II

RESEARCH ARTICLES

THE CASTLE: A LEAN MICRO-DWELLING

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ABSTRACT

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. Responding to a demonstrated gap in the housing market, the brief for The Castle demands a dwelling that is small, mobile, autonomous and spatially clever. Aside from important social and pedagogical agendas The Castle explores 'leanness' in timber construction. Three prototypes have resulted in 'panitecture,' a highly adaptive construction system composed of CNC-router cut folded plate plywood wall panels integrated with built-in furniture. Panitecture results in an overall reduction in material waste, direct applicability to a low-skilled workforce and opportunities for mass-customisation, accommodating infinite design configurations to be processed without the need for continual redesign. Options are also available for deployment onto site—as a digital file, as individual components, assembled panels, an assembled carcass or as a completed dwelling.

KEY WORDS

plywood, micro-dwelling, mass-customisation

1. INTRODUCTION

Youth Futures, a neighbour to the School of Architecture and Design, is a respected youth accommodation and employment service. Youth Futures director Harry Tams explains that many of their clients are young people from stressful domestic situations, caused in part by inadequate space in the family home. If a young person's need for independence is restricted it can become a contributing factor to family tension, relationship break down and ultimately to young people contemplating leaving home prematurely, often with little or no means of support. Harry cites a program run by "Kids under Cover" in Melbourne, Australia whereby micro-dwellings are deployed into driveways or backyards in order to temporarily relieve family stress.

The stimulus for development of The Castle was that a similar concept, with significant design improvements, would be equally successful in the regional city Launceston, Tasmania which has a long standing youth homelessness problem. The proposition is to deploy autonomous micro-dwellings from a 'housing bank,' either to the property of the spatially stressed household or to the property of a supportive third party willing to assist a young person at risk of homelessness. An associated scenario was to provide mobile on-site accommodation for Youth Futures employment clients who are currently forced to travel long distances to get to and from their work sites.

The third partner in the project is Studentworks, a 'workshop alternative' for high school students, providing training environments in metalwork and cabinetry as a complement to classroom based learning. The Castle would provide a vehicle for the establishment of a training environment, whereby students could gain experience in the construction industry. Many of the Studentworks students themselves experience accommodation difficulties, many of them coming from outlying rural areas.

The project partners proposed that the School of Architecture & Design coordinate design development of The Castle, Studentworks be responsible for serial fabrication and Youth Futures manage and maintain the housing bank. The organisations shared a belief in addressing the immediate needs of local youth but an underlying agenda was to promote a micro alternative to existing mainstream housing options. The average new Australian house is big. In

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terms of environmental sustainability the 'bigger is better' mentality undermines all improvements in construction and energy performance. The environmental impact of a dwelling's size—consumption of land and materials, as well as increased heating and cooling costs—goes largely unchallenged. We hoped that the Castle would promote some discussion on the implications of size.

There was a commitment to an extended design development period involving at least three working prototypes. There were no preconceived ideas as what the end result might be. The project partners were keen that the solution would emerge from the research and experimentation of the three groups of young people—architecture students, Studentworks' workforce and youth at risk of homelessness. Youth Futures clients would assist in the role of clients and Studentworks early involvement would ensure that the chosen construction technology would be appropriate for their workforce.

The Castle would be the most ambitious project attempted by the School's Learning by Making (LBM) program. For twenty years the LBM program has delivered community orientated design and build interventions as an essential component of the architectural curriculum, stimulating amongst the participating students a sense of social, environmental and professional realism, responsibility and purpose (Clayton and Burnham, 1998). The LBM program actively engages the School in projects that are clever, kind and connected. The philosophy is based around the act of making, with success being dependent on, and indeed defined as, students becoming as committed as the teaching team. The priority for those who teach within the LBM program has always been to provide an educational adventure (Green and Parnell, 2001). Although the studios are dynamic and the outcome entirely unknown there is a faith that a supportive workshop environment and a sound teaching process facilitates the students to produce a quality and constructible architectural solution. The client engagement mimics, albeit in a highly condensed form, the pattern of standard architectural practice; introducing the brief, providing feedback, approving progress and celebrating collective achievements with the students. Most LBM projects belong within the typology of 'shelter' (as opposed to fully habitable buildings), and most are designed to be pre-fabricated, within a relatively narrow palette of materials and building technologies. The Castle provided the opportunity for the LBM program to be involved in a long-term project within a committed community partnership and has revealed for us several clear benefits for the culture of the School:

- experiences shared between those students involved in each subsequent phase of the project.
- creating opportunities for community organizations and their clients to become regular visitors.
- incremental experimentation at 1:1 allowing a rigorous investigation of alternative methods of making.
- a productive rythmn of work that balances periods of reflection with intense activity.

The School of Architecture and Design has a strong commitment to sustainable design and was keen for the Castle to apply sustainable building practices and servicing, drawing on practices outside of the mainstream construction industry. We were particularly keen to explore the concept of 'leanness.' In the context of timber construction we are seeing 'leanness' as being measured by the ability of a structure to reduce the volume of material required to enclose a given volume of space and reduce the amount of material waste. It also has a relationship to the required skill level of the workforce and its applicability to mass-customisation, in terms of design, deployment and delivery. This paper will briefly describe the development to-date of The Castle through its three prototype phases, focussing on the evolution of panitecture—an innovative construction system—and its projected applications.

2. BACKGROUND—ESTABLISHING THE BRIEF

The brief, developed between students, the project partners and their clients began with the simple premise that The Castle provide short to medium term accommodation for a single person and their guests (intimate or non-intimate). Student researchers investigated more detailed specific performance requirements for The Castle and explored existing micro-dwelling options.

2.1. Performance Critieria

Discussions with Youth Futures and their clients determined that The Castle should not be a single mass-produced object. The process of dwelling or 'making home'—even within the short timeframe proposed—was dependent on the capacity for the dwelling to be customised or express difference, even if this capacity is only in potential. Mass-customisation—the ability for an object to have multiple customised iterations without losing the efficiencies of mass-production—became the critical point of departure for the brief and has emerged as the most challenging and stimulating aspect of the project. Other components of the brief were based around the functional and logistical requirements of the project. The Castle must be or be capable of being:

- deployed to small domestic scale outdoor spaces such as driveways or backyards, meaning that size, weight, mobility and flexible delivery modes (eg. flatpack or demountable options) became critical considerations.
- transported on Tasmanian roads without the need for permission or 'oversize/wide-load' status.
- built at a comparable in cost to optimised timber framing construction.
- incorporated into a youth training program.
- extended, adapted and maintained with hardware store 'vernacular' building products.
- classified by local authorities as a temporary or relocatable structure.
- fully-serviced without connections to reticulated services, suggesting potable and grey-water storage, dry composting toilet, solar hot-water, photo-voltaic panels and gas cooking.

2.2. Available Options

There are several micro-housing options available on the market, ranging from highly specialised designs to off-the-shelf products (see Table 1). M-ch is a highly specialised autonomous micro-dwelling—a contemporary interpretation of the Japanese tea house, marketed as a residential version of the cool, 'no frills' Smart Car. Tumbleweed market a range of trailer-based dwellings, most of which are miniaturised Victorian houses. At the other end of the spectrum 'park cabins' use a panellised timber frame construction. Shipping containers—the base element for the Outdoor Direct and the 'aspirational' Future Shack—offer a robust and ready-made package of structure and enclosure. Caravans rate well in terms of their tight spatial arrangement, weight optimised construction and the support of an entire industry of secondary components and services.

None of the available options scored well across the full spectrum of criteria required by The Castle. The led us to discount certain fundamental approaches. While the shipping container is cheap and immediate space it is heavy and is not easily adapted or extended. The caravan scored well in most respects but was weak in terms of its application to low-skilled workforce and its potential for customisation in production. The specialised micro-dwelling options—MCh and Tumbleweed—were also weaker in these criteria, as well as being relatively expensive.

TABLE 1. Table analysing micro-dwelling precedents against criteria required by The Castle.

	Customisation	deployment/ mobility	low-cost	low-skill assembly	adaptability/ extendability	creative spatiality	(autonomous) servicing
M-ch	•	•••	•	•	•	•••••	(•••••)
Tumbleweed	•••	••••	••	••	•••	•••	•••••
ParkCabins	••	•	••••	••	•••	•	•••••
Modular	•••	•••	•••	••	•••	••	•
ShippingContainer	•	•	••••	••	•	•	•••••
KUC Bungalow	••	••	••	•••	••••	••••	•
Caravans	••	•••••	•••	•	•••	•••	•••••

Source: (Burnham 2008)

2.3. The Spatial Test-Rig 'C1'

A devise was designed and built by students in order to experiment with spatial configurations, within transport constraints. The factors that contribute to the psychology of living in small spaces—light, material, views, thresholds, relativity—could not be accurately conceived or assessed without a device that could describe space at 1:1. The student group were, with the 'test-rig' able replicate spatial scenarios stimulated from visits to prospective domestic driveway sites, a caravan factory and the yacht of solo round-the-world sailor Ken Gourlay. The rig could also demonstrate architectural strategies devised to manipulate or extend the sensed dimensions of tight spaces, such as an underscaled threshold or an accentuated diagonal axis -. The rig comprised of two separated pairs of timber portal frames sliding on timber rails, with each pair of frames being capable of extension in the vertical axis. Enclosure was replicated with cardboard honeycomb panels. The rig was somewhat cumbersome to adjust but was decisive in confirming that the plan dimensions of a small-medium sized caravan were more than adequate, especially when combined with an elevated ceiling, mezzanine sleeping loft, enlarged openings and careful consideration of the occupant's visual focus. Other decisions derived from the test rig were an optimum balance between built-in and 'brought-in' furniture, the minimum spatial requirements for various body and social settings (eg. sitting up reading in bed, two chairs on a verandah), and the elements of the dwelling most critical in promoting a sense of home and individual identity—threshold, roof shape, cladding, kitchen bench and table. The Castle would aspire to distinct private and public areas allowing occupants to choose between a variety of degrees of social engagement or withdrawal.

2.4. The first habitable prototype 'C2'

C2 was designed and built within a 14 day studio by 23 architecture students. Their brief, based on the proceeding student investigation included the following parameters: the use of stressed skin panels (composed of 40.45mm hardwood framing with skins of 7 and 12mm C/D plywood), a 2400 by 3600mm dual axle trailer base, a palette of cladding materials and a full set of autonomous service components (including composting toilet, photo-voltaic system and caravan stove).

FIGURE 1. (left to right) test-rig; sliding the test-rig; C2 model-making; C2 framing on the trailer base.

Source: Richard Burnham.

FIGURE 2. (left to right): the 'bookends'; C2, attaching the folding deck; C2, exterior; C2, drawings describing the external and internal arrangements.

Source: (Burnham 2008).

Several rounds of rapid model-making and the gradual coalescing of ideas from the entire group the final design was submitted and approved by the client (Youth Futures and Studentworks), the engineer and the workshop manager before construction commenced. The design incorporated a concept that went some way to facilitating mass-customisation. 'Bookends' were a separated and easily replicable 'core' that would provide basic spatial enclosure, structural stability, a service wall and mezzanine floors. The bookends could be separated for a larger dwelling or brought together for a smaller dwelling. The spaces between the bookends, the roofshape and the cladding would offer opportunities for introducing variety of planning options, apertures and identity for each Castle. Options for internal spatial organization within the given dimensions were found to be limited. A fold down deck and caravan-style side awning doubled the area of usable spac. A CNC router was used to fabricate a storage wall that covered one wall and included the kitchen. Two mezzanine floors contributed to a feeling of spatial generosity.

3. METHODOLOGY—DEVELOPMENT OF 'PANITECTURE'

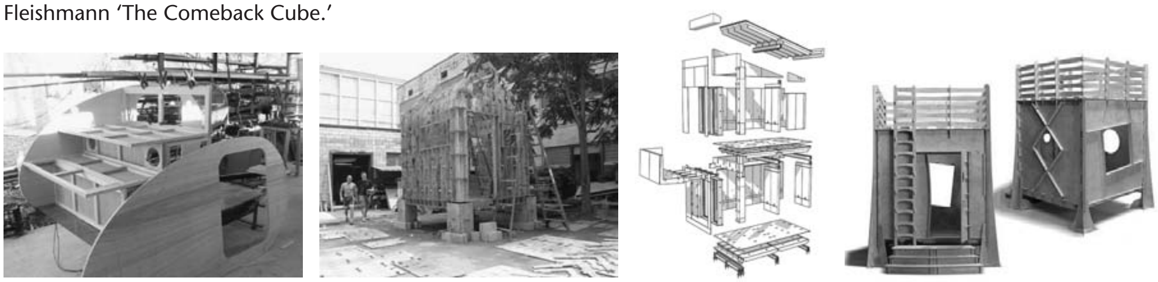
The difficulties experienced with the C2 stressed skin plywood panels—including structural redundancy, low precision, weight and material waste—led to a complete rethink of the construction system based on the use of built-in furniture and the CNC router. Carefully placed furniture could contribute to the inherent stiffness of the wall in the same way as a teardrop caravan uses single skin plywood side panels stiffened by a combination of curved roof surface and internal cabinetry. Engineer Rod Neville suggested that, subject to deflection testing, if the effective span of a wall panel could be guaranteed to be no more than 1200mm we could use single skin plywood wall panels of 17mm plywood.

3.1. Digital Fabrication and Sustainability

Digital design and fabrication became an aspiration for The Castle initially because of the implications for a low-skilled workforce, and later for the opportunities of parametric application and material efficiency. The School's CNC router has been used extensively for architectural model-making, for fabricating individual components of previous LBM studios and for making furniture in the School, such as screens, bookcases and 'office tidies.' There were three examples of digitally fabricated buildings that stimulated our interest; MIT's 'Instant House' (Sass and Botha, 2005), Digital House by Bell Travers Willson (Spring, 2007) and the Comeback Cube by Gregg Fleishmann (Fleishmann, 2008).

Applicability to a low-skilled workforce is particularly important to The Castle because of the project's training component. A construction system that relies less on specialised knowledge and accuracy for fabrication will have the effect of involving more people in design and construction. The Instant House and the Comeback Cube were assembled by a low-skill workforce—using crowbars and rubber mallets—and relied on friction for the connections. The high levels of precision available in digital design/fabrication allow tolerances to be adjusted depending on the degree of friction required; the difference between a connection needing a tap with the heel of the hand and a connection needing a rubber mallet is approximately 0.1mm. The Castle, being

FIGURE 3. (left to right) Aussie Teardrop Caravan carcass; MIT Instant House; Bell Travers Willson 'Digi-box'; Greg Fleishmann 'The Comeback Cube.'



Sources: (Aussie Teardrop 2008); (Sass and Botha 2006); (Spring 2007); (Fleishmann 2008).

a transportable dwelling, would require more than friction but it was encouraging to see 'nested-base' approaches to component generation applied to a full-scale building. An associated benefit of digital design and fabrication is that scale models can be used as an accurate predictor of full-scale fabrication, meaning that experimentation in design requires a small amount of low-value material to test full-scale configurations.

Increasing efficiency in material use has direct implications for resource depletion, embodied energy and for land-fill. McKeever suggests that in the US new-build construction industry as a whole, approximately 11% of wood and wood based products end up as land-fill (McKeever, 2005). The potential of digital fabrication to produce lean architecture is a factor of the following variables: the structural efficiency of the chosen construction system, the shape and size of the constituent components and the sophistication of the component 'nesting' on the material sheet. The precision 'nesting' of components, as demonstrated in the kitchen cabinet industry reduces waste to an extremely low level. The three architectural applications described above use very different construction logics.

The Instant House transfers the components of conventional stud framing—studs, noggins and sheathing—to a comparable set of digitally fabricated components. Their decision to base this experimental project around the Wood Frame Grammar meant that the change from saw, hammer and nail to CNC router made relatively little difference to the logic of construction. The result was that 114 standard sheets 3/4 inch plywood were used to cut 984 separate components to build a 8' by 10' space. The Comeback Cube by Fleishmann uses a different construction logic. A single skin construction with minimal lodgers applied to the exterior results in an extremely high ratio of enclosed volume to area of sheet material. The Cube uses about 80% less material than the Instant House for a comparable size of enclosed space. While the components that comprise the Cube could potentially have been cut with a non-digital process (jigs for example), the geometric precision and high tolerances of the digital design and fabrication process make this type construction logic practical and replicable. The Digital House, a terraced house extension, uses panellised hollow box components described by the authors as 'casettes.' The Digital House is the only project of the three that required compliance with building regulations and it was subject to a commercial analysis of material quantities. The Quantity Surveyor estimated that the cost was 22% less than an equivalent building of concrete block and render (Spring, 2007).

The third potential advantage of digital design and fabrication for The Castle is the direct application to mass-customisation. As Bryce and Kerry Moore, founders of furniture company Unto This Last suggest, "there may come a time when instead of going to IKEA buy your furniture, you'll visit a local manufacturing center. This manufacturing center will have license to produce many designs, IKEA's included, but will make them for you right there. This accomplishes several manufacturing sustainability goals: it brings the production of the product closet to the consumer, combines manufacturer's budget dollars which in turn increases investment in the local job economy, and reduces waste by producing only what there is a demand for" (Alter, 2008). Replacing the infrastructure of the big box furniture store, they envisage a network of local shops that can make furniture locally, distribute it locally and keep the labour and investment local. The kitchen cabinet industry demonstrates how parametric software, when applied to a system of components with known properties, allows infinite configurations based on specific requirements. Several architectural component manufacturers use parametric software to generate on-line 'configurators,' whereby designers or customers can control a variety of design decisions. The Instant House applies parametrics to the design of a complete dwelling. Sass and Botha generate a framework for customisation based on stud framing, the Wood Frame Grammar. They suggest that parameters be based on regional criteria, with a set number of variations assigned to each parameter. "Parameters include climate, location, spatial constraint, vernacular influence and stylistic variation. A unique morphology is generated by combining variation sets. This is done in either a random or preferential manner, with a shape variation developed for each morphology and the results in turn mapped to design taxonomy" (Sass and Botha, 2005). In essense this means that design decisions made at any level of the building design, whether roofshape or kitchen drawer configuration, is directly associated with the generation of a component cutting pattern, eliminating the need for time-consuming redesign.

3.2. Development of Panitecture

Digitally fabricated furniture has a pervasive presence in the School and may have had a influence on the development of the building system. Much of this furniture is derived from variations produced from a 'box tool'—a parametric Vectorworks template developed by our colleague Justin Beall—which creates a simple 'drawer-like' element from a base and surrounding flange. The template is parametric in that through a dialogue box it allows a box of any specified dimension to be created, with the connecting slots and tabs remaining in perfect alignment to a specified tolerance.

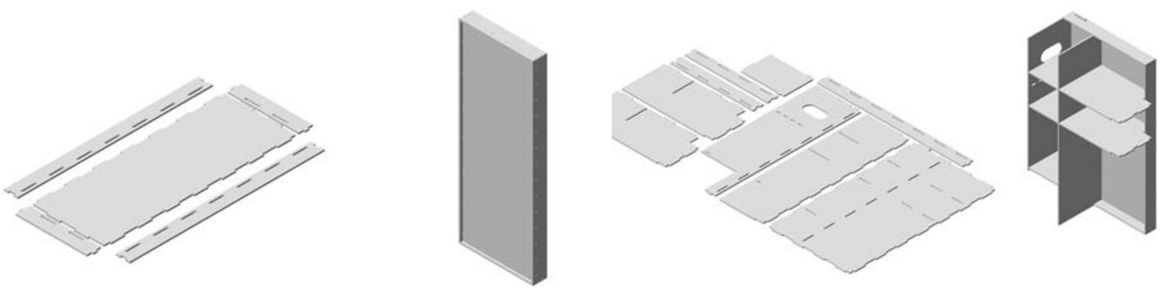
The 'box tool,' with the addition of a central stiffener, was used to create 1180 by 2380mm test panels, using a variety of plywood thicknesses. The panel is essentially a folded plate, having similar attributes to a sheet of paper that has been creased and folded around the perimeter to achieve a degree of rigidity. The surrounding flange in these test panels was 150mm deep with the drawer 'bottom' set 25mm up from the bottom of the flanges (See Figure 4). The connecting slots and tabs have an approximate length and spacing of 150mm. The central lodger has one slot/tab connection into the flange. The components were designed with a joint tolerance of 0.2mm and all joints were glued with a low-toxicity polyurethane adhesive. The joints were clamped together with 10g 45mm screws.

The deflection testing of the panels was performed by students and staff, again under the supervision of a consulting engineer. The allowable deflection, with the panel continuously supported along its ends was 4.8mm—equivalent to 1/500 the panel length—under a loading of 100kg/square metre. This is equivalent to 160km/h winds. The results of the testing were that the panels made from 12mm, 17mm and 19mm performed more than adequately, with the following deflections at the specified loading: 4.6mm; 4.0mm and 3.8mm respectively. Two panels composed of 15mm plywood—one with a central stiffener and one without—both failed. We believe that the non-stiffened panel failed due to critical weakness in the flange material and in the stiffened panel due to a combination of material weakness adjacent to the stiffener slot and screw holes. The 12mm folded plate panel was comparable in deflection resistance to the panels used for C2 and ultimately failed at approximately the same loading—1200kg. The weight of the 12mm folded plate panel was 28kg, around half that of the C2 panel.

3.4. Turning Panels into 'Panitecture'

The advantage of the folded plate panel over stressed skin panels is that a single structural skin—the 'drawer bottom'—performs three important architectural roles; the enclosure of space, the transference of vertical loads and bracing. The space occupied by the wall is reduced to the thickness of the surface. The advantage of folded plate over stud flame is that less framing elements are required, again optimising the use of the restricted internal dimensions of the small dwelling. The lodger prevents the flanges from

FIGURE 4. Basic panel component layout and assembled panel; storage wall component layout and assembled panel.



Source: Richard Burnham.

bowing out under loading. The flanges extend beyond the surface on both internal and external faces of the wall in order to create a stronger joint and to provide a recess for insulation. The position of the surface relative to the depth of the flanges can be adjusted to suit the specific requirement of the climate. In the context of a wall the individual flanges of neighbouring panels combine to make, in the case of panels using 17mm plywood, a substantial structural member of 150.34mm. The combining of panels results in the creation of a de facto frame, in both the horizontal and vertical axes (see Figure 5).

Despite 12mm plywood satisfying structural requirements, 17mm plywood was chosen as the preferred stock material for building the next prototype, C3. The advantage of 17mm plywood is that claddings, attachments and internal fixtures can be nailed or screwed anywhere, except on the exposed endgrain of the flange. It has always been an important criteria for The Castle that additions could be made without specialised systems, materials or equipment. C4, the most recent iteration, reduced the stock plywood down to 15mm, reducing the overall weight of the Castle by 15%, but retaining the advantages of universal fixing.

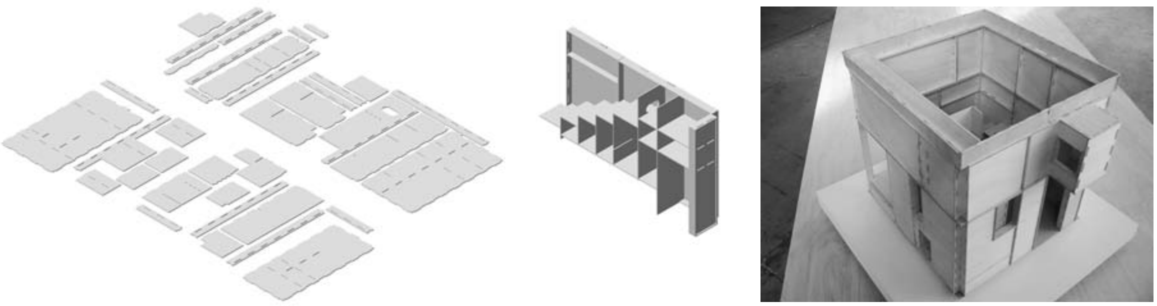
The development of a simple folded plate panel into what we have termed 'panitecture' occurs when the flanges and lodger start to perform additional functional roles within the dwelling, most commonly becoming part of integrated pieces of furniture. At its simplest the central lodger can be deepened to become a shelf, or lowered and deepened further to become a seat. Flanges and lodger can become part of a storage unit or stairs. Extended flanges and lodgers have the effect of further stiffening the wall panel. The aspiration for panitecture is for every single component to perform multiple roles and that as few as possible are required solely for structural reasons. At its most efficient all components in the system are either performing a role of enclosure or furniture. Shigeru Ban's Furniture House 1 is based on a similar principle, where storage units double as wall panels.

3.5. Testing Panitecture in C3

One fundamental change to the functional brief was for C3 to be capable of being removed from its trailer. This resulted in the maximum allowable transportable width of the dwelling to be increased from 2500 to 3400. Corner jockey wheels, to be used for finer on-site adjustment, were added to ensure that The Castle remained classifiable as a 'temporary' or 'relocatable dwelling.' The brief for the third prototype was designed to test the following hypotheses regarding panitecture:

- panitecture would result, in comparison with C2, in a significantly lighter dwelling;
- a dwelling carcass.with integrated furniture could be constructed from 50 sheets of 17mm plywood;
- an engineers approval for transportation could be obtained;
- component cutting and fabrication of the plywood carcass could be completed in 4 days;
- the resultant panels would result in a suite of elements capable of generating multiple dwelling configurations.

FIGURE 5. Component layout for storagewall/stairs and 3d view; model overview, showing de-facto frame.



Source: Richard Burnham.

The design for C3, distilled in four days of model-making from 21 individual proposals, called for a simple cube with a small projection over the entrance. The 32 individual panels form what are essentially four rings (see Figure 6); lower wall panels; mezzanine floor/ringbeam (single ply thickness); upper wall panels and roof/parapet. Most of the flanges and lodgers of the lower wall panels were successfully integrated into a piece of furniture but most of the upper flanges, particularly the vertical ones, remained 'unused.' The most successful application of panitecture was in the storage wall/stairs (see Figure 6) where all but one flange found a use.

After gaining the required approvals for the design from client, engineer and workshop manager, the students developed the panel components into drawings in Vectorworks. The configuration was regularly tested during design by re-scaling their digital files and cutting the components in 3mm MDF on the router. The model was able to precisely predict issues for the full-scale assembly, a rewarding educational experience that gave students a sense of the intimate connectivity of digital design and fabrication. This phase of the design process prevented innumerable mistakes going through to full-scale cutting. Coordination between panels, both in terms of dimensions and configuration, became the most challenging aspect of the process. As panels were completed their constituent components were placed into a 'masterfile' from where component nesting was organised. Due to the late arrival of several panel components the nesting was far from optimum and sheet usage was not sufficiently monitored. The 286 separate components were cut in approximately 32 hours from 56 sheets of plywood and the individual panels fabricated in about 16 hours. Only 17 components required re-cutting.

Panels were screwed through their bottom flange into the perimeter steel of the floor frame. The corner detail was designed so that panels meet at their internal corners, allowing for the very slight dimensional 'creep' (2–4mm) that inevitably occurs when three individual panels are combined to make a wall. The corner detail employs a steel angle with plates welded top and bottom, to connect corner panels and to tie each of the four rings down onto the steel floor frame.

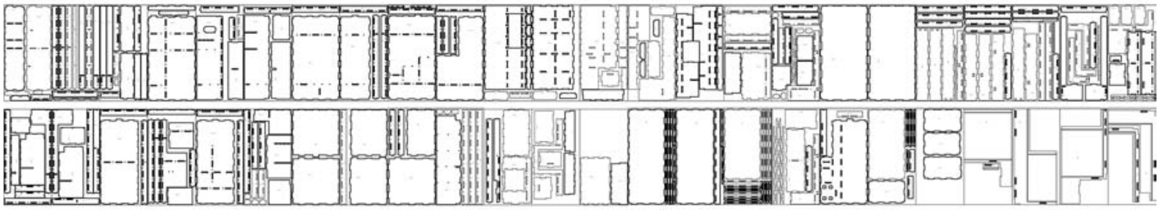
FIGURE 6. Lower wall panels assembled; mezzanine and service wall; model; and external corner.

Source: (Burnham 2008).

FIGURE 7. C3, Progressive accumulation of panitures: wall panitures with integrated staircase/storage; lower floor panitures; integrated ring beam and mezzanine; mezzanine wall panitures; parapet with roof structure.

Source: (Burnham 2008).

FIGURE 8. C3 Component layout.



Source: (Burnham 2008).

4. FINDINGS

C3 is a very strong and lean little building. The student team accomplished all tasks, except cladding, within the studio period. The initial assessment of panitecture is that the system is competitive in terms of cost, weight and speed of fabrication with both stressed skin panels and conventional timber framing, and that the required skill level is substantially lower. The percentage of material waste was approximately 8%. This has subsequently been improved with the introduction of more sophisticated nesting software. Panitecture enables The Castle to now be deployed as a flatpack, as a set of individual panels, as an assembled carcass or as a completed dwelling. C4, the first commercial sale of a Castle, improved the component connections, the nesting and reduced plywood consumption to under 50 sheets.

4.1 Assembly process and applicability to a low-skilled workforce

Of the twenty architecture students who were involved in the C3 studio only one had prior construction industry experience and the majority had little or no experience of 'making.' The quality of construction was of an acceptable industry standard, with the main problem being excessive glue residue on the internal joints. Each panel was assembled by students who had not been involved in the design of the components, suggesting perhaps that assembly was relatively simple. The scale model proved invaluable as a guide to the assembly procedure for the more complicated panels. The components were coded on the digital file and by the router to reduce the possibility of a mix-up.

The scale 'process model' revealed several places where the complex combination of furniture components and their slot/tab connections was either difficult or impossible to assemble. In these locations the solution in the full-scale version was to either resort to a screw connection or to introduce an additional component. The component 'fit' varied considerably from panel to panel—0.2mm through to 0.5mm—due to confusion over how to apply tolerances within the Vectorworks drawings. More serious difficulties were encountered where furniture components were intricately connected from panel to panel. This was compounded by the lack of precision in the dimensions and the 'flatness' of the steel floor frame. The bend in the steel was completely removed however when the ground floor wall panels were eventually fixed in place.

Tabs on the top of the lower wall panels and the bottom of the upper wall panels were intended to connect into slots in the mezzanine floor/ring beam, in an attempt to 'fool-proof' the overall assembly. The tolerance of these slots needed to have been lower (ie. the slot dimensions 1-2mm larger) to allow for the very slight creep in the structure's overall dimensions.

The polyurethane glue, rated at 1.5 out of 5 in terms of toxicity, is the least satisfactory aspect of panitecture. An alternative adhesive with lower toxicity and comparative structural capacity is urgently required.

The heaviest panel, with its associated components, weighed in at 52kg and was capable of being safely manoeuvred into place by two people. Another important OH&S consideration was that the four layers of the building could be safely constructed on the ground and were, in the final hours of the studio, hoisted into place and screwed together.

4.2 Measurable Leanness

A comparison with the Instant House (Sass and Botha) suggests that panitecture is a more efficient application of digital fabrication. C3 used less than half the amount of plywood to enclose more than twice the volume of space. Fleishmann's Cube uses slightly less material than C3 (approximately 10%), based on a given volume of space. We feel that this is partly due to the 30% shorter wall dimensions of The Cube requiring less lateral stiffening and the requirement for The Castle to withstand highway wind-loadings. Making a direct comparison between panitecture and conventional timber framing is worthwhile but not easy, remembering that a completed panitecture carcass comprises a fully braced structural frame, basic environmental enclosure and built-in furniture. Timber framing requires separate internal lining and can use steel strapping, instead of plywood, for bracing. The following comparison, based on a wall of 3600 by 2400mm high with no openings, assumes the timber framing being compliant with the Australian Timber Framing Code, Optimum Value Engineering (OVE) and assumes the use of 12mm plywood for bracing. The panitecture wall assumes the use of 15mm plywood. The integrated furniture in panitecture is seen as a bonus and is not assessed in this comparison.

	Timber Framing	Panitecture
Volume of material (cubic metres)	0.2042	0.1863
Weight of material (kg)	112.37	103.2
Wastage of material (%)	1.5%	3.4%

The comparison of material wastage was somewhat of a surprise. On reflection the comparison needs to take into account the fact that framing for openings and internal linings are not addressed here. We believe that while OVE can result in very little waste of wall and floor framing, the internal and external fit-out will rarely achieve such high rates of efficiency. Panitecture, by comparison, requires no internal lining and waste from trimming out openings is eliminated through efficient nesting. While the theory has not been tested yet, there is a strong suggestion that construction systems utilising the same material for the entire carcass of the structure results in less waste than systems that rely on a combination of many materials or component types.

There are several means by which the leanness of panitecture, as applied in C3 and C4, can be significantly improved. C5 will save more than four sheets of plywood (8% less material) by eliminating the top and bottom flanges from each panel; the tabs being located directly into slots in the floor panels. In addition the steel in the floor frame will be reduced to a simple perimeter, using a similar logic to that employed in the ceiling/roof panels.

4.3 Deployment and Customisation

The requirement that The Castle be capable of multiple unique iterations was always considered the most challenging component of the brief. The requirement was based on the need for each young person to feel as though the Castle in which they were living was a one-off, that it felt as though it was 'theirs' for the period of their residence, and that it was capable of responding more closely to a given set of site constraints than a generic design solution. There are at least three approaches to mass-customisation that are applicable to The Castle.

The first and most simple approach is to customise the wrapping. Victor Papanek's low-cost radio for Indonesia is an excellent precedent for this approach (Papanek 1974). A single Castle carcass can have multiple cladding options. This approach is simple to conceive in the context of The Castle where the bare plywood carcass performs all roles except weatherscreen. Cladding could be as substantial as timber weatherboards or as flimsy as canvas. C3 will have a cladding of printed pvc that will be changed depending on its situation or use. The availability of insulating paints means that cladding could be as simple as the application of two coats of paint.

The second approach, starting with the wall panels that comprise C3, has been to develop a broader suite of panels, all of which use panitecture as their basic logic. Within three given footprints (2400.2400mm, 2400mm.3600mm and 3000.3000mm) the addition of a further 18 panels, some of which are simply mirrored from C3 originals, increases the number of discrete planning configurations to at least 96. This approach is currently being tested through the development of a physical model kit and the development of an on-line configurator.

The third approach involves the application of parametric software. This would, as previously described, allow changes in one aspect of the design to be instantly taken into consideration by some or all other components. Applying parametrics would allow alternative building forms to be efficiently explored in panitecture without manually rebuilding the detail design model for each scenario and without incurring a cost premium for design alterations. The application of parametrics could occur at a number of levels within the panitecture system. The design of a new panel can take advantage of cabinetry software that automatically calculates the optimum slot/tab relationship and machining pattern of given components. A more sophisticated custom application of the same software would be capable of turning the entire dwelling into a parametric object, in a similar way to The Instant House. 'Rules of construction' would ensure that the configuration remains within Panitecture's structural constraints, maximum transportable dimensions and material sheet sizes. Users of a design configurator would be able to manipulate every aspect of the Castle object based on climatic variations, site constraints, functional or stylistic preferences.

A fourth approach to customisation emerges from the digital production process itself rather than on user preference. Because all components that comprise the carcass are sorted on the basis of optimum nesting, the effect of painting Sheet 5 red would result in a particular distribution of red components throughout the building. Even a small change to the design configuration of the dwelling would, through the various steps of the digital process, lead to a different distribution of red components through the structure.

Combining these three or four approaches leads to exciting possibilities. It also leads to the question: "How much choice is too much choice? At what point does customisation become merely an exercise in producing variations. Applying parametrics to the entire structure seems at this point to be unnecessary. From our initial trials of a customisable design process the first two approaches appear to address most of the important options regarding the building envelope and spatial configuration. Parametrics could however effectively be applied to those aspects of dwelling that are not covered by the 'wrapping' and the 'interchangeable parts' approaches and in addition, those decisions that are likely to be regarded as important for satisfying individual 'home-making,' such as shelving configurations and window placement.

The current investigation is looking at what constitutes an optimum level of decision-making and how to organise that sequence of decisions.

CONCLUSION

The Castle will be evaluated on the basis of performance against three criteria: as a concept (deployment to stressed families); as a process that enhances students' education experience and delivers youth training; and as a product, an efficiently made, flexibly generated autonomous micro-dwelling.

The concept has yet to be tested fully. C2 and C3 will be deployed as soon as their servicing is fully operational. Fabrication of the first private commission has commenced at Studentworks. C4 will be deployed in April this year by a local youth service organization. An assessment of this initial deployment, given predominantly by the first occupants and based on the cultural and physical adequacy of the dwellings, will provide invaluable feedback and will to some extent determine the future direction of the project. The project partners are talking with a range of other client bodies interested in deploying Castles as tourist accommodation, mobile coffee stands, granny flats and backyard studios. Profits from private commissions will enable us to develop The Castle further and to construct dwellings for the local housing bank.

Engagement by Schools of Architecture in community projects often derive substantial benefit from the arrangement for the students but seldom does the benefit run equally in both directions. Youth Futures and Studentworks have brought their considerable professionalism into our workshop, which, along with the world-views of their young people, has broadened the agenda of the LBM program. Throughout the Castle's development Studentworks have been closely involved so that the transfer of responsibilities and skills can occur relatively smoothly. It remains their intention is to offer, through the vehicle of The Castle, training opportunities in digital design-fabrication for application in construction and cabinetry. The first step in that process is currently underway with the construction of the first order—testing panitecture's applicability to serial production by a low-skilled workforce. The School of Architecture & Design is intending to establish an 'in-house' design practice based around The Castle, exposing our students to a range of sustainable building experiences: exploring non-mainstream housing options; working alongside community organisations; developing and applying an innovative construction system; learning digital fabrication techniques and involvement in an ongoing 'socially sustainable' local initiative. The intention is that orders will be assessed and adapted as required by students, processed into toolpaths and sent electronically to Studentworks for cutting and assembly.

The assessment of The Castle as a designed and engineered product, the main focus of this paper, is overwhelmingly positive. Panitecture appears to satisfy, in potential at least, all the requirements of the initial brief. On reflection, there is no single aspect of the panitecture system that is particularly innovative or novel. What we believe does set it apart is the way that multiple ideas have been drawn together into a simple building system and the variety of sources from which those ideas have been drawn; boatbuilding, caravans, kitchen cabinetry and workshop storage boxes to name a few. The projected cost of the product, whether as a pack of components or a completed dwelling, seems to provide a very competitive alternative to the range of micro-dwellings currently on the market. A full appraisal of the demand for The Castle will not be known until the model-kit and the web-based 'configurator' are available.

The acceptance of an extended timeframe for development has allowed us to focus on a system rather than a single 'end product' and allowed for a rigorous architectural, pedagogical and social scrutiny based on a rythmn of hypothsis, experimentation and reflection.

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