Developing a prefabricated timber and straw-bale wall panel for Aotearoa New Zealand

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Abstract: Making greater use of materials that sequester carbon, like timber and straw, is one way of reducing carbon emissions in the construction industry. In Aotearoa New Zealand building with straw bales has been perceived as a fringe technique, undertaken mostly in rural locations and often by owner-builders. For the past twenty years, however, and in the face of escalating climate change, practitioners have looked to prefabrication to advance the process of building with straw. Prefabricated timber and straw-bale wall panels have been developed in Europe, the United Kingdom, North America and Australia. They have been used to construct stand-alone houses, medium density housing, schools and medium scale commercial projects. This paper reports on Project Pātūtū, a research project aiming to develop a straw-bale panel system suitable for use in Aotearoa. International examples have been investigated before designing six panel options. Scale model panels were built and analysed in terms of their suitability for both community participation in the construction process and mainstream commercial construction. A small house was designed using the panels and analysed in terms of compliance with building regulations and the practicalities of construction

Keywords: Prefabrication; straw-bale; low carbon.

1. Introduction

Carbon emissions from the construction industry are estimated at 39% of the worldwide total, and in Aotearoa New Zealand, the figure is 20% (NZGBC, 2022). The Building Research Association of New Zealand, suggests a number of ways to mitigate these, including adopting “solutions and tools for designing and constructing buildings with a long useful life and low embodied carbon over their life cycle” (BRANZ, 2022). Making greater use of low carbon materials, those that sequester carbon, is therefore an important way of achieving this. Timber is the most widely used low carbon building material and is the predominant structural element used in Aotearoa. Straw, a by-product of the cereal grain industry, is also a low carbon material; but until now its use for building has been limited to the fringes of conventional construction, occurring mostly in rural locations and often involving owner-builders.

Farmers in Aotearoa are adept at growing grain and therefore straw, but despite changes in arable farming methods over the past ten years, where more straw is being ploughed back into the soil, at least

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20% of it is still considered waste and is often burned in the field. Estimates show that there is sufficient excess straw available to produce timber and straw wall panels for over 2,000 stand-alone houses annually (Hall, 2019).

This paper explores the potential of this wasted material by outlining progress to date on Project Pātūtū, a research project begun in 2019, which looks to develop a sustainable prefabricated timber and straw-bale wall panel system. It also looks to address the current housing crisis by asking how such a system could be suitable for papakāinga and other group housing projects where community sweat equity has the potential to reduce costs. International precedents have been investigated and analysed in terms of their suitability for the geography and climate of Aotearoa, the existing regulatory system, the makeup of the construction industry, and the potential for community involvement. Six panel types were designed and prototypes at one-third scale were built. After analysis one of these was developed further and integrated into the design of a compact two-bedroom house.

The paper concludes with a discussion about the next steps, including carbon footprinting and hygrothermal analysis, and the challenges to be faced when introducing a building technology traditionally regarded as unsophisticated into a conservative construction industry and marketplace.

2. Background

Although building with straw and grasses is common in many forms of traditional vernacular architecture, using straw bales is comparatively new. Ever since baling machines were invented towards the end of the nineteenth century, straw bales have been used for construction. Houses over one hundred years old are still being used in the USA and France, and their history is documented in Steen et al's *The Straw Bale House* (Bainbridge, 1994). Straw fell out of favour during the twentieth century, but in the 1980s some looked to it again in response to the increasingly evident environmental crisis. By the turn of the century, a global straw-building network emerged. A rundown of this more recent history is provided in Barbara Jones' *Building with Straw Bales* (2015), and Gernot Minke and Benjamin Krick's *Straw Bale Construction Manual* (2020).

The first straw-bale house in Aotearoa was completed in Marlborough in 1995, and by 2010 there were 34 in the Nelson/Tasman region alone (Hall, 2012). Although no official record has been kept, it is generally accepted within the close-knit straw-bale building network that there are now several hundred scattered throughout the country. Over the past 30 years construction techniques have developed. Generally, straw-bale walls are constructed insitu with an integral timber frame taking the majority of the roof loads. Hybrid systems, where some of the load is taken by the straw-bale walls, have also been developed, and some builders have used a tilt up method where the straw-bale walls are built flat on a concrete slab and then lifted to the vertical. To date, most straw-bale houses have plaster finishes inside and out, but these have changed from being cement-based plaster on wire mesh, used in the 1990s, to predominantly external lime and internal earth plasters applied directly on to the bale surface or with a fibreglass mesh. Plastering is time-consuming, and along with weather constraints, often makes onsite straw-bale construction a slow process. This has led some practitioners to look to offsite prefabrication.

Prefabrication means panels can be built in a controlled environment whatever the weather. Scaffolding is not required: panels are constructed on horizontal surfaces, which also makes plastering easier. In Aotearoa, Sol Design of Geraldine have experimented with prefabricating walls for a small building in a nearby shed and then transporting them to the building platform (Forsyth et al, 2014). Other builders are experimenting with prefabrication but, at the time of writing, no fully developed systems are in operation. Internationally, however, there are a number of successful systems where prefabricated wall panels are constructed off-site and transported to site. Project Pātūtū aims to contribute to the development of such a system for Aotearoa by looking first to examples from North America, Europe, the United Kingdom and Australia.

3. Existing prefabricated timber and straw bale systems

3.1. Introduction

In *Essential Prefab Straw Bale Construction,* Chris Magwood outlines his own experience with straw-bale building in Ontario, Canada including prefabrication of walls (Magwood, 2016). He has developed a methodology for designing prefabricated systems, identifying some of the key decisions to be made: panel size, the structural frame make up, materials for interior and exterior finishes, bale orientation, panel to panel fixings, integrating services, accommodating openings, and panel to foundation and roof connections. This methodology is also useful when analysing existing systems.

A number of prefabricated timber and straw-bale systems have been developed internationally, the most well-known being ModCell® from the UK and Ecococon from Lithuania. These two systems along with Rainbow Ecosystem from Ukraine, Situps from Australia, and Gryphon from the USA have been studied and analysed to inform the development of a system suited specifically to Aotearoa.

3.2. ModCell®

The ModCell® Core panel comprises an engineered timber frame with straw bale infill. Panel sizes and thicknesses vary but are generally whole wall components up to 4m wide. They are made to suit specific designs. The perimeter frames are full depth glulaminated elements with vertical timber I-beams within, separating vertically stacked straw bales. Panels leave the factory fully closed in with sheathing boards inside and out, ready to receive their chosen finish on site; or with final finishes pre-installed (Modcell, 2022).

3.3. Rainbow Ecosystem

The Rainbow Ecosystem factory in Ukraine manufactures narrower width panels, 1200mm, using sawn timber frames and then combines them within the factory to create full walls, complete with windows. These are finished inside and out with lime or clay plasters before being transported to site (Rainbow, 2018).

3.4. Ecococon

Ecococon panels are generally smaller than ModCell®, ranging in width from 800mm to 3m. Frames are sawn timber and, rather than using bales, the straw is compressed into each frame using a patented system. Panels arrive on site with both straw surfaces exposed or protected by a wrap and can be either plastered on to the straw or lined with a variety of sheathing boards inside and out (Ecococon, 2022).

3.5. Situps

Situps is the brainchild of John and Susan Glassford, pioneering straw-bale builders in Australia. The panels use a full depth plywood frame and range in size from 600 to 900mm wide and up to 3m high. They are designed to be handled by two people but are generally lifted off the truck with a tractor or other small-scale lifting equipment. Situps panels arrive with both straw surfaces exposed ready for finishing on site (Glassford, 2022).

3.6. Gryphon

The Gryphon panel is being developed by New Frameworks in Vermont, USA. The panels are 600mm, 900mm and 1200mm wide and are constructed in a modest scaled workshop using a simple purpose-built steel-framed jig to compress vertically stacked straw bales into sawn timber frames. Panels are partially finished in the factory with an Intello wrap to the interior, and plywood and battens to the exterior. Final finishing is completed on site using dry systems (New Frameworks, 2022).

Table 1: Features of five prefabricated timber and strawbale wall panel systems

System	Panel width (mm)	Frame material	Wet or dry finish	Factory finishing interior	Factory finishing exterior	Specialised factory equipment	Bale orientation
ModCell®	limited only by truck capacity	engineered timber	either	optional	optional	yes	vertical
Rainbow	limited only by truck capacity	sawn timber	wet	yes	yes	yes	horizontal
Ecococon	800-3000	sawn timber	either	no	no	yes	NA
Situps	600-900	plywood	either	no	no	somewhat	horizontal
Gryphon	600-1200	sawn timber	dry	no	no	somewhat	vertical

3.7 Summary

Table 1 summarises the attributes of each system. All use the enclosing timber frames as the main structural element for taking vertical loads, whether that be engineered timber as for Modcell, plywood as per Situps or sawn timber with some plywood for Ecococon, Rainbow and Gryphon. The internal timber I-beams in the Modcell panels also take some of the load, thus permitting larger width panels to be made. Rainbow make their large wall panels by joining smaller ones together in the factory.

Chris Magwood identifies the choice of wet or dry processes for finishing as being the first decision to make. Wet systems include lime or earthen plasters and dry systems: plywood, gypsum plaster board, and wood fibreboard. Wet systems are less common for prefab because of the increased weight they add to the panel, complications with joining panels on site, and their increased vulnerability to damage during transport. Although it is still possible to use plaster finishes for all the systems, Rainbow is the only company to actively promote it. Their panels leave the factory pre-finished inside and out, the other systems involve varying levels of onsite finishing.

Modcell began operating out of ‘flying factories,’ using existing farm or industrial buildings located no more than 20Km from the building site, but the panels are large and over time permanent manufacturing facilities have been created. Rainbow and Ecococon have made considerable investment and built bespoke machinery to manufacture their panels, particularly with regard to compressing the straw or straw bales into the timber frames.

The desktop study of these five systems, along with Magwood's analysis, helped identify some key factors to consider when developing a wall panel for Aotearoa: size of panel, scale of manufacturing operation, structural components, internal and external finishes, and bale orientation.

4. Developing the Pātūtū Panel

4.1. Objectives

Project Pātūtū has clear objectives which influenced decision-making around developing the panel. Firstly, there needs to be a clear pathway to satisfying specific clauses of the New Zealand Building Code (NZBC): B Stability, C Protection from fire, E Moisture, and H Energy Efficiency (MBIE, 2022). The panel design also needs to take account of the availability of materials and skills, public perception, embodied CO_2 emissions, and the scale of operation. The latter is important when considering a commercial or community-led enterprise.

4.2. Prototype designs

Following the analysis of existing systems, three panels were designed in 2019. Consideration of the NZBC requirements and public perception influenced decision-making specifically with regard to exterior cladding. To avoid being limited to a direct plaster finish to the exterior, it was decided to include a ventilated cavity for all panel options. This allows a broad range of material finishes to be considered depending on the context and availability of materials. The cavity also makes satisfying Clause E2 External Moisture straightforward.

Table 2: Details of six panel designs using timber and straw bales

Panel	Panel width (mm)	Frame material	Bale orientation
C-2019	2000	Sawn timber and plywood	horizontal
IC - 2019	2400	Sawn timber, plywood, engineered timber	vertical
LVL-2019	1000	Engineered timber	horizontal
C-2021	2000	Sawn timber and plywood	horizontal
GR-2021	1000	Sawn timber and plywood	horizontal
Pātūtū-2022	1200	Sawn timber and plywood	horizontal

Table 2 provides details of the three initial designs and three subsequent iterations. The C panel built on ideas developed by Ryan Pringle in his thesis *Straw into Gold*, where timber C sections constructed from framing timber and plywood form the frame for 2.0m wide panels (2017). The IC panel combines the C exterior frame with internal I-joist posts, as used in the Modcell Core panel, with six rows of bales stacked vertically to create panels 2.4m wide. The LVL panel uses engineered timber for the entire frame, much like the earlier Modcell panels, with one stack of horizontally laid bales creating a 1.0m wide panel.

The next stage involved constructing one-third scale models of the panels; one-third because of the availability of small straw bales from local garden centres which at 150mm wide, 120mm high and 300mm long, happen to be one-third the size of a typical straw bale: 450mm wide, 350mm high, 900mm long. The first models were constructed in 2019 during Resource Matters, an elective course within the Bachelor of Architectural Studies programme at Unitec Institute of Technology. A team of fourteen students and two lecturers constructed seven C panels and assembled these into a small one-third scale structure which became the centrepiece of their *Straw into Gold* exhibit at BuildNZ, the largest trade show in Aotearoa. The panels were prefinished with earthen plasters inside, recycled softboard to the exterior under a ventilated cavity, and a combination of plywood and profiled metal cladding completing the exterior (Figure 1)

After a one-year hiatus caused by the global pandemic, the project was picked up again in 2021. The C-panel was modified to reduce thermal breaks identified during construction of the *Straw into Gold* model, and the GR panel was designed based on the Gryphon panel. One-third scale models were built, focusing on the structure rather than the finish (Figure 2). The key differences between the GR panel and the C panel are the reduced size, fully framed sides rather than C sections and locating the cross ties on the exterior. The final iteration, the Pātūtū panel (Figure 3), is based on the GR panel but with the straw bales stacked on their edge, reducing the wall thickness by 100mm.

Figure 1: 'Straw into Gold' model 2019.

Figure 2: One-third scale models L to R: GR -2021, C – 2021, IC – 2019, LVL – 2019

4.3. Pātūtū panel

The design of the Pātūtū Panel integrates learning from the precedent study and the earlier designs. Other considerations were availability of skills and materials, and the NZBC requirements. Size was determined by considering bale lengths, 800-1100mm, which result in panels 900-1200mm wide; a useful range when looking to use off-the-shelf sheathing products. Light timber framing, the most widely used construction method in Aotearoa, has been adapted to suit bale sizes. Essentially this means that double 90 x 45 studs are located at each end of the bale, separated by spacers to suit the bale thickness. Strips of wool blanket insulation are proposed for filling the gaps between framing members as shown in Figure 3.

The intention of the first iteration of the Pātūtū Panel was to integrate it into the design of a small house which could then be analysed in terms of its structural and hygrothermal performance. To that end a standard width of 1200mm was chosen with a maximum height of 2820mm (6 bales).

4.4. Pātūtū house design

The best way of assessing how the Pātūtū wall system complies with the NZBC was to design a house using the panels. A simple rectangular house was designed using 1200mm wide by 2820mm high (6 bales) panels, see Figure 4. A timber foundation and sub-floor system was chosen along with a simple prefabricated single pitch roof truss system, deep enough to allow generous ceiling insulation. Internal finishes include earth plaster, gib board to service areas, and plywood ceilings throughout. Exterior finishes include vertical timber cladding and profiled metal roofing.

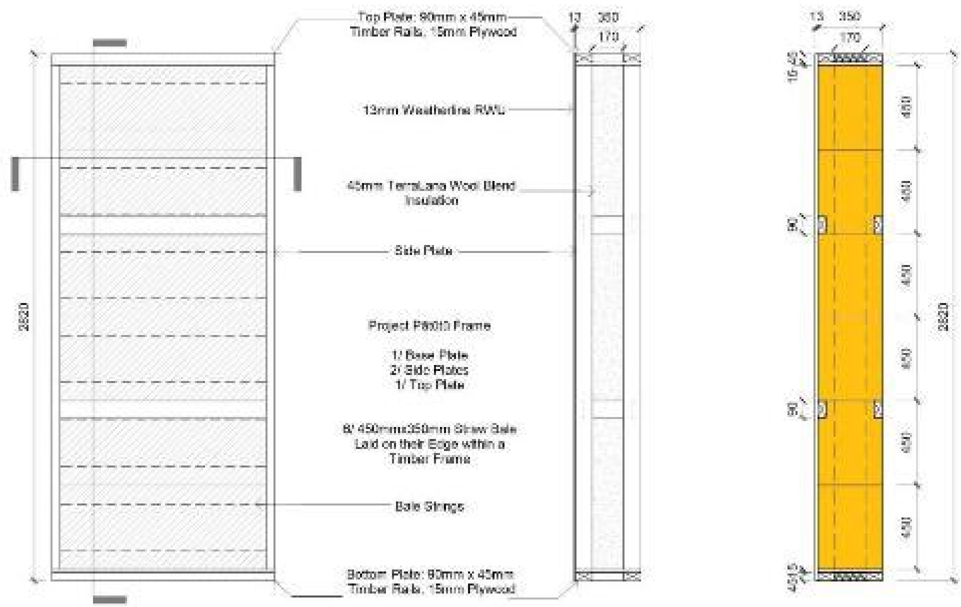

Figure 3: Pātūtū Panel: elevations and section

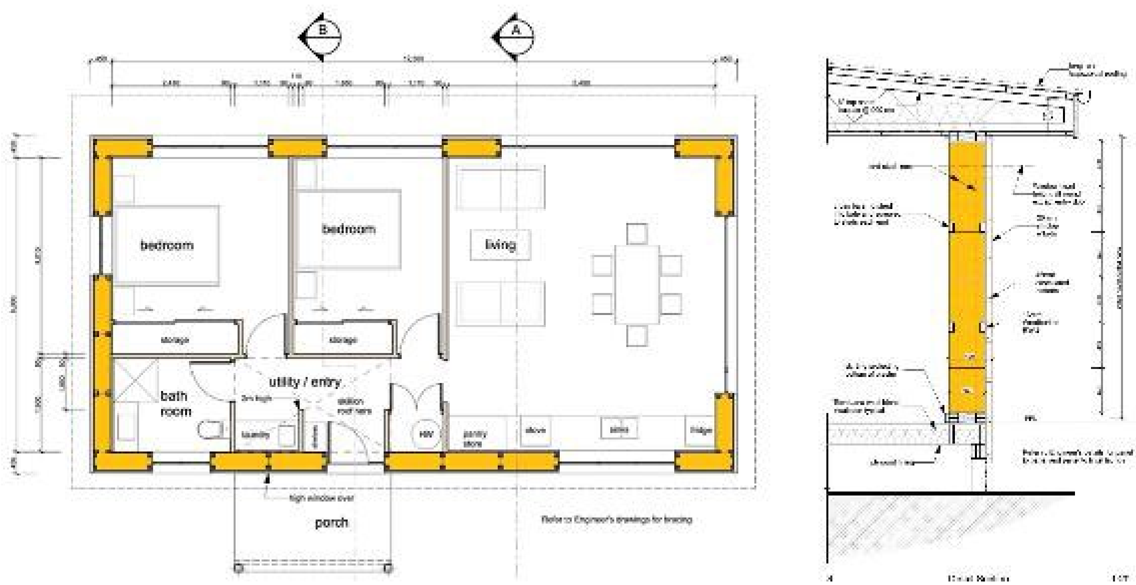

Figure 4. Pātūtū House: floorplan and section

A structural analysis was carried out by engineer David Reid of Lignum Structural. His analysis assumed the house was located in the most demanding wind and seismic zones covered by Clause B1 of the NZBC, and found the house would perform well. Part of his analysis included specifying panel to panel, panel to lintel, panel to foundation and panel to roof structure fixings.

Detailed design of the external envelope was carried out with satisfying Clause E2 in mind. Going forward, the next stages of the analysis will include a hygrothermal forecast, life cycle analysis, and accumulating existing data for fire and thermal resistance to satisfy clauses C and H respectively.

5. Discussion

One of the key reasons for looking to prefabrication is to speed up the build by reducing time on site. However, unlike traditional insitu straw builds where the main structural framework and roof are constructed before the straw bales arrive on site, prefabricated wall panels need to be assembled before the roof can go on. The existing systems studied either use wraps, which are part of the finished system, or temporary tarpaulins to protect the panels for this stage of construction. Either way, it is important that the roof goes on as soon as possible.

Keeping the panel size small enough to be handled by up to four people or small-scale lifting equipment was important when factoring in the potential for community engagement in the process. Panel size is also affected by the size of straw bales, except where straw is compressed directly into the timber frame, as for Ecococon. At this stage of Project Pātūtū, both larger scale commercial and community production options are still being considered. Therefore, the panel size has been limited to 1.2m wide to suit possible bale lengths and readily available sheathing products. Smaller panels permit greater flexibility for design regarding window and door openings, and they can also be joined to make bigger panels before leaving the factory, as in the Rainbow Ecosystem.

Building the one-third scale models was an important part of the panel development, and they have been extremely useful for demonstration purposes. However, there are limitations. While it is easy enough to use one-third scale timber and straw bale elements, this is not the case with fixings, particularly the gauge of screws. In most cases timber elements were slightly larger than a straight one-third scale in order to accommodate the 'oversized' screws. This aside, even at one-third scale the impossibility of compressing straw bales into the prebuilt frames without the frames bowing in the middle became obvious. Magwood identified a number of strategies to address this, using timber cross-ties located either centrally in the wall or on the exterior, both require notching of bales to get a snug fit (2016). Mock-ups of mid-wall and exterior cross-members were tried; it was easier to get a tight fit with the latter. Ecococon use centrally located cross-ties, suggesting it is easier to use this system when the straw is being compressed directly into the frames rather than using bales.

One of the aims of Project Pātūtū is to use homegrown materials. This is easy to achieve with regard to timber and straw bale, but where it was not possible to find products using raw materials from Aotearoa, home manufactured products have been preferred over imported ones. For instance, there is a lack of locally produced insulative sheet linings like those used for Modcell, Ecococon and Gryphon. It is a sad truth that globalisation has seen the demise of locally manufactured goods using locally sourced raw materials. Despite having an abundance of raw wood fibre, manufacture of low-density wood fibreboard in Aotearoa ceased in 2007 (Isaac, 2008). Since then, the only available product is imported from Germany. The only viable options for sheathing materials manufactured in Aotearoa are paper-faced gypsum fibre board (known as gib board) using imported gypsum, and plywood and medium density fibreboard (MDF) which both use homegrown timber. Given the sheathing material also needs to provide lateral bracing, the two options being considered are gib board or plywood. At this stage of the project both options are still being considered, the final material to be determined after hygrothermal analysis of the complete wall sandwich has been carried out.

The decision to incorporate a ventilated cavity means that it is easy to comply with Clause E2 and also to 'normalise' the appearance of straw-bale construction by enabling the use of a variety of commonly used cladding materials. Straw-bale houses can sit alongside those built using conventional construction and appear no different. Superficial maybe, but considering appearance is an important first step towards countering negativity towards a fringe construction technique.

One drawback to building in straw has been the complicated and often difficult building consent process where applicants must show how their proposals satisfy the NZBC. Anecdotal evidence suggests however, that the informative appendix on straw-bale construction in the recently updated New Zealand standard, *NZS4299: 2020, Earth buildings not requiring specific engineering design* is already making the process easier for both applicants and the building consenting officers processing those applications (SNZ, 2020). This bodes well for Project Pātūtū.

Designing a small house using the Pātūtū panels was an opportunity to engage with methods of satisfying the relevant clauses of the NZBC. Although standard timber framing elements are proposed their spacing does not comply with NZS:3604, an acceptable solution for Clause B1. The structural analysis carried out by Lignum Structural, however utilised the verification methodology in B1 to show that it was a straightforward exercise to comply. Similarly, the proposed timber elements comply with B2 Durability.

There has been no testing for fire or thermal resistance of straw-bale walls in Aotearoa but results from overseas testing have been used successfully for building consent applications for insitu builds to demonstrate compliance with the NZBC. Internationally, Modcell, Rainbow and Ecococon have had their systems tested for fire and thermal resistance, while Situps and Gryphon use laboratory test results by others to prove the rating of their panels. This latter approach is also intended for Project Pātūtū although it would be useful to carry out testing for both fire and thermal resistance in the future.

6. Conclusion

The importance of addressing the unsustainable carbon footprint of both the agricultural and construction sectors in Aotearoa cannot be overstated. Making greater use of locally grown and, in the case of straw, underutilised carbon sequestering materials for construction has the potential to reduce the footprints of both. But in order to do this at the scale necessary to make a significant impact, more efficient construction methodologies, like off-site prefabrication, will be required.

This paper set out to document progress to date on Project Pātūtū which explores the potential of straw as a component of a sustainable prefabricated wall panel system. Four key objectives have been explored: using homegrown materials, suitability for community-led projects, meeting the requirements of the NZBC, and strategies for countering public perception of straw-bale construction. The most difficult objective to satisfy is using entirely homegrown materials and a compromise has been made to include materials that are at least manufactured in Aotearoa. Panel sizes have been kept small so that small scale production is possible and expensive infrastructure is not required. This is also important when considering community-led projects. International precedents demonstrate how prefabricated timber and straw panels have been used successfully and that houses constructed with them can appear no different than those constructed using more conventional methods. Like the precedents, Pātūtū panels incorporate a ventilated cavity, meaning that not only can any number of cladding materials be used but it is also easy to comply with Clause E2 of the NZBC. Similarly, light timber framing, the most widely used structural system in Aotearoa, was adapted to accommodate straw bales and analysis shows it complies with Clause B1. Although the project is yet to be concluded, there is a clear pathway for satisfying other relevant clauses. If consenting is easier, if straw-bale houses can 'fit in', and if public attention can be focused towards the environmental benefits, then carbon sequestering straw-bale construction, at scale, could become a reality.

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