EQC Biennial Grants 2020

Final Report: Application BIG 067 2020

Title: Understanding the Seismic Performance of

Structural Insulated Panels for Use in New Zealand

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Introduction and Summary

New Zealand has an urgent need for quality housing that can be built quickly and affordably. Using structural insulated panels (SIPs) is one possible solution, particularly for residential applications. SIPs are sandwich panels made of two face layers and an insulating inner core, as seen in Figure 1. They can be prefabricated and assembled quickly on site for walls, floors and roofs and are one potential solution which could be used to increase construction speed and reduce overall building cost. While SIPs have been widely used overseas, less is known about their performance in a New Zealand context. Following on from the Canterbury earthquake series in 2010 and 2011, there has been increased interest in prefabricated building systems where larger building segments are constructed in factories and assembled on site. SIPs fit this paradigm extremely well and are already being used for stand-alone houses, multi-unit residential buildings, schools and other commercial structures across New Zealand.

Figure 1. Typical SIPs with Timber-Based Outer Face Layers

SIPs having wood-based panels as the outer face layers have been used for residential construction in North America since the early 1990's and have also proven effective in seismically active parts of the world including Japan [1]. The growth in SIP usage in North America has resulted in increased research and documentation on the design and detailing of SIP structures. These activities have culminated in a joint ANSI/APA Standard 610.1-2018 [2] that provides requirements and test methods for qualification of SIPs for use within building standards such as the International

Residential Code [3]. These inclusions of SIPs suggest that these systems will perform adequately under all required loading scenarios but these are specific to North America. It is therefore important to consider the seismic structural performance within the New Zealand context to ensure the behaviour of these systems is understood, trusted because findings are backed by evidence, and will be suitable for use within the local compliance regulations.

An initial project objective was to determine which SIPs were commonly used in the residential built environment. Investigations revealed that SIPs using timber-based panels as facings were used to a larger extent than metal or Magnesium Oxide counterparts and so timber-based skinned SIPs were used in all investigations in this project. Another objective of this project was to determine how SIP structural bracing systems perform when subjected to seismic loading and how this performance aligns with New Zealand requirements for structural systems in buildings. Testing and analysis have provided load and displacement data on SIP wall configurations to evaluate structural seismic performance. Additional tests utilising bracing systems commonly used in New Zealand residential buildings were also conducted. Comparisons were drawn between the SIPs performance and the seismic performance of the other systems. This was done to assess the ability of SIPs to be used in conjunction with other bracing systems used throughout New Zealand as well as to compare critical performance parameters between SIPs and more commonly understood bracing systems.

This structural work is part of a larger project at BRANZ focused on increasing the understanding of SIP performance and includes experimental testing to evaluate SIP durability and a literature review of SIP fire performance. Data from the experimental work will provide the evidence base for understanding SIP performance in New Zealand conditions. Results will be used to support the development of a compliance pathway for use of SIPs in New Zealand. Currently, SIPs are considered to be an alternative solution under the New Zealand Building Code, which requires an engineering assessment before a building consent can be issued. This step adds additional time and cost to a project. A simplified consenting process would benefit a wide range of industry players from manufacturers, regulatory bodies and designers to current and prospective building owners.

Test Specimens and Methods

Because the SIPs using timber-based panels as facings are more commonly used in residential applications, it makes sense to test and analyse the seismic behaviour within the context of NZS 3604:2011 [4]. It is acknowledged that NZS 3604:2011 has been developed for light timber frame (LTF) wall systems, but the structural performance of SIP systems is based on the interaction between the outer skins and perimeter timber framing members, similar to a plywood clad LTF wall. It is also understood that designers of SIP houses in New Zealand have used NZS 3604:2011 as a basis for their buildings and have found it reasonable to do so. Bracing ratings required for wall systems for use with NZS 3604:2011 can only be determined by testing according to the P21 Test Method [5]. Testing for this project was conducted using this method in order to evaluate seismic performance. The range of configurations tested up to the time of writing this report is provided in Table 1. As can also be seen from this Table, as a comparison, additional tests utilising bracing systems commonly used in New Zealand residential buildings were also conducted. This was done to assess the ability of SIPs to be used in conjunction with other bracing systems used throughout New Zealand as well as to compare critical performance parameters between SIPs and more commonly understood bracing systems.

Table 1. Configurations Tested Using P21 Test Method

Test Configuration	Side 1	Side 2	Hold-Downs?
BPB1	Bracing Plasterboard	NA	Yes
BPB2	Bracing Plasterboard	Bracing Plasterboard	Yes
PLY1	7 mm plywood	NA	Yes
PLYPB	7 mm plywood	Standard Plasterboard	Yes
FC	6 mm fibre cement	NA	Yes
SIP-PS-NHD	NA	NA	No
SIP-PU-NHD	NA	NA	No
SIP-PS-HD	NA	NA	Yes
SIP-PU-HD	NA	NA	Yes

The wall constructions for the plasterboard, plywood and fibre cement configurations follow typical methods documented in NZS 3604:2011 [4] with all using 45 mm x 90 mm SG8 Radiata Pine timber framing with studs at 600 mm centres. No nogs were used for any of these specimens. The fixing of panel materials to the framing was done in accordance with typical construction practices according to manufacturer literature. This included concentrated patterns of screws for the plasterboard specimens in the corners and the adherence to recommendations on fastener type, spacing and edge distances. Handibrac® hold-downs were included with all of these configurations because the systems were all considered to be bracing systems that would have significant resistance to wind and earthquake loads. Different brands of panel products and generic details were used so that the results from these tests could be considered non-proprietary and not specifically relatable to a single manufacturer or product.

Different SIP manufacturers specify different ways of assembling their systems which means that these systems will potentially behave differently under seismic loading. This project was not aimed at providing specific bracing ratings for proprietary SIP systems, but rather to consider the generic structural performance of SIP systems used for lateral bracing in buildings. Therefore, non-proprietary systems were used for the wall test configurations using SIPs in order to avoid reliance on any particular manufacturer or structural system. A range of SIP systems were considered as input so that the tested configurations would be at least somewhat representative of how these systems are configured using current construction methods.

Two different types of SIP products were tested for this research. They differed in that one had an insulating core of expanded polystyrene (EPS) with the outer skins glued on and the other had polyurethane (PU) cores where the PU serves as the insulation and the adhesive between the core and the outer skins, as seen in Figure 1. The different SIPs also had different timber-based skins, with both being panel products manufactured from reconstituted timber and intended for use as structural sheathing for walls, floors and roofs. Specific details on these SIPs are intentionally omitted to avoid identifying the manufacturers, but both are viable products for the New Zealand construction market. All tests were conducted using 1.2 m x 2.4 m SIPs with an overall thickness of approximately 115 mm (90 mm insulating core and two 12-mm thick skins).

While LTF construction is well understood in New Zealand, the methods for building with SIPs are different and needed to be well represented by the P21 testing conducted. In general, the panels are installed using typical top and bottom plates as with LTF. Rebates in the panels (Figure 1) allow 90 mm x 45 mm SG8 Radiata Pine timber to be installed around the perimeter of each panel. The top and bottom plates provide fixity to the floor and roof/ceiling, respectively, and fit within the top and bottom rebates in the panels. The side rebates are used for installing vertical members or splines that serve to connect panels to adjoining panels or allow fixing for other building components such as internal walls. Plates and vertical members were fixed through the timber-based skins using 2.8 mm x 50 mm flat head galvanised nails at 150 mm centres, approximately centred on the 45 mm timber members and starting at 50 mm from each corner.

The bottom plates of all SIP specimens were secured to the test frame using 12 mm diameter threaded rods passing through the timber foundation beam and secured to the steel beams of the P21 testing frame. These rods were centred 100 mm in from the end of each plate and 50 mm x 50 mm x 3 mm square washers were used. SIP specimens using hold-downs also included 1 mm x 25 mm x 400 mm steel straps which were centred beneath the bottom plate at each end of the specimen and secured to the panels using 2.8 mm x 50 mm flat head galvanised nails. Nails were installed through existing holes in the straps so that on each side there were three nails in the bottom plate and six nails in the stud, as shown in Figure 2.

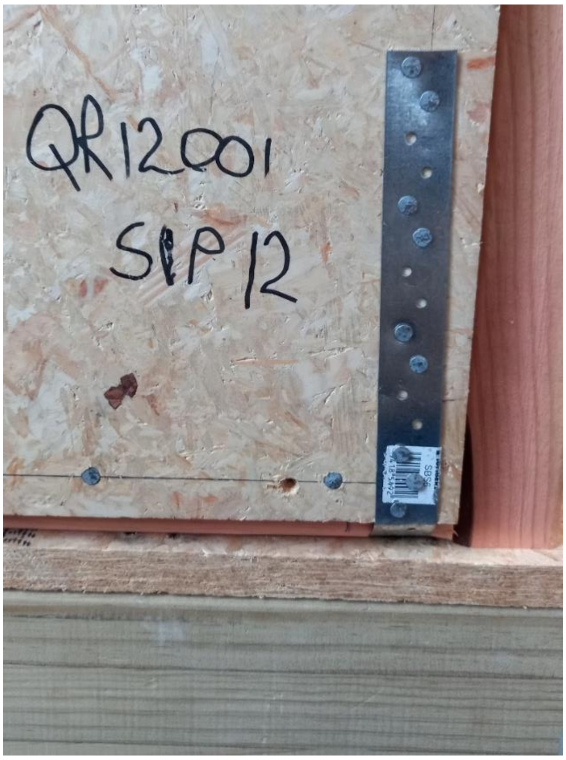

Figure 2. Steel Strap Hold-Downs Used for SIP Specimens

All tested P21 test specimens were installed in a rigid steel loading frame as shown in Figure 3. P21 end restraints were installed in accordance with the recommendations of the BRANZ P21 testing procedure [5] available on the BRANZ website. Horizontal load was applied to the centre of the specimen top plates using a 30 kN closed loop servo-hydraulic actuator and loads were measured using a 25 kN load cell. Out-of-plane movement of top plates was prevented by mechanical restraints located as close as possible to the ends of the specimens. A linear potentiometer was used to measure the horizontal displacement of the top plate. The test load and displacement measurements were recorded using a computer-controlled data acquisition system.

Figure 3. Typical P21 Test Specimen Installed in Testing Rig

Tests were conducted according to the recommendations of the BRANZ P21 test method [5]. The loading sequence consisted of three displacement-controlled cycles of the specimen top plate to displacements of ±9, ±15, ±22, ±29, ±36 and ±43 mm. As suggested in the test method, each configuration listed in Table 1 was tested using three replicate specimens to ensure consistency and reliability. Data provided through testing allowed for the development of loads versus displacement plots, which can be used to relate the capacity of the bracing systems with applied seismic loads as required by New Zealand standards. Observations made throughout testing provided qualitative information on the seismic performance and failure mechanisms of SIP and other bracing systems. These data and observations made possible comparisons of seismic performance with more commonly used bracing systems in New Zealand.

Results and Comparisons

Testing conducted on SIPs and other systems previously described provided valuable information on the seismic performance of SIPs and allowed for comparisons with commonly used bracing systems for residential buildings in New Zealand. The objective was not to provide bracing ratings for specific SIP systems, but to determine the general response to seismic loading of SIPs and to understand how they would likely perform as part of the lateral load resisting system for a building with the New Zealand context.

The seismic performance of the four non-proprietary SIP systems tested was considered good in general and was consistent with the expectations of commonly used bracing systems. The observations are based primarily on strength, stiffness and the ability of the systems to deform without failure (ductility) and also dissipate energy during loading. Examples of generated load versus displacement plots are shown in Figure 4 through Figure 7 for configurations using the different SIP types and with and without hold-downs. The different SIPs have been labelled as A and B to retain anonymity of tested systems.

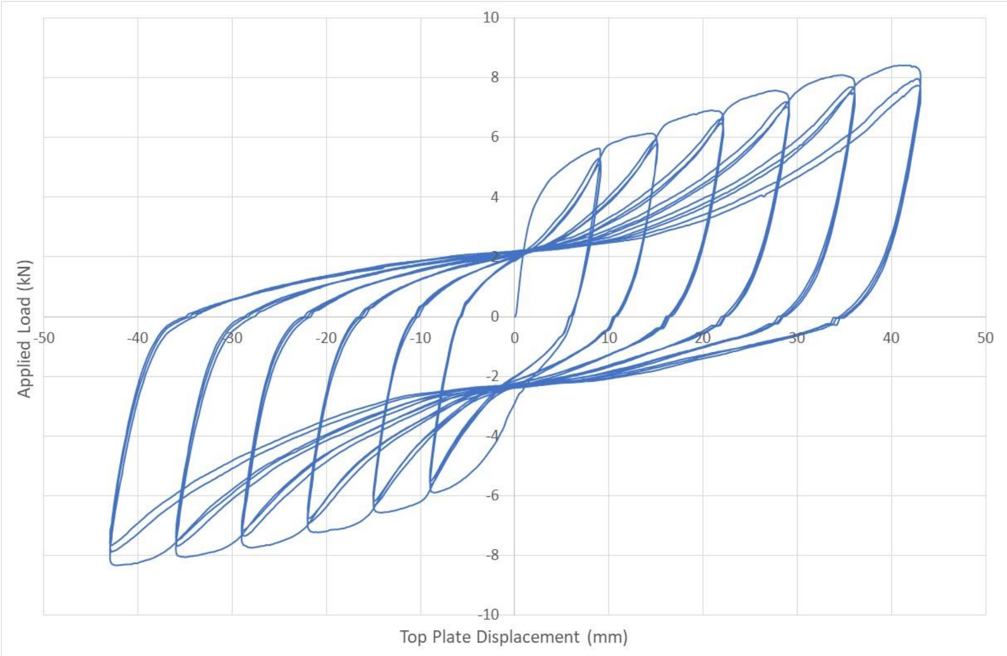

Figure 4. Typical Load vs Displacement: SIP A with No Hold-Downs

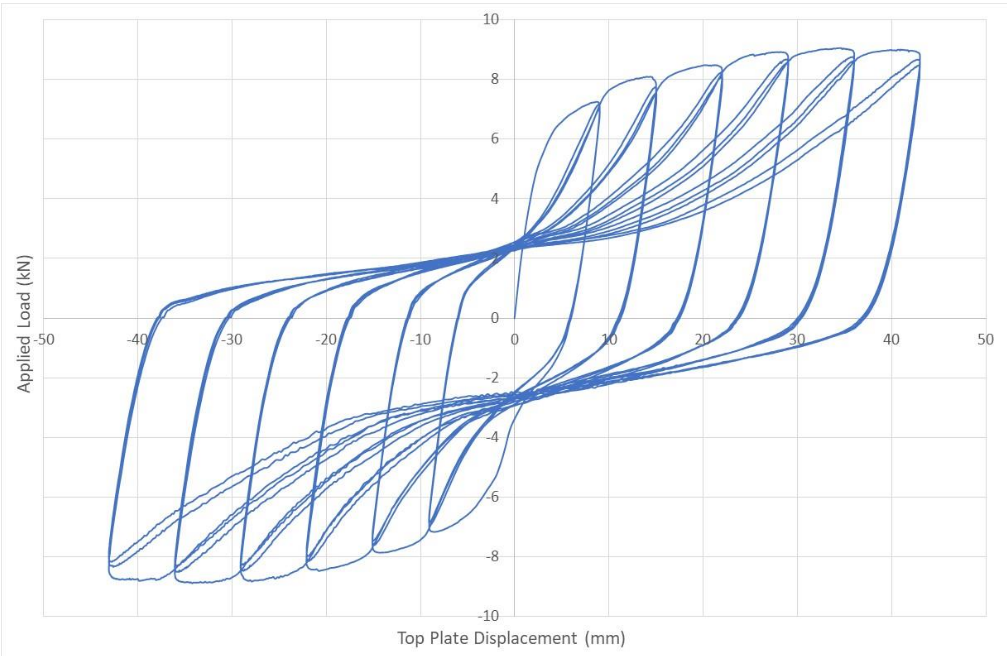

Figure 5. Typical Load vs Displacement: SIP B with No Hold-Downs

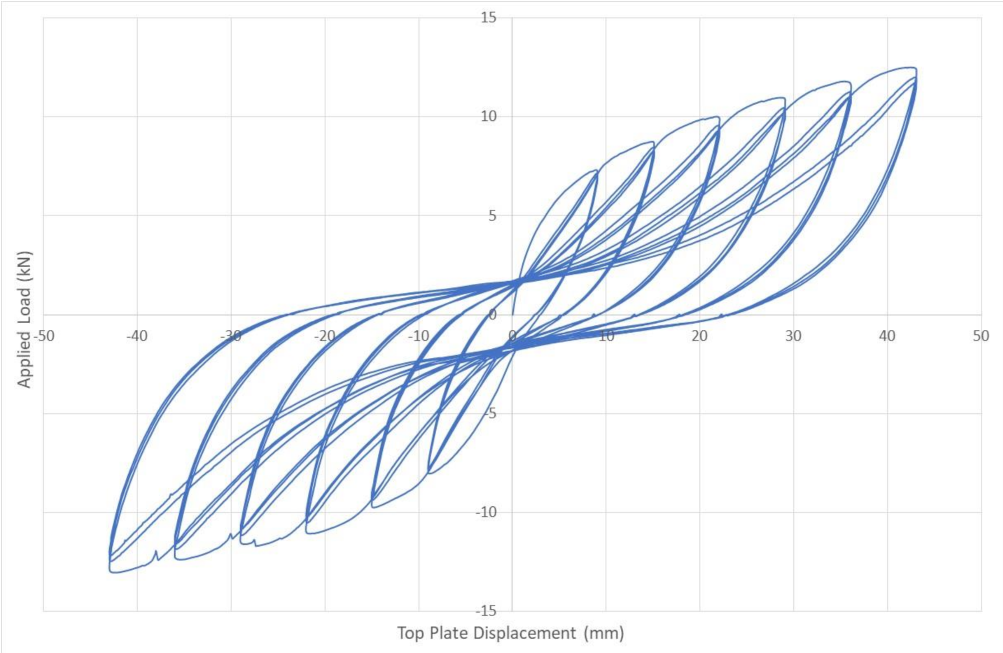

Figure 6. Typical Load vs Displacement: SIP A with Hold-Downs

These plots show that the tested SIP configurations exhibit similar seismic response characteristics of bracing systems that are used globally consisting of timber-based panels fixed to timber framing using nails. These systems are used not only for low-rise residential buildings but also for mid-rise multi-storey buildings up to six storeys in height [6]. Damage was observed due to bending and slight withdrawal of the nails between the outer skins and the timber perimeter members with little or no damage occurring to the timber components, as seen in Figure 8. This was observed mostly along the bottom plate, with the remaining perimeter nails appearing to be intact and in the original positions. This damage was seen for all SIP configurations. Nail bending is considered a desirable mechanism for controlling damage, providing ductility and for dissipating energy in timber structures.

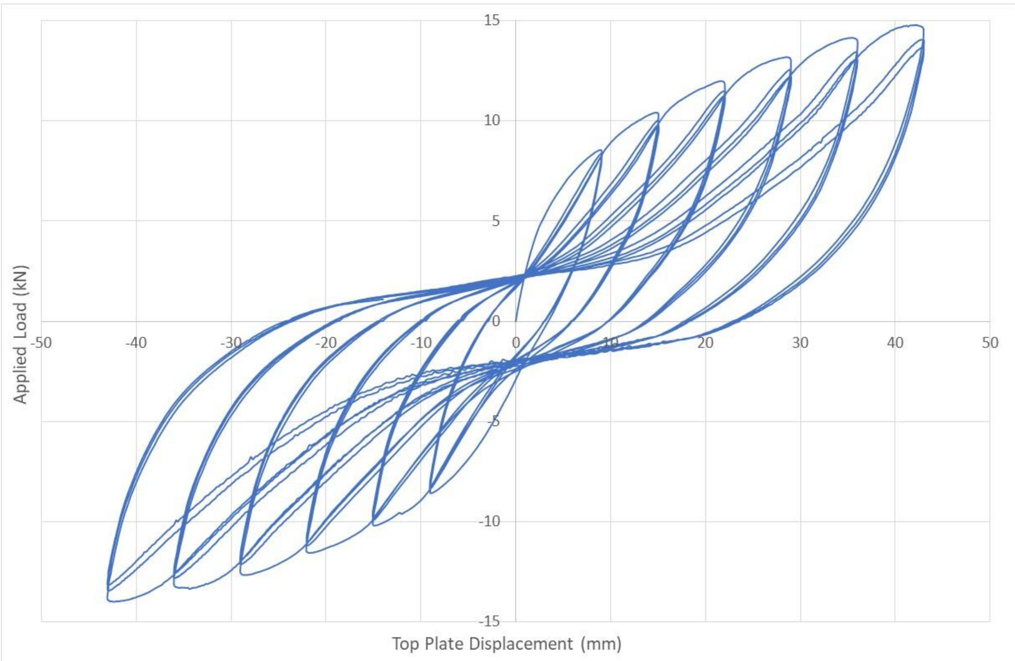

Figure 7. Typical Load vs Displacement: SIP B with Hold-Downs

Figure 8. Typical Damage of SIP Configurations Following Testing

Damage to the plasterboard, plywood, fibre cement and combination systems varied between configurations. Single-sided plasterboard systems with hold-downs suffered damage to the plasterboard as the fixing screws tore the outer paper and dug away at the plaster core all around the perimeter of the specimens. Similar damage was observed for the double-sided plasterboard specimens with hold-downs, and on both sides. Damage on these plasterboard systems tended to be more severe near the bottoms of specimens. Single-sided plywood systems with hold-downs showed nail head rotations and some nail withdrawal at later stages in the testing and mostly along the bottom plate. Minimal damage was observed in the plywood and was always around the nails. Combination plywood and plasterboard systems with hold-downs showed similar damage to the single-sided configurations previously mentioned, but damage was less severe to the plasterboard and slightly more severe to the plywood, with some instances of nails tearing through the edge of the plywood at the bottom corners along the bottom plate. Damage to fibre cement systems with hold-downs occurred as the fixing nails caused damage to the surrounding panel material and pulled through either the edges or the panel thickness. In some cases, corners of the fibre cement panel between nails tore out. There were also instances where the specimens were so damaged that the lower half of the panels were completely dislodged from the timber framing.

Energy dissipation was apparent in the SIP load versus displacement plots and this can be calculated by the area of the loops created from the cyclic loading during testing. Because the loops are "fat", this indicates they are effectively dissipating energy, which means that other parts of the building would not have to absorb the energy from an earthquake and risk potential damage. It is worth noting that there is some damage to the surrounding timber in the framing and panels, and therefore there could some residual displacement following an earthquake. Another observation was that the system continued to resist the applied loads throughout the testing and there was no sudden drop in load, this suggesting that there was not a brittle failure. This ability to continue to deform without losing significant load is what characterises a ductile structural system and is typical of light timber frame systems that are known to have good seismic performance. Another positive performance aspect of the SIP configurations is that following the first cycle, there were only minor reductions in load resistance for the repeated cycles as well as when going on to the next displacement increment. The narrower, and less "fat" second and third cycles is a phenomenon called pinching and is typical of timber-based structural systems and this is caused by crushing of the timber around the nails.

The inclusion of hold-downs for the SIP configurations resulted in some differences in performance. Clearly the loads were greater when hold-downs were included due to the loads being carried not only by the perimeter nails into the timber, but also by the straps. The loops have different shapes when hold-downs were included and while they were not as wide as those configurations without hold-downs, because of the increased loads it is assumed that the energy dissipation would be greater since there were additional nails used to attach the straps providing additional yielding. The straps themselves provide some energy dissipation but have the potential to fail suddenly at greater displacements and this was observed for some of the tests at the greatest displacement cycles. Bracing ratings for the hold-down configurations ranged between 20% to 50% greater than comparable systems having no hold-downs.

Strength and stiffness evaluations have been considered in terms of comparisons with bracing systems tested using the P21 method. These systems are known to provide adequate strength and stiffness for buildings designed using NZS 3604:2011 [4] and also to have achieved acceptable performance levels during the Canterbury earthquake sequence of 2010 and 2011 [7]. All of the systems tested exhibited non-linear behaviour from very low displacement levels and, therefore, none were considered to be elastic systems that would be able to resist load without some level of damage. At lower displacement levels this damage was hard to perceive, but it would still make a quantitative estimate of initial stiffness very difficult.

Rather than provide an extensive series of overlaid plots, which become difficult to interpret unless enlarged significantly, a summary of comparisons among the different configurations tested is provided by the following observations:

1) The structural responses of the bracing systems using SIPs were very similar between the different SIP types for configurations with and without hold-downs. This includes initial stiffness, strength and energy dissipation of the systems.
2) When comparing SIP systems with and without hold-downs, there were increases in strength with the hold-downs, but other parameters were similar regardless of the presence of hold-downs. It is noted that using hold-downs provides a level of redundancy over solely relying on the perimeter nails for resisting lateral loads. It is also important to consider that different SIP systems using different hold-down configurations may have different responses and should be considered when designing SIP bracing systems.
3) Single-sided plasterboard bracing systems with hold-downs provided slightly less initial stiffness and peak strength than SIP systems without hold-downs. The plasterboard peak applied loads were reached after the second set of displacement cycles and began dropping from there, indicating irrecoverable damage as well as reduced ductility compared to the SIP systems.
4) Double-sided plasterboard systems with hold-downs had greater stiffness and strength than SIP systems without hold-downs and greater energy dissipation. These plasterboard systems reached their peak applied loads during the third set of displacement cycles, and while they did lose load after that, the load reductions were less than the single-sided configurations and specimens were still resisting significant loads at the end of testing.
5) Double-sided plasterboard systems with hold-downs had similar stiffness and strength to SIP systems with hold-downs but slightly less energy dissipation.
6) Single-sided plywood systems with hold-downs had significantly less stiffness than either of the SIP systems and comparable strength to the SIP systems with no hold-downs. The energy dissipation of the single-sided plywood systems was slightly less than the SIP systems with no hold-downs, but greater losses were seen in the plywood systems with increased displacements, which suggested there was more damage to the surrounding timber and plywood than was present with the SIP systems. In terms of overall seismic response, the

single plywood system with hold-downs was considered similar to the SIP systems without hold-downs.

7) Combined plywood and plasterboard systems with hold-downs had much greater strength than SIP systems without hold-downs, with slightly less stiffness and similar energy dissipation. The load decreases for subsequent displacement cycles were less for the combined system than for the other plasterboard or plywood systems, but these decreases were still greater than what was observed with any of the SIP systems.
8) Combined plywood and plasterboard systems with hold-downs had slightly less stiffness, strength and energy dissipation than SIP systems with hold-downs. In terms of overall seismic response, the combined plywood and plasterboard system with hold-downs was considered similar to the SIP systems with hold-downs.
9) Single-sided fibre cement bracing systems with hold-downs provided similar strength and stiffness as SIP systems without hold-downs, but because they suffered significant damage following the fourth set of displacement cycles, the energy dissipation and ductility of these systems were reduced.
10) Single-sided fibre cement bracing systems with hold-downs provided decreased strength and stiffness compared to SIP systems with hold-downs, with significantly less energy dissipation.

The observations and comparisons made above provide an understanding of how generic SIP systems resist lateral loading, as would occur during earthquakes, through laboratory testing. While it is acknowledged that no testing protocol exactly replicates the demands of earthquakes, the methods used have been shown to adequately represent bracing systems for New Zealand and provide at least indicative measures of performance. Testing, observations during testing and subsequent analysis of data have indicated that SIP bracing systems, with and without hold-downs, exhibit the kind of seismic performance that is considered desirable for effective earthquake resistance. This includes stiffness, strength, ductility and energy dissipation. The observed damage to the SIP systems also suggests that these systems can be advantageous for instances where lower damage is desired so that a building can be reoccupied quickly following a significant seismic event.

The SIP systems tested were intentionally not designed to represent any particular manufacturer or SIP system currently being used, but rather to gain a general understanding of how these systems perform and compare with commonly used bracing systems. For specific details and structural design parameters and methods it is necessary to consult SIP manufacturer technical information which should provide test data and detailing to provide code-compliant designs. The systems tested for this study were considered conservative compared to systems being employed in New Zealand and around the world and therefore it is assumed that these results are on the lower end of what would be expected from SIP systems. It is noted that these data only consider the structural performance of SIP systems and do not address other building code clauses or requirements that would need to be considered for compliance and consenting.

Findings and Conclusions

Testing and analysis have provided data on SIP wall configurations to evaluate their structural seismic performance. Only SIPs having timber-based skins were included within this project as an initial assessment concluded that these were the most commonly used SIPs for residential applications. As a comparison, additional tests utilising bracing systems commonly used in New Zealand residential buildings were also conducted. The sections above provide qualitative comparisons that were drawn between the SIP systems performance and the seismic performance of the other systems. This was done to assess the ability of SIPs to be used in conjunction with other bracing systems used throughout New Zealand as well as to compare critical performance parameters between SIPs and more commonly understood bracing systems.

Based on the testing conducted and observations the following key messages have been developed:

- Using commonly used SIPs with timber-based panel skins, several configurations have been tested for seismic performance using the P21 test method with and without hold-downs
- Additional P21 testing was conducted on commonly used bracing systems for comparison
- These SIP systems provided suitable energy dissipation, ductility, strength and stiffness for prescriptive and specific engineered wall bracing designs
- Damage observed during cyclic loading was less for these SIPs than most of the more commonly used bracing systems
- Energy dissipation and ductility was provided through nail bending which is considered a reliable and effective method
- There were no indications that panel delamination was an issue in relation to seismic performance on the unaged specimens that were tested
- There were no significant performance differences among the different types of SIPs tested having timber-based panel skins
- Using steel straps as panel hold-downs provided increased seismic performance for SIP systems over systems with only nailed bottom plate connections
- Using SIPs in conjunction with other structural bracing systems is feasible but differences in stiffness should be minimised to limit damage and possible irregularity between bracing systems
- SIP configurations tested were intentionally not meant to replicate existing proprietary SIP systems, therefore designers will need to consult manufacturer literature for detailing and performance characteristics of specific SIP systems

References

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Current and Future Outputs

In alignment with EQC objectives around engaging with critical stakeholders such as MBIE, regional councils, manufacturers and design practitioners, this project has included extensive planning around this engagement and included a science communications plan. This plan was developed in conjunction with Nicola Little and Coen Lammers from EQC and was managed by Catherine Nicholson from BRANZ with input from David Carradine and Anna Walsh, both of whom are part of the BRANZ team working on the SIPs project. The full BRANZ project includes investigations into not only the seismic performance, but also the durability and a review of the fire performance of SIPs for use in New Zealand. In addition to the communications plan the following outputs have been generated so far:

1) One-page infographic explaining the full BRANZ project on SIPs
2) A short video featuring David Carradine explaining the P21 testing and how it relates to the seismic performance of SIP walls (https://youtu.be/Vb-K5MytKQE)
3) Article in Build Magazine describing the full BRANZ project on SIPs (Issue 180 – October/November 2020)
4) Press release on the full BRANZ project on SIPs (October 2020)
5) Second video giving an overview of full BRANZ project (including seismic, durability & fire workstreams) which won the Royal Society Te Apārangi 180 Seconds of Fascination Video Competition (October 2020)
6) BRANZ webinar aimed at practitioners and consenting officials to share the project objectives with them and also inform them around the SIPs testing conducted and how it relates to building performance (November 2020)
7) Poster presented at the QuakeCoRE Annual Meeting (December 2020)
8) Attendance by Anna Walsh at the Open Day held at a job site of NZSIP near Invercargill (April 2021)

Future engagement and dissemination around the work with the seismic performance of SIPs include the following activities:

1) Presentation at the WoodWorks conference (September 2021) on SIPs research including case studies
2) Additional video developed in collaboration with EQC that includes animations and summarising of full SIPs project (September/October 2021)
3) Potential article in the Bulletin of the New Zealand Society for Earthquake Engineering (late 2021)
4) Potential article in Build Magazine including results from full SIPs project (late 2021/early 2022)