A Strategy for Complex-Curved Building Design

Design Structure with Bi-Lateral Contouring as Integrally Connected Ribs

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Abstract. This paper presents an algorithmic approach to design rationalization that supports physical production as well as surface production of design models. Our approach is an alternative to conventional rapid prototyping that builds objects by assembly of laterally sliced contours from a solid model. We explored an improved product description for rapid manufacture as bi-lateral contouring for structure. Infrastructure typically found within aerospace, automotive, and shipbuilding industries, bi-lateral contouring is an organized matrix of horizontal and vertical interlocking ribs evenly distributed along a surface. These structures are monocoque and semi-monocoque assemblies composed of structural ribs and skinning attached by rivets and adhesives. Alternative, bi-lateral contouring discussed is an interlocking matrix of plywood strips having integral joinery for assembly. Unlike traditional methods of building representations through malleable materials for creating tangible objects, this approach constructs with the implication for building life-size solutions.

1.0 Introduction

Shapes in designs created by architects such as Gehry Partners (Shelden, 2002), Foster and Partners, and Kohn Peterson and Fox rely on additional computational processes for rationalizing complex geometry for construction. Unfortunately, for many architects the rationalization is limited reducing solid models to surfaces or spreadsheet data for contractors to follow. Rationalized models produced by such firms do not offer strategies for construction or digital fabrication. For the physical production and construction of CAD description, an alternative to the rationalized description is needed. This paper examines the coupling of digital rationalization and digital fabrication with physical mockups (Rich, 1989). Our aim is to explore complex relationships found in early and mid stage design phases when digital fabrication is used to produce design outcomes. Results of our investigation will aid architects and engineers in addressing the complications found in the translation of design models embedded with precision to constructible geometries.

The approach undertaken in this research investigates a method of creating a bidirectional structural network that defines the complexity of free-form surface designs.

Three algorithms are presented as examples of rationalized design production with physical results. The first algorithm deconstructs an initial 2D curved form into ribbed slices to be assembled through integral connections constructed as part of the rib solution. The second algorithm deconstructs curved forms of greater complexity. The algorithm walks along the surface extracting surface information along horizontal and vertical axes saving surface information resulting in a ribbed structure of slight double curvature. The final algorithm is expressed as plug-in software for Rhino that deconstructs a design to components for assembly as rib structures. The plug-in also translates geometries to a flatten position for 2D fabrication. The software demonstrates the full scope of the research exploration.

2.0 Objectives

In this study, the aim was to investigate bi-lateral contouring as a set of algorithms for deconstructing form for fabrication using a two-dimensional cutting device. Lateral slicing is the process of slicing an object parallel to a chosen axis. Horizontal slicing therefore connotes laterally slicing parallel to the X and Y axes, whereas vertical slicing is parallel to the Z axis. The concurrency of slicing happens in both the horizontal and vertical directions which create perpendicularity. The relation of the bidirectional slicing of the object denotes the term bi-lateral contouring.

Studies published by Dodgson argued that innovation technology (IvT) (Dodgson, Gann, Salter, 2004) helped in solving projects like the Guggenheim in Bilbao, the leaning Tower of Pisa in Italy, and the Millennium Bridge in London. Similarly, the method discussed in this paper looks at innovative methods of solving complex design forms with the use of computational methods that derive physical artifacts during the stages of design. The design processes have focused on different computational methods for constructing digitally representation of design artifacts, but remain stagnant when deriving more generic solutions to address fabrication procedures. Although, there have been many approaches for materializing design, the solutions are more prescriptive than generic, which makes the result a project-based solution. This paper examines a general approach that can be used in multiple design disciplines for materializing a design that has been created by means of CAD applications. The product of this research is a plug-in tool for Rhinoceros that facilitates the creation of physical artifacts from a surface object that has been produced by computation technologies.

3.0 Development

3.1 Structure and Assembly

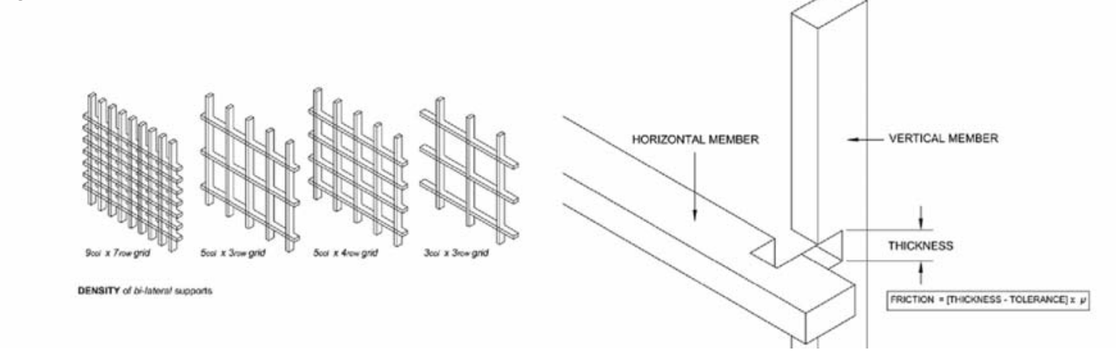
Three parameters contribute to the structural strength of the assembly: density, thickness, and friction. In order to optimize the structure, each of these parameters must be considered to resist the live and dead loads with the least possible materials and the most efficient assembly. The ultimate goal for a complete understanding of the structural performance of a bi-laterally contoured assembly would include mathematical equations describing its efficiency relative to each of these three parameters.

3.1.1 Density

The strength of a bi-laterally contoured structure may imply a direct relationship to the amount of vertical and horizontal ribs comprising the structure. However, each of these two types of structural members does not perform the same task in the assembly and thus does not increase the total strength of the assembly at the same rate. As the vertical members resist the majority of the load force under typical loading conditions, an incremental augmentation of strength can be perceived with each addition of another vertical rib to the assembly. However, as the primary direction of the live and dead loads of a building wall (under typical loading, where wind loads are not a crucial issue) is parallel to the gravitational constant (Schodek, 2001), we found that increasing the amount of horizontal ribs beyond a certain threshold does little to augment the overall strength of the assembly system and, in fact, performs the inverse effect of adding extraneous dead load with little-to-no structural purpose.

Through physical testing of various densities [Figure 1.0] of bi-laterally contoured walls, we have found that, while the assembly process is quicker when the wall is composed of very few elements, assemblies requiring a larger magnitude of member density (for structural reasons) can in fact be easier to assemble. The reason for this phenomenon is the following: while time of assembly is increased in an incremental fashion with each new rib, the difficulty of lining up members is mitigated by a higher resolution (denser) grid. From this, it can be inferred that the assembly efficiency factor also acts to equalize the number of horizontal ribs relative to the number of vertical ones. In all other respects, however, the desire to moderate the difficulty of assembling a bi-laterally contoured wall, in the case of higher relative magnitudes of loading, will act contrary to the goal material efficiency but parallel to that of structural strength.

Figure 1.0



the point that the structure becomes inefficient both in terms of unnecessarily increasing the weight (dead load) of the structure and the extraneous use material. As for assembly efficiency, wall thickness is directly related to the difficulty factor of assembling a bi-laterally contoured wall: as the ribs grow in width, such does their weight and thus the difficulty of on-site manipulation of these heavy components. And, as each structural member is here assumed to be continuous throughout the wall, rib weight is a non-trivial concern when using human labor.

3.1.3 Friction

The friction forces involved in bi-lateral contouring have no direct implication on the structural strength of the system. Nonetheless, it is this force that binds the vertical and horizontal ribs together, allowing them to maintain their position within an optimized load distribution matrix.

Friction is a factor of the materials being joined and the normal force between the two joined parts of that material. (Czichos, 1978) [Figure 1.0]: Mathematically, friction is defined as $F_{Friction} = F_{Normal} \times \mu$, where μ is the coefficient of friction of the given material pairing. (Ibid.) Any two materials have a constant μ that determines their adhesion to each other relative to the force at which they are pressed together (F_{Normal}). It is to be noted that the surface area of contact between the two materials does not affect the friction force that binds them. (Bhushan, 1999) Thus, stud or beam thickness has no implication on the strength with which the two are joined in the bi-lateral matrix.

Introducing a tolerance variable does however augment the force of friction in a given joint by increasing the normal force between the two members. On the other hand, doing so makes more difficult and time consuming the assembly of the system, as the force required to insert one member into another is amplified. Thus, increasing the strength of the joints would require those assembling it to hammer more vigorously. Therefore, the physical limitation of human labor becomes a limiting factor.

3.2 Algotithm

The research was conducted using Rhinoceros 3.0, Microsoft Visual Studio .NET 2003, and a Universal® Laser Systems lasercutter.
The interface of the plug-in is designed to incorporate the variables discussed in the "Structure and Assembly" section of this paper. The algorithm uses these variables to construct the bi-lateral network for the form. The system accepts a surface as the seed and evaluates the seed based on [Figure 2.0]

HORIZONTAL RIBS – the lateral sections that divide the surface horizontally.
The algorithm uses this variable by slicing the surface into the divisions specified by the user. The slices are constructed though a horizontal contouring of the surface from z = 0" to z = height of form. The distance between the ribs is constant based on division calculated by

$$\frac{FormHeight}{NumberOfDivisions}$$

VERTICAL RIBS – the lateral sections that divide the surface vertically.
The algorithm uses this variable by slicing the surface into the divisions specified by the user. Unlike horizontal contouring, the vertical construction is based on locating the center of the form and projecting a curve from center that intersects with the form. If an intersection is formed, it becomes the vertical contour of the form.

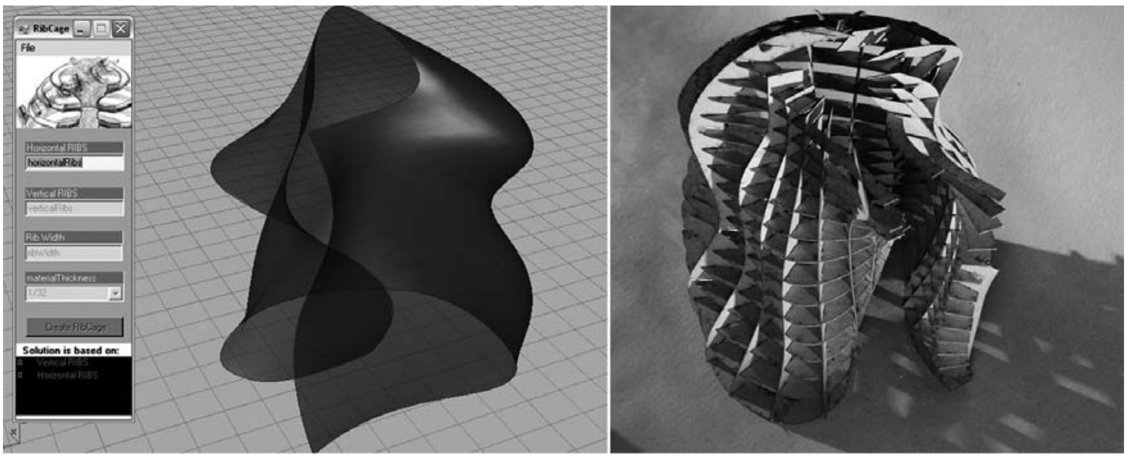


FIGURE 2.0 : Plug-in and input shape to be deconstructed / Assembled model of input shape

RIB WIDTH – the width of each rib that constructs the support structure. The width is the distance from the interior of the surface from vertical contouring intersection towards the center of the form specified by the user.

MATERIAL THICKNESS – the thickness of the material used for creating the notches for assembly. The thickness and the tolerance variables are that are added to efficiently create friction that would bind the bi-lateral structures at the meeting points. The notches are created by using rivet-like geometries that are used to extract the necessary material from the ribs at location of horizontal and vertical intersection.

The horizontal and vertical ribs are laid out on the x,y plane for fabrication with labeling for assembly. The method used by the lasercutter is a two-dimensional process that cuts the material based on the outline of each rib as plan view. After the ribs are fabricated they are assembled instructed by the labeling to create a bi-lateral network structure [Figure 2.0].

4.0 Conclusion and Observations

The research presented offers a computational tool for exploring design options through the deconstruction of form into a bi-lateral network of ribs. This paper validates the use of bi-lateral support as a structurally sound approach for investigating design artifacts as it implies the future exploration of scalability (Botha, Sass, 2006). The research was conducted in a controlled environment to test the algorithm using study models. The research proved successful in creating the bi-lateral network and would therefore need scalable models to continue investigation of life-size solutions. Future exploration will examine structural data that can intelligently suggest to the user the ideal number of bi-lateral supports necessary for the form. Hypothetically, designer may assume that the increase of bi-lateral contours will make the system stronger; however, the algorithm can supply a graph that explains the benefits of increased contours in order for the designer to make the decision for limiting the material used. This paper contributes to the development of tools that can be used as generic solutions rather that project-specific alternatives. The research conducted examined an abstract approach to free-form design and physical computation for fabricating design solutions.

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