsional Load Condition: Figure 6 shows the graphs for ratio of perforated models forces to control model versus percentage of perforation for the models under torsional load condition.

Both array and spiral arranged models have almost identical forces ratios for all the perforation percentages except for the tangential force where the ratio is only identical when the percentage of perforation is small (approximately 10%). Gap gradually opened up between both patterns with an increase of perforation percentage for tangential force only. Array arranged models exhibit higher increment rate for the tangential force as compare to spiral arranged models.

Torsional load creates twisting effect on the cylinders. For the control model, shear force is the major component while internal forces in the longitudinal and tangential directions are considered as minor. For perforated models, longitudinal and tangential forces are generated after the disruption in the smoothness of load path by the openings.

The load path for torsional load condition is spiralling downwards to the cylinder base. The spiral arranged openings provide smoother and more direct path to the torsional load whereas the array arranged openings create disruption to the load path which results in force diversion in the array arranged models. This phenomena might be able to provide explanation to the finding that array arranged models show high increment rate for tangential force, N_t.

CONCLUSIONS AND RECOMMENDATIONS

From the results of analysis of the 11 models, the following conclusions can be drawn:

- For case of compressive load, it can be reported that increment in perforation percentage leads to high internal forces for spiral arrangement models. Increment in opening size has insignificant effect to the tangential force for models with array arranged perforations. Generally, array arrangement performed better under compressive load.
- For the case of flexural load, increment in the size of the holes for spiral arranged models resulted in high tangential forces. Array arrangement of perforations shows desired performance under flexural load.
- For case of torsional load, spiral arranged models performed better than array arranged models base on the results of N_t.
- From the observations of the internal forces under the three load conditions, perforation percentage between 30 and 40% are recommended as a limit to achieve acceptable reduction in structural capabilities.

Further studies on structural behaviour of the perforated hollow section are strongly encouraged. The following works are recommended:

- Effect of perforation percentage can be investigated by using the approach that fix the perforation size and changing the numbers of perforations.

- More variety of geometry and pattern of perforations can be added to obtain wider understanding on the effect of percentage of perforations on structural behavior.
- Research on the materials of perforated hollow structure can be carried out in order to increase the percentage of perforations without significant effect in the structural capabilities.

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