Parametric modelling and the tessellation of architectural surfaces

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ABSTRACT: Parametric modelling is gaining in popularity as both a fabrication and design tool, but its application in the architectural design industry has not been widely explored. This form of modelling has the ability to generate complex forms with intuitively reactive components, allowing designers to express and fabricate structures previously too laborious and geometrically complex to realise. The key aim of the paper is to address the increasing need for seamless and bi-directional connectivity between the design, modelling and fabrication ambit.

Despite its benefits, the process of parametric modelling can be lengthy and complex, without the level of intuitive programming required to make it a viable technique for use in architectural design. The ability to design small repeatable components and apply them to a larger governing surface geometry is one area of parametric modelling that has great design potential. This two level modelling control, of component and overall surface, can allow designers to explore new types of form generation subject to parametric constraints. This process, coupled with Rapid Manufacturing (RM) and Computer Numerically Controlled (CNC) machines has the potential to significantly reduce the interface between design and fabrication.

Keywords: Parametric Modelling, Rapid Manufacturing, Design, Fabrication

INTRODUCTION

The current process of design and building has long been recognised as an inefficient and lengthy process with very little effective networking or collaboration between the parties involved. (Eastman.) The progression of a design travels from architect to engineer to shop fabricator to construction, becoming more compromised and convoluted at each step. Within other industries (such as automotive and aerospace), parametric modelling is used to refine this process and limit endless reworking.

The well established conventions within the building industry are inexorably changing towards a new paradigm of design aided by computer generated forms and methods of fabrication. With this change comes an added level of complexity in the definition of form and structure in architecture. In order to take these digitized forms and rapid manufacturing in our stride, a new process of building realization needs to be reached. A new specialised and intuitive level of integration between design, modelling and fabrication needs to be implemented. This is not a matter of developing new programming technology as all of the requirements previously discussed are currently available in either separate programs or other industries. To develop a cohesive process, the practice as it stands needs to be understood in all areas from conception to completion.

Recently, this form of collaborative design has been employed by Frank Gehry and Associates, who address this issue by adopting CATIA (Glymph et al, 2004) to create 'Digital Projects' for design, lifecycle management, and fabrication of complex building form. While this work relates to the use parametric strategies for forming complex surfaces with planar facets, it addresses the entire process of construction requirements, design and modelling based around a collaborative system. This form of parametric modelling is also demonstrated (Burry, 2004) in the completion of Antoni Gaudi's Sagrada Familia.

A different approach to the parametric design to fabrication process is taken in the area of, rapid manufactured (RM) textiles (Bingham et al, 2007). Bingham et al (2007) describe and define the production and modelling requirements of RM textiles. In this work, the problem is seen from the manufacturing point of view as the

Rapid Manufactured (RM) Textiles have been selected as a modelling experiment to understand the limitations of current parametric modelling in the tessellation of complex surfaces using repeatable components. The chain mail based textiles are made up of inter-linking torus which, geometrically, allow for relatively basic RVE components. In reducing the complexity of the overall tessellated form as well as the RVE, the parametric process can be more accurately assessed.

To understand the full potential of the parametric modelling process, key criteria in intelligent modelling need to be identified and tested in varying degrees of geometric complexity. The aim of this paper is to identify the requirements for creating structural array through testing the capacity of form generation and component efficiency. This is carried with the aim of successfully controlling a repeatable element, known as a Representative Volumetric Element (RVE), within the parameters of a larger governing surface geometry to create a unified structural array. The paper reports on the application and tessellation of RVE's across larger surfaces of varying geometric complexity, by addressing the following programming controls:

1) Control of the component individually and within an array;
2) Analysis and meshing of complex surfaces using finite elemental analysis techniques; and
3) Consideration of the final production requirements and material properties.

The results of the evaluation will help to achieve an accurate computer model for the purposes of both design and fabrication of repeatable component arrays over architectural surfaces.

1. MODELING REQUIREMENTS

The paper describes three requirements for achieving the above goals: the use of a Representative Volumetric Element for representing the repeatable component, the definition of the carrier surface using meshing techniques and the incorporation of manufacturing and production requirements.

1.1. Representative Volumetric Elements (RVE's)

Representative Volumetric Elements are a representation of the smallest repeatable element within a given tessellated form (Bingham et al., 2007). In terms of RM Textiles this definition is applied to a set of three torus links, (Figure 2.4) this is very different to a single link. Although a link is the base geometry of the RM Textile, when applied in an interlinking form, it requires multiplication as well as rotation in relation to the surface. An RVE is the smallest set of geometric components that can be orientated to a surface and create a tessellated array without any further rotation.

The Requirement for dealing with RVE's in relation to a separate surface geometry is where parametric programs excel over traditional CAD packages. Programs such as Studio Max and Microstation were used to trail an application of RVE's but the array function can only deal with objects in a two dimensional plane. This requires each component to be orientated individually, making the process lengthy and unfeasible.

Not all parametric programs have the ability to deal with separate RVE and Surface control. Solid Works is one example of a program that has the ability to form assemblies of individually defined parts with given parameters but cannot deal with components in a surface array situation.

While there are many programs on the market with varying levels of parametric capabilities, Generative Components (GC) has been used to complete the following trials. This program was selected for its scripting basis which gives a great amount of freedom in the modelling of complex components.

1.2. Finite Elemental Analysis (FEA)

Finite Elemental Analysis is one of the biggest issues that needs to be overcome in both traditional CAD and parametric programs. (Bingham et al., 2007).FEA refers to the analysis of any given surface or shape to determine a mesh made up of equal facets. In terms of RM Textiles, this mesh determines the facets that will align with the defining facet of an RVE. Most programs have a degree of meshing capabilities but none of the trialled software had the ability to create uniform facets across even a surface of basic curvature. Stand alone FEA meshing software does exist and although, very well suited to the task of surface and RVE control, have not as yet been incorporated into parametric software. The current process for dealing with curved geometry is to export the form into an FEA meshing program, analyse the form within the required parameters and import the completed mesh back into the parametric software for RVE population.

1.3. Fabrication Requirements

To successfully create any parametrically driven model, a clear understanding of the end product is required. The ability to tessellate effectively with the entire array is one crucial element in an RVE's modelling, but consideration into the final products material strength, manufacturing accuracy and required aesthetic or functional needs are all equally important. If these are determined before modelling begins the process of trail and error is cut down significantly. In a previous paper, we have determined the minimum production requirements for a component (Pitts, Datta, Kao. 2007)

The following equations are an example of the modelling and fabrication requirements that need to be included in the modelling of an RM Textile RVE.

Equation to determine minimum link size	
$\frac{MMC}{2} + RMA = R_1$ $RMA \times 2 + R_1 = R_2$ $D_1 \geqslant R_2 \times 2$	2 LINKS - $R_2 \times 4 \leqslant D_1$
$\therefore RMA \times 2 + D_1$ $= D_2$	4 LINKS - $R_2 \times 5 \leqslant D_1$
$\therefore (R_2 + R_1) \times 2 + D_1$ $= D_3$	6 LINKS - $R_2 \times 6 \leqslant D_1$
$\therefore D_1 \times 3$ $= D_4$	

MMC = Minimum Material Capacity

RMA = Rapid Manufacturing Accuracy

MMC can be substituted for desired link sizing to suit the end product.
RMA should always be a consideration when collapsing double curved surface to minimize area. RMA will always be a minimum height addition to ensure that links are not created fused together.

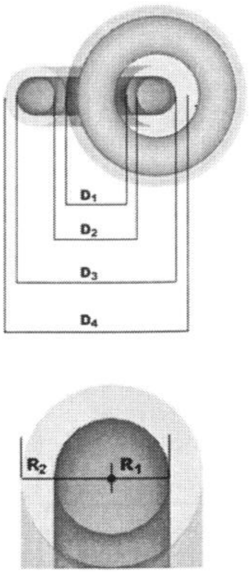

Figure 1.1: Minimum Production Requirements for Textiles
(Pitts, Datta, Kao. 2007)

2. Tessellation of Architectural Surfaces

The governing ideas developed in the previous section were then tested using four types of typical architectural surfaces encountered in design, namely, planar surfaces, developable surfaces (such as a cylinder), spherical surfaces and finally surfaces of double curvature or complex surfaces. Generative Components (GC) was used for trailing the application of RVE components to a governing surface geometry. GC has a scripting based interface, and standard geometric tools for parametric modelling. Further, it is well suited for the population of a carrier surface with components.

Unlike traditional CAD programs, GC operates from a scripting tree that orders the model and modelling process in a hierarchy of events, each based on the last. It is this setup which allows the user to go back and make changes that will affect all subsequent actions in the scripted tree. This makes changes or amendments very quick and easy and also allows for the programming of parametric variables along the way, which will control the end model.

The trials that were undertaken using GC were carried out in order of geometric complexity. In this manner, each successful application of the technology could be applied to the next, more complex form. The surface forms used in order of complexity were the flat plane, the cylinder, the sphere and the torus. (Figure 2.2)

2.1. Carrier surfaces

Although GC is capable of meshing objects both automatically and through various parameters, all the point division is calculated on a flat plane, or UV axis. These are then projected in the Z direction and onto the surface. (Figure 2.1)

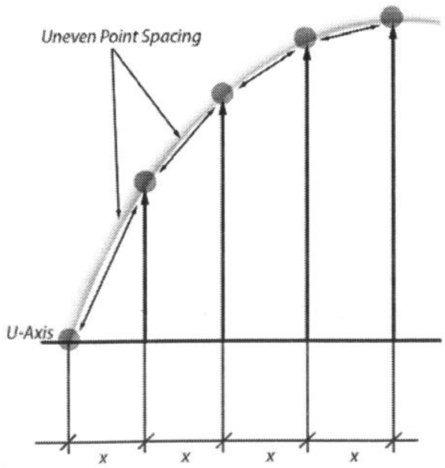

Figure 2.1: (Section) Dividing a Curved Surface by Projecting Points from a Flat Plane.

As demonstrated in Figure 2.1, even though the points are spaced evenly along the flat plane, when they are projected up onto the surface, the spacing becomes uneven. This can create warping, fusing and incorrect tessellation between RVE's.

Due to this method of surface meshing, manual programming alternatives are required to force an even division of the surface into planar facets. Stand alone FEA pre-processing software could be used in conjunction with GC. These specialised programs can mesh a given surface and then export it back into GC for RVE population.

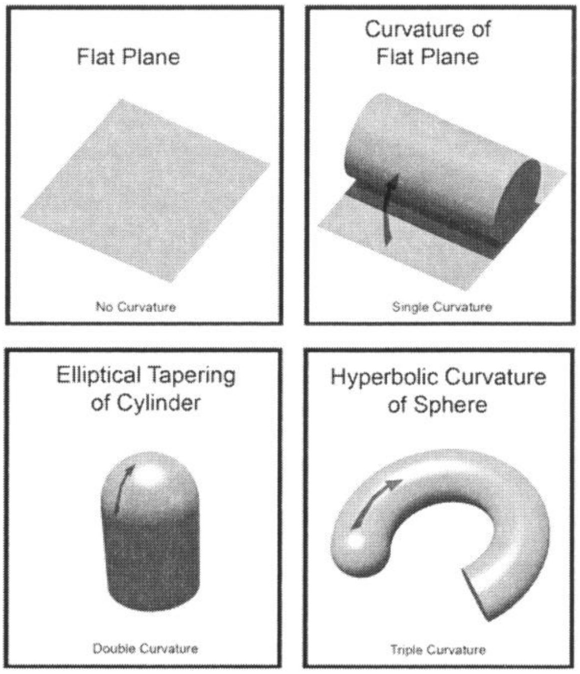

Figure 2.2: Increasing Geometric Complexity by Adding Curves to a Plane.

2.2. Populating a Planar Surface.

The population of a planar surface requires very few model parameters. The main requirement is in the RVE and its accuracy. Once this is completed, GC or even most conventional CAD programs, have little trouble creating an array in any given direction. (Figure 2.3)

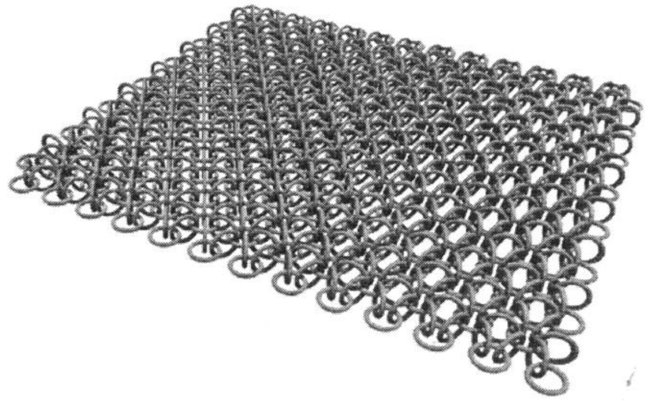

Figure 2.3: Replicating an RVE across a Planar Surface.

2.3. Populating the Surface of a Cylinder.

The addition of a curved element to the modelling process requires different treatment of the RVE's. For the generation of the RVE's a construction plane was used, allowing all the links to be based from a singular element. In this way, the links were programmed to react and change in relation to the surface. The orientation of the RVE need's to be in relation to the surface it is occupying. To achieve this, a coordinate system was attached to the construction surface and the links oriented in relation to its Z-coordinate. (Figure 2.4)

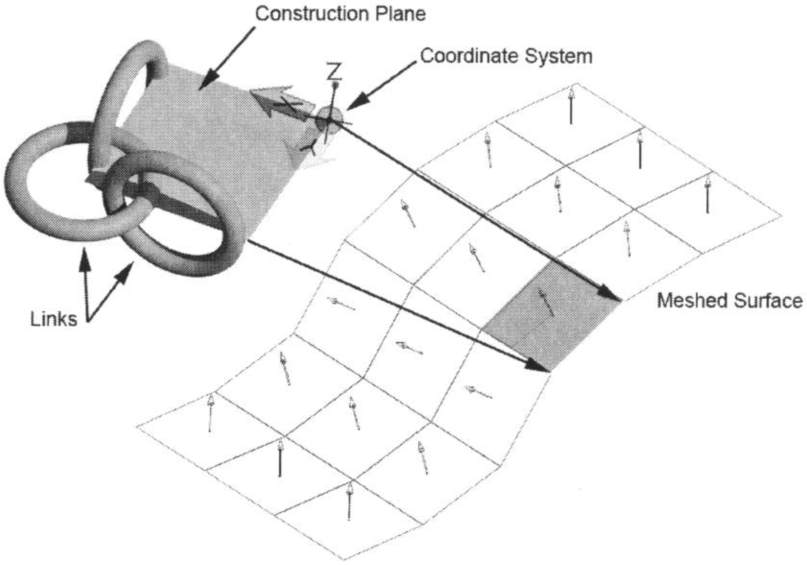

Figure 2.4: Demonstration of RVE Hierarchy and Application.

The programming hierarchy was then as follows:
-the links orientated to the coordinate system,
-the coordinate system attached to the plane,
-the construction plane defining how the RVE populated the surface.

The next step in the process was to constrain the surface mesh within acceptable parameter points. This could be done by exploiting two of GC's functions. The first is the ability to build elements that depend on the actions of previous points. In this instance, a line was created between two points and on this line a third point was attached. A circle was then built using the third point as an origin. The result of this is that any movement or manipulation of this third point will also, in effect, 'carry' the circle with it. This then allowed for the use of a second of GC's functions. This third point could then be multiplied across the line at set intervals by programming the point with a 'Series' equation. The same could then be done for a fourth point that was attached to the circle. This then gave an even distribution of points along the perimeter of all the circles while the circles themselves were spaced evenly along the defining line. In this way the planer facets could be manually controlled through adjustable spacing variables. From this array of points, a mesh could be defined. Each connection of the mesh at the points formed a planer facet that an RVE could then be attached to. (Figure 2.5)

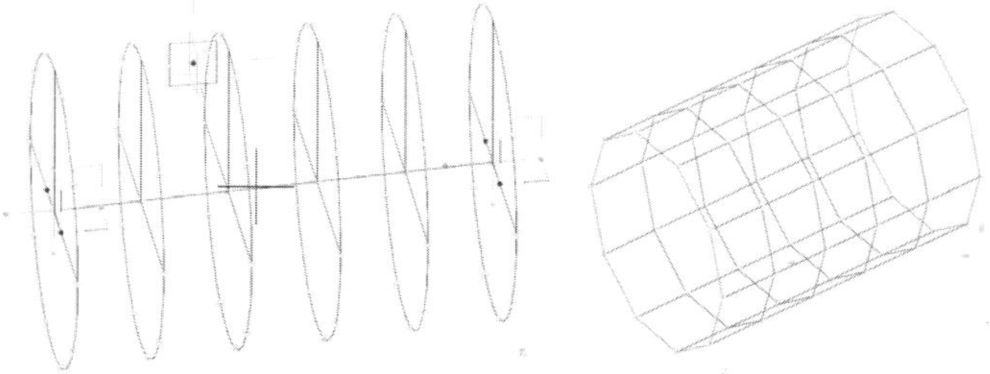

Figure 2.5: Planar Facets Defined by Points.

Each of the RVE's was automatically fitted into one of the facets, evenly populating and tessellating the surface with an RM textile weave. The nature of the RVE's construction allows them to stretch and warp to fit within a surface facet. This is due to the use of adaptive formulas, rather than fixed units, to define the link's sizing. This allows for a better tessellation and scaling of the RVE's to suit any surface, but its success relies on accurate surface division and meshing. (Figure 2.6)

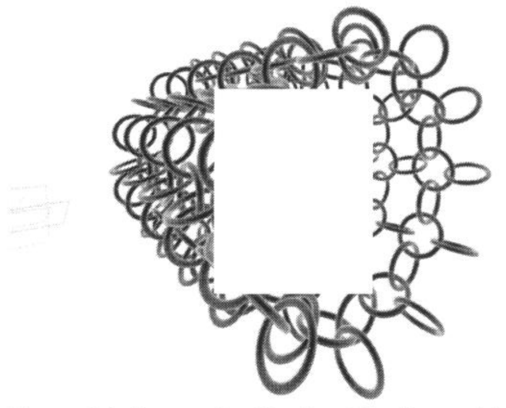

Figure 2.6: Perspective Render of the Parametrically Populated Cylinder.

This method, for creating an RM textile cylinder, was successful in its parametrically defined tessellation and uniform scaling. From the GC program, the model can be converted to a STL or a STEP file which can then be used for production by a 3D printer.

2.4. Populating the surface of a Sphere.

For this test, the top portion of a sphere was used in an attempt to constrain the mesh, and subsequently the RVE's, across a surface that curves in lateral directions. (Figure 2.6) Using the creation of the cylinder as a basis, two identical curves were created from a series of points and lines. The second curve was built from a single origin point that was attached to the first curve. In this way, the first curve acted a path parameter that the second curves origin point could move along. This method was based on the same principal of construction hierarchy as the one employed in the cylinder model.

Due to GC's method of dealing with point division on a flat plane, the meshed surface once again had to be constrained manually by spline curves. (Figure 2.7) Without FEA analysis, this process was still not an ideal solution, and caused a tapering of facets towards the edges.

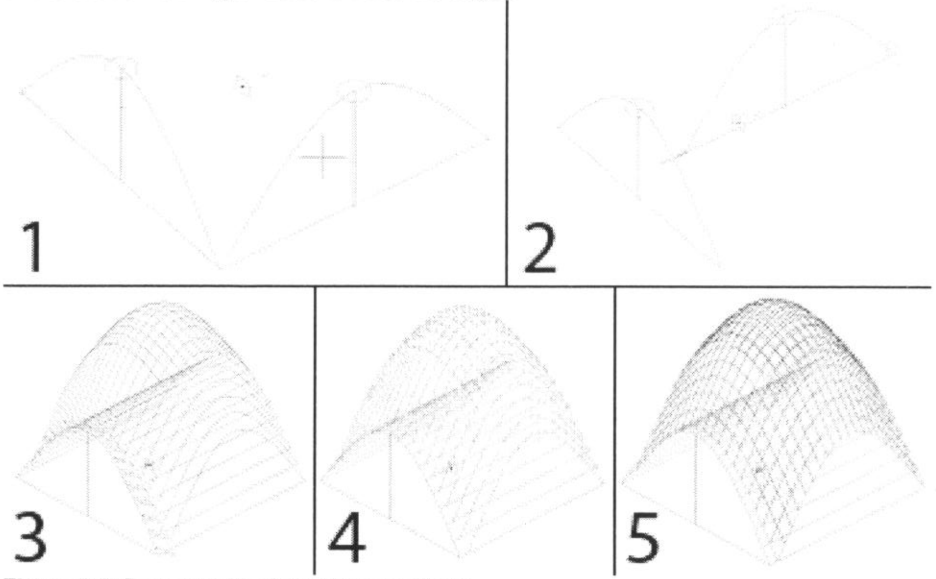

Figure 2.7: Process of Defining Surface Mesh

This tapering was the result of the point numbering system used by the program. As can be seen in Figure 2.7, the points are numbered according to their position on a given curve. The first number delineates which line they are situated on, while the second refers to the point number in relation to its order in the point chain. The automatic function in GC joins 'like' points, connecting them in relation to their position in the series. For a more accurate mesh to be created, this function needs to be overridden. In doing so, the facets can be constrained to more uniform shapes to limit warping of the RVE's. (Figure 2.8)

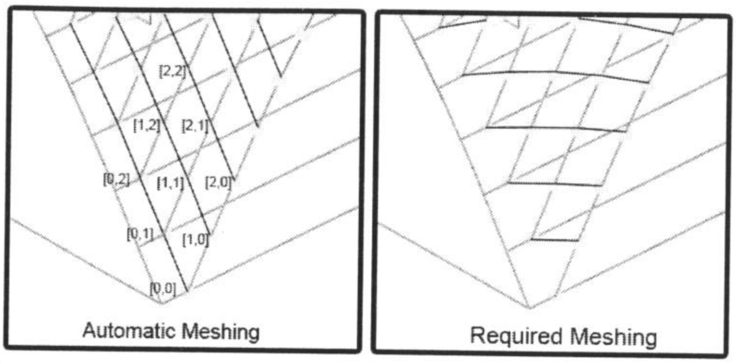

Figure 2.8: Comparison of Meshing Patterns.

Despite the meshing issues, the application of the RVE's to the surface was still relatively successful. The warping of the RVE's, although unintended, still formed a tessellated pattern despite the difference in scaling. Crowding of the links began to occur at the corners of the shape, but the majority of the model was a successful free moving RM textile. (Figure 2.9)

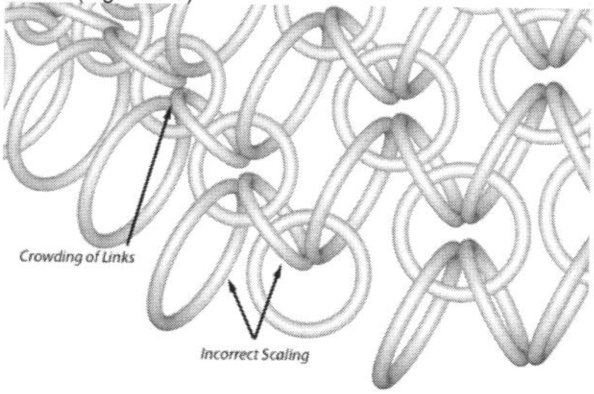

Figure 2.9: Modelling Issues.

To successfully mesh a sperical or freeform shape, a more accurate method of surface division and RVE control is required. Achieving this in GC is still a lengthy process requiring a lot of user input to define the surface and constrain the component.

2.5. Populating Complex Surfaces

The population of a complex surface with triple curvature was undertaken in two stages:

1) The use of a planar defined RVE, and
2) The use of a component defined within two related planar facets.

Through attempting to apply the single plane RVE to a complex surface it was quickly found to be an unsuccessful method of RVE control.

The results demonstrated that the vertical links were affected more dramatically by a change in the surface than the horizontal links. This is a result of the single plane used to create the RVE. The radius of the links was directly related to the facet length. Due to this, there were large scaling variations between the links of a single RVE. The horizontal element's diameter was linked to both the length and width of the facet, resulting in less dramatic deformation.

This trial demonstrated that a single two dimensional plane is not enough to control a three dimensional component.

To achieve greater RVE control over surfaces with triple curvature, more specific parameter definition is required. (Figure 2.10) The single plane control works relatively well for simple surface forms but to fully tessellate a complex surface, a three dimensionally constrained RVE is required. Each plane is required to have its own coordinate system to orient the component faces relative to the governing surface rather than global (standard CAD XYZ) orientation. In doing this, the component geometry is forced to line up and accurately tessellate with bordering components.

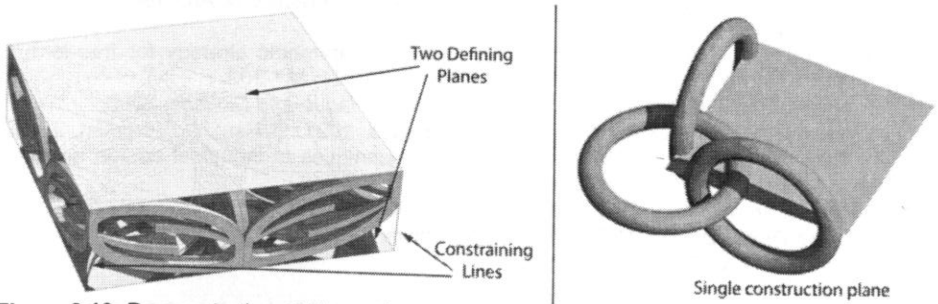

Figure 2.10: Demonstration of Planar Constraints.

For professional practice this is not the ideal solution, as the user has to script a functioning RVE as well as a double skin to constrain the component. This type of lengthy programming needs to become a more intuitive process to be implemented in design practice. (Figure 2.11)

While, in many ways, GC is a very powerful parametric program with great scope in the range of possible application, it lacks any intuitive focus that would be required to be of benefit to most building design. In situations such as this elements of alternate CAD packages would be beneficial. Solid Works has the ability to align surfaces (faces), therefore forcing tessellation, while FEA software would reduce the deformation required of any given component.

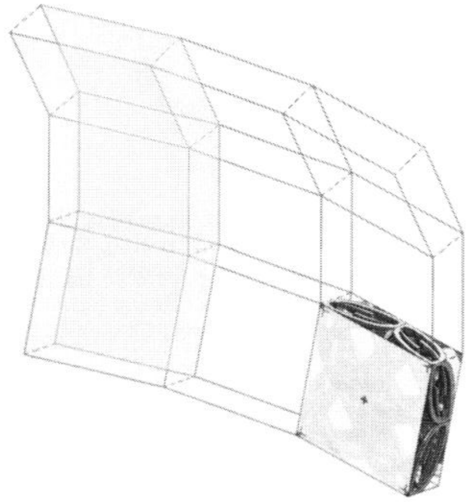

Figure 2.11: Component Constrained Within Surfaces

A more elaborate component was used to trial the use of two related planes, to demonstrate the application of a micro designed RVE that can be applied to a surface to create a complex screen. This process allows each component to be extrapolated and fabricated to create an exact physical replica.

CONCLUSION

In this paper, the results of a series of experiments in the tessellation of a carrier surface with repeatable components are described. The paper describes how the tessellation of a carrier surface with repeatable elements can be undertaken in a seamless manner. Using the concept of a representative volumetric element drawn from mechanical modelling, geometric components can be given additional parameters that maintain their orientation and shape within constraints. Using uniform FEA meshing techniques, arbitrary surfaces can be uniformly subdivided for population with RV elements. Finally, production constraints from manufacturing such as material constraints can be integrated in the geometric modelling phase to allow for rapid manufacture (RM).

A number of new areas need to be addressed. The analysis and uniform meshing of complex surfaces, the design and control of RVE's and the ability to extrapolate and fabricate elements that work together as a building system rather than a mass of unrelated objects. By addressing some of these issues with either new innovation or a combination of existing program capabilities, parametric modelling could be integrated into every day design practice. This will subsequently open up new avenues of exploration into building form, function and intelligence that were previously too labour intensive to consider. All of the programming requirements discussed and the potential for application within the design and construction industry has not been widely realised. Further research into component geometry, carrier surface meshing and material constraints is necessary to bridge the gap between the simple textile RVE and the intelligent building component.

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