EXPLOITING THE DESIGN FREEDOM OF RM

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Abstract

This paper details how Rapid Manufacturing (RM) can overcome the restrictions imposed by the inherent process limitations of conventional manufacturing techniques and become the enabling technology in fabricating optimal products. A new design methodology capable of exploiting RM's increased design freedom is therefore needed. Inspired by natural world structures of trees and bones, a multi-objective, genetic algorithm based topology optimisation approach is presented. This combines multiple unit cell structures and varying volume fractions to create a heterogeneous part structure which exhibits a uniform stress distribution.

1. Introduction

Current product structures are not optimal; they are generally designed to meet a set of specifications identified in the conceptual design stage. If optimisation is considered to be a process of improvement, then provided a design is within these acceptable design limits, it need not be improved upon further. Most industrial optimisation work is usually applied via a manually iterative approach often termed 'over engineering' which, although may improve a design's performance, it does not yield a truly optimal solution as parts are often unnecessarily overweight (Mattheck 1998). At present, even if a truly optimal design is conceived it will still become compromised during the manufacturing stage due to the inherent limitations of conventional manufacturing technologies. For instance, injection moulding requires: the introduction of draft angles to allow the part to be removed from the tool; introduction of split lines; near constant wall thicknesses and the absence of overhangs within the design (Degarmo 1997). In addition, further design considerations are required for assemblies to allow multiple parts to be assembled correctly, increasingly compromising a potentially optimal design. These Design for Manufacture and Assembly (DFMA) considerations (Boothroyd *et al.* 1994) effectively stifle designer's freedom when creating new products and prohibit the production of globally optimal design solutions.

Rapid Manufacturing (RM), due to its additive, layer-by-layer build nature, offers a notable alternative. RM allows the creation of virtually any given geometry without any need for tooling, allowing the fabrication of complex end-use parts that would be unmanufacturable via other means (Hopkinson *et al.* 2005). In addition, RM offers the ability to reduce part counts in assemblies by consolidating component parts into fewer pieces and, in some cases, can reduce the need for post production assembly operations by building components pre-assembled (Wohlers 2005). Although still the subject of extensive research and development, RM is now a valid manufacturing method (Hopkinson *et al.* 2005).

RM offers increased design freedom by removing the restrictions previously imposed by the DFMA considerations of conventional processes (Hopkinson *et al.* 2005). As a result optimal designs will have fewer compromises with RM becoming the enabling technology that will break the DFMA shackles of design. As suggested by the previous works of Campbell *et al.* (2003), Hague *et al.* (2003) and Mansour & Hague (2003), the advent of RM as a valid fabrication alternative compared to traditional processes will require a new methodology of Design for RM

(DFRM) to exploit this increased design freedom. It is the aim of this paper to propose a new design methodology that is capable of exploiting the increased design freedom offered by RM. This is achieved initially by reviewing the optimisation found in the natural world followed by the inspection of numerical methods capable of simulating the design rules that Nature has followed in creating her optimal structures. This background is followed by the investigation of an existing freeware software (DesignLab) where the main topics of interest identified in the literature review are already combined, namely; Genetic Algorithms (GAs) and topology optimisation. The preliminary investigation highlights the benefits of a GA based topology optimisation system, but also points out the shortcomings of the particular software investigated, namely the inability to consider variable densities of a single material. Finally, the results of this investigation are used to shape the proposed new methodology of truly optimal DFRM which is then presented. This novel GA based topology optimisation approach considers a single material of 3D unit cells, varying in volume fraction and form, to create a heterogeneous part structure. This method allows increasing part functionality through intelligent design towards an optimum.

2. Literature Review

2.1 Natural World Optimisation

The Natural World has long been a source of inspiration for the problems that man faces with the field of Biomimetics dedicated to this technology transfer. Historical examples include the principal of flight, the fabric fastener Velcro® and the structure of the Eiffel Tower. More recent examples include Gecko tape, (Geim *et al,* 2003) and swimwear based on sharkskin, (Speedo 2005).

Billions of years of evolution have led to the natural designs we see in the World today. Each natural design in existence is optimal for it's specific environment, for if it were not, it would not have survived the test of time (Darwin 1859). Bones and trees are classic examples of optimal structures seen in the Natural World. Bones are able to adapt their microstructure to a changing loading environment over time, effectively adding more material where it is required and removing material where it is no longer needed. This process is known as Wolff's Law, (Wolff 1892). Trees are also able to adapt their structures to changing loading environments as shown in numerous works by Mattheck (1998). Mattheck has shown that trees use their cambium growth layer to perform adaptive growth, quickly laying down additional material where high notch stresses occur and enabling shape adaptation to minimise the effects of prevailing winds (Mattheck 1990). Unlike bones, however, trees are not able to remove material where it is no longer needed. Mattheck suggests this is due to bones belonging to animals that are required to move whereas trees remain stationary. Whatever the reasons for this behaviour, it is clear that Nature follows different design rules from mankind. If the optimal structures found in the natural World are considered to be the blueprints for optimal design, then the fundamental design rules that Nature follows, namely the efficient use of material and maintaining a uniform stress distribution, should be followed in engineering design.

2.2 Genetic Algorithms

Nature's process of survival of the fittest is a brutally efficient method of ensuring that only optimum design solutions survive. As such, the evolution process itself can be considered as an extremely powerful optimisation process and can be simulated in an accelerated form by the use of GAs. GAs are general search and optimisation routines based on the mechanics of natural selection and the Darwinian theory of evolution. Initially conceived by Holland (1975) and subsequently developed by the seminal work of Goldberg (1989), GAs harness the transfer of good genetic material from parent solutions to offspring solutions through the genetic operators of reproduction, crossover and mutation.

The application of GAs as a means of component optimisation is usually performed in a parametric manner, where the GA is used to find the optimum values for all of the predefined component parameters (Renner & Ekárt 2003). However, this type of optimisation does not allow for topological changes in geometry, such as the introduction of additional holes to reduce weight, (new parameters cannot be created), and as such only modifications to existing designs can be found instead of radical new design solutions. It is for this reason that a topology optimisation approach is needed.

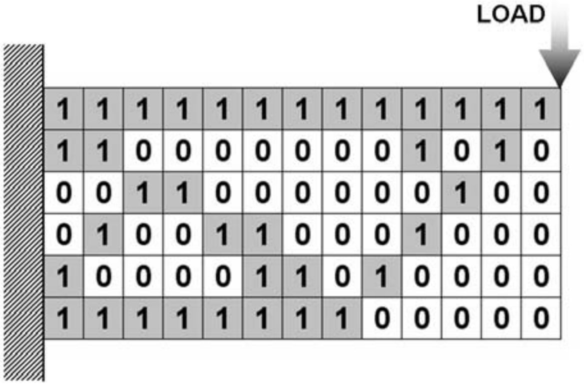
2.3 Topology Optimisation

Nature's design rule of only depositing material in structures where it is required with no excess to maintain a uniform stress distribution is the fundamental principle of topology optimisation; that is the economical distribution of material within a predefined design space. Hence topology optimisation is often referred to as the *material distribution method*. Topology optimisation is a numerical simulation technique that generates the optimal topological shape of a structure for a given mechanical load. The basic method solves the common engineering problem of determining the optimum arrangement of material distribution, with a limited amount of structurally isotropic material, within a given design space called the *design domain*.

In order for the material distribution and therefore the mass and associated structural behaviour to be represented adequately, the design domain is divided into many small discrete elements or cells. Loading and boundary conditions are applied by the user to the necessary discrete elements, thus completing the model. Without any further guidance or decision making required from the user, the optimisation process systematically and iteratively eliminates and redistributes material throughout the design domain until a suitable structure is obtained (with regards to the objective function, constraints and termination criteria), thus yielding the final solution. Typically, this iterative process is implemented by either the addition or removal of elements from a Finite Element (FE) model.

Many topology optimisation techniques are based on the *Homogenisation Method*, by Bendsøe & Kikuchi (1988), based on the use of an artificial composite material with microscopic voids using a variable density approach. Instead of elements representing purely material being present or void of material, elements are allowed to have various densities (ranging between solid and void) throughout the optimisation process, yielding a solution in the form of a perforated composite material with a distributed microstructure. Indeed, it is the presence of the distributed microstructure with varying densities used in the homogenisation method that enables the resultant geometrical solutions to exhibit a uniform, and therefore optimal, stress distribution throughout the entire structure. From a conventional manufacturing point of view, the perforated regions within the composite structure representing the regions of intermediate density have little practical value and consequently these densities are usually forced towards either a 1 (representing solid) or a 0 (representing void of material) to define the final topology. However, if RM is considered to be the chosen fabrication process, the occurrence of cells of intermediary density is less of a problem and is something that can be exploited to increase part functionality and create a more uniform stress distribution.

GAs can be applied directly to topology optimisation problems as shown by Kane & Schoeunauer (1996). The binary encoded string representation of the GA individual can be simply mapped into the design domain as a two dimensional (2D) array, as the cantilever beam example in Figure 1 shows. Here the solid and void regions are represented by the 1's and 0's of the binary code respectively.



1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	0	0	0	0	0	0	0	1	0	1	0
0	0	1	1	0	0	0	0	0	0	1	0	0
0	1	0	0	1	1	0	0	0	1	0	0	0
1	0	0	0	0	1	1	0	1	0	0	0	0
1	1	1	1	1	1	1	1	0	0	0	0	0

Figure 1 - Encoded Binary String Mapped into a 2D Cellular Array of a Cantilever Beam

This application of GAs to topology optimisation can also be extended to 3D problems by mapping the binary string into a 3D array. When topology optimisation problems are solved by implementing a GA, the entire process will benefit from the nondeterministic search pattern that a stochastic process exhibits, therefore minimising the likelihood of premature convergence on a local optimum. This is arguably the opposite behaviour of methods that are variations of the deterministic homogenisation approach, where behaviour between successive iterations can be readily predicted and as such these methods are often trapped by local optima unless the number of discretised elements is high for a relatively small design domain. By using a GA based topology optimisation approach, multiple materials can also be considered by moving away from a binary representation and introducing additional digits, as is shown in Figure 2 where 0's represent void areas, 1's represent material 'A' and 2's represent material 'B'.

1	1	2	2	0	0	1	1	0	1	2	0	

Figure 2 – Encoded String for Multiple Materials

3. Preliminary Investigation

3.1 Introduction

As seen previously it is possible to combine a GA within the topology optimisation process, however, there is a lack of commercially available software packages capable of performing this function. One example that exists is a freeware, beta version software currently called 'DesignLab 2005' by DevDept (2005). This software was briefly investigated by the authors using a simply loaded cantilever beam problem. The software combines a GA and FE analysis with topology optimisation to create 3D components from either a single material or multiple materials by adopting a 3D array consisting of several different digits to represent the various materials.

DesignLab uses a basic GA that equates individual solution fitnesses by using a weighted sum of several objectives – weight, deflection, Factor of Safety (FOS), and introduces a penalty factor that reduces the combined fitness depending on how much an individual solution violates an objective. The fitness and penalty values are combined for each individual solution to calculate a *cost* or objective function. It should be noted that the cost function and associated cost values assigned in the software are merely a quantifiable measure of feasibility and have nothing to do with ecomomic or financial costing whatsoever. It is currently impossible for the user to inspect or alter the weighting of the weighted sum in the beta version software.

DesignLab was investigated to explore it's potential as an RM design tool. For this investigation, a simple cantilever beam problem was considered where the design domain was divided by 20 cells in X, 10 cells in Y and 1 cell in Z with each cell having a length of side of 10mm. The design domain for this study was 3D but can be considered as 2½D being a simple extrusion in the Z-axis. The design domain was fully constrained down the left hand side and a downward point load applied to the top right hand corner as can be seen in Figure 3.

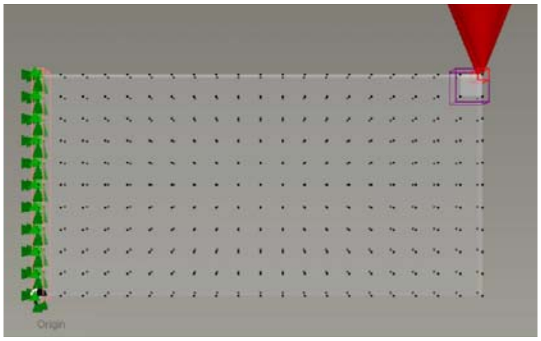


Figure 3 – Cantilever Beam Problem Defined in DesignLab

The parameters used to control the behaviour of the GA throughout this investigation were the default parameters, namely:

- initial population size of 120 individuals with a population of 60 individuals maintained thereafter
- initial mutation probability rate of 0.015 dropping by 0.0025 for every 10 generations where results do not improve
- desired FOS of 2.25 with a penalty of 25 applied to individuals that violate this
- a minimum hole size of 1 cell
- mating by single point uniform crossover
- parent pairs selected by a weighted ranking of fitness values

These parameters were entered into the initial problem definition but were not altered at any stage of the investigation to ensure consistency.

Initially only a single material was selected (Steel), allowing the GA to distribute solid material cells and void cells throughout the design domain. This first scenario was repeated five times (trials A to E). The five beam structures of the first scenario were analysed to see if any cells were solid or void in all of the five trials. This was performed by superimposing the five structures on top of one another and adding them together. Cells that remained 0 were void in all five trials, cells that totalled 5 were Steel in all five trials and cells that were either 1, 2, 3 or 4 were Steel in some trials and void in others. The cells that remained solid or void throughout trials A to E were used to further constrain the design domain, thus steering the optimisation problem towards more desirable solutions based on the previous experience of the first scenario. The additional constraints were added to the cantilever beam problem definition creating a second scenario, which was also run five times (trials F to J). The five trials of the second scenario (F to J) were analysed in the same manner as those from the first, by superimposing the five beam structures on top of each other and adding them together to form the combined structure. This combined structure could be used to further constrain the beam problem design domain in additional scenarios.

The effects on the overall stress distribution of introducing another material into the problem were of particular interest so the original cantilever beam problem was repeated with two materials, Steel and Aluminium. This third scenario was also run five times (trials I to M).

The five beam structures of the third scenario, where two materials were considered, were also analysed in the same manner as before. However, this time, it was to see if any cells remained void, Steel or Aluminium in all of the five trials. The analysis was performed by altering the values of the cells for the different materials by a factor of ten so that Steel cells were represented by a 10, Aluminium cells were represented by a 1 and void cells were represented by a 0 as before. When the five structures were added together, cells that totalled 50 were Steel in all five trials, cells that totalled 5 were Aluminium in all five trials and cells that remained 0 were void in all five trials as before. Cells that were anything other than 50, 5 or 0 in the combined structure fluctuated between Aluminium, Steel and void in the five trials.

3.2 Preliminary Results

The individual results of a single trial from the first scenario are shown in Figure 4, with both solid steel cells and void areas present. The stress distribution plot of Figure 4 shows that there are several areas of localised high and low stress; these have been circled in white. This solution can therefore be improved upon further to remove these localised stress concentrations and create a more uniform stress distribution.

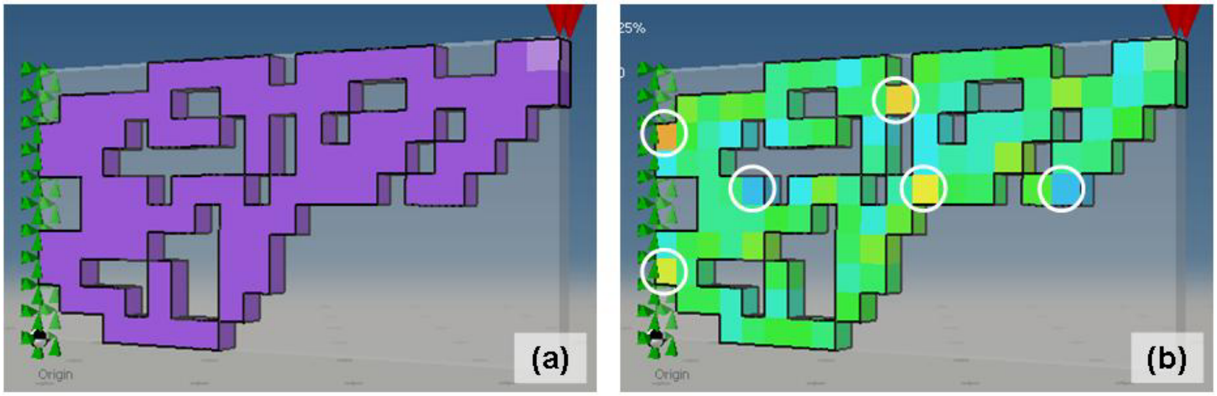


Figure 4 – Cantilever Beam Result from DesignLab for a Single Material, Showing Material Distribution Plot (a) and Stress Distribution Plot (b) with Areas of Local High and Low Stress Circled

Similarly, the individual results of a single trial from the third scenario can be seen in Figure 5, with solid Steel cells (dark grey), solid Aluminium cells (light grey) and void areas present. The stress distribution plot of Figure 5 shows that there are fewer areas of localised high and low stresses when compared to the stress plot of the single material problem of Figure 4. This suggests that the stress distribution is more uniform and therefore the structure is more optimal than the single material structure of Figure 4.

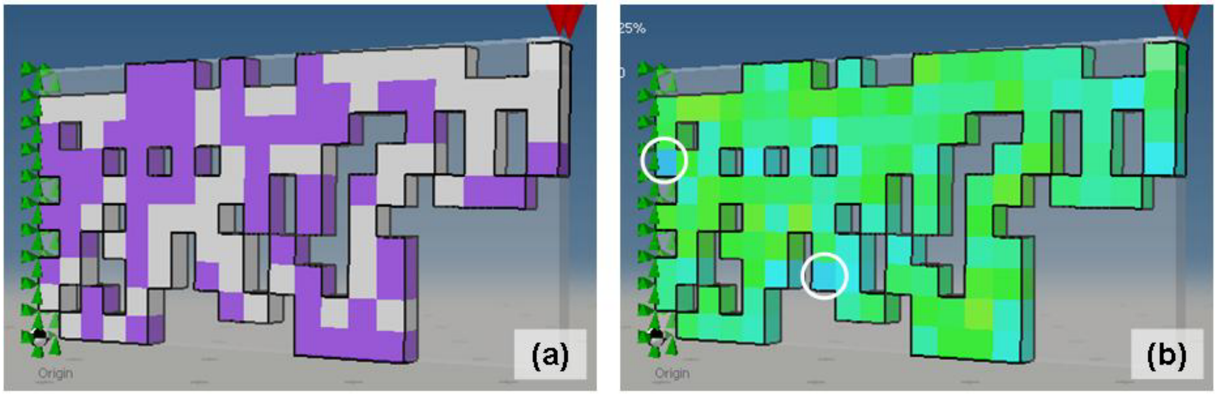


Figure 5 – Cantilever Beam Results From DesignLab for Two Materials, Showing Material Distribution Plot (a) and Stress Distribution Plot (b) with Areas of Localised Stress Circled

4. Discussion

It was noticed that the average number of generations reduced from the first scenario to the second scenario. This can be explained by the presence of additional constraints imposed on the second scenario based on the analysed results of the first scenario. These extra constraints effectively remove many structural permutations from the vast possibilities of the original problem, increasing the efficiency of the GA by preventing it from wasting time calculating already known poor solutions. Likewise, the average number of generations for the third scenario (two materials) is much greater than either of the single material scenarios due to the increased number of permutations possible for the structure. The GA now has to consider three options for each cell, namely void, Steel or Aluminium, as opposed to just the two of solid or void. By imposing additional constraints gathered from the analysis of the third scenario combined structure, it should be possible to reduce this average number of generations in subsequent scenarios. The introduction of additional constraints would once again reduce the number of permutations the GA may consider, thus increasing the efficiency of the GA in reaching a solution in a shorter time.

The overall objective for these DesignLab optimisation problems is to minimise the cost function. The cost value is calculated by a weighted sum (as described earlier in Section 3.1) which is likely to include the weight of the solution structure, the maximum displacement (directly related to the stiffness or compliance of the structure) and the range of the FOS across the structure which bears a direct relationship to the stress distribution. The average cost value from the first scenario to the second scenario was seen to improve and there was further improvement between the second and third scenarios. In each case the average FOS range has reduced resulting in a more uniform stress distribution across the structure (as was witnessed from Figure 4 to Figure 5). The average weight also reduced through all three scenarios, however, the maximum displacement reduced in the single material scenarios then increased in the two material scenario. This is due to the inclusion of a less stiff material within the structure (Aluminium) which will deflect more readily than the stiffer Steel structures of the previous two scenarios. The maximum displacement values may not be included in the weighted sum of objectives that form the cost function or, if they are included, do not have a large weighting as this increase does not seem to have a noticeable effect on the cost values.

The most important observation in the results that should be noted is that the third scenario (two materials) had an improved average cost value and reduced FOS range when compared to either of the single material scenarios. The stress plots of the structures in Figure 4 and Figure 5 show that the stress distribution is more uniform where multiple materials are considered compared to a single material with a homogenous structure, suggesting that future GA based topology optimisation systems should consider multiple materials in order to achieve a uniform stress distribution. The use of multiple materials within RM to increase part functionality has been considered by many researchers in the form of Functionally Graded Materials (FGMs), (Agarwala *et al.* 1992, Siu 2002, Tolochko 2003). However, there are many fabrication issues to be addressed in such cases in addition to the dilemma of recycling components fabricated of multiple materials.

It is for these reasons that a single material only will be considered in the proposed methodology of optimal DFRM. It should be noted that at this stage that although a single material is under consideration, the results from the first and second scenarios of the preliminary investigation (both single material only) suggest that a uniform stress distribution will not be achieved if cells are only allowed to be either 100% solid or 100% void. However, this phenomena is purely dependent on the size of the unit cells used compared to the size of the design domain. In order for any system to reach a truly globally optimal design solution, the geometry and topology should be completely free to 'evolve' into an ideal solution. However, this could only be achieved if the design domain is discretised into many small solid cells (voxels). This would have a considerable negative effect on required computation power, as a direct result of increasing the length of the GA bit string. Despite the advances over recent decades in computing power, coupled with the decreasing cost of such equipment, the requirements of the idealised solution are still far beyond the resources of an average design engineer.

The solution to the same cantilever beam problem obtained via the homogenisation method would yield a structure with a uniform stress distribution by permitting the density of the material to alter across the structure of the beam by varying the microstructure. The two material DesignLab solution of the same problem (shown previously in Figure 5) includes materials of considerably different densities, namely Steel and Aluminium, yielding a solution with a significantly more uniform stress distribution than any of the single material solutions. In effect the Aluminium cells could be considered to be Steel cells of intermediary density. This phenomenon suggests that, in the absence of significant computing power to generate the voxel-sized elements (as outlined above), in order to achieve a uniform stress distribution across a solution structure consisting of a single material, variable densities of that material are a potential solution. This is only achievable when using an additive RM approach and must therefore be implemented into the new DFRM methodology. The DesignLab software has proved itself useful in these initial investigations, however, the ability to consider variable densities of a single material is beyond it's capabilities and as such the author is developing an alternative GA based topology optimisation software that is capable of this requirement.

4.1 Proposed Methodology of DFRM

The preliminary investigation of the DesignLab software in addition to the fabrication and recycling issues associated with Functionally Graded Materials has highlighted that a single material GA based topology optimisation system should be considered, where the uniform stress distribution is achieved by permitting variable densities of a single material. If the density of a single elemental cell is considered to be the volume fraction of solid material within the whole unit cell, then this cell density or volume fraction can be varied by controlling certain feature parameters that describe a unit cell structure. Figure 6 shows a Computer Aided Design (CAD) model of a simple cell structure with various volume fractions achieved by altering the parameters of the hole features within the unit cell.

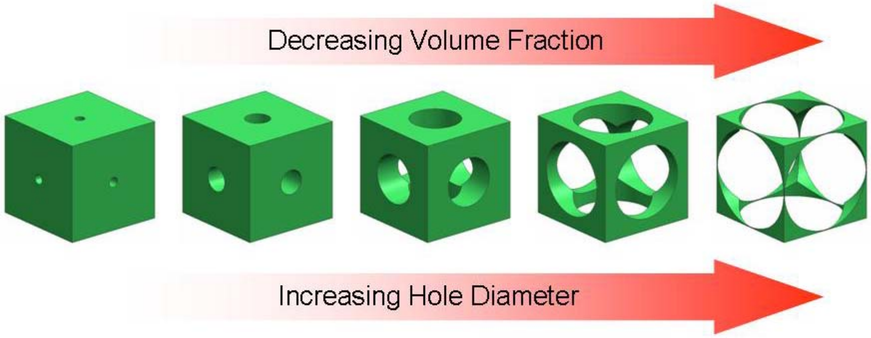


Figure 6 – Varying Cell Volume Fraction by Alteration of CAD Parameter, in this Case the Hole Diameter

In addition to altering the volume fraction of a cell structure by controlling defining feature parameters within the 3D unit cell CAD model, it is also possible to create structures that have the same amount of material usage (identical cell volume fractions), that are capable of exhibiting different mechanical behaviour to differing loading conditions. This suggests that cellular structures could be created that are suited to specific loading conditions, *i.e.* tailored specifically to the design needs. Some work in this field (mainly 2D) has been performed by Sigmund (1994) and Sigmund (1995). However, neither works considered mixing different unit cells within the same design domain, they merely solved the material distribution problem for an individual unit cell then arrayed that structure into a larger homogeneous assembly. In order for one structure's mechanical behavioural response to be directly compared to another, they must have equal volume fractions. This will show which structures have the best distribution of material within each 3D cell. Examples of various cell structures with a 50% volume fraction can be seen below in Figure 7.

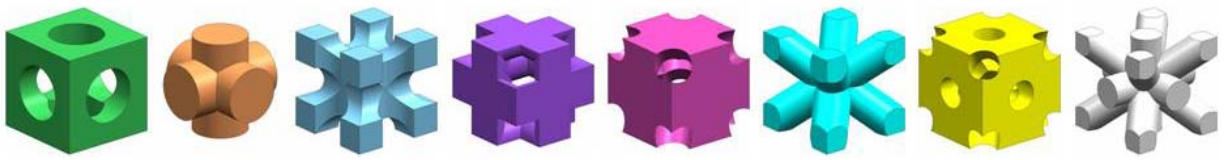


Figure 7 – Possible Cell Structures at 50% Volume Fraction

A topology optimisation process that uses a GA to create components consisting of a single cellular structure in varying densities as proposed should be able to create a cantilever beam similar to that shown in Figure 8a. The same approach, if considering multiple cellular structures, may create a cantilever beam component similar to that shown in Figure 8b. It must be noted that the proposed methodology of DFRM put forward is not a completely ideal solution to finding the globally optimal solution of a topology optimisation problem, as the optimisation will be limited to the various cell types that are defined in the initial problem. As mentioned earlier, the ideal solution would be to use many tiny elemental cells but this is currently prohibited by the high computational power required by such as a system compared to typical computational resources available today. It is for this reason that there is a need for the proposed methodology of DFRM, as a current solution to creating optimised structures using readily available everyday computing resources to create the geometries and the evolving RM technologies as a means of fabricating these otherwise unmanufacturable designs.

The proposed system will have three objectives. These are; firstly to minimise the mass of the geometry; secondly to minimise the maximum displacement (thereby increasing the stiffness); and thirdly to minimise the difference between the maximum and minimum Von Mises stress values. The third objective will be a measure of how uniform the stress distribution is throughout the structure. In order to fully explore the trade offs and relationships that these objectives have on one another athey will not be combined into a weighted sum but will be all be measured equally using a Multi-Objective Genetic Algorithm (MOGA). The use of a MOGA will enable a Pareto set of equally optimal solutions to be generated and explored by the user.

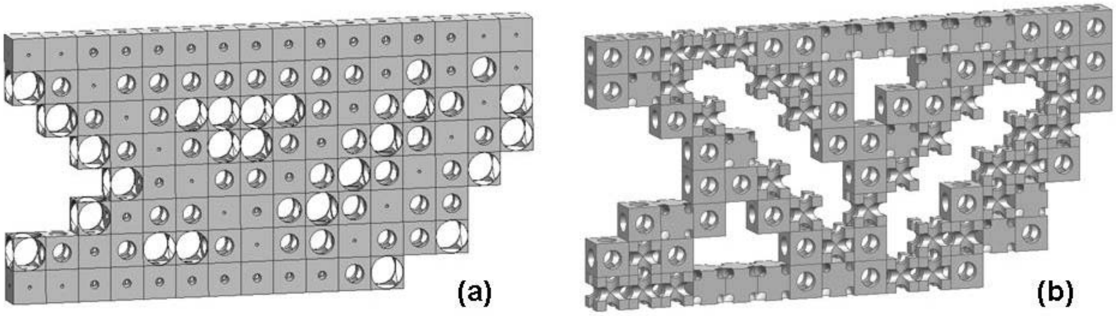


Figure 8 – Possible Cantilever Beam Geometry Created From (a) a Single Cellular Structure with Varying Densities and (b) Three Cellular Structures each with 50% Volume Fractions

The author is currently considering a simplified structural analysis where the test problems are simple load case scenarios with proven known results in order to validate the proposed methodology and refine the system parameters. The optimal structures devised by Australian mathematician Michell (1904) will be used for this benchmark purpose in addition to simply loaded cantilever beam problems that should result in the solution structures depicted schematically in Figure 8.

6. Conclusions

The previous sections have highlighted how current product designs are not optimal due to the compromises that have to be made for the DFMA considerations of conventional techniques. Literature has shown that Nature follows a different set of design rules to man, namely the efficient use of materials and maintaining a uniform stress distribution. Nature's design rules can be mimicked by implementing the topology optimisation method and the evolution process itself can be simulated by a GA, both of which have been combined in the DesignLab software. In the DesignLab investigation the stress distribution of the cantilever beams created using two materials was more uniform, and therefore more optimal, than either of the single material scenarios due to the presence of unit cells with differing mechanical properties. The homogenisation method relies on the creation of cells with varying densities in order to achieve a uniform stress distribution but this can cause manufacturing difficulties if fabrication is not via RM. The results of the preliminary investigation have showed that the DesignLab software is not capable of creating beam geometries with a uniform stress distribution unless multiple materials are considered. The ideal solution to a single material system would be to have many small solid elemental cells making up the design domain. This ideal system would be too computationally expensive as the GA bit strings would be extremely long. A new methodology and software system is therefore needed to allow these difficulties to be overcome. This has been presented as a current solution, and therefore a compromise from the ideal system mentioned above.

The new design methodology for the creation of optimal structures that has been proposed uses a GA based topology optimisation approach based on the homogenisation method's variable density approach. Part functionality is increased by simultaneously considering various cellular structures and densities to create a heterogeneous structure made from a single material. This proposed methodology will be able to exploit the increased design freedom that RM technologies offer, enabling optimal design solutions with uniform stress distributions as seen in the natural World to be created that could not be manufactured via conventional techniques.

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