Eliminating Building and Construction Waste with Computer-Aided Manufacturing and Prefabrication

97

Gerard Finch and Guy Marriage

Abstract

Affordable computer-aided manufacturing has made possible a new category of timber structure. Components can now be intricately detailed to a high level of precision on a large scale. This approach has meant the increasing use of timber-only joints and more intelligent structural solutions that exploit the inherent qualities of the material. This study suggests that these construction parameters, enabled by computer-aided manufacturing, are advantageous when attempting to eliminate lifecycle building and construction waste. In this research existing and specifically designed low lifecycle waste construction solutions that have used computer-aided manufacturing are compared to conventional platform light timber framing. The study finds that using computer-aided manufacturing technology to fabricate advanced assemblies can lead a 67% reduction in the time required to recover building materials for reuse (versus the cost of reusing materials from traditional construction techniques). The use of a single material with integrated sophisticated jointing conditions is also seen to lead to the potential total elimination of adhesives and composite materials.

Keywords

Computer-aided manufacturing • Sustainable practices • Sustainable buildings

97.1 Introduction

Today more than 40% of all waste material produced globally comes from the building and construction industry [1]. To reduce this figure and improve the long term environmental impact of the sector, the way construction materials are deployed needs to change. Materials need to be shaped and assembled in a way that promotes effortless and economically attractive material reuse. Designing for reuse is widely recognised as the most effective waste management strategy as it pre-emptively eliminates the possible production of low-value materials. This preventative design approach excludes all fixings and adhesives that have the potential to damage or contaminate the principal materials.

It was hypothesised that computer-aided design and manufacturing (CAD/CAM) methods have the potential to enable high levels of material reuse though the mass-fabrication of simply assembled components. It was therefore the aim of this study to develop a highly efficient, computer-aided manufactured structural system that directly facilitated material reuse. As a final objective this analysis aimed to quantify the impact of CAM's ability to facilitate material reuse in the construction industry.

G. Finch (✉) · G. Marriage
Victoria University of Wellington, Wellington, New Zealand
e-mail: ged.finch@vuw.ac.nz

G. Marriage
e-mail: guy.marriage@vuw.ac.nz

I. Mutis and T. Hartmann (eds.), *Advances in Informatics and Computing in Civil and Construction Engineering*,
https://doi.org/10.1007/978-3-030-00220-6_97

97.2 Background, Motivation and Objective

The building industry has begun to address the problem of waste during the construction of buildings through the implementation of on-site waste sorting. Life-cycle waste production, however, remains a significant concern. Of note is the estimated 90% of construction waste (and therefore 38% of total global waste) that is a product of renovation and demolition practices [1–4]. This is waste material that is generated after the aforementioned recycling schemes have left the building site. Direct reuse of materials retrieved from a building at the time of renovation and/or demolition is rare as materials are often badly damaged and have no attractive reuse or recycling pathway. Strategic deconstruction of buildings using today's methods of construction is possible, yet the cost of doing so often exceeds the resale profit of the largely low-value materials that are recovered [5]. These barriers are a product of modern building techniques; the widespread use of construction adhesives, low-value materials, epoxy sealants and structural connections never intended to be reversed. Studies investigating the possible reuse of existing light timber frame members (platform and balloon framing) earmark economics and measurable structural performance of recovered members as key reuse limitations [5].

A potential solution to this long term sustainability and waste management challenge is to design buildings that facilitate material recovery and reuse. This approach is referred to as Circular Economy (CE) design: a process in which the architect ensures that all materials incorporated into the design of the building at the outset can be recovered in an economically viable way at the end of the structure's useful life [6]. The consequence of CE design is two-fold: materials are either specified or fixed in a way that ensures they can be easily recycled into new components, and/or, the materials are shaped in a way that enables reuse. Direct material reuse is the most desirable waste minimisation strategy as it calls for no additional material or energy inputs between use cycles. The applied result of a CE design approach like this are massively modular building elements with simple, durable connections that can be easily reversed. To eradicate the possibility of material contamination this design agenda also calls for components with geometric features that are simple to assemble and eliminate the need for supplementary contaminating/damaging fixings. This level of component detailing is beyond the scope of conventional modern construction approaches in which we rely on composite jointing mechanisms to enable rapid material assembly. It is foreseen that computer-aided manufacturing could address many of these circular economy design requirements in a way that was never previously possible. Not only can such manufacturing approaches deliver the necessary component detailing on a large and affordable scale, but they can also create products with a superior level of material efficiency.

The complex 'composite' nature of architectural assemblies makes it difficult to determine which specific building components need to be redesigned to enable material reuse of all components. The authors of this study identified the structural system was a critical starting point for enabling a CE. This choice was based on the influence a structural system has on determining how associated building elements are fixed into position. Similarly the structural system was also identified as a key influence on the modulation of the architectural geometry. This modulation effects how supplementary building layers in that architectural assembly are shaped. A distinctive lack of modulation may result in a large quantity of materials whose physical size make them undesirable, and therefore uneconomical, for reuse. Likewise some structural systems will integrate necessary envelope layers into a single product i.e. structurally insulated panels (SIPs) which include insulation and lateral and gravity load resisting structural elements. A structural system designed for a circular economy would reject the notion of permanently joined layers of differentiating materials (such as SIPs). Within the range of structural systems there are also a wide selection of possible materials. To control the scope of this study and better align it with the realities of the building industry (see below) structural materials were limited to manufactured plywood products. This allowed the research to focus primarily on fabrication, geometric and jointing conditions, with the design outputs potentially transferable to alternative materials in the future.

The researchers selected computer numerically controlled (CNC) routing/cutting as the core manufacturing process. This was seen as a tool that would provide the advanced manufacturing potential while ensuring the input timber material remained a readily available and affordable product with strong sustainability credentials. Within this lifecycle framework CNC routing permits the timber material to remain in a more authentic format versus that of additive manufacturing methods (3D printing) where timber is reconstituted and mixed with resin to form a wood/plastic composite. Supporting this agenda to maintain material purity there is a current push for the application of natural adhesives in sheet timber products (notably Ligate by SCION) and the use of natural moisture-resistant treatments [7]. These features would enhance the performance of such processes to deliver a circular economy based structural building solution where there is no risk of damage to environmental or human parties at any stage of the product's life cycle. CNC routing of timber components is also measurably more cost effective than current timber-composite additive manufacturing methods [8].

97.2.1 Summary of Study Aims

1. Develop a highly efficient structural system that directly facilitates material reuse and uses computer-aided manufacturing processes in its production.
2. Holistically quantify CAD/CAM's ability to facilitate material reuse in the construction industry versus conventional building methods.

97.3 Method

This study measures the holistic 'circular economy' performance of a given structural system that uses computer-aided manufacturing versus the performance of conventional platform timber framing. Key measures for 'Circular Economy' and 'waste-free' performance in this study included [3, 8] (see Table 97.1 for results):

- Weight of timber required for structure (kilograms) per unit of wall;
- Required cut length of CNC routing (meter) per unit of wall;
- Time taken to assemble (seconds) a unit of wall;
- Solid Waste produced at fabrication (kilograms) (where measurable);
- Sawdust Waste produced at fabrication (kilograms) (where measurable);
- Number of components—complexity (count) per unit of wall;
- Time taken to disassemble components (minutes) for a unit of wall;
- Time taken to prepare components for reuse (minutes) for a unit of wall;
- Recovery rate of materials (percentage) per unit of wall.

In all instances a lower score is perceived as better performing as this collection of measures works to quantify the waste reductions (if any) and improved material reuse potential of a given structural system. To produce accurate quantifiable comparisons all systems were detailed to meet the following criteria:

- Gravity/lateral load resisting capacity for light timber framed buildings (NZS3604).
- Internal finished lining (plasterboard or plywood fixed to framing members).
- Waterproof barrier (between cladding and framing members—differs for all tests).
- Visual cladding (fixed to exterior of framing members—same for all tests).
- Insulation (infill between framing members).

Table 97.1 Summary of results for various construction systems circular economy performance

Measure (per 1 m^2 of wall area)	Platform	Click-lock	Click-raft	X-frame
Timber structure weight (kg)	7.02	14.76	8.22	15.48
CNC routing cut length (m)	N/A	129.8	85.5	149.6
CNC with common edge (m)	N/A	87.5	53.5	85.1
Time to assemble (min)	20	18	16	15
Sawdust waste (kg)	1.12	2.16	0.72	1.45
Solid fabrication waste (kg)	0.78	0.37	0.12	0.12
Number of components	3	3	2	3
Disassembly time (min)	47	32	30	27
Time to prepare components for reuse (min)	18	0	6	0
Recovery rate (%)	58	78	96	97.5
Lifecycle waste (kg)	14.9	Unavailable	Unavailable	1.96

To produce the quantifiable values a portion of each system was built at full-scale and then deconstructed. Deconstruction took place in workshop conditions with only basic construction hand-tools. Additionally, recording the CNC router cut length for each system indicates the potential cost differential. Refer to section six to review potential limitations of this testing methodology.

97.3.1 Technical Summary of Examined Systems

Platform Light Timber Framing. Platform light timber framing (LTF) is the predominant construction method for low and medium density buildings (up to four stories) in the United States of America, Canada, Australia and New Zealand (Fig. 97.1). This system has been used as the comparative basis for measuring the circular economy performance

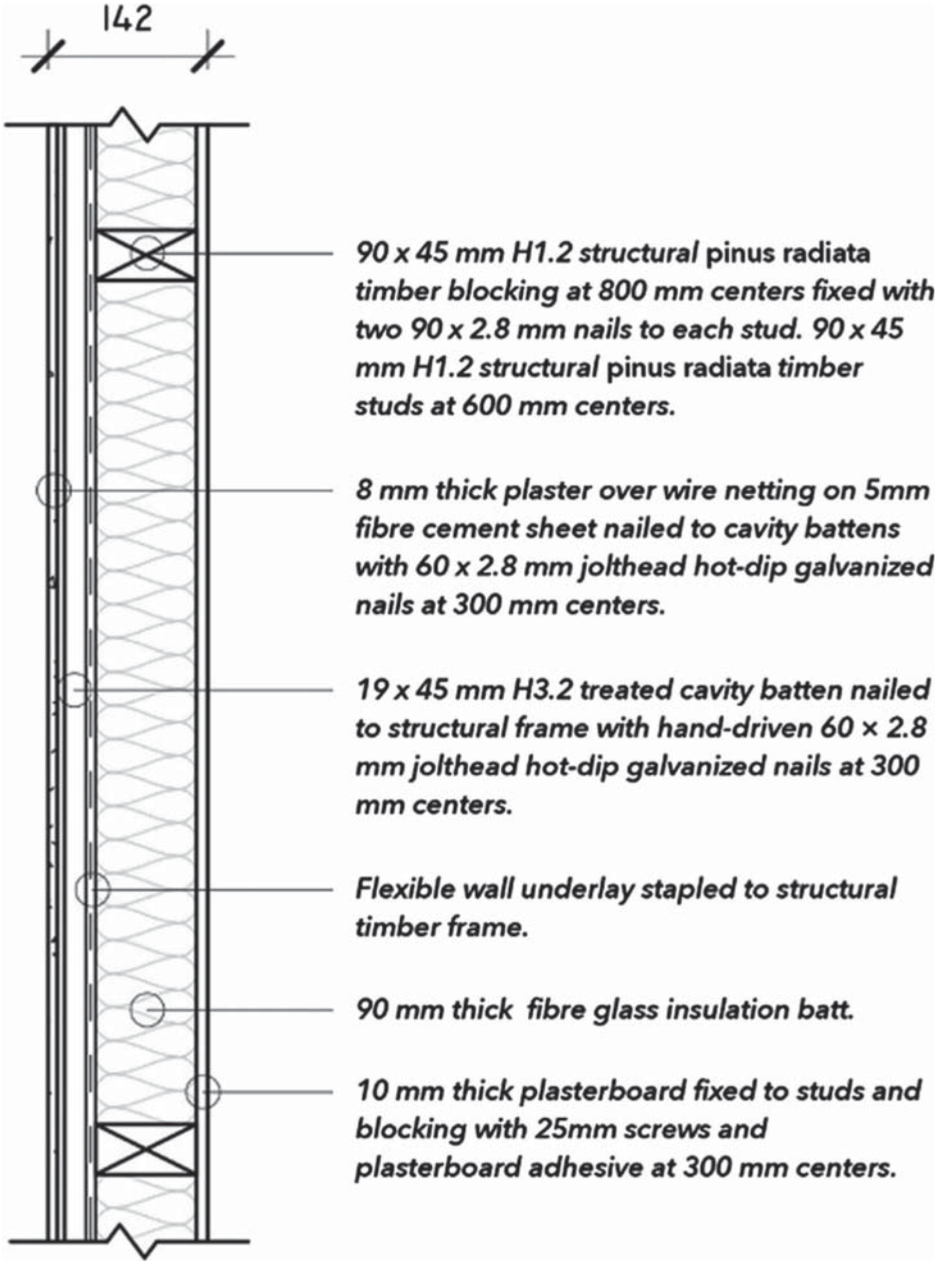

Fig. 97.1 Platform light timber framing wall section detail

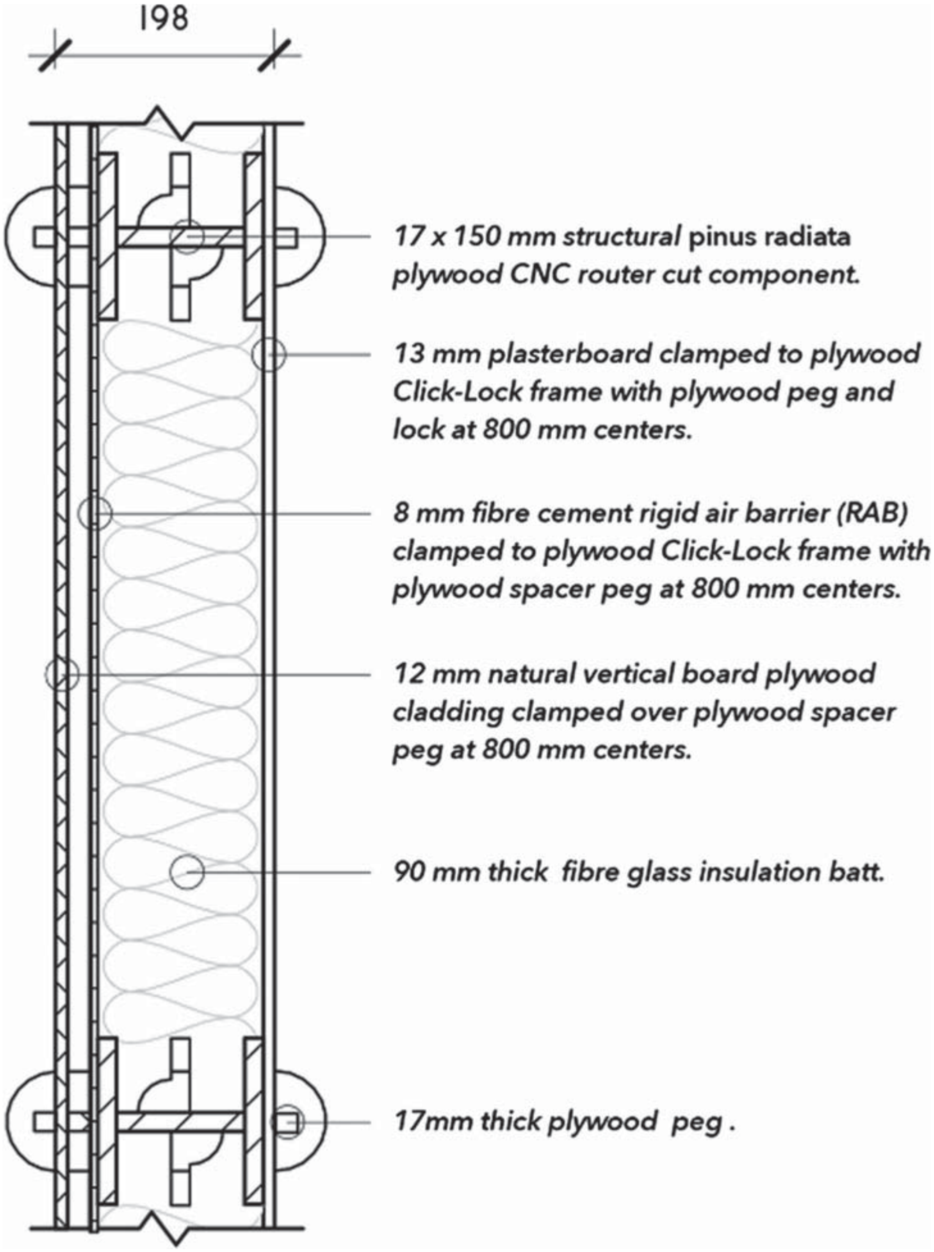

Fig. 97.2 CNC fabricated plywood click-lock wall section detail

improvements of construction systems that use computer-aided manufacturing methods. Platform framing typically comprises of a timber bottom plate, studs (vertical load bearing members), blocking (nogs/dwangs) and a top plate. These members are nailed together to form a gravity load resisting frame. To achieve sufficient lateral load resistance (against earthquakes and wind) LTF usually relies on sheet materials glued, screwed and/or nailed to the studs and blocking.

Click-Lock (Marriage & Warrander). Click-Lock is a CNC router-fabricated linear structural grid frame that uses 17 mm thick plywood [9] (Fig. 97.2). The frame is made up of three principal rectangular elements that ‘click’ and ‘lock’ together without the need of conventional fixings such as nails or screws. Click-Lock includes a modified double-stud detail that allows sheet linings to be fixed to the wall, again without the need for adhesives, nails or screws.

Click-Raft (Moller). Click-Raft is a sophisticated two-piece CNC router fabricated non-orthogonal structural frame [9] (Fig. 97.3). *Click-leaves* are slotted together under strain to from an inherently lateral-load resisting frame. Click-Raft can

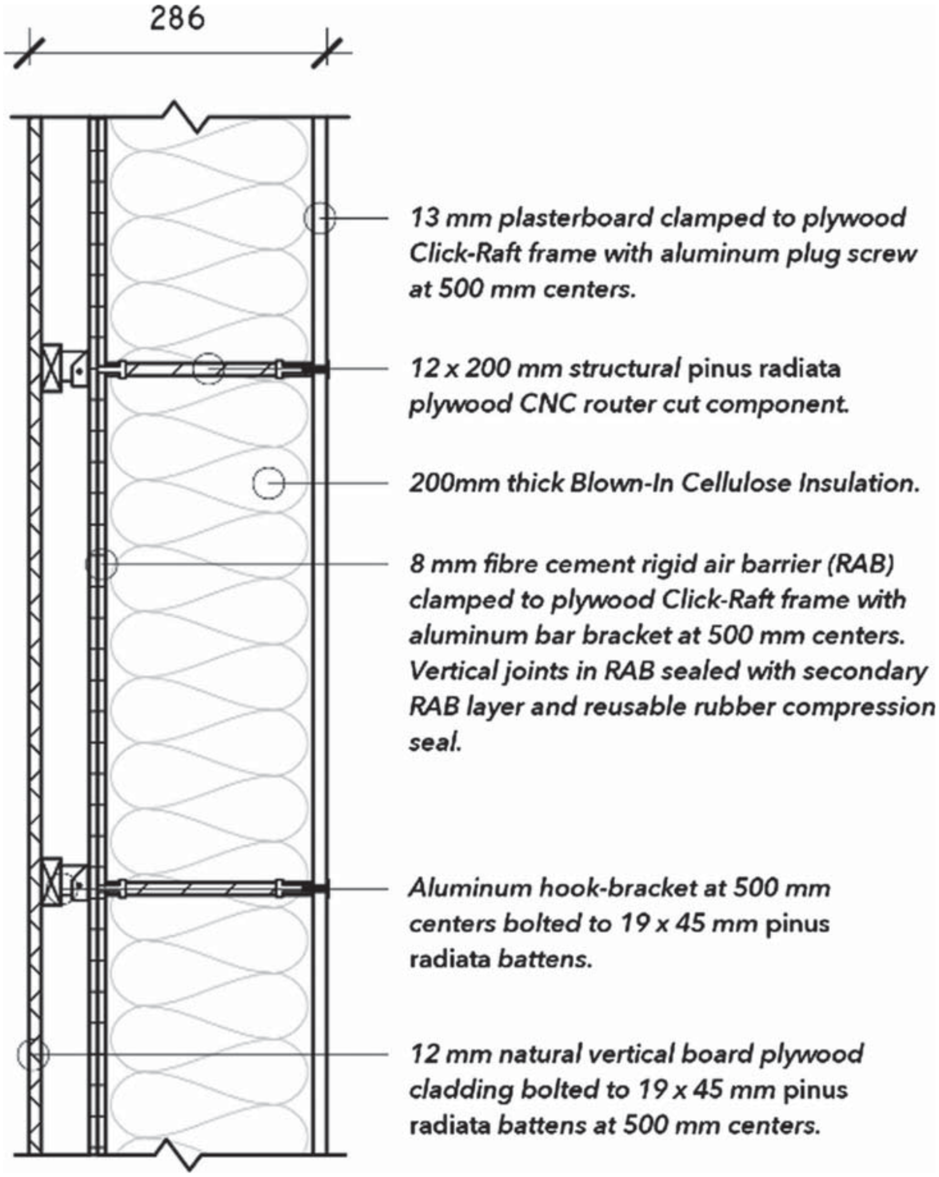

Fig. 97.3 CNC fabricated plywood click-raft wall section detail

use a range of various thickness plywood products depending on the required horizontal span loads. The authors have integrated a reversible waterproof, cladding and internal compression based lining layer system for this test. Moller's original proposal included a separate polycarbonate cladding system [10]. For the purposes of comparison this has been replaced with plywood sheeting.

X-Frame 7 (Author). X-Frame 7 is a product of this study and designed by the authors to specifically facilitate material recovery at the end of a building's useful life (Fig. 97.4). It uses 17 mm structural plywood in a modular diagrid geometry to create an inherently lateral-load resisting structural frame locked together by mortise and tenon plywood joints. The structure is designed to promote disassembly and reuse by being suitable for both horizontal and vertical building elements. The diagrid geometry is designed for maximum flexibility to allow windows and openings in the frame without the need for additional frame or beam (lintel) elements.

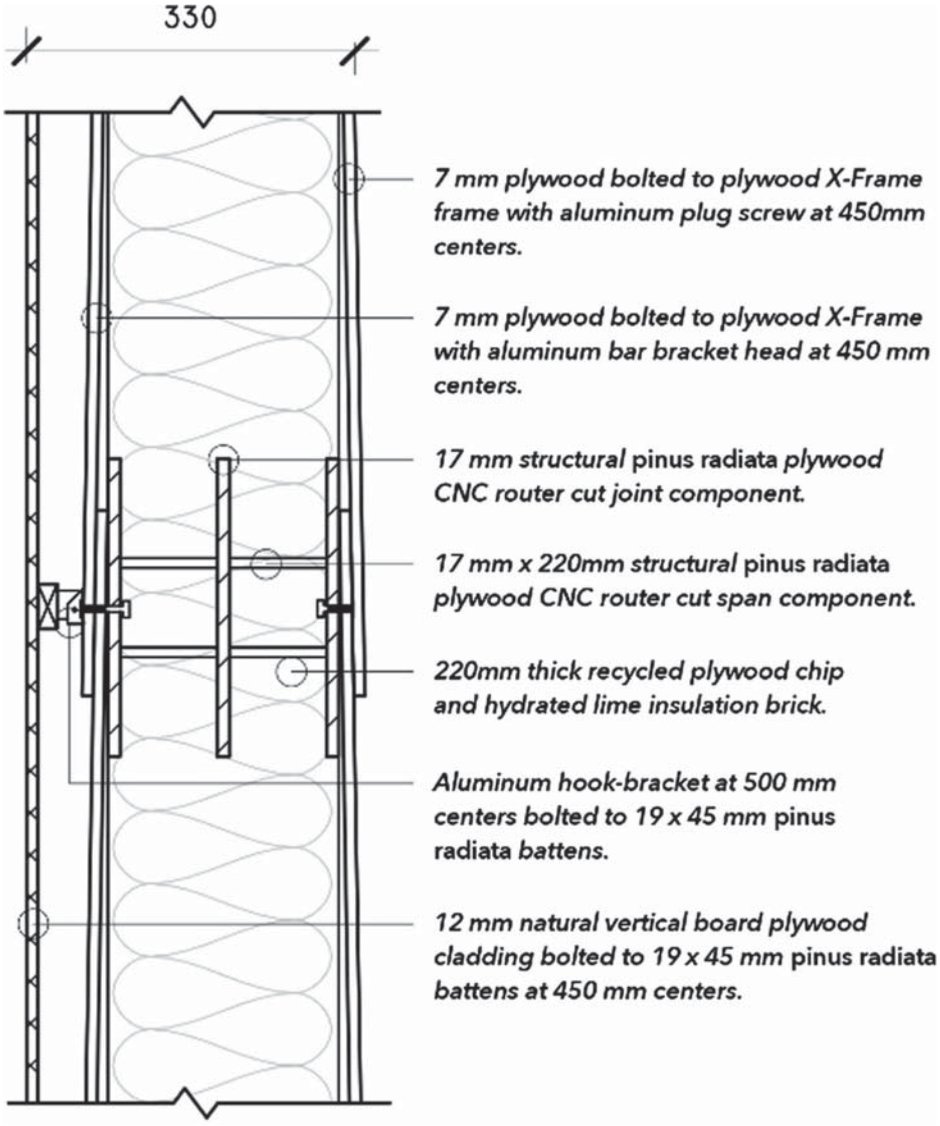

Fig. 97.4 CNC fabricated plywood X-frame wall section detail

97.4 Analysis Results

See Table 97.1.

97.5 Discussion

97.5.1 Overall Performance

These results suggest that computer-aided manufacturing has a significant role to play in enabling the faster recovery of materials from buildings with higher rates of recovery versus that of conventional light timber framing. The total elimination, in some instances, of the need to clean or process materials after their removal from a building, made possible by self-jointing materials, is significant. This allows materials to be recovered from one site and be taken directly to another for reuse. However, no construction approach achieved 100% material recovery. Even in the case of X-Frame, the system with the highest rate of retention, the woven and triangulated geometry had potential to snap during separation. This weakness is a consequence of an integral design feature of X-Frame and is therefore unlikely to be resolved easily. Click-Raft performed almost equally as well in maximizing the quantity of undamaged materials but was seen to suffer long-term deformation of the structural elements. This observation requires further testing in larger scale situations to identify if the deformation is a significant structural concern and barrier to reuse.

97.5.2 CNC Manufacturing

The key advantage offered by computer-aided manufacturing and the advantage being exploited here is the sophisticated detailing of timber components to integrate assembly parameters. This often took the form of mortise and tenon joints, as well as slotted and tabbed components with plywood pins. Critically these joints did not damage either the primary structural material or the joining component when separated after use. Integrated fastening capability effectively simplified the construction and deconstruction process. The majority of structural connections and load-bearing joints are inherently fulfilled by simply positioning the frame components in the desired shape and conveniently located connection details receiving each element. Integrated joints like these are made possible through precision CNC cutting with carefully controlled tolerances. Over the extended length of each use cycle, diverse environmental conditions, such as humidity and temperature, can affect the dimensional properties of the material. In a worse-case-scenario this would mean the swelling of plywood joints resulting in inseparable components and the irreversible damage to the structure during disassembly. The reliance of the systems on friction jointing is also a potential weakness through multiple reuse cycles. It was noted that plywood pins were more reliable over multiple reuse cycles versus mortise and tenon only connections.

A similar tolerance issue arose as a result of the material specification. Low-grade plywood (specified as C.D. grade in New Zealand) was selected to keep material costs competitive with platform framing. C.D. grade represents the 2nd lowest grade of plywood available at the time of testing. The lowest grade (D.D.) proved to have too many imperfections in the surface (knots and splits) to achieve sufficient adhesion to the vacuum bed of the CNC router. Providing the C.D. grade sheets were not warped, adhesion was adequate and manufacture was successful. Issues with C.D. grade plywood arose, however, during assembly tests. Due to plywood manufacturing inconsistencies there is a greater degree of thickness variation in the C.D. product than higher grades. In some instances the sheet thickness varied by more than 0.75 of a millimeter. This deviation was enough to result in jointing failures—friction based joints with insufficient resistance between elements. Preliminary experimentation suggests that this thickness variation is consistent in a range of alternatively branded plywood products. It is also important to note that any grade of plywood sheet stacked unevenly or stored in a location exposed to rapid moisture and/or temperature fluctuations was prone to warping. If this was not identified before cutting commenced the material would move around on the table of the router resulting in incorrectly shaped components. If a warped sheet was identified it was screwed to the sacrificial sheet (18 mm MDF) above the vacuum bed. This meant that almost any sheet could be cut successfully but at a cost of increased loading and unloading times.

It is widely accepted that reductive manufacturing technologies, such as CNC routing, are prone to producing large quantities of waste. This is a consequence of the pre-sized sheet material (in this instance 1200 mm by 2400 mm sheet plywood) conflicting with the desired forms being cut. Although the design can be highly optimized to make use of the available material there is always some degree of wastage (sometimes only the sawdust created by the thickness of the cutting piece). Click-Lock's geometry resulted in 16% of the input material being converted to low-value sawdust waste. It is important to note however that sawdust waste was revealed to not be directly related to the length of the CNC cut. The perimeter shaping of an element and its potential to be nested on a plywood sheet significantly affected waste produced at the time of fabrication. Computer-aided additive manufacturing (3D Printing) processes are recognised to have the capacity to entirely eradicate waste produced at the manufacturing stage as material is only 'consumed' or 'delivered' where needed. The research to date has not utilized this technology due to economic and material toxicity concerns. The aim of this study is to deliver a product that does not introduce barriers to total lifetime material management. The thermal composite material used to 3D print timber is limiting in this regard. Further investigations will aim to explore the potential of reusable cost-effective bio-polymer additive-manufacturing technologies.

A cost comparison of each system has not been published here, however, the required CNC router cutting length implies cost variations between each 'CAM' structural system. Within this comparison a significant concern was X-Frame and its requirement of 75% more routing than Click-Raft. This increased cut length translates directly into a more expensive manufacturing process that produces larger quantities of waste. Reacting to this concern steps were taken to improve fabrication efficiency and, as such, X-Frame components were nested using a common-edge cutting workflow. Common-edge nesting locates the components onto the sheet material in spacing's that correspond with the width of the router cutting piece. This allows a single head movement to cut two parallel lines at the same time. To further reduce the cost of manufacturing a 9.75 mm solid carbide compression bit was used in the CNC router. This made possible a single cutting pass through both 12 and 17 mm plywood sheet products. Using a compression bit also ensured that no finishing work was required to the cut components. For whole systems comparable cost examinations refer to Defab; Prefabricated Architecture for a Circular Economy [8] and Experimental Construction in a Timber House [9].

97.6 Study Limitations and Continuations

This quantifiable comparative analysis does not take into consideration the additional complications of incorporating openings and spatial allocations that do not match the module parameters of a prefabricated system. Under these measures X-Frame and Click-Lock are likely to excel as they both offer greater module flexibility within the context of existing construction techniques. Greater flexibility is not only seen to reduce waste and the need for specialist components at the time of construction but also as an important factor in ensuring the reuse of these materials. Further research is needed to expand this study from a closed analysis of the technical reuse potential of CAM construction solutions, to a study that measures if these materials are then adopted by builders and contractors on a frequent basis in new buildings. A range of other factors, such as the skill level of the labor, tools available, unique finishing and connection details, the integration of services as well as the integration of windows and larger structural elements also all affect the accuracy of the reported quantitative measures.

To validate these results in a wider context a larger range of non-CAM fabrication inclusive construction methods need to be examined in a comparative manner. This analysis may suggest that although CNC cut plywood construction methods are superior in a CE approach against conventional LTF, they are not the best CE solution. It is likely there are a range of 'low-tech' solutions, such as straw-bale and Hempcrete, which offer superior CE performance due to their material properties. The most successful CE construction manifestation may therefore be a hybrid incorporating both low-tech and CNC fabricated elements. Furthermore structural testing of the systems to determine if material can be removed from the configurations may improve their respective performance. A notable opportunity is to test X-Frame and Click-Lock with 12 mm plywood products. By-products of this change will be a decrease in the fabrication waste, faster cutting times and a lighter structural grid. For further validation a detailed investigation into the sawdust and solid waste produced at the time of material fabrication also needs to be undertaken. If it is found that the saw-dust waste produced during the fabrication of conventional timber lengths matches or is greater that of the sawdust waste produced during the manufacture of plywood, the respective performance of each system will shift.

97.7 Conclusions

Results indicate that the use of CAD/CAM technology to fabricate an alternative structural design can lead to a 67% reduction in the time necessary to recover building materials for reuse (versus the cost of reusing materials from traditional construction techniques) (Table 97.1). This finding is useful for researchers and practitioners alike as it indicates that CAD/CAM based construction systems are more economical to recover at the end of their useful life and therefore more appropriate for a CE. The increase in deconstruction speed is a result of the CNC fabricated building components inherent capability to be assembled, modulated and remain free of contaminating materials through use cycles. CAD/CAM in this sense enables the mass fabrication of detailed building components at competitive economic rates that are highly optimized for cyclic use. However, computer-aided manufacturing also introduces a range of challenging issues. Manufacturing waste produced during CNC routing is a key concern as it represents a new source of waste as well as adding additional costs to the building process. Similarly, computer-aided manufacturing's ability to create precise friction-only joints can become compromised due to inconsistencies in the raw material product.

In conclusion, this holistic study highlights the complex issues that arise when attempting to design for a Circular Economy in the building industry using CAD/CAM. Based on the metrics reported in this study researches and practitioners need to look beyond sophisticated manufacturing and product-based solutions if they are to ultimately deliver successful CE building solutions.

References

1. Environmental Protection Agency: Advancing Sustainable Materials Management: 2014 Fact Sheet Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States. United States of America (2016)
2. Environmental Protection Agency: Characterization of Building-related Construction and Demolition Debris in the United States. Franklin Associates Prairie Village, KS. United States of America (1998)
3. Inglis, M.: Construction and demolition waste—best practice and cost saving. In: Proceedings of the New Zealand Sustainable Building Conference. Ministry for the Environment. New Zealand (2007)
4. Resource Efficiency in the Building and Related Industries: Why REBRI? Building Research New Zealand. New Zealand. BRANZ Website, http://www.branz.co.nz/REBRI. Last accessed 18 Feb 2018
5. Forbes, N.: The Structural Reuse of Pinus Radiata in New Zealand. Thesis. Victoria University of Wellington, New Zealand (2018)
6. Braungart, M.: Cradle to cradle: remaking the way we make things. Farrar, Straus and Giroux, UK (2002)
7. SCION: Ligate™ bioadhesives from 100% renewable resources. Scion Crown Research Institute Website, https://www.scionresearch.com/science/bioproducts-for-sustainable-industries/bioadhesives. Last accessed 18 Feb 2018
8. Finch, G.: Defab: Prefabricated Architecture for a Circular Economy. Thesis. Victoria University of Wellington, New Zealand (2018)
9. Marriage, G.: Experimental construction in a timber house. In: Aurel-Schnabel, M. (ed.) 50th International Conference of the Architectural Science Association 2016, pp. 685–694. Australia (2016)
10. Moller, C.: CMA + U. Click-Raft Blog Website, http://click-raft.blogspot.co.nz/. Last accessed 25 Apr 2018