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Applications of Topology Optimization in Structural Engineering: High-Rise Buildings and Steel Components

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ABSTRACT

This study introduces applications of structural topology optimization to buildings and civil engineering structures. Topology optimization problems utilize the firmest mathematical basis, to account for improved weight-to-stiffness ratio and perceived aesthetic appeal of specific structural forms, enabling the solid isotropic material with penalization (SIMP) technique. Structural topology optimization is a technique for finding the optimum number, location and shape of "openings" within a given continuum subject to a series of loads and boundary conditions. Aerospace and automotive engineers routinely employ topology optimization and have reported significant structural performance gains as a result. Recently, designers of buildings and structures have also started investigating the use of topology optimization, for the design of efficient and aesthetically pleasing developments. This paper examines two examples of where topology optimization may be a useful design tool in civil/structural engineering in order to overcome the frontiers between civil engineers and engineers from other disciplines. The first example presents the optimized structural design of a geometrically complex high-rise structure and the optimal design of its architectural building shape. The second one focuses on the optimization and design of a perforated steel I-section beam, since such structural members are widely used nowadays in the vast majority of steel buildings and structures while they provide numerous advances. Conclusions are drawn regarding the potential benefits to the more widespread implementation of topology optimization within the civil/structural engineering industry.

KEYWORDS: Topology optimization, Structural optimization, Architecture, Conceptual design, Perforated beams.

INTRODUCTION

Structural optimization is concerned with maximizing the utility of a fixed quantity of resources to fulfill a given objective. Three categories of structural optimization exist; shape, size and topology. Structural topology optimization is the most general of the three categories yielding information on the number, location, size and shape of "openings" within a continuum. The first solutions to a topology optimization problem (Fig.1) were presented by Michell (1904). Modern topology optimization techniques can be applied to generalized problems through the use of the Finite Element (FE) method, as a relatively recent innovation. Aerospace, automotive and mechanical engineers have successfully utilized topology optimization in order to achieve weight savings in structures. Enthusiasm for topology optimization in the field of civil/structural engineering, where weight savings are seen as less critical due to the one off nature of building structures, is generally accepted as being more muted (Pucker and Grabe,

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2011). However, in the era of sustainable and resilient infrastructures, where the concept of redundancy plays a significant role, we should reconsider optimizing every single structure to the best of its efficiency. Indeed, the one off nature of every civil-structural engineering project necessitates the use of rigorous optimization techniques to drive efficiencies on the increasingly complex projects of today.

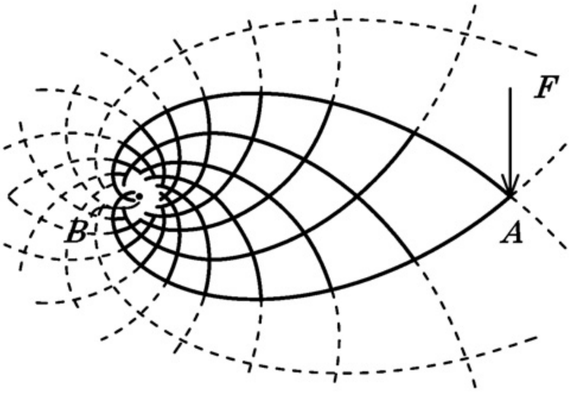


Figure (1): One of the first proposed solutions to a structural topology optimization problem

Topology optimization has found several novel applications in the field of civil engineering, most notably; a novel technique for geotechnical analysis (Smith and Gilbert, 2007) and reinforcement layout optimization in concrete structures (Kim, 2002). The main focus of this review study is applications of topology optimization to the design of large-scale structures and structural engineering components.

This paper briefly details the two most popular topology optimization techniques currently available; presents the theoretical background and practical implementation of the most commonly used Solid Isotropic Material with Penalization (SIMP) technique; and reveals previous applications of topology optimization in both structural engineering and architecture. Moreover, the implementation of topology optimization within the field of structural engineering and potential opportunities beyond the present frontiers are examined through various examples. A description of studies conducted by the authors using the topology optimization technique for: (i) the design of a high-rise structure, and (ii) the development of a novel steel I-section with atypical web opening configurations, is also presented.

TOPOLOGY OPTIMIZATION IN STRUCTURAL ENGINEERING AND ARCHITECTURE

Background

During the 20th century, architects and engineers have used innovative and novel methods to develop optimum forms of structures and sculptures. Of particular note would be the works of Antonio Gaudi, Félix Candela, Frei Otto, Pier Luigi Nervi, Heinz Isler, Richard Buckminster Fuller and Robert le Ricolais (Otto and Rash, 1996; Abruzzese and Tursi, 2003; Isler, 1961). All these individuals shared the “key theme” of attempting to create structurally efficient and functional forms that are architecturally pleasing at the same time.

Whilst the techniques employed by these innovators generated efficient and aesthetic forms, they shared a common limitation. All of the techniques employed required that the number of holes within the structure had to be known apriori to the structural form finding exercise, which usually involves the use of a physical analogue model. Topology optimization is not restricted by this limitation and it can effectively “carve” the optimum structure form from a block of material defined by the designer. In addition, the increased freedom of being able to optimize the number of openings within a structure offers an exciting new chapter in the study of improved structural forms.

Topology optimization has been used randomly in the structural design process and has no clear defined role. It has been described as “an intellectual sparring partner” (Bendsøe and Sigmund, 2003) during the early conceptual design phase. In some cases the results of a topology optimization study have been directly translated into the geometry of the final structure in a process called Computational Morphogenesis (Ohmori, 2008; Rudavski, 2009). The results of many topology optimization exercises often show a strong resemblance to structures that are found in nature (Xie et al., 2011; Frattari et al., 2009) and are usually structurally efficient as well as aesthetically pleasing.

Topology Optimization in Structural Engineering Applications

Significant work on the design of bracing systems for high-rise structures using topology optimization has been presented (Beghini, 2013). Engineers Skidmore, Owings and Merrill (SOM) have utilized the theoretical work on high-rise bracing design, in order to develop conceptual designs for high-rise buildings that are both aesthetically pleasing and structurally efficient (Stromberg et al., 2012).

Topology optimization was used to derive the optimal number, location and shape of holes in the exterior reinforced concrete walls of an office building near to the Takatsuki JR Station in Japan (Ohmori et al., 2005). The walls were modelled as simple rectangular plates and optimized for vertical and horizontal loading combinations. The result (Fig. 2a) was found to be both aesthetically pleasing and structurally sound. It should be noted that the architecture of the entire building was totally governed by structural considerations arising from the results of the topology optimization study.

Topology optimization has also been used for purely architectural purposes. The architectural aspiration of the Doha Education Center's roof canopy support was to mimic the form of a Sidra tree (Burry and Burry, 2010). Topology optimization studies were performed in order to define the geometry of the canopy support structure. It was found that the resulting form has strong resemblances to a tree trunk indeed (Fig. 2b).

Another support structure, for a doubly curved roof canopy, was designed using topology optimization and constructed from reinforced concrete as shown in Fig. 2c (Dombernowsky and Søndergaard, 2009). Computer Numerical Controlled (CNC) milling technology was employed to create the formwork for such a geometrically complex topology form. In general, it is worth noting that advanced manufacturing practices are required in cases where topology optimized designs are to be implemented on a larger scale.


(a) (b) (c)

Figure (2): a) An office building in Japan with topology optimized walls; b) A topology optimized support structure; c) Topology optimized support structure for a Canopy in Doha

TOPOLOGY OPTIMIZATION TECHNIQUES

Theory

The term “topology” is derived from the Greek word “topos”, meaning position/place. The application of topology optimization extends to the number of holes, their location, their shape and the connectivity of the structural domain (Bendsøe and Sigmund, 2003). Shape optimization and sizing optimization are more limited than topology optimization in the respect that the designer must specify the topology of the proposed structure which is then fixed throughout the optimization process. The general form of the topology optimization problem is to determine the optimum distribution of material within a designable domain to fulfil a given objective (Fig. 3).

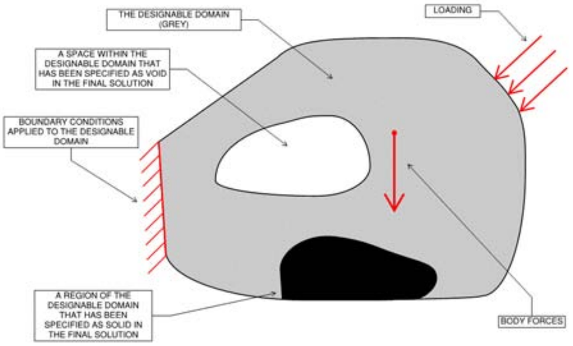


Figure (3): Basic terms used in topology optimization

An in depth review of all the topology optimization techniques suggested to date is beyond the scope of this paper. Currently, the two most popular ones are the Solid Isotropic Material with Penalization (SIMP) technique and the Evolutionary Structural Optimization (ESO) technique. Both of them involve the discretization of the designable domain into the finite elements and utilize the FE analysis technique to determine the response of the structure to be optimized. Whilst ESO has received significant research interest (Xie and Steven, 1993; Querin et al., 1998), it is generally criticized for being a heuristic technique that does not guarantee convergence to an optimum solution (Rozvany, 2008; Eschenauer and Olhoff, 2001). The SIMP technique is generally accepted in the literature as being the most prevalent tool for the topology optimization of linear elastic structures (Rozvany, 2008; Eschenauer and Olhoff, 2001). Solution methods for nonlinear, dynamic and buckling responses are currently under investigation and are not yet at a stage of maturity to enable their application in routine design. The only commercially available technique for solving nonlinear topology optimization problems currently is the Equivalent Static Loads Method (ESLM) (Park and Park, 2005). The lack of techniques for solving problems involving more complex behaviors is a major barrier to the more widespread implementation of topology optimization in civil and structural engineering.

ESO Technique

ESO method is one of the structural optimization methods especially effective for the topology optimization such as homogenization method, genetic algorithm and bubble method. ESO method is based on a simple concept that the step-by-step removal of the inefficient parts from the initial structure leads the structure towards a more optimized configuration. However, there is no consistent rule for the determination of the control parameters needed in the evolutionary process of ESO such as rejection ratios, evolution ratios and tolerance parameters for convergence. Additionally, it is worth to note that the operations done in the process of the original ESO are only those for removing inefficient parts.

Living things have been evolving their shapes to survive under various environments. They are thought to evolve themselves towards better shapes by removing unnecessary parts, and on the other hand, by extending necessary parts as well. In the natural world, the evolution of the creatures is made not only by removing unnecessary parts but also extending parts. Based on this concept, Extended Evolutionary Structural Optimization (XESO) method has been proposed (Cui et al., 2003) with two ideas: (i) the introduction of contour lines, and (ii) the bi-directional evolution.

In the ordinary ESO method, rejection of the inefficient part of the structure is carried out referring to the value of rejection ratio, which is given as a definite value in advance for computation. Consequently, the rejection procedure is performed throughout the whole evolutionary process of computation based upon that definite initial value, while no attention is paid on the situation of the structure on evolution. The utilization of the contour line is introduced as a new idea by Cui et al. (2003), for evolutionary process to actively control the rejection ratio as well as the portion of evolution.

In the original ESO method, only the rejection procedure has been done, thus there must be the necessity of the additional procedure for the structure to keep up the proper evolutionary process. For this purpose, a new approach for the addition in the evolutionary process has been introduced by Cui et al. (2003). The procedure for addition is composed of two different steps; the first step for calculation of the stress values at the cross points of the grid followed by the formation of the contour lines, and the second step for settlement of the new design domain along the contour line corresponding to the prescribed value.

SIMP Technique

The basis of the SIMP technique is to determine the optimum structural shape by varying the density of the material within the designable domain (Bendsøe and Kikuchi, 1988). The designable domain is generally discretized while the FE analysis technique is employed to determine the behavior of the structure to be analyzed. Conceptually, the use of a discretized design space may be considered thus; "one may consider the design domain as a black and white television screen divided into a lot of small pixels (finite-elements) and by turning the material on and off in each pixel, one can produce a picture of the optimal structure" (Sigmund, 2000). Computationally, the SIMP technique involves the FE analysis of the design space followed by an optimization of the density of each finite element within the mesh. The structure, with the altered element densities, is then re-analyzed and the optimization performed again. The procedure continues until the convergence.

It is desirable to develop the so-called "0-1" design, where the final distribution of material within the design space is comprised entirely of either solid material or voids (no material). The solution of the "0-1" problem has been attempted; however, it is generally the case that the application of such techniques is computationally prohibitive due to the number of finite elements necessary to model the design space. The SIMP technique addresses this problem by defining the material within each of the finite elements as a continuous design variable. By converting the design variable from discrete to continuous, it is possible to use more computationally efficient mathematical programming methods for the solution of the original problem (Bendsøe and Sigmund, 2003).

Intermediate density material, which neither takes the value of solid nor void, is generally not desirable, since it is not possible to correspond such intermediate densities to real world structures. In order to avoid the presence of intermediate densities, within the final design, a penalization is used to disproportionately decrease the benefit derived by the presence of intermediate density material. Penalization of intermediate densities is achieved within SIMP, by relating the stiffness of the material to the density, thus:

$$E = \rho^P.$$

Two basic approaches to topology optimization using the SIMP technique exist as follows:

- *Minimum Compliance Design*; the minimization of a specific performance measure subject to a constraint on the available resources. Usually, the compliance of the structure will be defined as the optimization objective with a constraint on the available material. This constraint is generally defined in terms of a fraction of the material in the designable domain prior to the optimization.
- *Minimum Weight Design*; the minimization of the mass of the structure with constraints on specific performance measures. The specific performance measures will usually be defined as stress, displacement, buckling load factor or any combination thereof.

The minimum compliance approach has proven to be effective at identifying conceptual structural design, but it has been criticized by some practicing engineers for not enabling any specific performance targets such as the stress or the displacement to be included in the optimization process (Paris et al., 2007). Whilst the minimum weight design would seem to be an obvious solution to this problem, the topology optimization problems containing specific performance constraints such as the maximum stress, buckling load or displacement are significantly more complex to solve (Zhou, 1996; Rosvany, 1996).

TOPOLOGY OPTIMIZATION IN HIGH-RISE STRUCTURAL DESIGN

Background

Requirements for high-rise structures as solutions to overcrowding in modern cities and as landmarks pose a significant challenge for structural engineers. This challenge is elegantly described by the "premium for height effect" (Khan, 1969) whereby the material required to construct taller buildings is disproportionately greater than for low-rise construction due to the increased bracing requirements. An even more significant structural challenge in the 21^{st} century is the increasing tendency for architectural aspirations in high-rise construction to tend towards "aerodynamic", "twisted" and "free" forms (Ali and Moon, 2007). The geometric complexity of "twisted" and "free" form structures often causes engineering intuition to fail when attempting to determine the optimum structural layout. An overview of an investigation into the use of topology optimization for the design of a geometrically complex high-rise structure, conducted by the authors, is presented.

Optimized Complex High-Rise Structures

In order to convince the civil engineering community to use the topology optimization technique in the design of geometrically complex high-rise structures, a proposal for a tower with a "freeform" architectural intent was sought. The Bionic Tower is an architectural proposal for a high-rise Tower in Abu Dhabi. The project reached the feasibility stage in 2007, but was never progressed. An investigation was conducted herein to determine how topology optimization could have been used at the conceptual structural design phase.

Pre-processing

A Rhino 3D CAD model was received from LAVA architects to act as a reference for the reproduction of the Bionic Tower within Hypermesh. It was necessary to convert the Rhino 3D CAD file to a format readable by Hypermesh. Solid Thinking was used to convert the original file to the versatile IGES file. When inspected, the floor plates were found to be comprised of a large number of facets that introduced subtle angles to the floor plate profiles. It was concluded that these facets could be simplified to ease in the construction of the initial model whilst still maintaining the general shape of the floor plate. The plates were also trimmed to create a hole for the core. The core is not for structural purposes, but rather to accommodate various lifts and services, thus the simplifying assumption of a constant structural core was made. The exterior envelope of the building was defined by constructing surfaces between every tenth floor plates using the ruled surface tool within Hypermesh. Interpolated surfaces, between each of the floor plates, were then created.

This initial approach generated an exterior profile that approximately followed what is intended by the architects (Fig. 4). The inclusion of more of the floor plates would have created an even more satisfactory exterior profile. Towards the base of the tower, the exoskeleton structure begins to diverge from the floor plates. This was modeled by creating a surface between the outer perimeter of the exoskeleton and the floor plate at the tenth floor (Fig. 5). The space between the inner and outer surfaces was also modelled as a solid to allow the definition of a tri-dimensional design space.

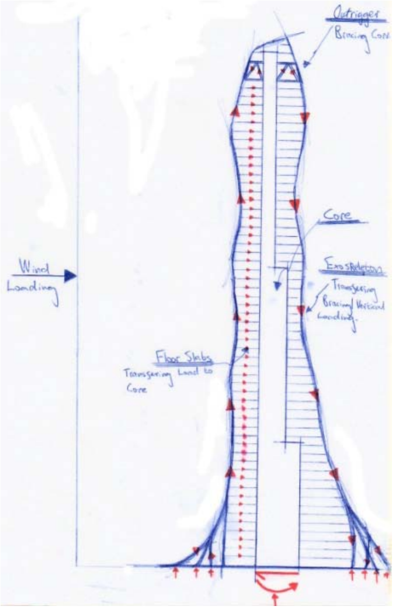
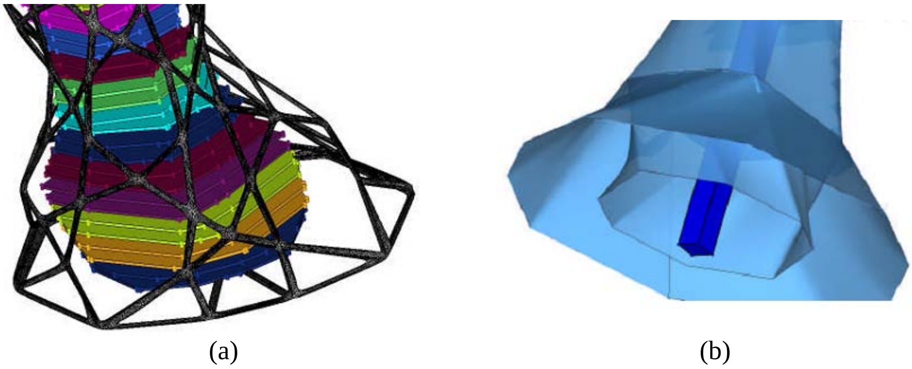


Figure (4): Braced outrigger structural concept adopted for the Bionic Tower


(a)

(b)

Figure (5): a) Diverging exoskeleton; b) Modelled surfaces

The number of finite elements within the initial model is to be limited in order that any analysis or optimization is expedient. To limit the number of finite elements, the size of each individual element will be relatively large. The surfaces of the model were defined using bi-dimensional quadrilateral and triangular finite elements. The finite element mesh generated contained 3333 nodes and 4179 individual elements (Fig. 6). A separate mesh was also created to incorporate the divergent area at the base of the structure. The solid mesh was using tri- imensional tetrahedral finite elements. The mesh generated contained 6430 nodes and 18194 elements (Fig.6).

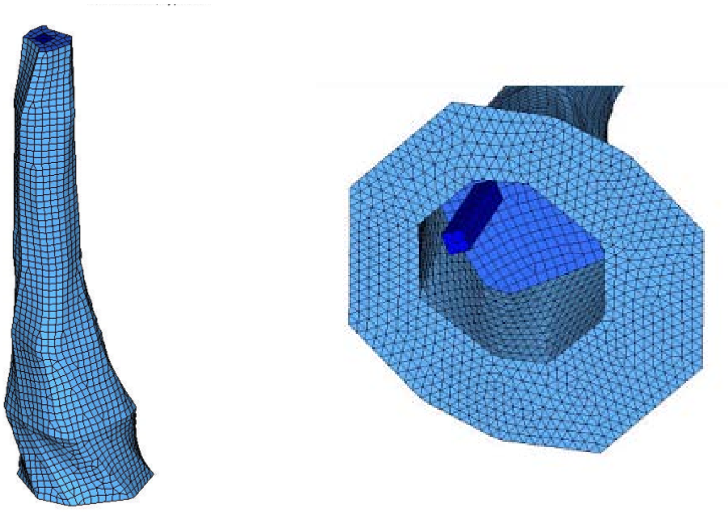

(a) (b)

Figure (6) a): Initial rough finite element mesh of surfaces; b) 3D tetra mesh of solid volume defined towards the base of the tower

It has been assumed that the core is fully restrained at its base. The base of the exoskeleton is assumed to be free to rotate but restrained against translational movement.

Gravity and lateral loading are to be considered when performing the topology optimization. The gravity loading acting on the floor plates was calculated as 14.8kN/m and it has been derived based on EN1991-1-1. This was increased by a factor of ten to account for the floor plates ignored in the initial model. The gravity loading was applied as a uniform pressure load over the entire plate.

High-rise structures are susceptible to sway and wind induced oscillations under the action of wind loading. The irregular shape of the Bionic Tower further complicates the determination of wind loading. For the purpose of this initial study, it was decided to use a notional method of applying wind loading to the model. It was decided to use an approximate procedure based on the derivation of wind loading for a polygon given in EN1991-1-4. This procedure produced a wind loading profile on the structure that was irregular while mimicked the irregular loading that would undoubtedly result from such a complex form. It was further decided that the wind loading would be applied directly to the core of the tower. This was to enable the variation of wind loading at each storey to be modeled, since it was intended that the wind loading will be transferred to the core, via diaphragm action of the floor plates. A pressure of 2kN/m^2 on the entire exterior envelope was assumed to represent pressures on the windward face and suctions on the leeward face. Four separate wind loads were defined, acting from opposite directions.

Optimization Process

The structure that is emergent from the topology optimization is entirely dependent on how the problem is defined. The definition of the design space, objective functions and constraints as well as the penalization factors was investigated to determine the most effective problem definition. Recommendations are then made for how to best produce a detailed topology optimized exoskeleton.

A braced outrigger structure acts to prevent the rotation of the core, and consequently deflection, by transferring bending and compression into the perimeter columns. In light of this, the initial constraint applied to the topology optimization problem was a deflection constraint for the top of the core (apex) of ±50mm. The objective of the optimization procedure was defined as minimizing the volume fraction of the exterior surface subject to this constraint. The results of the optimization procedure are best presented using an element density plot (Fig. 7). The element density plot shows the density of the finite elements in the optimal solution. A blue element is of low density (representing a void) whilst a red element is of high density (representing a solid). Intermediate colors represent intermediate densities. Constraints on the maximum member size, minimum member size and stress in the elements were all investigated in an attempt to produce a more pleasing and structurally useful solution after a few iterations.

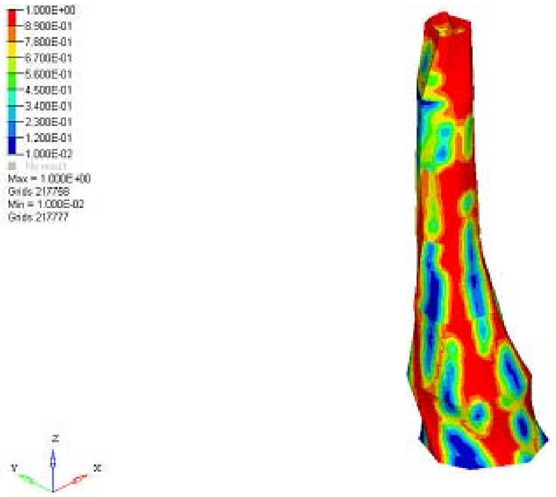


Figure (7): **Element density plot of optimization results for minimization of exterior volume subject to deflection, minimum member, maximum member and stress constraints**

The general poor emergence of a practical design that satisfies the architectural requirement, without the use of numerous constraints that significantly increase the computational resource usage, made the general performance of the optimization procedure using a deflection constraint with the objective of minimizing volume, dissatisfactory. It was felt that this method would not be appropriate for a more detailed study.

An alternative approach for the identification of an optimal structural layout was then attempted. The objective was to minimize the total weighted compliance of the structure, subject to the five load cases, whilst satisfying a constraint on the volume fraction of the material within the exterior surface. Whilst specific performance objectives were not satisfied using this approach, such as limiting the deflection of the core or limiting stresses, it can demonstrate the optimum positioning of material within the design domain.

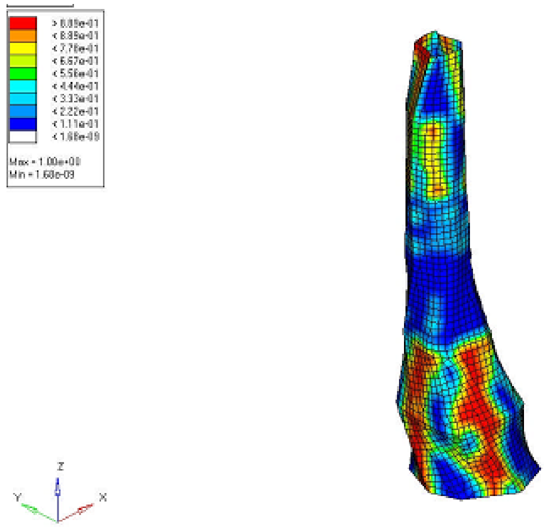


Figure (8): Element density plot of optimization results for equal compliance weightings

The optimization studies using a weighted compliance objective did not produce satisfactory emergent designs, since no material was distributed in the middle of the tower (Fig. 8). In an attempt to transfer more of the applied loading into the exterior surface and prevent the lack of emergence of structure in the mid part of the tower, the core was removed from the structural model. A weighted compliance optimization was performed (Fig.9). Initially, the volume fraction constraint was defined as 0.4. This was later reduced to 0.2 and the optimization re-run (Fig. 10). A more rational structure was found to emerge in the lower regions of the tower. The issue of material being completely removed from areas of the tower did, however, re-occur. Reducing the volume fraction was also found to improve the clarity of the results.

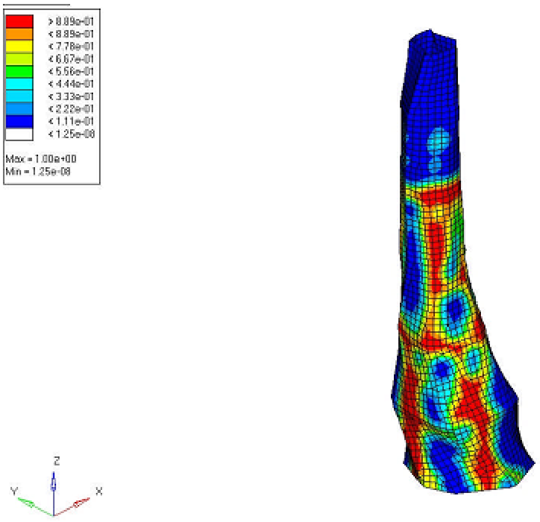


Figure (9): Element density plot of optimization results for model with no core and a volume fraction constraint of 0.4

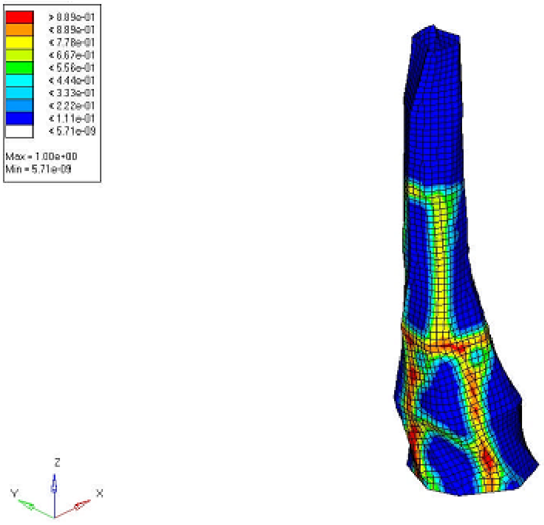


Figure (10): Element density plot of optimization results for model with no core and a volume fraction constraint of 0.2

SIMP Technique

The penalization factor used in the SIMP formulation is used to control the emergence of intermediate material densities in the optimum density distribution. The material is not desirable as it obscures the emerging design, a high penalization factor is generally preferable. A factor that is too high will, however, prevent some desirable detail of the structure from emerging. It was found that a penalization factor in the range of 2 to 3 generally prevented the emergence of significant areas of intermediate density material. However, it was noted that the ideal value of the penalization factor depends on the specific model and optimization setup. During the more detailed investigation, a default value of the penalization factor of 2.5 was used, unless it was noted that areas of intermediate density material emerge in which case the penalization factor will be increased.

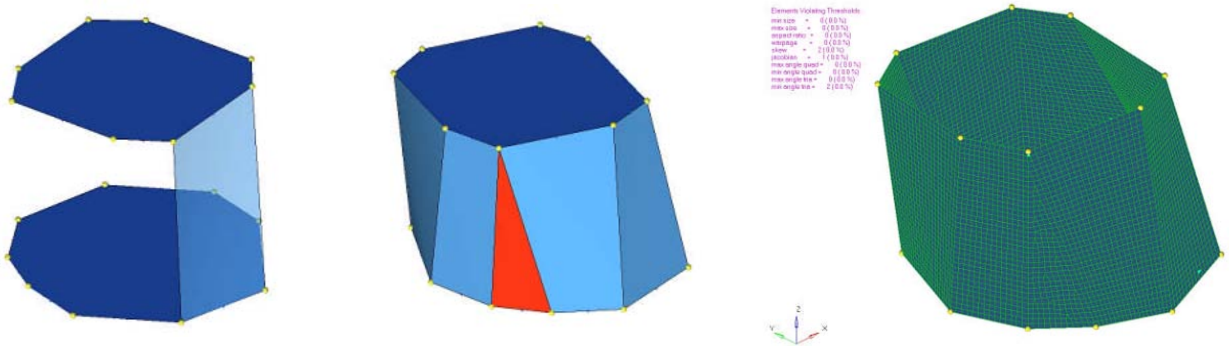
Control of Material Distribution within Design Domain

It was found that the optimum material distribution suggested by the optimizer may contain discontinuities between floor plates as well as have a higher distribution of material towards the base of the tower leading to a lack of structural emergence towards the apex.

Both of these issues may become more problematic with the inclusion of more floor plates and must therefore be addressed. In the initial feasibility study, the exterior surfaces of the tower assigned to a global volume fraction constraint. During the optimization process, the available material is free to be distributed anywhere within the domain. This results in some surfaces having a volume fraction higher than the constraint of 0.1, whilst some contain less. A local constraint on the volume fraction of material in each of the surfaces was proposed. Constraining each of the exterior surfaces individually prevents the preferential distribution of material towards the base of the tower as well as the discontinuities. However, using localized constraint increases the computation time required in the optimization procedure.

Mesh Quality

The procedure used to model the exterior surfaces of the tower generated complex surfaces that tended to twist and curve in a highly irregular fashion. During the course of the investigation into mesh refinement, it became clear that the automesh function was not generating finite element meshes of a sufficient quality to enable a robust finite element analysis. An element quality plot was then produced, since it is necessary to develop a detailed and robust finite element mesh for the investigations to follow. A different procedure for defining the exterior surface was adopted, while constructing an individual linearly interpolated surface between each facet of the floor plates, where the number of facets on adjacent floor plates varied triangular filler surfaces were used (Fig. 11). The suggested method was found to improve the quality of the finite element mesh.



(a) (b) (c)

Figure (11): a) Improved method of exterior surface definition; b) triangular filler surface between floors with differing facet numbers; c) Element quality plot of finite element mesh generated using the improved surface definition method

Re-modelling

Each one of the 60 floor plates was included in the final model, and the number of facets of each floor plate was increased to more accurately capture the originally defined shape. Surfaces were then constructed between the facets as described (Fig. 12). A total of 816 surfaces were constructed to model the exterior envelope of the Bionic Tower.

It was felt that some of the smaller surfaces produced may potentially create anomalies in the results that would prevent the emergence of a useful structural layout. The small features were identified and replaced to produce larger and flatter surfaces (Fig. 13), which maintained the shape of the exterior and expedited meshing the model. The total number of surfaces was reduced to 509.

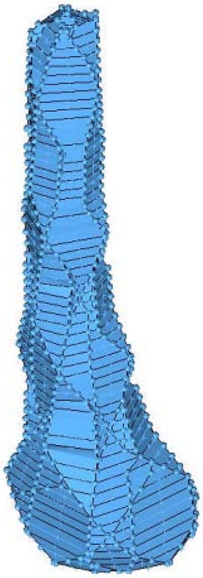
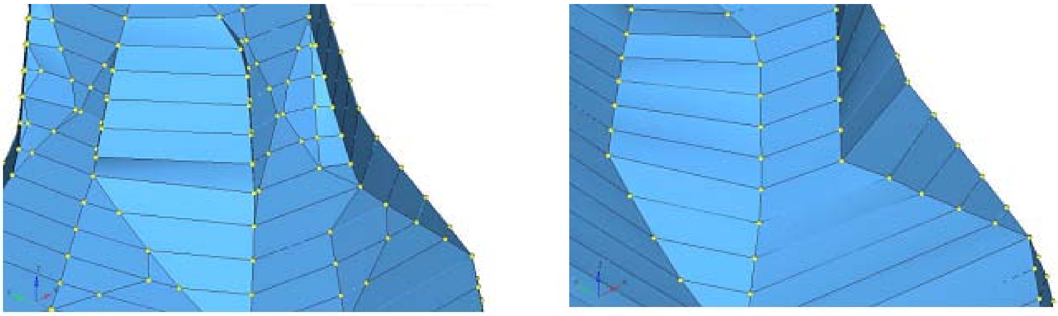


Figure (12): Detailed surfaces defining exterior envelope of Bionic Tower in hypermesh



(a) (b)

Figure (13): a) Accurately defined exterior surfaces with complex features; b) Simplified surfaces to define exterior

The individual floor plates were then created using the edges of the surfaces defined during the simplification process (Fig. 14). A total of 8 outriggers, two stories deep were defined at the top of the tower corresponding to an outrigger stretching from the core to the midpoint of each facet of the exterior (Fig. 15).

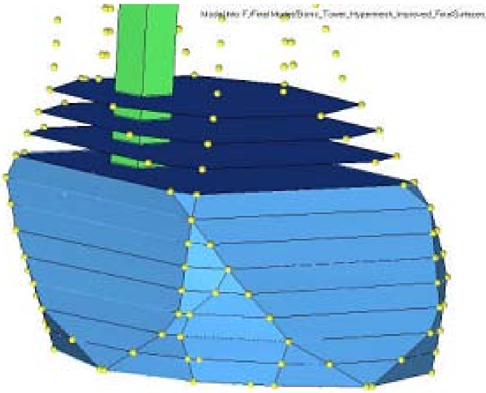


Figure (14): Floor plates modeled in hypermesh from surfaces defining the exterior envelope of the building

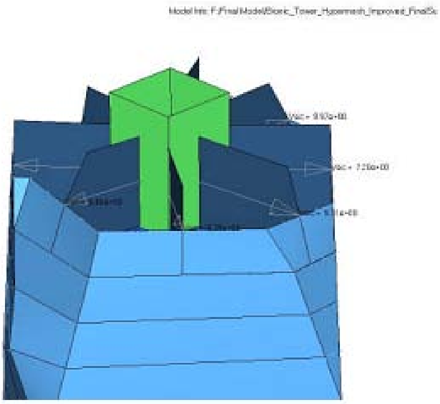


Figure (15): Outriggers connecting the core of the exterior surfaces at the tower apex

Optimizing for Wind Loading Only

The primary purpose of the exoskeleton in the braced outrigger arrangement is to support the outriggers when lateral loading is applied. A study was conducted only considering the wind load acting on the core. The floor plates were removed from the model to reduce the element number within the model. Since the wind loading is applied directly to the core, the diaphragm action of the floor plates is not necessary and they would only serve to unnecessarily complexity for the optimization process.

The objective of the optimization was defined as minimizing the weighted compliance of the entire structure subject to two wind loads. Initially, the weightings were defined as equal. The constraints were defined as volume fractions of the exterior surface and the outriggers. The maximum volume fraction of the outriggers was defined as 0.4. Three optimizations were then performed with constraints on the volume fraction of the exterior of 0.3, 0.15 and 0.05, respectively.

It was concluded that the maximum volume fraction constraint of 0.15 produced the most pleasing results (Fig. 16). The results showed good emergence of clearly defined structural elements and a pleasing aesthetic. The optimization results were interpreted using the OSSmooth function, embedded within Hypermesh. OSSmooth generates surfaces from the topology optimization results based on an element density threshold. A Laplacian smoothing technique was then used to smooth the resultant surface edges and produce a more manufacturable design and aesthetically pleasing design. The solid Thinking was used to produce a render of the output.

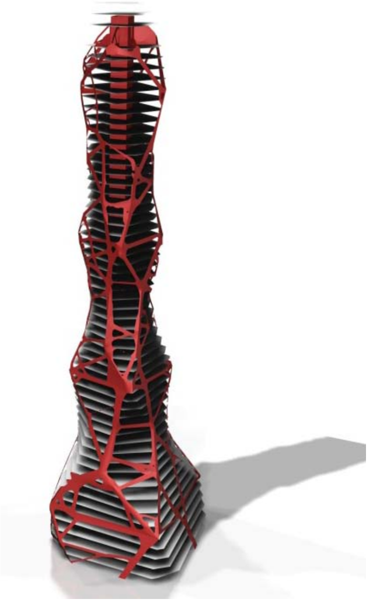
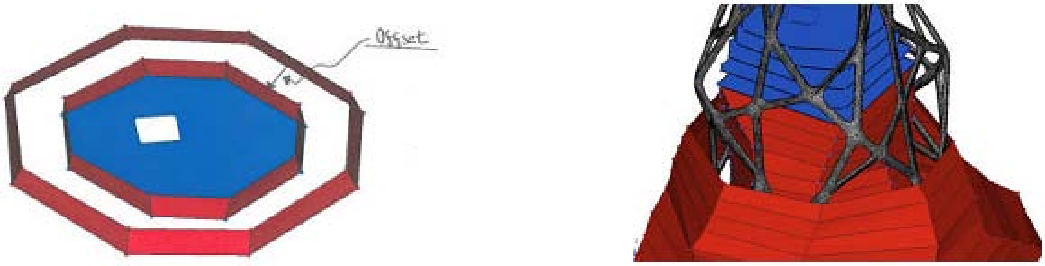


Figure (16): Results of a topology optimization study considering the exterior of the Bionic Tower as the designable domain



(a) (b)

Figure (17): a) Offsetting of exterior surfaces to define 3D design domain; b) Surfaces defining the 3D design domain encapsulating the originally proposed exoskeleton

Optimization within a 3-Dimensional Designable Domain

The detailed studies described thus far, have limited the designable domain to 2-dimensional surfaces that describe the defined geometry of the Bionic Tower. The use of a 3-dimensional designable domain, within which a topology optimized exoskeleton can emerge, was also investigated. Solids were created by offsetting the exterior surfaces (Fig. 17) constructed for the model described above, so that the exoskeleton was encapsulated within the solids created. The resulting solids had a total volume of 298,329m^3. The outriggers, previously defined as surfaces, were replaced by a 3-dimensional domain connecting the core to the exterior.

The volume tetra mesh tool was used to generate a finite element mesh based on the solids. A nominal element size of 0.75 meter was used to generate the finite element mesh. The resulting mesh contained 2,543,980 finite elements. It is worth to mention that the total time required to create the model was approximately 20 hours.

At this stage, an optimization study was performed considering vertical floor loading only. The exterior, outriggers and floor plates were also defined as designable domains. To keep the computational cost to a minimum global volume fraction, a constraint was assigned to each of the designable components. If the results of the initial studies are found to be dissatisfactory, a localized constraint on volume fraction was to be employed. The maximum volume fractions for the floor plates and outriggers were defined as 0.2 and 0.4, respectively. Two optimization studies were performed with maximum volume fraction constraints of 0.1 and 0.075 on the exterior volume. The threshold that produced the most definite structure was selected for each optimization for the ease of comparison. Plots for the 0.1 volume fraction constraint and 0.075 volume fraction constraint were prepared (Fig. 18).

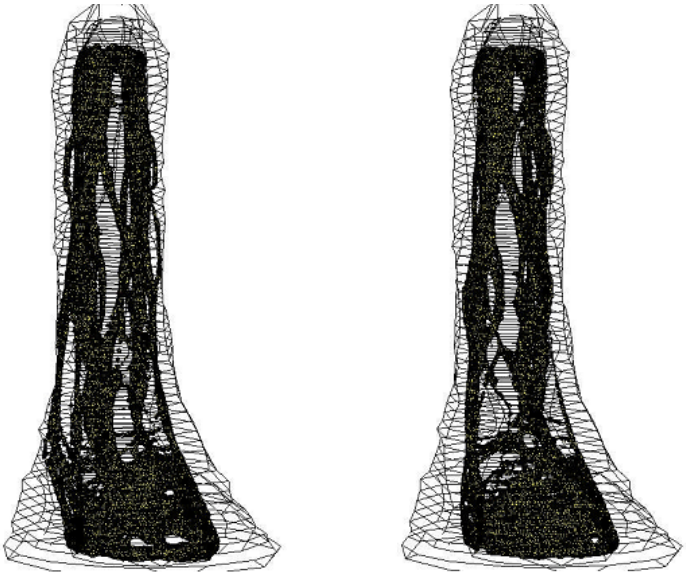

(a) (b)

Figure (18): a) Plot of elements with a density greater than 0.7 in the tri-dimensional design domain at a volume fraction constraint of 0.1; b) Plot of elements with a density greater than 0.7 in the tri-dimensional design domain at a volume fraction constraint of 0.075

Both optimization studies were found to indicate a promising emergent structure. Neither optimization indicated that it was able to distribute material away from the inner surface of design domain at the base of the tower, as it was originally intended. Large areas of solid material emerged around the base of the tower, which is not architecturally desirable due to the need for openings at this level.

The emergence of the floor plates was found to be poor using the global approach while constraining the maximum volume fraction with large areas of material emerging at lower levels and little at higher levels in the tower. The pragmatic approach of reducing the constraints, by assigning constraints to grouped floors and exterior solids, was taken. They were grouped into fours resulting in 30 individual constraints on the volume fraction. The volume fraction for the exterior was defined as 0.075 for each component and the volume fraction for the floors was defined as 0.2. It was concluded that the optimization procedure was successful with this reduced number of constraints. A number of element density plots showed that the localized constraints improved the quality of the emergent structure, although large amounts of material continued to accumulate around the base of the tower.

Localizing the constraints on maximum volume fraction also improved the emergence of a potential beam layout for the floor plates (Fig. 19). Material was also distributed to floor plates at higher levels of the tower when the localized constraints were used.

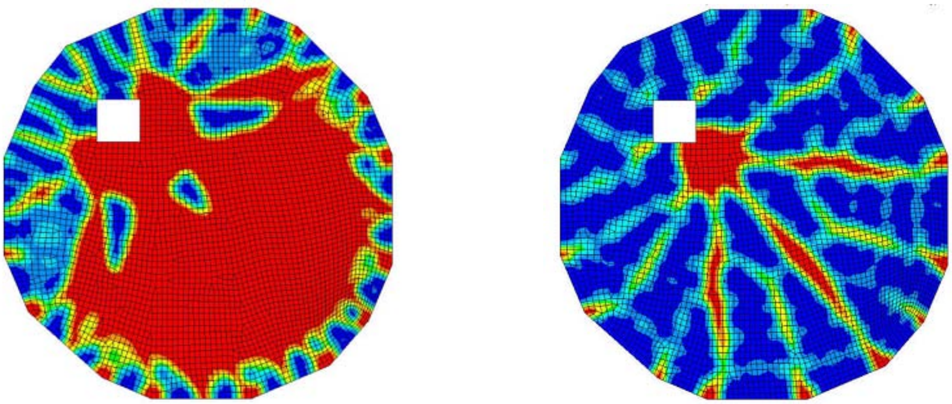

(a) (b)

Figure (19): a) Element density plot of results at 1st floor with global volume fraction constraint; b) Element density plot of results at 1st floor with localized volume fraction

The final results were found to have an unusual and organic aesthetic. Numerous small features, where the exoskeleton diverged away from the floor plates, also emerged that created some interesting details. The method of interpreting the results of the topology optimization using OSSmooth was not found to produce as clearly defined structure as for the bi-dimensional design domain. The results could at best be described as rough. To generate an aesthetically pleasing presentable image, manual interpretation was required (Fig. 20).

Finally, a braced outrigger structural arrangement was selected for the Bionic Tower, whereby the structural core is stabilized by a series of structural elements on the perimeter of the building. The core is connected to the external bracing elements by a truss at the pinnacle of the tower. The braced outrigger was selected on the basis that it fulfills the architectural intent of an externally visible structure and provides a viable structural solution for a tower of this height. The core is connected to the perimeter columns by a series of horizontal trusses. Lateral loading was applied to the tower and topology optimization studies were performed on the entire exterior surface as well as on the trusses connecting the core to the perimeter surface.

Despite the highly irregular shape of the tower, it was found that a series of discrete structural load paths could be identified from the results of the topology optimization. An inspection of the trusses connecting the core to the perimeter surface (Fig. 21) showed completely rational truss layouts with strong similarities to typical optimal truss layout solutions found in the literature. Furthermore, the aesthetics of its structural layout were compatible with the “free-form” architectural initial intent of the architect and the client.

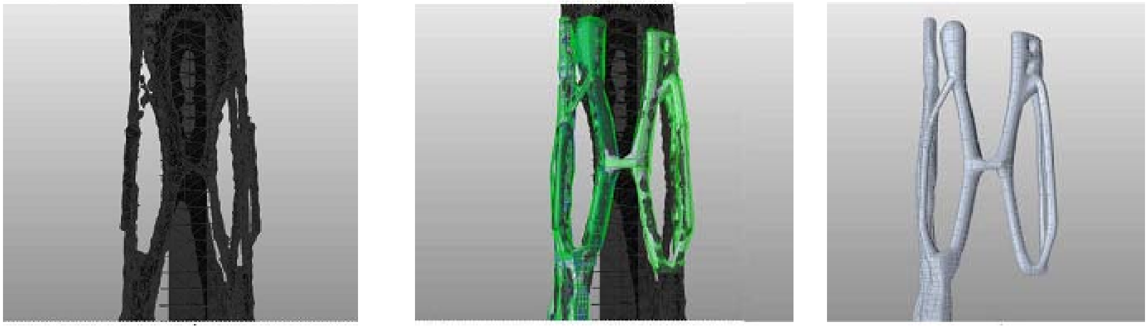

(a) (b) (c)

Figure (20): **a) OSSmooth output to be used as a reference; b) Creating of surfaces based on results; c) Final surfaces generated**

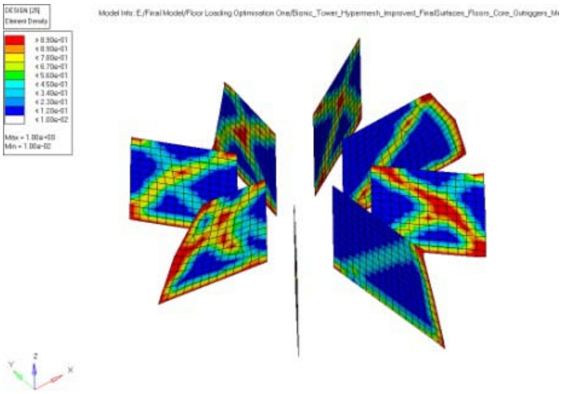


Figure (21): Rational truss structures suggested for the outriggers in the results of the topology optimization study

It is worth noting that the topology optimization technique has been applied to the structural design of irregular and twisted high-rise structures previously; however the example presented is the first of its kind, where the topology optimization has been applied to a completely “free-form” geometry. The results exemplify how topology optimization is a useful design tool for designing structures for complex forms, where intuition may fail.

TOPOLOGY OPTIMIZATION IN STRUCTURAL DESIGN OF MEMBERS

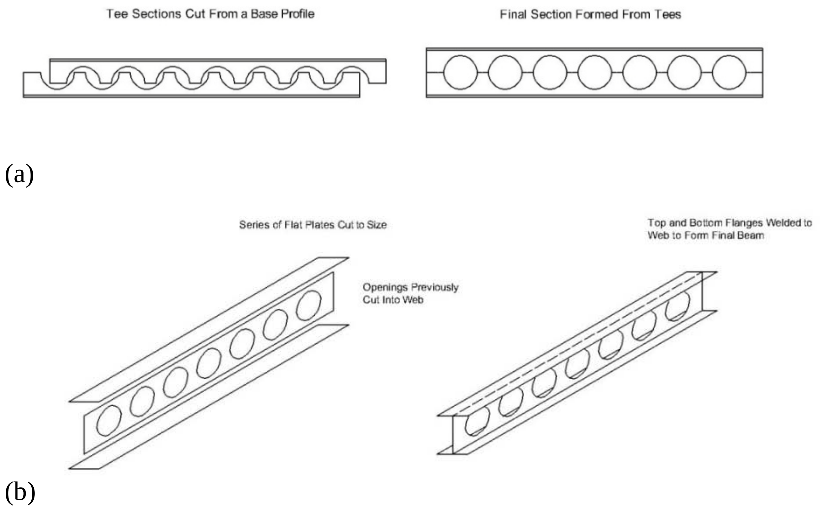
Background

The judicious placement of holes in the webs of steel beams has been employed to design lighter and stiffer beams for over 100 years. The original concept of creating a beam with web openings can be attributed to Geoffrey Murray Boyd (Knowles, 1991), who patented what is now known as the castellated beam.

Castellated beams are formed by the expansion of a parent I-section to form a deeper stiffer section with web openings (Fig. 22a). Cellular beams, which contain circular openings, are currently the most widely used perforated beams due to their beneficial weight-to-stiffness ratio and the ability to pass services (eg. hydraulic pipes, electric wires,…etc.) through large holes, while the stresses are distributed evenly in the vicinity of the circular holes. An alternative to the castellation process of fabrication is the plate assembly.

Plate assembly involves the fabrication of the I-section from a series of three flat steel plates (Fig. 22b).

Nowadays, the industry has focused solely on the latter technique, as it provides flexibility in the design process, meaning the actual location, size and shape of the holes, the avoidance of stiffeners providing wide web-posts, and under the concept of performance-based design of each one of such components. It is apparent that this technique can be used in conjunction to the achievements of the current work, as later presented. It is worth to note that even world-wide industrial leaders patenting and using the castellation technique for many decades (eg. ASD Westok, Ltd.), have now moved with the plate assembly technique taking advantage of the free-form of the final product and the high tolerances provided.



(a)

(b)

Figure (22): **a) Castellation technique; b) Plate assembly technique for fabricating perforated beams**

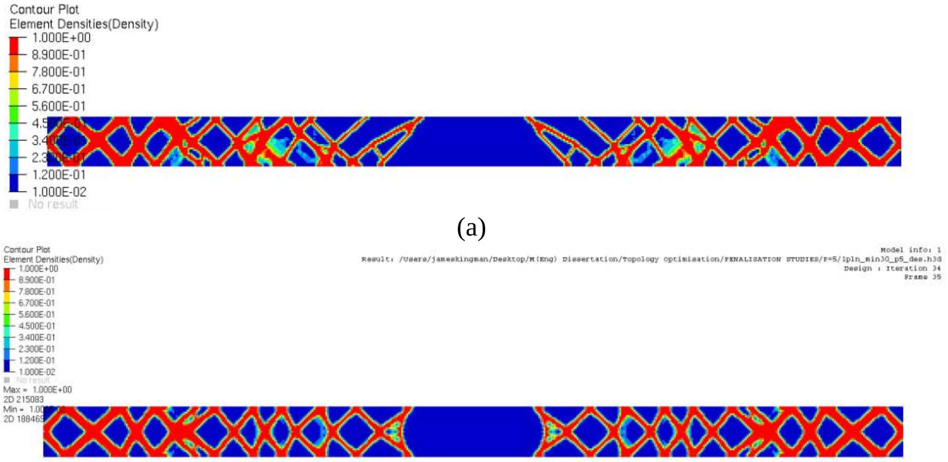
The constant desire for improvement and mature level of understanding of the structural action of perforated steel sections has recently led to novel opening shapes, such as ellipses, being investigated (Tsavdaridis and D'Mello, 2012). These novel opening shapes were proposed as they promote an efficient and economic fabrication, improved structural performance and aesthetic qualities when compared to the standard opening types.

Optimized Perforated Steel Beams

A comprehensive investigation was conducted with the use of topology optimization techniques for the optimal design of the web openings in structural steel beams used in Civil Engineering applications (Kingman et al., 2013). The use of the continuum structural topology optimization approach for the design of an I-section beam web has not previously been presented in the literature. The SIMP technique was implemented in this study. Various constraints and objectives were investigated.

The study was conducted on a standard 305x165x40 Universal Beam (UB). The section was selected on the basis that it has been widely used in prior to both experimental and numerical studies (Tsavdaridis and D'Mello, 2012) and represents a typical 5m span section in building construction. The beam was subjected to uniformly distributed loading along the top compression steel flange to simulate the load from a steel-concrete composite (SCC) or reinforced concrete deck with partial shear strength (i.e., lateral stability was not provided).

The topology optimization was performed on the beam web only with the objective of maximizing the stiffness of the beam subject to a constraint on the area of the beam web that must be massless. In perforated beams like this, the web plays a very important role in providing the vertical shear capacity, forming the so-called Vierendeel mechanism as well as providing resistance to the out-of-plane web-post (steel part between two consecutive openings) buckling failure mechanism. Both these local failure modes are directly associated with perforated beams, hence the study of the web only. On the other hand, steel flanges are providing the global bending capacity and hence they are not considered in the current investigation. Initially, it was specified that a minimum of 60% of the beam web should be open (massless). The topology optimization results (Fig. 23a) suggested a truss-like structure for the entire length of the beam, with a large opening in the centre where maximum moments but low shear forces exist. The overall design appeared to follow the lines of the principle stresses within the beam web and the openings took a rhomboidal shape. In order to rationalize the results of the topology optimization, a complementary study was conducted where the results were constrained so as to be symmetrical about the longitudinal axis of the beam web. The symmetry constrained study resulted in a similar design with rhomboidal openings, but it was better balanced along the length of the beam (Fig. 23b).



(a)

(b)

Figure (23): a) Results of a topology optimization study on a beam web; b) Results of A topology optimization study on a beam web incorporating a symmetry constraint

The results of the topology optimization study were post-processed in order to generate the finalized geometry of the optimized beam web (Fig. 24-top). In order to further investigate the structural performance of the beam web in comparison to a typical beam with circular web openings, a nonlinear FE analysis was employed. The size of the circular web openings was determined based on the maximum size generally used widely in industry, equal to 0.75 times the depth of the web. A total of 17 web openings were placed along the length of the beam, in order to make the weight of the cellular beam as similar as possible to the optimized one, whilst retaining the same flange dimensions. It was desirable to compare a cellular beam of a similar mass in order to be able to draw valuable conclusions regarding the structural efficiency of the topology optimized design.

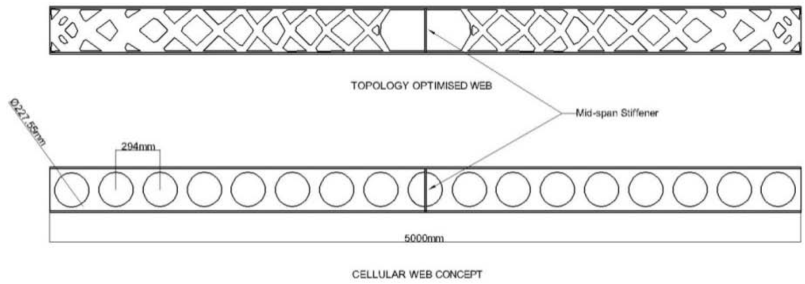


Figure (24): Geometry of topology optimized beam web (top) and geometry of cellular beam web (bottom)

Cellular beams often exhibit complex failure behavior which may include localized buckling modes (eg. Vierendeel mechanism, web-post buckling, buckling due to local compression,… etc.) or yielding and redistribution of stresses in the vicinity of the openings. Previous FE studies (Tsavdaridis and D'Mello, 2011) were used to verify the FE model and provide accurate assessment of the effectiveness of the topology optimized beam web.

The basis of the FEA method employed is a three-step process, whereby an initial pre-stress is applied to the FE model and a linear static analysis performed. The results of the linear static analysis are then used in an eigenvalue analysis of the FE model to determine the first buckling frequency and its associated mode shape. Imperfections are applied to the FE mesh, using the mode shape taken from the eigenvalue analysis, with a magnitude of the web thickness divided by 200. A geometric and materially nonlinear FE analysis is then performed to determine the load response of the beam. It is worth to note that the geometric complexity of the topology optimized beam web design necessitated the refinement of the FE mesh adding to the time required to complete the analysis process. The analyses were performed using the commercial FE package ANSYS v.14.

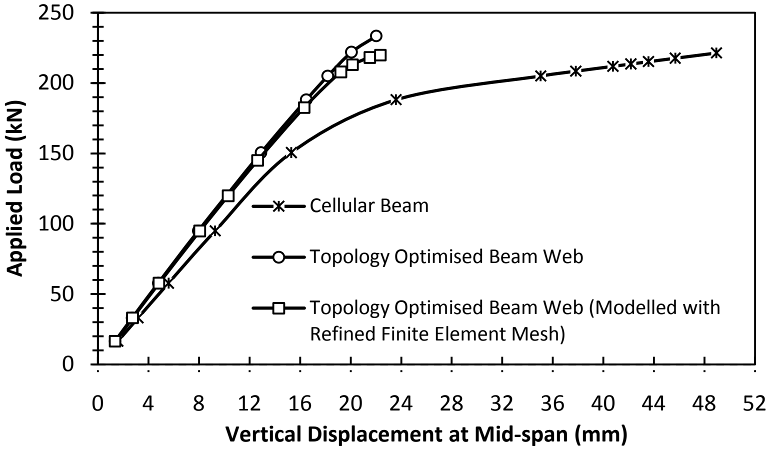


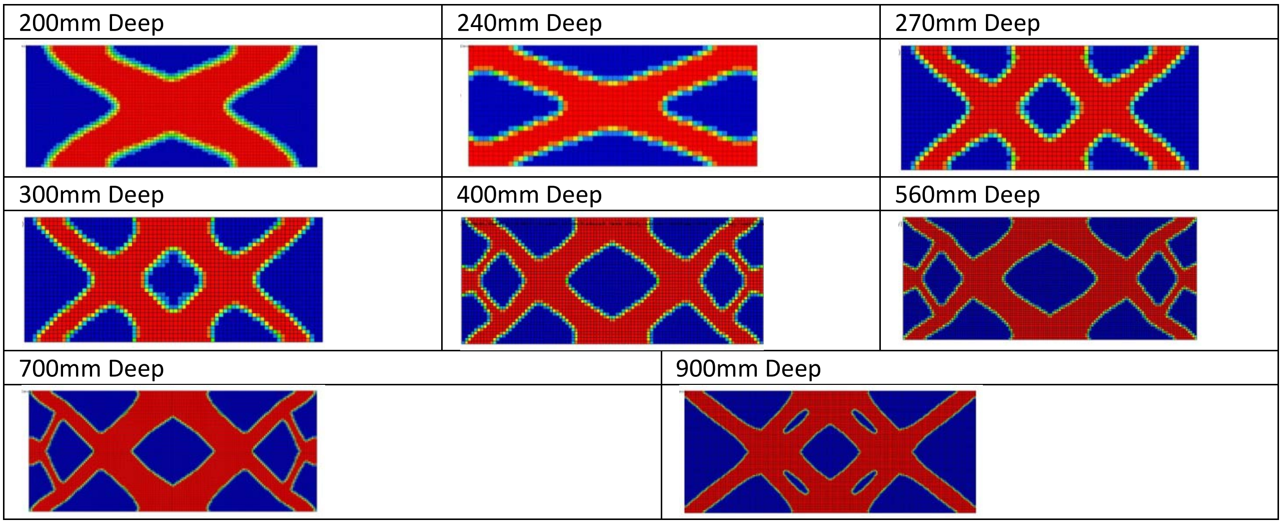
Figure (25): Load displacement results for comparative study of beam with cellular and topology optimized webs

The results of the FE analysis suggest that the beam with an optimized web has a higher yield load and a greater stiffness in the linear range compared to the cellular beam (Fig. 25). Since both of the beams are formed from the same amount of structural material, it can be concluded that the use of material in the topology optimized design is more efficient; therefore the proof-of-concept was achieved. The results also demonstrate that at the yield load level, the stresses in the web of the cellular beam increase towards the support. Oppositely, it was found that the stresses in the optimized web, particularly close to the critical area of the supports, were uniform despite the localized stress concentrations at the corners of openings.

Novel Web Opening Architecture

In light of the results detailed above as well as other researchers studying similar structural components (Edgar, 2008; Von Buelow, 2008; Briseghella et al., 2013; Sarkisian, 2011), it is concluded that the topology optimization is a useful tool identifying alternative improved structural beam configurations and improving the in depth understanding of their structural behavior. However, when it was applied to a full length section, the resulting design is generally complex and somewhat difficult to justify and be used in most practical applications. Consequently, a localized study approach was later established in order to identify optimum web opening shapes and locations. In the local study, a short beam section was modelled while shear forces and bending moments were applied directly to the section and the topology optimization was then performed.

Further, a parametric investigation on a large number of cross-sections indicated that only the depth of the section alters the optimal topology of the web openings (Fig. 26). It can be concluded that for beams of depth between 270 mm and 700 mm, the optimum web opening topology is the same. Based on these results, a web opening configuration is suggested that offers advantageous structural performance.



200mm Deep

240mm Deep

270mm Deep

300mm Deep

400mm Deep

560mm Deep

700mm Deep

900mm Deep

Figure (26): Results of topology optimization studies on localized beam sections of varying depths

Therefore, a topology optimized beam web tends to offer improved structural performance compared to the typical perforated beams. The major disadvantage of directly applying continuum topology optimization algorithms to the design of a long-span beam is the geometric complexity of the resulting design and the associated difficulty to determine analytically the load capacity of the section.

A local approach was implemented in order to identify a more generalized opening type. Based on the results of this study, a novel opening architecture has been suggested (Fig. 27). It is anticipated that this new configuration is possible to be fabricated using the plate assembly technique, while no cost implies, compared to any other opening shapes. Further study is, however, required to examine various failure mechanisms that might have been introduced due to the complexity of these web openings as well as derive an analytical and/or empirical method to determine the load carrying capacities.

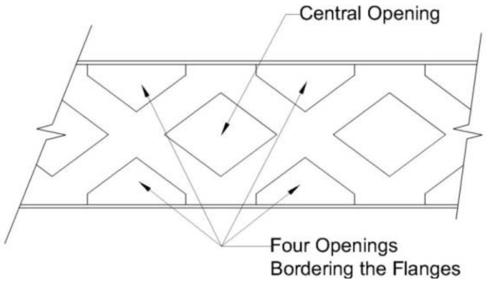


Figure (27): Suggested web opening configuration based on the results of the local topology optimization study

CONCLUSIONS

In this paper, advanced and non-standard optimization techniques are used by operating complex processes in developing optimized structural forms found in Civil Engineering applications and examine their structural behavior on two different levels: on the global scale (structural system), and on the local scale (structural component). The concept is based on the basic ingredients of Performance-Based Optimization of Structures; the optimal 'layout' (i.e., the interplay between the form-finding or morphology, the structure and the structural material). This research is driven by limited resources in the research area of Civil Engineering and technological competition which demand lightweight, low cost and high-performance structures.

Topology optimization offers significant opportunities in Civil/Structural design and Architecture. It has been suggested as a tool that can lead to greater collaboration between engineers and architects during the conceptual design process. A limited number of examples of topology optimization being used in structural engineering and architecture can be found in the literature. The work of the authors on the topology optimization of a high-rise structure and the topology optimization of perforated steel beams is presented in more detail. In both cases, it was found that topology optimization is a useful design tool which promotes efficient designs.

At present, the major barriers to the widespread implementation of topology optimization methods are: (i) the complex geometry of the optimized designs, and (ii) the difficulty in solving problems involving non-linear behavior (such as buckling) and dynamics. The increasing use of advanced manufacturing techniques such as CNC machining and 3D-printing may offer a solution to the complex geometry often arising during topology optimization studies. Methods for solving topology optimization problems involving non-linear behavior as well as dynamics are currently under investigation with a promising area of research being the Equivalent Static Load (ESL) method.

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