Digitally Fabricated Single-skin Plywood Construction: The Castle & ‘Panitecture’

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ABSTRACT: The Castle assists youth at risk of homelessness by deploying micro-dwellings to households experiencing spatial and emotional distress. The Castle questions common assumptions about housing and responds to a demonstrated gap in the accommodation market. The Castle requires a dwelling that is small, mobile, autonomous and spatially clever. Five prototypes have been designed and built by architecture students in collaboration with a school alternative workshop and a homeless shelter. The School of Architecture & Design is responsible for design development, Studentworks is responsible for component cutting and Youth Futures is responsible for training, deployment and management. One design has proceeded to serial manufacture by long-term unemployed under an Australian federal government employment-training program.

The Castle design process is moving towards mass-customisation through the development of a comprehensive construction grammar, based around CNC router cut plywood components arranged into an integrated and frameless combination of wall and built-in furniture. The ultimate aim is the eradication of any independent structural framing elements. Assembly is being tailored specifically for low-skilled labour through the development of a reliable component jointing regime, a limited material palette, minimal tools (mallet, screwdriver, glue and paintbrush) and a legible communication of assembly instructions. The portability of the manufacture process means that the entire production/training facility can be deployed to regional centres in need of employment training in a shipping container. Architecture students are involved in the project development in two ways: firstly in the collaborative development of innovative design solutions in a workshop-based studio environment and secondly in research and testing on the materials, hardware, jointing and autonomous servicing that support design.

The application of digitally cut components to a low-skilled workforce has proven successful, although achieving the required levels of accuracy of connections throughout the component set has proven a challenge. The Castle team has developed CAD tools to ease the process of joint pattern selection and ensure high levels of accuracy. The construction grammar is evolving to a point where the rules not only govern structure and connections but also support patterns of habitation. The goals of the next stage of project development are to reduce material wastage by designing components for more efficient sheet ‘nesting’, integrating a more diverse range of applicable sheet materials and continuing to explore the opportunities of mass-customisation.

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INTRODUCTION

The Castle, a long-term collaboration between the School of Architecture & Design and local youth-service organizations, intends to assist youth at risk of homelessness by deploying micro-dwellings to households experiencing spatial and emotional distress. The project was initially inspired by the successful deployment of studios by Melbourne organisation ‘Kids Under Cover’ and locally by Youth Futures’ Director Harry Tams. If a young person’s growing need for independence is restricted it can become a contributing factor to family tension, relationship breakdown and ultimately to contemplating leaving home prematurely, often with little or no means of support. Responding to this gap in the housing market, the brief for The Castle, developed in partnership with youth shelter clients, demands a dwelling that is small, mobile, autonomous and spatially clever. Castles are deployed from a ‘housing bank’ on a short to medium term basis. Four prototypes have been designed and built by staff and students at the School of Architecture & Design, as part of the School’s Learning by Making Program (Burnham and Green 2009), with the assistance of staff and clients of Youth Futures, a neighbouring youth shelter and Studentworks, a ‘school alternative’ workshop. One of the early prototypes has
been successfully deployed to two properties in regional Tasmania, assisting a potential client of the shelter to remain at home, connected to their social and family networks.

Aside from important social and pedagogical agendas The Castle aspires to ‘leaness’ in timber construction. The brief for the construction system had to satisfy four basic principles: an efficient use of a renewable resource, low weight, applicability to a low-skilled workforce and that it offered opportunities for mass-customisation. Research and development by students and staff at the School of Architecture and Design, have resulted in ‘panitecture’, an adaptive mono-coque construction system composed of CNC-router cut plywood components where walls, floor and roof are integrated with built-in furniture.

1. EARLY PROTOTYPES

Following initial prototypes of the Castle that employed a stress-skinned plywood panel, Castle 3 was the first attempt to apply digital design and fabrication to an entire building. The system we called ‘panitecture’ (a combination of panel and furniture) was inspired by teardrop caravans, kitchen cabinetry and the ‘Furniture House’ by Shigeru Ban. Panitecture was initially based on the following principles:

- to reduce weight and material wastage.
- to improve dimensional reliability.
- to reduce construction tooling and hardware to a rubber mallet, glue and a battery powered driver, thereby being applicable to a low-skilled workforce.
- to develop a predictable and reliable process of assembly that mimics, albeit at a larger scale the design methodology of kitchen cabinetry and other flat-pack furniture.

More specifically the system was based on a folded-plate panel, resembling a drawer, assembled from five digitally cut components. Connected by ‘slot and tab’ edge patterns the panels could be assembled with a rubber mallet, glue and screws. When applied to the design of the dwelling, wherever possible panel flanges (the ‘drawer’ sides) were extended internally and integrated into furniture, such as stairs, benches or storage cabinets. The carcass of C3 was composed of around 270 components, cut from 67 sheets of 17mm plywood and was assembled by the student group in less than three days. Ring-beams – one being the mezzanine floor - helped to maintain the structural integrity and dimensional accuracy of the panel system. Two further versions of C3 were built using scaled components that related to plywood thicknesses; a 3000mm cube built from 15mm ply and a 1800mm cube built from 9mm plywood.

The larger two versions of C3 raised issues that affected the future development of the Castle project. Firstly, the width and weight (around 2200kg for the 17mm version) considerably impacted mobility, with lights and flags required by the towing vehicle. A decision was made to reduce the on-road width of the next prototype to less than 2500mm, eliminating the need for special towing requirements but also, importantly, meaning that The Castle could be registered as a motor vehicle. Registration as a motor vehicle had the distinct advantage that there was no requirement to comply with the Building Code of Australia, which had raised some planning difficulties for a micro-dwelling, particularly in relation to stairs, mezzanine safety and provision of an airlock between bathroom and kitchen. Instead, compliance would be relevant to the Caravan Industry of Australia Design Code and other relevant Australian Standards.

Source: Richard Burnham

Figure 1: Model of C3 (left) and C3 stair wall assembly (right).

The second issue related to the philosophy underpinning the construction system. While each discrete panel was strong and easy to assemble, when the panels were attached to their neighbour the flanges resulted in a ‘de-facto frame’, contributing significantly to the large number of parts and to overall weight. For example, at the junction of mezzanine, lower and upper wall panels there were nine individual components coming together. In addition, many of the flanges,
including most of the vertical flanges, could not be easily integrated into furniture. Horizontal surfaces were much more useful, in terms of habitation, than vertical framing elements. Thirdly, the cost and time required for the installation of the insulation and cladding (sheetmetal in the case of the larger C3 Castles) was almost equal to the entire plywood carcass. The question was raised as to whether a mono-coque plywood construction system could be configured in such a way as to obviate the need for an independent cladding?

2. CASTLE 5

In early 2010 The Castle received substantial funding from the Federal Government Department of Employment and Workplace Relations (DEEWR) as part of their ‘Get Communities Working’ program. The submission was based around the establishment of an employment-training program and the construction of twelve Castles. The School of Architecture has been responsible for design development, Studentworks for component cutting, and Youth Futures for the supervision of the training program and the establishment of the workplace environment. Participants, including clients of the shelter and long term unemployed with learning difficulties, were to gain basic workplace experience as well as an introduction to building construction. The Castles produced would be used by Youth Futures as part of their ‘housing bank’ or leased to other youth service organisations. The project has just about delivered in terms of construction, training and employment placement targets. Ten of the twelve required carcasses have been assembled and over the funding period 46 participants achieved over 300 Statement of Attainment in ‘Construction Pathways’. Twenty participants have been placed into twelve construction jobs and eight participants have secured employment in other industries. Six trainees have been employed by Youth Futures and are now doing their Certificate II Building and Construction.

Castle 5 (known as C5), the design developed for assembly under the DEEWR funding, is a distillation of all that we have learned – both in terms of construction and habitation - from previous prototypes. As far as space is concerned, several design techniques have been employed in order to contribute to the ‘tardis effect’, where a physically small space is perceived to feel much larger. An instinctive but untested theory that space is perceived at eye-level rather than at foot-level resulted in the technique of ‘stepping out’, where the design in section maximises the dimensions at eye level, while minimising dimensions at foot-level. Another technique is to prioritise the perception of the diagonal dimensions by placing seating and openings in or close to the corners. Placing the major opening opposite the door and reducing the effective ceiling height at the threshold contribute to a sense of transparency and relative openness respectively.

2.1 The fold-out

The most dramatic feature of C5 is the large fold-out section that allows the on-site width of the Castle to extend by about a metre and the floor area by around three square metres. The fold-out incorporates the two major openings – the door and a large corner window. The fold-out section is composed of three elements – floor, wall and roof – that are pivoted in a configuration that allows the entire extension to fold into the main part of the Castle carcass. The intention is to manage the weight of the floor and roof of the fold-out in such a way that they effectively counterbalance each other, making the physical act of folding and unfolding relatively easy, capable of being undertaken by either one or two people. We hope to achieve this without the assistance of gas struts or other mechanical aids. When folding out the weight of the floor section pushes the roof up into position. When folding in the weight of the roof section pulls the floor section back into the carcass. Current experience suggests that a dampening device may be needed to prevent the motion gaining too much momentum, particularly towards the end of the motion.

The initial inspiration for the configuration of the fold-out came from a combination of C4, designed by a student group in 2009, and subsequently the 1950s ‘Prop-it’ folding caravan. The difficulties encountered in developing the fold-out from a 1:10 cardboard model into a full-scale prototype came from the precise positioning required for the pivot points, the space required in the main carcass for the motion and final ‘parking’ of the fold-out elements and that the closed position was weather protected. The configuration of the mezzanine and kitchen in particular had to be continually adjusted to allow
the fold-out components to park successfully. The geometry of the fold-out is based on the relationship of six circles and is ultimately related to a proportional relationship to two chords.

As a whole C5 is constructed from 67 sheets of 12mm plywood, 1500 screws, 12 tubes of polyethylene glue, weighs approximately 1300kg (including the dual axle trailer base) and is capable of being autonomously serviced with a composting toilet, PV panels, solar hot water and a methane stove. Single skin plywood has very limited insulating properties and insulating paint, if it proves to be effective, would be an ideal solution. Several Castles have been painted with the NASA developed product but we aim to undertake a detailed analysis of its effectiveness. C5 is also the first application of a construction ‘grammar’ developed in response to the early attempts of applying panitecture. The DEEWR funding was an excellent opportunity to test one of the most important criteria for the Castle, applicability to a low-skilled workforce. The remainder of this paper describes the elements of the construction grammar and the experience of the Youth Futures workforce in assembling Castles.

3. THE PANITECTURE CONSTRUCTION GRAMMAR

The aspiration for a coherent set of construction rules came as a result of a need to communicate the system to software programmers, with the ultimate aim of developing a proprietary plug-in. The construction grammar described by Sass in the development of The Instant House was another important reference. As described earlier the initial panel-based system used in C3 was fundamentally reconsidered by editing vertical components that were redundant in terms of their capacity to be used as a piece of furniture. Taking this approach a step further led to an overriding principle; the possibility of completely eliminating and independent structural frame, thereby ensuring that every component is either fulfilling a role of spatial enclosure – as wall, roof or floor - or contributing to a piece of furniture. The outcome of this approach was a design based around four complete or partial horizontal ring-beams located at useful heights; seating, bench, shelving and mezzanine. The ring-beams all tied into the one element in the design that did not make sense as a series of horizontal rings, the shower. Windows were located in positions where stiffeners were already required. In C5 the desire to eliminate independent structure was almost achieved, except perhaps for the grillage components within the depth of the floor and a central rafter. The individual elements of the construction grammar are as follows:

3.1. Jointing Patterns
Panitecture is based around four ‘slot and tab’ joint patterns, designed to be applied predominantly to 12mm structural plywood. These patterns are the core of the system, facilitating location, configuration and assembly. The patterns, now known as ‘slobbing patterns’ (a shortening of ‘slot and tabbing’), have developed out of a combination of traditional joinery
patterns, such as the dovetail, and patterns already used extensively in the CNC furniture industry. A tolerance of 0.2mm is built in to the relationship between components, allowing a friction fit for structural plywood. All internal corners have a radius (slightly larger than the diameter of the router bit) removed to allow the end profile of the tab to be inserted. These are known as ‘mouse-ears’. The suite of patterns provides a solution for every connection encountered. Within each of the patterns illustrated below there are variations available in terms of whether a slot is cut blind, the length and spacing of tabs and in the shape of the cut-edge by using a variety of router-bits profiles. The combination of male-female tolerance and router-bit profile provides options in terms of the required level of tightness or looseness of the fit. In certain circumstances, where a large number of tabs need to be located, a slightly looser fit is required in order for slight variation in material to be accommodated. The four patterns illustrated are known as internal slot and tab, external slot and tab, supported dovetail and halving.

Source: Richard Burnham

Figure 5: Graphic description of four jointing patterns
3.2. Maximum component size
The largest possible dimension of an individual component is 2380 by 1180mm, in order to comply with a standard 2400 by 1200mm sheet size. Where an element needs to be larger a connection between components (in the same plane) must always be supported by a perpendicular component, through use of the ‘supported dovetail’.

![Figure 6: Graphic description of joining components in the same plane](image)

3.3. Maximum unsupported span
Deflection testing of the earlier ‘drawer’ panels used in C3 determined that for 12mm structural plywood the maximum unsupported span be 1050mm, in either dimension. In other words the length of an ‘unstiffened’ component can be 2380mm as long as the width is no more than 1050mm. In order to construct an element larger than this there are three techniques available (bearing in mind that vertical stiffeners that do not contribute to habitation are not permitted); ‘folding’, ‘grillage’ and ‘curving’. ‘Folding’ involves introducing steps or creases in the wall plate to enhance its overall stiffness. Projecting the stairs through the wall is a useful device in stiffening a wall. Curving the wall or roof surface and applying grillage to the internal face of the walls similarly increase the inherent stiffness of the wall.

![Figure 7: Illustrations of folding, curving and grillage](image)

3.4. Minimum width of a component
All panitecture components, whether they be joists, stiffeners or part of the building enclosure must be at least 150mm deep.

3.5. Tartan planning grid
The most recent development of panitecture coordinates all component dimensions and the positions of connections. All components comply to the 150mm grid and joints to perpendicular components comply to the 12mm grid. Jointing patterns are coordinated to the grid - with 75mm tabs and slots always occurring in the centre of the 150mm gridlines. The 150mm dimension has been chosen because it coordinates with sheet dimensions and complies with a desirable height for benches, seating and other furniture elements.
4. APPLICATION OF PANITECTURE IN THE D.E.E. W.R. PROGRAM

In pursuing the principles of panitecture there is an underlying intent to make the experience of building available to a broader spectrum of people and, in the use of digital technologies, to give the participants in the DEEWR program an introduction to processes and technology that may become the future of manufacturing, whether furniture, vehicle or architectural. There was an expectation that while many of the DEWR participants would have some experience in basic DIY, all would probably have had some experience in assembling a flat-pack piece of furniture, using a simple tool and a set of instructions. The aim of panitecture therefore is to take the experience of building a house as close as possible to assembling a flat-pack kitchen.

If the assembly of panitecture components could be made reliable and predictable the DEEWR participants, in the context of their relatively short placement in the program, would be able to focus on developing levels of competence in those few core skills necessary; sanding, using a rubber mallet to friction-fit the components, applying glue neatly, screw-fixing accurately with a battery driver and painting. It was hoped that the ability to quickly gain confidence in these relatively simple tasks would increase the confidence of participants and their enjoyment of the act of building.

During the design phase, models at a variety of scales were built in order to test the alignment of components and to test the sequencing of the assembly process. While the digital models, built from strawboard and MDF, suggested reliable and predictable component connections, the move to full-scale production led to a series of delays that frustrated the early months of the program. Connections that worked at 1:5 and at 1:3 were not working at full-size. The pliability of the strawboard and the router settings in using MDF had allowed numerous small alignment errors between slots and tabs to go unnoticed. Other factors impacting on the predictability of assembly included a slight variety in the dimensions of the plywood, the pre-painting of components prior to assembly and occasional errors in supervising the CNC router.

Throughout the assembly of the first DEEWR Castle participants were forced to adapt joints in order to make them fit, a habit that proved extremely difficult to break, even when the connections were perfected. Participants would reach for the power tools as first resort before testing alternative means of achieving a fit. The other habit that understandably became difficult to break was that all components were systematically dry tested before applying glue and screws, resulting in a significant assembly slowdown. Dry testing each of the 175 connections resulted in at least an extra day of assembly. In order to more easily determine the cause of each instance of component ‘incompatibility’ it was decided to cut two sets of components from the updated file, and to pre-paint only one of set. If the same issue occurred in both sets the likely cause was the file itself, while if only one set had an issue the cause could be traced to either material, paint or the sheet moving on the router. We continued the same pattern of cutting two sets of amended and updated files through the rest of
the program. Thus, six versions of C5 have been assembled, each subsequent version assembling more smoothly than the previous. The assembly time reduced from nearly a month for Version 1 down to a week for Version 6.

Major improvements in assembly predictability were achieved by loosening the ‘slobbing’ tolerances on particular sheets and by including pilot screw-holes in the cutting files. The greatest improvement however came from applying the tartan grid, towards the end of the program.

CONCLUSION

Having tested the rules of the construction grammar in the design of C5 and the application of panitecture to a low skilled workforce, we feel that the system warrants further development and investment. The next phase will be in developing the system to the extent that it can be sold as a flat-pack package, along the lines of well-known Swedish furniture. This will require several areas of investigation, including research and experimentation into the following: paper based and electronic means of communicating assembly instructions; router profiles that aid the predictability of assembly; alternative jointing patterns; and developing a palette of sheet materials that can be interchanged with 12mm structural plywood, based on specific circumstances such as using recycled HDPE sheets in wet areas or polycarbonate to increase lighting and transparency.

Another area of investigation that would ultimately aid the commercial viability of the project, including a flat-pack option, would be improving the material efficiency of the construction system through ‘bottom-up’ component design that prioritises sheet nesting and faster router cutting. In this scenario components would be sized to achieve an optimum balance between structural capacity and nesting efficiency. Automating the application of joint patterns to the individual components would have a significant impact on improving the productivity of designing with panitecture. Currently students spend a disproportionate amount of time applying slobbing patterns and tend to lose touch with the bigger picture aspects of the design task. Ideally the jointing patterns would be capable of being applied in relation to the tartan grid (or with the option of being off-grid), with adjustable tolerances and basic parametric properties. Initially this would be the capability of slots to ‘follow’ tabs; if a set of tabs are amended then the slots would be altered accordingly. Application of the rest of the panitecture construction grammar would be added to the plug-in incrementally. The aspiration is for a single software package to support both design and production, and to be capable of selecting and applying a appropriate jointing pattern at a single mouse click (or perhaps two). Several software packages (including Vectorworks, Solidworks, Sketch-Up and Rhino/Grasshopper) are on the shortlist for future investment. We are currently seeking advice on the package in which we should invest time and programming resource.

In conclusion we believe that The Castle takes a strong approach to social and environmental sustainability. Socially, the intended outcomes of the project are most clear: providing access to an accommodation alternative for a precarious demographic; making long-term links between diverse professional organisations and their client groups; creating access to dwelling construction to a low-skill workforce; and for design students The Castle provides an example of a socially productive role for architecture. The environmental outcomes are less easy to assess or prove but the intentions are similarly clear; building small, prioritising a single renewable resource and aiming to reduce waste through efficient component cutting and reducing structural redundancy.

REFERENCES