GLUEHOUSE

Towards an Open, Integrated Design-To-Fabrication Workflow for Realizing Variable-Geometry Stress-Skin Plywood Cassette Panels

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Abstract. This paper documents the development and application of an open, flexible, and highly integrated design to fabrication workflow capable of resolving complex geometries into a stress-skin panel system ready for direct construction. The system was developed in late 2016 and has been tested at full scale by being utilized to build a complete 225 m² single-family dwelling.

Keywords. Digital Fabrication; FIle-to-Factory; Automated Construction.

1. Background

1.1. BACKGROUND

The Gluehouse is a 4 bedroom, 225 m² (2500 ft²) house (Fig 1) acting as the case study for the research and development of an integrated design-to-production workflow that generates a bespoke structural plywood cassette prefabrication system that focuses on a high degree of flexibility in design coupled with ease of fabrication and assembly. This system has resulted in a full-scale proof of concept on the basis of preliminary structural dynamic and load bearing tests. While mass-customisation is an often referred to ambition within the discipline, the Gluehouse displays a bespoke approach to prefabrication, where each panel and subcomponent is geometrically and dimensionally differentiated yet self-similar overall. In particular, an aspiration of the work is to push the expressive potential of the system to augment spatial effect and with reference to Meredith (2010), using parametric software tools to create ornate architectural expression (or rather, a specific spatial affect) that escapes semiotic referents.

1.2. INTEGRATED WORKFLOWS

Since the time of the Albertian shift in the role of the discipline purely upon representation, rather than as the master builder in the Brunelleschian sense, architects have operated with drawing as the primary intermediary between
design and execution (Pigram and Maxwell 2014). Recent decades have seen the possibility for digital design tools to form a bridge across this divide. Generally, the work described herein exemplifies the disciplinary shift to the post-representational where design, fabrication, and output form a continuous feedback loop directed to a tested and validated prototype (Burry 2012). The authors are actively seeking to shift the boundary between designer and builder via the facility of digital processes, as with Pigram and Maxwell (2014), construction drawings are no longer the reference for construction, but rather the machine instruction code that is directly output from a parametric process that has embedded within it the constraints of material and fabrication. This locates craftsmanship into the space of the digital model, and thusly, places the architect at the centre of the construction process. As in this case, tight integration and intelligent incorporation of material and tool constraints into the design process is required, allowing for questions of both technical and formal complexity to be addressed in a profound way that was not possible previously in the context of construction. (Kolarevic 2008).

![Figure 1. The Completed Case Study House.](image)

1.3. PREFABRICATION VERSUS TRADITIONAL CONSTRUCTION

Many of the advantages of prefabrication stem from disadvantages to traditional building techniques. For example, a non-linear construction process which allows trades to work concurrently, is generally agreed to compress total building time. Increased quality control, consistency, and precision are oft-cited major benefit to working in controlled conditions with access to digital and automated production tools. Perhaps the most advantageous benefit is the ability to utilize integrated digital design and production workflows, something the general construction industry has been historically slow to develop (Kieran and Timberlake 2004).

There are, however, some advantages to traditional building techniques that are not often acknowledged amid the allure of prefabrication. Most obviously, the techniques are well understood and labour is relatively plentiful with a high baseline of skill. This follows with a second advantage: materials and techniques allow for a great deal of flexibility coupled with a relatively low level of required specificity. Construction information (drawings) for even moderately complex shapes are abstract and contain few dimensions as it is generally understood that a builder’s experience will allow for missing information or other contingencies. Additionally, the inherently high level of structural redundancy and the ready availability of standardized materials allows for changes to a structure over its
lifetime; traditionally built structures are easily renovated, added to, or even stopped and started again with a revised scope at a later date.

Conversely, prefabrication also has disadvantages which merit mention. The reliance on a predefined system and its inherent limitations and constraints is chief among them. Additionally, many of these systems do not generally allow for a high degree of customization. Rather the majority of systems have a distinct stylization or formal vocabulary which requires a prospective owner be amenable. Additionally, the owner must fully commit to a chosen system within its own scope; one cannot generally integrate incomplete portions of a system. Finally, there is the issue of cost; many prefabricated systems - especially ones oriented towards design rather than economy - generally cost more per unit area, particularly in areas without an established market.

2. Aims

The Gluehouse Project is an attempt to create a bespoke prefabrication system that addresses the strengths and weaknesses of both construction types. Specifically, the system is geared toward maximizing design freedom by being both formally agnostic and structurally flexible; there is no predefined kit of parts or imposed aesthetic, and structural constraints are generous as is accommodation of non-standard geometry. The system is also capable of being applied to walls, floors and roofs without changing the structural schema (Fig 2) Most importantly, the system described here can be applied as these elements on an ad-hoc or changing basis; floors and/or roofs can use the system but walls can be traditionally framed or vice-versa. This variable level of integration also applies to the system’s ability to interface with other traditional construction techniques such as masonry and structural steel as is shown in the case study.

![Figure 2. Integrated system of Walls, Floors, and Roofs. Vaulted and Folded geometries are acceptable inputs.](image)

To accomplish this, the authors have developed a flexible and comprehensive design-to-production workflow that is capable of automating the processing of a wide variety of input geometry and outputting fabrication-ready data which is executable on a wide variety of commonly available 3-axis CNC routers.
From a fabrication standpoint, the system is designed to maximize benefits of file-to-factory workflows such as decreased production time and reliance on skilled labour through simplified assembly methods, enhanced waste management, and increased quality and precision, and significantly reduced need for drawings.

3. The Gluehouse System

The approach undertaken here utilizes a novel approach to stress-skin (monocoque) construction techniques (Fig 3). The panels utilize a 4mm (3/16”) plywood waffle core with 6mm (1/4”) skins, where glue is the only fixing. Analogous to corrugated cardboard, this results in a super lightweight, high strength-to-weight ratio building system that minimizes resource consumption and embodied energy. Panels are joined end-to-end with 15mm plywood joiner assemblies which are also procedurally generated. A grid of variable sized holes in the webs allow for the passing of ducting, conduit, and piping, and the cells between webs accommodates the insertion of various types of insulation.

Architecturally, this provides a high level of customization and articulation of assembly. In the case of this prototype, the plan and section illustrate a composition of subtly torqued geometry. What is effectively a “bar” type plan is cranked at the central stair core by 5 degrees, and the ceiling of the principle living area raked at 2.5 degrees. These moves have been deliberately incorporated into the house design to add a degree of complexity that would not be easily achieved with conventional site-crafted construction. Thus, this prototype is one of a myriad of mass-customized iterations of a domestic residential paradigm, using the efficiency of digital tools to add greater value (aesthetic, intrinsic, intellectual) to the realized object. (Fig 4)
4. Fabrication and Assembly

The prefabrication process follows a simple and standard procedure where cut-files are generated from the system and sent directly to the CNC for cutting. A reference index is printed for the operator to label the parts as they are cut, and they are subsequently sorted. An 1.4m wide x 8m long steel benchtop was fabricated for the assembly process. The panels are assembled with the finished face down on the steel, and they act as an index for all of the components as they are brought together. Once fully assembled and glue applied, the panels are pressed with bar clamps and left to set. This proved to be a limiting factor during the prototype construction - that only one panel could be made every 8 hours. Fabrication of components could be made at the capacity of the CNC, but the glue-curing was the bottleneck. Panels proved to be highly accurate throughout the entire process with on-site assembly shadow gaps of only 3mm achievable consistently (Fig. 5).

5. Implementation

For the purposes of maintaining geometric flexibility while ensuring information fidelity in this project through the early stages of development, a single integrated algorithm was developed in the generative algorithm design environment Grasshopper, a plugin for McNeel’s Rhinoceros NURBS-based modeler. The system was continually amended and augmented throughout the early prototyping
stages and even during construction as the need to address issues of fabrication and field assembly illuminated required refinements.

5.1. MODELS AND DATA
Typical scenarios incorporating digital production workflows make use of multiple types of digital models, developed at different project stages and for different immediate purposes; for instance, design-oriented models and construction-oriented models. These can have vastly different data requirements and mediating between the two is a major ongoing challenge (Sass, 2007) especially in construction as projects are subject to change at any time. The Gluehouse project offers a solution to this by automating the generation of construction and fabrication information through the algorithm, reducing the need to coordinate between multiple models. In effect the construction model is a fluid representation of the algorithm and exists primarily to support the delivery of relevant data at intermediary states such as geometric integrity or conflicts during resolution, or at end states such as quantity estimates and reference diagrams.

5.2. SYSTEM DESIGN AND GEOMETRIC RATIONALIZATION
The general arrangement of the system is a hierarchical structure of components and sub-components which are generated in a top-down manner starting with the input geometry. Input geometry is subdivided into rows of offset panels based on parameters which can be assigned as an application of manufacturing constraints or aesthetic choice, including minimum and maximum panel dimensions and panel offset. Since these constraints can conflict with each other and produce unappealing or incorrect results they are routed through a built-in genetic solver that produces options geared toward the minimisation of small or oddly shaped panels which the designer can choose from.

Once a panel arrangement is chosen the system is triggered to generate components and subcomponents (Fig 3 above). Optional components available for generation include integrated nailing battens for cladding and roofing.

In addition to geometric generation of components and assemblies, a core feature of this system is the integration of material and tool constraints directly into the system at various scales. Large scale parameters such as panel sizes or conduit hole sizes can be chosen based on equipment and material constraints or through aesthetic means. Medium scale parameters are generally enforced by the system based on material inputs such as plywood thicknesses which affect join conditions, web insets and spacings, glue slots, alignment tabs and similar parameters that affect fabrication and assembly. Small scale parameters can be either aesthetic, as in adjustment of panel reveals, or functional, as in the declaration of router bit diameter and global tolerances. That said, many of these parameters propagate through the system at various levels and influence each other; for instance tabs and slots for web alignment between skins are partially driven by bit diameter and tolerance parameters to ensure accuracy.

Bespoke detail options can also be integrated into the system, as shown with the decorative cutouts in the ceiling panels (Fig 7). In this case the cutouts serve to
add detail to the ceiling while integrating room lighting by masking the otherwise conspicuous light fixtures within a larger field. In the case study house the cutout shapes are also numbered and sent for laser-cutting from brass to insert into the ceiling.

Figure 6. Ceiling Detail Reference Diagram (left) and Cutouts in Finished Ceiling.

Processing time is generally very fast considering the complexity of the algorithm. A 64 square meter plate (8m x 8m or 688 square feet) with 25 panels takes about 90 seconds to fully propagate a detail model and output all pieces for fabrication, not including running the genetic solver or nesting pieces on sheets.

5.3. MANAGING COMPLEXITY

In any highly integrated system, components and modules interact with each other (correctly or incorrectly) both functionally and geometrically, which has an added effect of greatly increased internal complexity. This can lead to extensive time reworking or debugging a system if results are not as expected. Even worse, results can be algorithmically correct but not as intended (Scheurer, 2012), which may be noticeable if large scale or discovered very late during fabrication or installation if very small scale.

To address these potential issues, the authors have adopted two separate but complimentary strategies. Firstly, the number of input design parameters are minimized by emphasizing numeric relationships between elements whenever possible. Secondly, a strategy of internal error checking mechanisms which report on data integrity at critical points within the system was implemented. These range from simple checks that the number of panels at the beginning and end of the process are identical (no gross geometric errors) to planarity checks for surfaces, to verifying that the number of slots on a skin panel matches the number of tabs on the corresponding webs.

Measures to manage complexity are extended to assembly as well. Geometric variations ensure webs and skins are oriented correctly; mating tabs and slots for alignment are only on the top skin and top of a web, while the bottom skin contains only a glue-receiving channel. Other members, such as stitching tongues or nailing battens are made from stock lumber and are identically sized to reduce complexity and processing time.
6. Results

6.1. SYSTEM PERFORMANCE

The prototype panels developed as part of this research provide spans up to 7.2m (24’) while outperforming local code limits for conventional site built timber framing systems at a fraction of the mass. During loaded testing, span deflection proved to be 50% less than typical systems in the same depth. The system relies upon using 2 constituent parts: Finnish structural b-face birch plywood and marine-purpose expanding polyurethane glue. Both materials were assumed to be consistent in supply and quality, and readily available.

In terms of installation in situ, the system performed very well. The panelized modules are very lightweight, requiring a crane for bulk rather than mass. A full 7.2m panel can be easily lifted by two people. Panels were delivered to site in batches of 6-8 to complete a zone of the house, and took only one day including delivery and installation. The on-site assembly included the introduction of a joining tongue between panels, which is expressed in the final appearance of the project as a black shadow gap with variable pockets. Slight amounts of cutting and checking were required to correct human errors with measurement in the field (e.g. distance between support beams), but overall panels simply “dropped into place” on site. Sections were then waterproofed and the next section prepared for installation in the next phase. (Fig 8)

As discussed, the real-time variable level of integration shows its advantages during construction and installation. The combination of rapid fabrication and assembly, easy access to required equipment, and low skill requirement allows the system to be integrated with a fast turnaround time. For example, if a decision is made on-site to construct a roof from the panel system rather than traditionally framing, as-built measurements can be added to the model and fabrication can start almost immediately.

6.2. LIMITATIONS AND FUTURE DEVELOPMENT

While this paper documents successful competition of a 1:1 case study project with a relatively complex form, there are a few current known limitations of the system. Primary among these is the system’s inability to process certain geometries as either wall or plate assemblies, including curved or nonplanar shapes. It is possible to include 2d curves in plan orientations but more complex shapes are beyond the scope of the system as they would add to the complexity for fabrication and installation. While not a serious limitation, the system’s inability to process
more than one assembly (wall, floor, roof) at a time interrupts the throughput of the system as new elements are loaded, and can lead to system numbering inconsistencies if operators are not careful. Additionally, highly complex shapes, such as the floor plan of the case study house, should be manually broken into smaller quadrilateral shapes for best processing results.

The system is under active development and planned additions include the incorporation of pipelines for structural analysis, refinement to joining systems, and redeveloping into a standalone software plugin which will greatly increase speed.

7. Conclusions

The objective as set out at the beginning of this paper was to develop a digital design to fabrication workflow that would allow for integration of specific material and fabrication constraints for a project that uses a system of unique but self-similar components to constitute an assembled whole. Fundamental to this approach was the creation of an algorithmic workflow that could be readily updated and modified to suit changing requirements during the fabrication and construction process, allowing the making of the house in question to remain prototypical through successive iterations and applications of the fabricated system.

In the making of this system, we found that one can build a project with a similar level of abstract data that a framer can as in reading from drawings. However in this case, the abstract construction intelligence that would rest with a carpenter is displaced into the digital model: the understanding of tolerance, adjustment to material characteristics, and precision of fabrication is anticipated, observed, and adapted digitally. This achieves what Kolarevic (2003) describes a the ‘fluid amalgamation’ of design, fabrication, and construction.

This work is understood as part of a lineage of projects that place a digital fabrication approach at their core. Beginning with Preston Scott Cohen’s “House on a Terminal Line” (1999), one sees the novel use of cross-sectional waffle slabs to create the entirety of the project. Following on from this are similar works such as the Raybould House by Kolatan MacDonald (2003). One of the authors served as the site architect for the 2005 “BURST House” by systemarchitects. BURST represents one of the very first built instances of this ply waffle type, however the ply ribs act more like beams running between supports rather than as a homogenous system. Further on, Kieran Timberlake’s Loblolly House take a polemical stance using a modular approach. The Gluehouse contributes to this lineage by offering the digital workflow as part of the overall feedback loop in the project lifecycle to a house conceived of as the result of a system. There is no distance or separation between architect and builder, or between conception and execution. The digital tools developed for Gluehouse allow for the iteration and adaptation to continue as a live process from start to finish.

Former CTO of Gehry Technologies, Dennis Shelden, notes that “architects used to not care (about fabrication) at all, it was not supposed to be part of the architectural agenda and it was discouraged that you would even design buildings that were at that level of attention to fabrication...” (Knapp, 2014). While this
project faced certain challenges, limitations, and identified areas for improvement, the principle of creating a digital tool that is linked to real material and fabrication constraints illustrates an opportunity for architects to posit new value and quality into the built realm through the use of contemporary tools. The discipline now has fabrication intimately linked with design and ideation; Gluehouse is a demonstration of how these processes can play out at the architectural, residential scale.

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References