STRUCTURAL BEHAVIOUR OF GFRP MODULAR COMPOSITE WALL SYSTEM UNDER MONOTONIC LOADING

A Thesis submitted by

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ABSTRACT

The implementation of modular construction is growing rapidly due to its high quality, quick construction, and low environmental impact. Fibre reinforced polymer (FRP) composites are becoming an effective alternative to conventional building materials because of their high strength-to-weight ratio, durability, and speed of construction. However, there is still limited understanding of the structural performance of FRP composites for the modular wall systems, especially with reference to their behaviour under different monotonic loading actions. In particular, the effects of design parameters, such as wall width, connection details, and wall openings, on the behaviour of a composite wall system have not been determined yet. This research systematically evaluated the behaviour of modular walls made from the assembly of glass FRP (GFRP) composites under axial compression, flexural load, and in-plane shear.

The first study investigated the behaviour of GFRP wall systems under axial compression to simulate the effect of service live and gravitational loads in a building. The mechanical properties and failure behaviour of the constituent materials were evaluated. Compression tests using full-scale wall panels were then implemented to evaluate the effect of sheathing type and thickness, types of connections between the sheathing and the frame, and panel width. The results showed that the behaviour of full-scale GFRP wall panels is governed by the behaviour of their constituent material. Adhesively bonded panels provided a continuous connection between sheathing and frames and performed better than the riveted panels. Moreover, a significant increase in panel stiffness and strength was achieved by extending the wall studs. The finite element (FE) analysis validates through experimental results and predicts the failure behaviour, capacity, and stiffness of a full-scale extended stud panel configuration.

Moreover, the flexural behaviour under the effect of wind loading acting perpendicularly to the surface of the modular wall system was evaluated as part of the second study. The moment capacity of the full-scale panel under a uniformly distributed load (UDL) was comparable to that of four-point (4P) load. The results showed that the loading configuration had no effect on the flexural stiffness of the wall panel, but the UDL exhibited significantly higher bending strength than the 4P load, as it eliminated the local interlaminar delamination of wall studs under the loading point. Moreover, the adhesive – rather than the riveted – connection provided higher composite action, resulting in higher flexural capacity and stiffness, whereas an inter-panel bolted connection yielded higher flexural capacity and showed more progressive failure behaviour compared to bonded wall panels. The loading direction had a significant effect on the flexural capacity and stiffness, with the panels in a

longitudinal direction exhibiting better performance than those in a transverse direction. In conclusion, the simplified equation developed, which considers the ratio of initiation of sheet buckling load and ultimate sheet delamination load, reliably predicts the flexural strength and stiffness of the composite wall panels.

The third and last study investigated the performance of composite wall panels under an in-plane shear load to simulate wind loading acting parallel to the surface of the modular wall system. For this, 6 full-scale composite wall panels with different sheathing heights, wall openings, types of angle brackets, and numbers of wall panels were tested. The wall panel with a 10 mm offset from the bottom of the sheathing performed significantly better than the wall with a full sheathing height, as it minimised the compression stress in the sheathing and avoided premature delamination failure at the bottom plate. The presence of a wall opening reduced the shear stiffness of the wall panel, with the percentage reduction directly correlating to the ratio of the wall opening area to the total wall area. The two customised angle brackets attached at the diagonal corners made the wall panel stiffer and stronger. However, it must be noted that providing brackets in all corners will not further increase the loading capacity and stiffness of the wall. The normalised loading capacity per unit width in single- and double-frame wall panels is almost similar; however, the stiffness of the single wall panel is significantly lower than that of the double wall panel.

This systematic research provides an extensive understanding of how critical parameters and different monotonic loading conditions affect the overall performance of GFRP composite wall system. Moreover, the experimental results offer useful knowledge on its capacity, stiffness, and failure behaviour that is validated and predicted by an FE analysis. Additionally, the analytical results offer simplified design equations for future researchers, designers, and engineers to effectively design and develop a load-bearing modular composite wall system to uplift the confidence of engineers in this new construction method and to adopt this innovative concept for real-world applications.

CERTIFICATION OF THESIS

I, Arvind Sharda declare that the PhD Thesis entitled “Structural behaviour of GFRP modular composite wall system under monotonic loading ” is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes. The thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

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Student and supervisors’ signatures of endorsement are held at the University.

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STATEMENT OF CONTRIBUTIONS

The articles produced from this study were a joint contribution of the authors. The details of the scientific contribution of each author are provided below:

Manuscript 1: Arvind Sharda, Allan Manalo, Wahid Ferdous, Yu Bai, Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane (2021) "Axial compression behaviour of all-composite modular wall system". Composite Structures. 2021; Vol 268:113986.
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The overall contribution of Arvind Sharda was 60% related to the design of experiments, experimental works, analysis, and interpretation of data, drafting, and revising the final submission. Allan Manalo, Wahid Ferdous, and Yu Bai contributed to the concept development, design of experiments, experimental works, analysis, and interpretation of data, editing and providing important technical inputs. Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane contributed to reviewing and editing, and providing important technical inputs.

Manuscript 2: Arvind Sharda, Allan Manalo, Wahid Ferdous, Yu Bai, Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane (2023) "Flexural behaviour of composite modular wall systems under uniformly distributed and concentrated loads". Composite Structures.2023; Vol 303:116346.
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The overall contribution of Arvind Sharda was 65% related to the design of experiments, experimental works, analysis, and interpretation of data, drafting and revising the final submission. Allan Manalo, Wahid Ferdous, and Yu Bai contributed to the concept development, design of experiments, experimental works, analysis, and interpretation of data, editing and providing important technical inputs. Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane contributed to reviewing and editing, and providing important technical inputs.

Manuscript 3: Arvind Sharda, Allan Manalo, Wahid Ferdous, Yu Bai, Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane, "In-plane shear behaviour of prefabricated modular wall system assembled of fibre reinforced polymer composites" Case Studies in Construction Materials.2023; Vol 18:e01819.
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CHAPTER 1: INTRODUCTION

1.1. Background and motivation

In Australia, the demand of construction of new housing facilities is always a greater challenge for civil contractors and developers (Manalo 2013) due to tremendous construction backlog. It is anticipated that the gap in the housing development can be minimised through modular building construction (Boyd et al. 2013) combined with new fast lean manufacturing technologies (Innella et al. 2019). The trend of modular building construction or off-site construction (OSC) has increased significantly because of high speed construction process, superior quality than conventional construction like manufacturing mass production of modules in high speed automated factory environment and lower environmental impact (Ferdous et al. 2022). Developed countries such as Sweden contributed approximately 80% of its overall construction through modular building construction and similar trend can also be seen in other European countries (Ferdous et al. 2019). Whereas, in Australia this is only limited to approximately 3-4% of total construction (Lawson et al. 2012; Ferdous et al. 2019; Navaratnam et al. 2019; Thai et al. 2020). However, modular construction is a one of the key area of interest promoted by Australian government (Navaratnam et al. 2019) to meet the demand of required dwellings.

In general, prefabricated modules are manufactured offsite in a controlled environment, transported to site, and assembled to form a building structure. Prefabricated modules can further be classified according to their material of construction such as steel building and container van (steel), precast concrete (concrete) and wooden frame (wood) (Lacey et al. 2018). The easy availability of conventional raw materials, trained labour for fabrication and installation of conventional material modular building modules and well developed construction standards are the major advantages of these technologies (Ferdous et al. 2019). However, the prefabricated modules from conventional materials have their own limitations. The high chance of corrosion, high cost of transportation per unit weight and high maintenance cost is a major challenge for steel modules (Lacey et al. 2018). In addition to the transportation cost, in-situ connection requirements, and corner damage during transportation or lifting are most common issues for concrete modules (Lacey et al. 2018; Ferdous et al. 2019). Whereas wooden modules are highly prone to biological and pest decay (Mohammadi & Ling 2017). Heavy weight of conventional modules, space limitations of transportation trucks, high maintenance cost due to the physical, environmental or biological decays are the major challenge for conventional material modular building construction. Therefore, researchers advocated that these challenges can possibly be sorted by utilising fibre reinforced polymer (FRP) composite materials, because of their high strength to weight ratio, zero corrosion, minimum maintenance, resistance to pest and biological decay (Mohammadi & Ling 2017; Sharda et al. 2021; Ferdous et al. 2022). The presence of FRP composites in constructing emergency shelters (Winandy et al. 2006), office structure (Keller et al. 2016), pedestrian bridges (Stepinac et al. 2021), beams (Shi et al. 2017) and slabs (Satasivam et al. 2014; Satasivam et al. 2018) advocates the potential to use them for modular building construction.

Similar to all building structures, prefabricated modules need to withstand dead and operational loads such as compression load due to gravitational load, above floor levels and live load, and flexural and in-plane shear loads caused by wind actions. Load bearing wall modules are commonly used to reduce the dead load in modular construction by elimination of beams and columns (Liew et al. 2019). Composite wall system is generally fabricated as structural frame and bonded sheathing (Manalo 2013) and needs to withstand dead and operational loads. Previous researchers highlighted that under compression load, the width-thickness aspect ratio (Prabha et al. 2013), thickness of sheathing material (Qin et al. 2019), type of connections between fame and sheathings (Hilo et al. 2015) and width of wall panel (Wang et al. 2014) are the important parameters that affects the overall strength and stiffness of wall panels. Lei et al. (2019) explored the application of sandwich panel under axial compression made of unidirectional glass fibre reinforced polymer (GFRP) square hollow section (SHS) and GFRP sheathing bonded or bolted together. They reported that the global buckling, sheet wrinkling and crushing of GFRP studs were main failure modes observed in sandwich panel under axial compression load. However, Manalo (2013) highlighted that local sheet buckling can also occur during axial compression load. These design parameters, therefore, should carefully be considered and investigated to understand in detail the behaviour of composite wall panel under compression load.

The applications of composite sandwich floor panels are widely explored for type of connection between frame and sheathing bolted or adhesive under three or four-point flexural loading (Satasivam & Bai 2014, 2016; Satasivam et al. 2018). Interlaminar delamination, local sheet buckling, and stress concentration at loading points causing web shear bucking in frame of sandwich panels were the most common failure modes observed under flexural loading. However, in real world application the load bearing wall system will experience the uniformly distributed load (UDL) caused by wind. Under UDL, the sandwich panel experienced inward bucking of face sheet that caused the cracking from main frame joist (Islam & Aravinthan 2010). UDL also minimise stress concentration at loading points. Hence it is very important to evaluate and compare the moment capacity of composite wall panel under UDL and point flexural load. Generally, number of wall panels are assembled to form a wall for modules. The inter-panel connection is very important for the integrity of the whole structure, therefore apart from the connection between frame and sheathing, inter-panel connection also needs further investigation.

Under in-plane load, the diagonal cracking in sheathing is a most common failure mode of composite wall system (Manalo 2013; Dhonju et al. 2017). The presence of wall openings reduces the shear resistance of wall panels (Alimohammadi et al. 2019), and also causes stress concentration at the corners of opening (Anil et al. 2016) resulting in the premature failure in composite wall panels. Zhang et al. (2022) highlighted typical failure modes of shear wall such as flexural (including up-lift), flexural-shear, diagonal tension, diagonal compression and sliding shear. Up-lift and shear sliding are typically avoided by hold-down, anchor bolts and angel brackets (Casagrande et al. 2021). In composite wall system, the limitation in the availability of these standard fittings highlighted to develop customised fittings and that need to be tested for in-plane shear load. Therefore, it is crucial to evaluate the behaviour of a modular composite wall under different load actions to design these construction systems safely and reliably. To check the structural performance and to understand behaviour of FRP composite wall system, the experimental and analytical evaluation such as compression (to simulate dead and live loads), uniform loading and in-plane shear (to simulate wind load) need to be conducted.

This thesis systematically investigated the effect of critical design parameters influencing the structural behaviour of GFRP composite wall system under different loading conditions. It focussed on evaluating the effect of important wall parameters to optimise their design. Additionally, the FE simulation and analytical analysis were developed to help designers, engineers to effectively utilised GFRP composite wall system for modular construction.

1.2. Problem statement

Growing population and unforeseen climate disasters always put a pressure on infrastructure. Australian Housing and Urban Research Institute (AHURI) reported the enormous backlog of building infrastructure in Australia (Manalo 2013). A sustainable construction material could be another challenge for civil contractors or infrastructure developers. Conventional materials such as concrete, steel and timber are widely used for conventional construction, but they are highly prone to corrosion, biological and pest decay, longer construction time and high waste generation.(Lacey et al. 2018; Ferdous et al. 2019).

Modular building construction could be an answer to this problem. Prefabricated modules are manufactured in a controlled environment, transported to site, and assembled to form a building structure to assemble them into a structure. Modular construction can increase the construction speed up to 50% higher and can reduce the construction cost by 20% than conventional construction (Bertram et al. (2019). In addition to high-speed construction GFRP could be an alternative to conventional materials because of its high strength to weight ratio, zero corrosion, minimum maintenance, resistance to pest and biological decay (Ferdous et al. 2022).

There is a significant gap in utilising GFRP as construction material for modular building construction, which can be eliminated by understanding the behaviour of full-scale GFRP structural members under different monotonic loading conditions, which is the focus of this research. It will also explore the possibilities to utilise GFRP as a load bearing wall system for modular building construction.

1.3. Objectives

The main objective of this research is to investigate the structural behaviour of modular composite wall system under axial compression, flexural and in-plane shear loading. To accomplish these objectives, the following specific objectives were identified.

1 To investigate the axial compressive behaviour of modular wall systems with different sheathing materials, stud spacing, skin thickness and connections between sheathing and the panel frame.

2 To evaluate the flexural behaviour of modular composite wall systems under uniform loading or four-point loading considering with or without sheathing, riveted or adhesive connection between frame and sheathing and inter panel bolted or adhesive connection.

3 To investigate the in-plane shear behaviour of modular composite wall systems and assembly with and without window opening, height of sheathing, different angle brackets and single or double wall panel.

1.4. Scope of research

Modular composite wall system was experimentally investigated under monotonic loading conditions including axial compression, four-point or uniformly distributed flexural load and in-plane shear. Critical parameter highlighted in section 1.1 were considered during the fabrication of wall panels. Fig-1 highlighted the summary of critical parameters studied under different loading conditions. The new findings from each experimental works were analysed and incorporated to optimise the design of GFRP composite wall system.

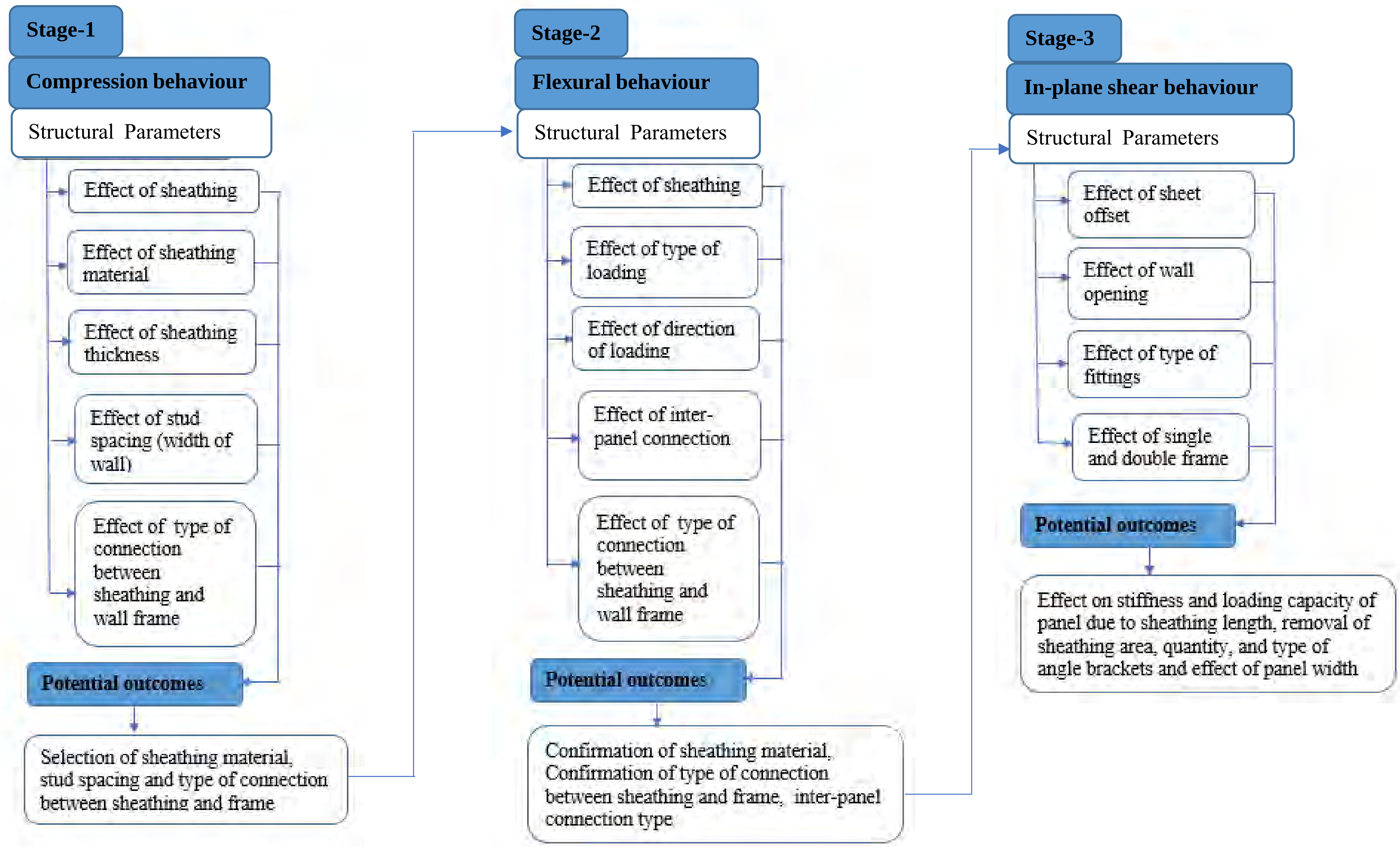


Figure 1: Critical parameter of wall panels under compression, flexural and in-plane shear load.

Multiaxial rectangular hollow section (RHS) 100mm x 75mm x 5 mm GFRP pultruded profile was used to fabricate the main frame of wall system. GFRP RHS sections were assembled by using 35 x 35 x 70 mm angle brackets to form stud and plate configuration. Under in-plane shear load, customised angle brackets were proposed to assemble wall frame and to provide additional stiffness and strength. GFRP or Fibre cement sheets were adhesively bonded or riveted to the main frame as sheathing material. M20 bolts were utilised as mechanical connection for inter-panel connections and compared with epoxy based adhesively bonded inter-panel connection. Chapter-3,4 and 5 provided the full information on the fabrication details of wall system under compression, flexural and in-plane shear load respectively.

1.5. Study limitations

This thesis investigates the structural performance of GFRP composite wall system under different loading conditions. However, there are some limitations associated to this study. Only one size of GFRP RHS pultruded profile 100mm x 75mm x 5 mm was used to fabricate the main frame of wall system, as this is the most common section available in the market. The mechanical properties of this RHS profile are established thorough coupon testing by (Hizam et al. 2019). However mechanical properties of RHS profile are also established and reported in this thesis by conducting full profile compression test in axial and lateral direction in chaper-3. The RHS profiles are manufactured and supplied by Wagners Composite Fibre Technologies and sheathing material is imported from overseas, therefore its mechanical properties are established by coupon testing and reported in this thesis.

All wall panels were considered 2400mm high by considering the general headroom clearance. Whereas width of the wall panels varied from 600 mm to 900 mm because of single or double frame configuration. One sample per parameter was tested due to the high cost of preparing large-scale testing samples and for the better understanding of experimental results various instruments such as strain gauges, digital image correlation (DIC) camera, laser or string pot for deflection and load cell were used. Abaqus finite element analysis (FEA) software package is also used to validate the test results and to predict the failure behaviour. Inter-panel bolted mechanical connections or adhesive connections were explored. However, connection between composite wall system and roof were not considered in this current research.

1.6. Novelty of research

This research is the first to investigate the structural behaviour of load bearing modular wall system made of multiaxial GFRP RHS frame assembled with mechanically or adhesively bonded GFRP or Fibre Cement sheets, tested under monotonic loading conditions such as axial compression, point, or uniformly distributed flexural and in-plane shear load. These loading conditions simulate the effect of gravitational and wind load with different critical structural parameters. This research provided new understanding on the failure behaviour of composite wall system under monotonic loads, provided a simplified FE simulation and analytical approaches that will be useful for designers, engineers and contractors to effectively design and construct modular wall systems based on FRP composites.

1.7. Thesis organisation

This research thesis is presented in the form of Thesis by Publication. It consists of six chapters and appendices. Chapter 1 is an introduction about the background and motivation to conduct study on composite modular construction, its objectives, and limitations. Chapter 2 provided a comprehensive literature review highlighting the state-of-the-art in the field, defining the challenges, opportunities, and specific research gaps, which facilitated the development of the objectives and the methodology as well as the justification of the research novelty. Then, three experimental studies were well planned and conducted with the important test results and research findings presented in Chapters 3 to 5 in the form of published journal papers. Finally, Chapter 6 concluded the main findings and significant contributions of this study with recommendations suggesting new opportunities and further research. An overview of three journal articles is shown below while the presentations of the significant outcomes in conferences are summarised in Appendix A:

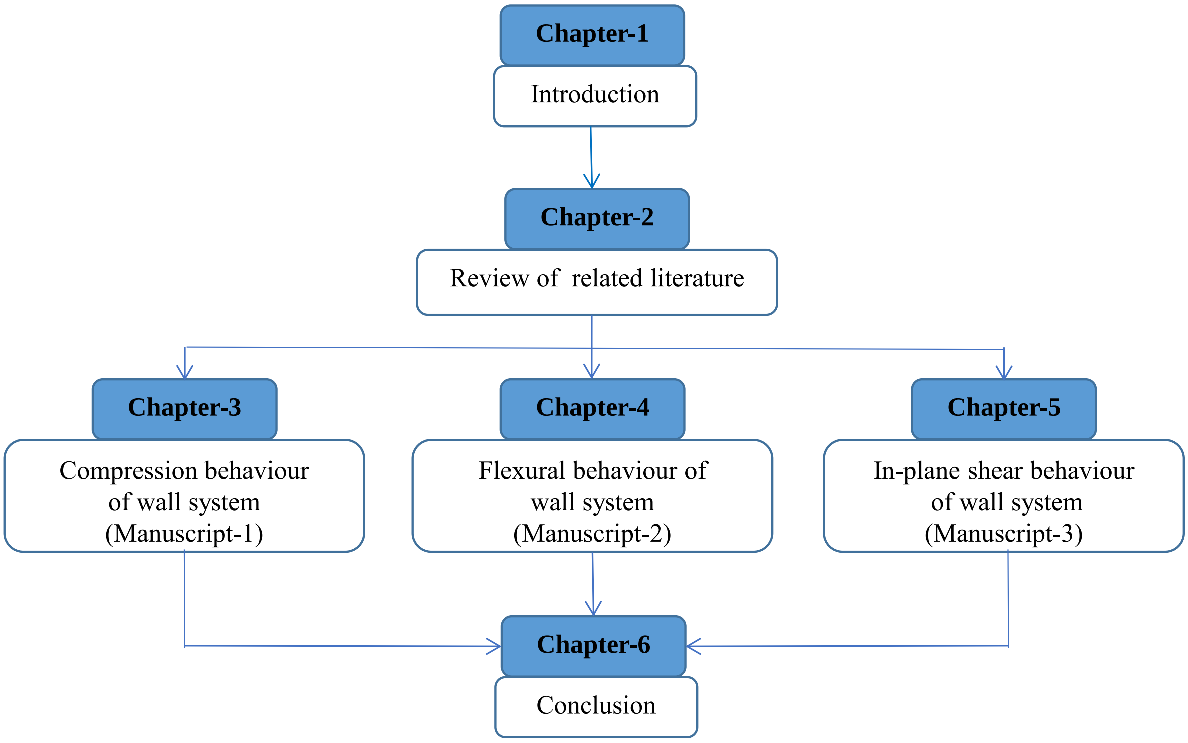


Figure 2: Organisation of thesis

MANUSCRIPT 1: Arvind Sharda, Allan Manalo, Wahid Ferdous, Yu Bai, Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane,(2021) "Axial compression behaviour of all-composite modular wall system". Composite Structures. 2021; Vol 268:113986.
DOI: https://doi.org/10.1016/j.compstruct.2021.113986

This manuscript addressed the first objective of the study to understand the behaviour of all composite wall system under axial compression load. The overall failure behaviour of wall system had similar failure behaviour of constituent material. Regardless of the panel parameters, the main failure behaviour was governed by the delamination of sheathing at top rectangular hollow section (RHS) plate because of the transverse deformation of top plate under axial compression load for extended plate configuration. To eliminate the transverse deformation of top plate, small scale extended stud panels were tested under axial compression. It was observed that extended studs panel exhibits 8 and 15 times higher overall axial stiffness and loading capacity, respectively. Finite element analysis (FEA) for full scale extended plate composite wall panel was conducted and validated through experimental results. Thereafter, FEA for full scale extended stud configuration with and without sheathing was conducted and compare with extended plate experimental results. FE analysis showed that extended studs will have at least 10 times higher panel stiffness and loading capacity than extended plate wall panels.

Candidate has more than 60 % contribution in this manuscript in terms of conceptualization, methodology, data curation, formal analysis, investigation, validation, writing – original draft.

MANUSCRIPT 2: Arvind Sharda, Allan Manalo, Wahid Ferdous, Yu Bai, Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane (2023) "Flexural behaviour of composite modular wall systems under uniformly distributed and concentrated loads". Composite Structures.2023; Vol 303:116346.
DOI: https://doi.org/10.1016/j.compstruct.2022.116346

The second objective of this research is addressed by this manuscript. The significant outcome from the first manuscript suggested to change the configuration of wall panel from extended plate to extended stud. A comparative study between frame with and without sheathing presented that the flexural stiffness of panel affected the local bucking of the top sheet. The highlighted equation helps to determine the initial sheet buckling and delamination load, thereafter, proposed buckling factor helps to determine the overall panel flexural stiffness. The moment capacity of uniformly distributed load was 2.12 times higher than four-point flexural load. The loading capacity and stiffness is lower in riveted frame and sheathing panel than adhesively bonded panel due to the slippage between frame and sheathing. Inter panel bolted and adhesive panel exhibit similar initial flexural stiffness but loading capacity of bolted panel was 1.4 times higher due to the yielding of bolts.

Candidate has more than 65 % contribution in this manuscript in terms of conceptualization, methodology, data curation, formal analysis, investigation, validation, writing – original draft.

MANUSCRIPT 3: Arvind Sharda, Allan Manalo, Wahid Ferdous, Yu Bai, Lachlan Nicol, Ali Mohammed, and Brahim Benmokrane, "In-plane shear behaviour of prefabricated modular wall system assembled of fibre reinforced polymer composites" Case Studies in Construction Materials.2023; Vol 18:e01819.
DOI: https://doi.org/10.1016/j.cscm.2022.e01819

The third objective of this research is addressed by this manuscript. The outcome of flexural loading test suggested that adhesive connection between frame and sheathing and bolted connection with two panels has high merits than riveted or bonder connection respectively. A comparative study for in-plane shear load between full sheathed panel and 10 mm offset from the bottom indicates that the loading capacity can be increased by 1.71 times by shortening the sheathing height. The reduction in shear stiffness due to the openings can be calculated by empirical equation mentioned in manuscript. Customised design of angle brackets similar to hold down helps to increase the shear stiffness and capacity by 1.52 and 1.29 times respectively.

Candidate has more than 70 % contribution in this manuscript in terms of conceptualization, methodology, data curation, formal analysis, investigation, validation, writing – original draft.

1.8. Summary

The acceptance of FRP composite in various structural applications points toward their potential use in modular building construction. However, understanding of the behaviour of composite load bearing wall under different loading condition is limited. This study systematically investigated the effect of important parameter under three monotonic loading conditions typically experienced by load bearing walls such as compression (gravitational load), flexural and in-plane shear (wind load). The panel configuration, type of sheathing material, connection between sheathing and frame, connection between panels, sheathing height, wall opening, and other important parameters are explored, and their effect are reported in Chapters 3 to 5. Understanding the structural performance of composite wall system under different loading conditions will help increase the confidence in using glass fibre polymer composites for domestic and commercial modular building construction.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a state-of-the-art review of the literature to identify the different parameters that may affect the performance of modular composite wall system under different load actions. Appendix-C discussed about the recent advancements in construction industry by modular construction. It is started with a brief overview of recent developments of modular construction around the world and its advantages over conventional construction systems. Thereafter, the applications and limitations of common construction materials such as steel, concrete and timber are reviewed and analysed. It then reviewed the potential of using fibre reinforced polymer (FRP) composites for modular building construction. Benefits of utilising FE analysis approach in predicting the failure behaviour are also reviewed and analysed. From this literature review, the gaps in current knowledge are identified to justify the novelty of this research work.

2.1 Global market and benefits of modular construction

Modular construction is a technique in which building block generally known as modules are fabricated in a factory environment and then transported to site to assemble a building structure. This technique is widely accepted in developed nations such as the United Kingdom (UK), Scandinavian countries, North America, Australia, Japan in Fig 3 and also emerging in developing nations such as China and Singapore (Ferdous et al. 2019). A report by Bertram et al. (2019) highlighted that modular construction can increase the construction speed up to 50% higher and can reduce the construction cost by 20% than conventional construction. They also anticipated that modular construction could claim up to $130B in United States (US) and European construction market by 2030. The high speed construction can be helpful to achieve the sustainable development goal by providing a quick accommodation to 100 million slum dwellers around the world (United Nations 2015) Similar comparison in terms of saving construction time and cost of modular house is highlighted by Kozlovská et al. (2014). Other benefits of modular construction are 50% lower water consumption, 70% lower impact on environment, 65% lower construction waste, 35% lower CO_2 emissions and lower embodied energy compared to conventional construction (Boyd et al. 2013; Zhang 2015; Moradibistouni et al. 2019; Tuladhar & Yin 2019). Apart from the financial and environmental benefits, modular construction can also help to improve the safety of workers, because it is more convenient to monitor and implement health and safety policies and procedures in a controlled factory environment rather than working on construction site with multiple contractors working on same time (Ferdous et al. 2022). Overall, it is observed that modular building construction is faster, economically viable, greener, and more safe than conventional construction.

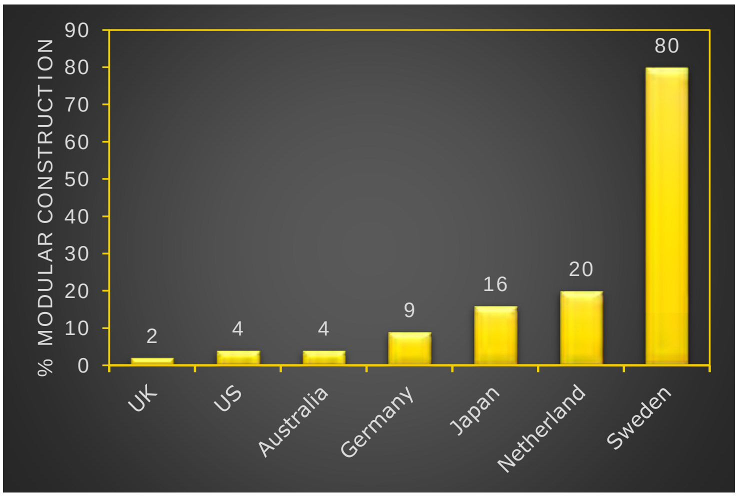


Figure 3:Percentage of modular construction in overall construction in developed countries (Steinhardt & Manley 2016)

2.2 A review of conventional material used in modular construction

Integrity of building structure depends upon the complete understanding of design standards, dead and operational loads, mechanical properties of construction material and best construction practises. Conventional materials such as steel, concrete and timber are widely used in conventional and in modular construction. (Lawson et al. 1999; Lawson & Ogden 2005; Ferdous et al. 2019; Liew et al. 2019; Howick 2022). Number of examples for modular construction using conventional material from units to multistorey buildings are highlighted by (Steinhardt & Manley 2016; Ferdous et al. 2019; Howick 2022) in Fig 4. However, modular construction mainly relies on the transportation of building modules from manufacturing facility to the construction site. Therefore, heavy weight, space limitations, brittle nature of concrete may impact the overall performance of these materials for modular construction (Ferdous et al. 2019). These limitations are reviewed systematically and discussed in the following subsections.

(a) Steel containers modular building (Howick 2020)

(b) Timber modular building (Ferdous et al. 2019)

(c) Concrete core modular building (Ferdous et al. 2019)

Figure 4:Examples of conventional material modular construction

2.2.1 Steel

Liew et al. (2019) highlighted that corner support and load bearing wall modules are the typical construction methods used for modular construction. Steel modules are generally manufactured as corner supported technique, wherein floor slabs distributed the load among structural member and then transfer through beams and columns to the foundation. Freight container (Giriunas et al. 2012), light steel frame modules (Howick 2022) are the typical existing examples of steel modular construction. Steel has high strength, stiffness, and ability to use for long and wide spans (Lawson et al. 2008; Lawson et al. 2014; Ferdous et al. 2019) and also can be assembled quickly by mechanical or welded connections. However, preventative maintenance of mechanical joints, prone to high corrosion decay, inferior thermal and acoustic insulation could be the major drawbacks of steel for modular construction (Ferdous et al. 2019; Liew et al. 2019). Especially, in Australia, where majority of population lives near to the coastal areas and structure are subjected to marine environment. An alternative material immune to corrosion will help to minimise the maintenance cost of the structure. Concrete could be one of the alterative, but it has various other limitations of modular construction highlighted in the following sections.

2.2.2 Concrete

Load bearing wall modules are generally made of concrete in modular construction. These walls eliminate beams and columns from the module to provide more room and reduce the dead load of the structure. The acoustic and thermal properties of concrete are higher than steel that make them suitable for residential purposes (Lawson et al. 2014). Additionally, concrete cover on the reinforcement acts as barrier and prevent corrosion in reinforcements (Neville 1998). However, concrete modules require on-site grouting for inter module connections, therefore curing increase construction time for concrete modular construction (Liew et al. 2019). Brittle behaviour of concrete may cause micro cracking during transportation which can initiate the corrosion in the steel reinforcements. Improper lifting can also damage corners of concrete modules that can reduce the strength of structure. Despite having superior physical properties, nevertheless heavy weight and brittle nature of concrete may limit its application of modular construction.

2.2.3 Timber

Timber is a most common construction material used for housing societies, small offices and emergency shelters in Australia, US and European countries due to its high strength and stiffness. Fire protection can also be achieved by Cross Laminated Timber (CLT) (Australia 2009) but International Code Council (ICC) and National Fire Protection Association (NFPA) recommend not to use timber as main structural member as counter measure for fire safety (Mohammadi & Ling 2017). Apart from the conventional building construction, the applications of timber can be seen in modular construction (Hausammann & Franke 2014; specifier 2014; Li et al. 2019). However, biological and micro-organisms deterioration is a biggest challenge of timber structures. Ferdous and Manalo (2014) highlighted that fungal decay is a most common problem in timber structures. Apart from environmental issues, lifting the timber modules can initiate the micro cracks (Ferdous et al. 2019) and unavailability of single bigger structural profile for beam or column also limit its application for high rise buildings.

2.2.4 Characteristics and properties of conventional materials

Hot rolled structural steel is recommended by international codes and standard for building construction (SAA 1998; BSI 2004; ASTM 2011). Australian standard AS 4100:1998 for steel structures states that the allowable yield stress in structural members under operational load shall not exceed 450 MPa and shall has more than 1.2 times ratio of tensile and yield stress (T/Y) (SAA 1998; Ban et al. 2011). Under tensile load steel exhibits elastic behaviour and deformed under yield deformation before ultimate failure at least cross-sectional area or point of stress concentration (Roger Brockenbrough & Merritt 2011). However, under compression steel tends to deform under buckling or crushing depending on the slenderness ratio of the column (Csernak & Csernak 2012). Average modulus of elasticity more than 200 GPa in structural steel grades G250-550 was reported by Mahendran (1996) highlighted the potential to utilise the steel for longer spans compare to other conventional materials. However, corrosion is the major environmental factor that reduces the strength and service life of the steel. Ferrous ions present in steel react with environmental oxygen and moisture to form ferrous oxide generally known as rust which chipped off from the base metal over the period of time (Subramanian 2008). This loss of cross-sectional area caused irregular stress distribution and stress concentration on the surface of steel that affects the structural performance (Kim et al. 2017). The reduction in tensile strength of steel can be evaluated by effective thickness of the corroded steel which is the subtraction of standard deviation from mean thickness (Kim et al. 2017; Zhang et al. 2020).

On the other hand, cold-formed steel is also used in various countries for building and housing applications due to its light weight (Rokilan & Mahendran 2020) and 50% higher yield strength than hot rolled steel (Zhang et al. 2020). Galvanised light steel sheets are generally cold pressed to form different shapes to be used for various applications such as wall panels (Mortazavi et al. 2018), beams or columns (Wong & Chung 2002) and modules of modular building structures (Veljkovic & Johansson 2006; Lawson & Ogden 2008). Light steel frames are generally drilled and chamfers for mechanical connections for quick and easy installations. However, corrosion exacerbates the cold formation effect at sharp edges that transformed the material into brittle (Zhang et al. 2020). This brittle transformation could result into the instant fracture failure in light steel rather than yield deformation prior to the ultimate failure. The annual loss due to corrosion was estimated as $276 billion dollars in the United States of America (USA) in year 2001 (Subramanian 2008). However, this significant loss of income due to corrosion can be eliminated by replacing steel with fibre composite for building construction. On an average a typical glass fibre reinforced polymer (GFRP) is five times lighter, three times higher tensile and compression strength than structural steel but has approximately 50% lower modulus of elasticity than structural steel (Roads 2014) in Table-1. GFRP also exhibits elastic behaviour but in contrary to steel, it failed instantly with explosion manner and had fibre fracture under tensile and compression load respectively (Knops 2008). However, considering appropriate factor of safety in design by constraining the operational stresses under elastic zone, immunity to corrosion and light weight for transpiration advocates to utilise GFRP for structural applications.

Table-1: Mechanical properties of construction materials (Roads 2014)

Material	Tensile Strength (MPa)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Density (Kg/m^3)
Structural Steel	300	300	200	7650
Concrete	5	50	28	2500
Timber	50	60	18	1100
Glass fibre composite ($V_f = 0.5$)	900	800	90	1300

V_f = Fibre volume fraction

Reinforced cement concrete (RCC) is a composite material generally consist of steel bars know as rebars acting as a reinforcement surrounded by concrete. The mechanical properties of rebars and concrete are significantly different from each other, hence the performance of steel concrete composite depends on their composite action. In general, concrete is used for compression applications and exhibits elastic behaviour under compression load followed by the ultimate brittle failure (Darwin et al. 2016). Whereas, under flexural load, rebars provide flexural stiffness, but failure initiated in the concrete forming vertical cracks at the bottom side affected by tensile load (Meda et al. 2012). This can be understood by the significantly low tensile strength of the concrete. The structural performance of reinforced concrete structure is highly affected by the corrosion. Corrosion caused swelling in rebars that increased the volume of rebars inside the concrete which caused tensile cracking in concrete (Coccia et al. 2016). In addition to cracking, corrosion affects the bond characteristic between rebar and concrete causing slip between steel and concrete. Various national and international concrete standards recommended to provide concrete cover around steel rebars as protection against corrosion (Beeby & Narayanan 2005; Subramanian 2008).

However, steel rebars can be replaced with GFRP rebars to eliminate the effect of corrosion. Number of studies has been conducted on utilising GFRP rebars in concrete columns (Karim et al. 2016; AlAjarmeh et al. 2019), slabs (Yang et al. 2023) and beams (Mohamed & Benmokrane 2016). Whereas, Deifalla et al. (2014) observed the larger deflection and wider cracks in GFRP reinforced beam as compared to steel reinforced beam with similar configuration. This is due to the lower modulus of elasticity of GFRP than steel highlighting the limitation of replacing steel rebars with GFRP rebars. Even though, with inferior mechanical properties than other construction materials, concrete is widely used as a main construction material due to its cheap price, high acoustic and thermal insulation and well-established design and construction standards (Ferdous et al. 2019). Presence of concrete in modular building construction can be observed in form of 9 storey residential building (Cao et al. 2015) and 25 storey student hosing (Lawson et al. 2012). However, lower strength to weight ratio, brittle behaviour raised a serious concern to utilise concrete in modular building applications.

Timber is a naturally sourced ecofriendly product exhibits high strength to stiffness ratio than structural steel and concrete. The anisotropic mechanical properties of timber depends upon the direction, moisture content, location and quantity of knots, density and annual ring width, type of timber, source location and deterioration during modifications (Johansson 2003; Ramage et al. 2017). In contrary to man made products like steel, concrete, or fibre composites, it is difficult to control the mechanical properties of timber due to its natural origin. Therefore, strength properties of timber can be estimated on basis of grading which is generally classified into visual or machine grading (Ridley-Ellis et al. 2022). The ability of grading system depends upon the accuracy of measuring characteristic properties of timber. Visual grading leads to the higher rejection rate than machine grading because of decisions were made generally on the basis of loss of strength due to the reduction in cross section area calculated by dividing the area of knot with actual cross section of timber (Stapel & van de Kuilen 2014; Kovryga et al. 2019). On the other hand, mechanical grading accurately measured the timber properties such as flexural strength, tensile strength and through series of destructive or non-destructive tests (Viguier et al. 2015; Bukauskas et al. 2019).

Mechanical properties can be enhanced through processing the timber through different techniques mentioned in Fig-5. Cross laminated timber (CLT) is widely used and recommended by various researcher, but the major issue with CLT is the poor connection performance (Frühwald et al. 2007), typically with dowel-type fasteners (Brandner et al. 2016) and that could be challenge for modular building construction. Additionally, environmental, biological and microbial degradation could be an another challenge for timber construction causing approximately $22 billion dollar annual loss worldwide (Wang et al. 2018). Therefore, uncontrolled mechanical properties and easy degradability suggests exploring other material options which could overcome these limitations.

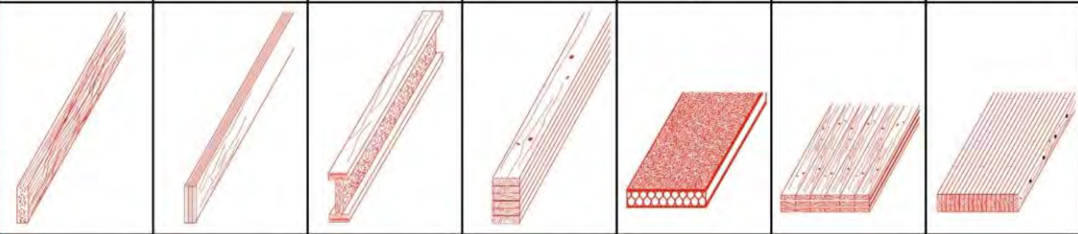
Engineered Timber Product	Parallel Strand Lumber (PSL)	Laminated Veneer Lumber (LVL)	I-Joist	Glulam	Structural Insulating Panel (SIP)	Cross Laminated Timber (CLT)	Brettstappel
Typical Detail							
Application	• Beams • Columns	• Beam • Columns • Cord	• Joist • Beam	• Beam (Long span) • High Loading	• Roof • Wall • Floor	• Roof • Wall • Floor	• Roof • Wall • Floor
Usage	Interior	Interior	Interior	Interior / Exterior	Interior	Interior/ Exterior	Interior/ Exterior

Fig 5: Engineered timber products (Ramage et al. 2017)

Overall, conventional materials exhibit high strength, easy availability and well developed construction procedures. However, high corrosion, heavy weight, environmental degradation and high maintenance cost limits their applications to modular construction. It is believed that these issues can be resolved by using FRP composites in modular construction.

2.3 Fibre reinforced polymer composites for modular construction

Fibre reinforced polymer (FRP) composite material has high strength to weight ratio, immunity from corrosion and pest decay (Kollar & Springer 2003; Sikarwar et al. 2014; Manalo et al. 2016; Barbero 2017; Al-saadi et al. 2019; Ferdous et al. 2019). Manufacturing of fibre composites can be done by various process such as pultrusion, resin transfer molding (RTM) and vacuum assisted resin transfer molding (VARTM) (Barbero 2017). Pultrusion is a manufacturing process that can produce any specific length of structural profiles with fixed cross section and also has low impact on environment (Halliwell 2010). The manufacturing of FRP composites in a controlled environment help to achieve high quality, strength, and stiffness. The applications of FRP composites for structural member are widely explored for slabs and floor (Satasivam et al. 2014; Garrido et al. 2015; Satasivam et al. 2018; Zhu et al. 2018), beams (Manalo et al. 2010; Shi et al. 2017; McCracken & Sadeghian 2018), decks and bridges (Zi et al. 2008; Keller et al. 2013; Osei-Antwi et al. 2014). Load bearing wall module is a most appropriate configuration for composite wall system, therefore these walls need to withstand all structural loads mentioned in Fig 6. All gravitational loads cause compression load on the wall system, whereas wind causes uniformly distributed load (UDL) and in-plane shear load on the wall parallel to wind direction.

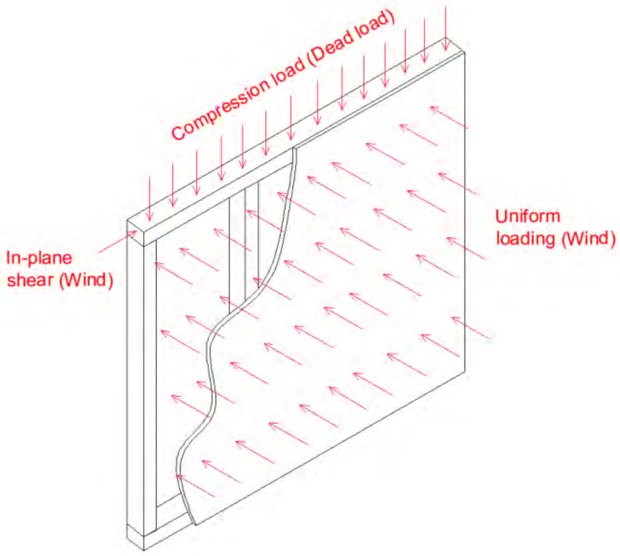


Figure 6:Typical loads acting on load bearing wall system

A typical wall panel assembly is consist of main frame and sheathing material, wherein frame is generally assembled as top and bottom plates supported by vertical studs (Manalo 2013). Frame and sheathing are generally assembled by adhesive or bolted connections and these connections are also meant to distribute dead and operational loads among all structural members (Satasivam & Bai 2014; Satasivam et al. 2014; Satasivam & Bai 2016; Satasivam et al. 2018). A typical failure modes under compression load are interlaminar delamination in sheathing, de-bonding between frame and sheathing, crushing of studs at load points and global buckling as reported by (Mousa & Uddin 2012; Lei et al. 2019) due to the low elastic modulus and shear strength of FRP composites. Mechanical connections are widely accepted in conventional construction methods due to quick assembly, however these connections create high stress concentration and cause pre-mature failures such as sheet shear, hole elongations and crushing (Cao et al. 2020). These failures are typically eliminated though bonded connections but adhesively bonded connection has a potential to failed instantaneously in a brittle fracture (Lei et al. 2019).

The applications of FRP composites are also explored for repair and strength enhancement of existing walls (Marcari et al. 2007; Del Zoppo et al. 2019), shear walls (Husain et al. 2019), concrete columns (Mohammed et al. 2020; Otoom et al. 2022). These studies suggested that FRP composites can improve the compression, flexural and shear resistance of existing structure. Diagonal cracking in sheathing is most observed failure under in-plane shear load (Marcari et al. 2007; Manalo 2013; Del Zoppo et al. 2019; Husain et al. 2019). Overall, past research indicates that fibre composites tend to deform under local failure, but significant strength and stiffness gain was also observed. In addition to mechanical properties, immunity from environmental and biological decays highly advocate to explore the opportunity to utilise fibre composites for modular building construction. However, in Fig-4 modular composite wall system should withstand all loading conditions. The overall strength and stiffness highly depend on number of parameters reviewed and analysed in the following sections.

2.4 Design parameters for load bearing composite modular wall system

Lei et al. (2019) highlighted that thin wall sandwich composite panels are highly prone to global bucking due to lower stiffness of FRP composites than steel. Number of research in section 2.3 highlighted local failure experienced by fibre composite sandwich panels. Therefore, for load bearing modular composite wall system should be further studied for its performance under different design parameters. The following sections reviewed and analysed the effect of important parameters for wall system.

2.4.1 Effect of connections

The connections between frame and sheathing are important for the overall strength and stiffness of FRP composite structure. Premature failures such as de-bonding of adhesive, interlaminar delamination, sheet wrinkling and local buckling reduce the overall efficiency of whole structure under load. These typical failure behaviours are observed in previous sandwich panel studies under flexure (Satasivam & Bai 2014; Satasivam et al. 2014; Satasivam & Bai 2016; Satasivam et al. 2018). They also observed that adhesive connection exhibits full composite action, whereas bolted connection provides partial composite behaviour because of the slip between frame and sheathing hence reduced the panel flexural stiffness of bolted panel (Satasivam et al. 2018). However, load carrying capacity in both adhesive and bolted panels was observed similar but different failure modes such as web flange shear in square hollow section (SHS) pultruded profile with inter laminar delamination in sheathing and local buckling followed by bolt pull out was observed respectively. Similar behaviour under axial compression load was observed by Lei et al. (2019), where debonding and delamination of sheathing have been observed in adhesive panel and local sheet buckling between two adjacent bolts was observed in bolted panel. However, ultimate loading capacity was observed similar in both cases. In both loading conditions, the failure is initiated by the sheathing which indicate the significance of sheathing material properties. Thus, the behaviour of wall panels may be enhanced by choosing multiaxial than uniaxial FRP composite sheathing. (Vedernikov et al. 2020) further highlighted that wall systems need to withstand with axial and transverse loads so multiaxial sheathing is more appropriate to withstand combined loading conditions.

The integrity of modular building structure depends upon the interlocking of modules. These modules are fabricated by assembling number of wall panels wherein inter panel connection are subject to structural static and dynamic load. Sturdy connection should transfer the load among structural members and various examples of interconnections include tie plate, side plate, shear rod for steel structures (Sanches et al. 2018; Lacey, Chen, Hao Bi 2019; Lacey, Chen, Hao, Bi, et al. 2019). Whereas lap joint is the most common practice to join FRP slabs or bridges (Reising et al. 2004; Manalo et al. 2016; Ferdous et al. 2019). In timber wall system angle brackets, nail plates, joist hangers, and metal straps attached to frame and sheathing by wooden nails are most common connections types (Pozza et al. 2014; Casagrande et al. 2021). However, hold downs and anchor bolts are widely used to connect wooden panel to the ground. These typical connections are widely explored and accepted in the construction industry. However, there exist a knowledge gap on the performance and suitability of these connection details for composite wall systems. Apart from the connections, physical dimensions of the wall system also play an import role while designing load bearing wall system. Therefore, the effect of panel width on wall performance is reviewed and analysed in the next section.

2.4.2 Effect of wall panel width and sheet thickness

Physical dimensions especially the width is an important parameter of load bearing wall system, which is related to the height to width aspect ratio. This parameter is very important for the shear resistance of a wall under in-plane shear. Salenikovich and Dolan (2003) found that the wall systems having aspect ratio less than 2:1 are equally stiff per unit width but the walls with aspect ratio of 4:1 have significantly lower stiffness because of higher deflection due to the rigid body rotation. On the other hand, higher panel width induces local bucking in sheathing under compression due to the high width- thickness ratio of sheathing (Prabha et al. 2013; Xie et al. 2018). The out-of-plane compression buckling and crack formation between sheathing plies was also observed by other researchers (Manalo 2013; Yang et al. 2016). However, Lei et al. (2019) found a minor variation in ultimate failure load between 300 mm and 400 mm wide composite panels under compression load. This is due to the wider panel may experience local sheet buckling under flexural loading that may impact the panel stiffness of strength. Therefore, the impact of panel width into the behaviour of a modular composite wall system needs further investigation.

Sheathing in sandwich panels provide structural stability by distributing the load to all structural members also providing additional axial, flexural and shear stiffness and improved the loading capacity of wall system. Qin et al. (2019) highlighted that increasing the thickness of sheathing increase the buckling stress level and improved the overall panel stiffness. Similar phenomenon was also observed by (Yang et al. 2016) in steel-concrete sandwich wall system and by Lei et al. (2019) for composite wall panel. Therefore, the effect of aspect ratio of wall height-width and width-sheathing thickness plays an important role in the overall strength and stiffness of wall system. Apart from the physical parameters such as type of connections, height, width and sheathing thickness, the behaviour of wall system under real world loading conditions is very necessary. Therefore, the effect of loading type on wall performance is reviewed and analysed in the next sub-section.

2.4.3 Effect of type of loading

In real word application, components of building structures are subject to compression, flexural and in-plane shear load as shown in Fig 4. A number of studies has been conducted on sandwich panels made of steel, concrete, timber, hybrid, or fibre composites as presented in previous sections. But there is still a significant gap to understand the behaviour of composite wall system under uniformly distributed load (UDL) caused by wind loading acting normal to the surface of the wall panels. ASTM E72-05 (International 2005) standard provides guidelines for strength test of panels used for building construction. Islam and Aravinthan (2010) conducted UDL test on fibre composite sandwich panel wherein they found that UDL caused inward deflection on the sheathing, which is in contrast to local sheet bucking induced by point load flexural tests as reported by (Satasivam et al. 2018). The inward deflection of sheathing under UDL caused buckling in the joist and cracking. The behaviour of composite wall system under UDL therefore warrants investigation. Apart from the experimental analysis of composite wall system, FE (Finite element) analysis can be implemented to simulate and predict the failure behaviour and capacity of wall system. This technique is well established and adopted by civil designers and engineer all around the globe especially for different materials and structures to minimise if not eliminate the cost of expensive testing. Therefore, the role of FE analysis in the analysis of the behaviour of composite wall systems will be discussed in the next section.

2.5 Finite element analysis of fibre composites

FE analysis is commonly used method to analyse and understand the failure behaviour of structural elements in detail. Moreover, it is not economical and extremely difficult to conduct a destructive test for modular structure in real life. Most common FE packages used by researchers for structural analysis are Abaqus, Strand7 and Ansys (Al-saadi et al. 2019;

Mohammed et al. 2020; Yu et al. 2022). A study simulate the progressive failure of multi-storey building to understand the effect of connection stiffness, number of bracing and provided the recommendations to use corner posts to re-distribute the load in entire structure (Luo et al. 2019). Environmental factors such as fire, seismic loading and different load cases can also be simulated through FE analysis (Lu et al. 2013; Lu et al. 2017; Suwondo et al. 2018; Belostotsky et al. 2019; Suwondo et al. 2019). Whereas, Mohammed et al. (2020), simulate the behaviour of composite jacket wrapped around the concrete column and predicted the failure behaviour of whole structure. Similarly, Lei et al. (2019) also simulate the behaviour of composite sandwich panel to predict the axial stiffness. Number of research has been carried around mostly about conventional material structures but there is still a gap for composite wall system. The extensive research on literature indicates that it is extremely important to conduct experimental studies on load bearing composite wall system made of multi-axial frame and sheathed material under compression, uniformly distributed load, and in-plane shear load. FE analysis is also required to validate and predict the results.

2.6 Research gap

The detailed review of literature highlighted that that there is limited information and available studies that evaluated the effect of type of connection between frame and sheathing and inter-panel connections, panel width, sheathing thickness, and material. Additionally, there is a limited information on the behaviour of all FRP composite wall system under axial compression load, uniform distributed load and in-plane shear load. This research will scientifically investigate the behaviour of FRP composite wall system under the different load actions through experiment, analytical and FE simulations. The literature review provided a good information regarding the current research gaps in the composite wall panels:

- Unidirectional pultruded square hollow sections with GFRP sheathing are mainly used for composite sandwich panels. Rectangular hollow section offers more space for thermal or acoustic insulation, piping and electrical conduits. Further, fibre cement sheathing is weatherproof, offer high resistance to water and fire. A combination of these materials can potentially be a good alternative of wall panels for modular construction.
- Axial compression behaviour of wall system from conventional materials like concrete, steel and timber is well explored while investigation on the behaviour of all FRP composites wall systems is very limited.

- The flexural behaviour of FRP composite wall system under point loading is investigated by a few researchers. However, wall systems under wind actions are subject to uniform load. The behaviour of composite wall systems under this loading condition warrants investigation.
- There is a huge knowledge gap in understanding the behaviour of FRP composite wall panels under in-plane shear load. The effect of important design parameters in the in-plane shear behaviour of composite wall systems needs to be investigated.

CHAPTER 3: COMPRESSION BEHAVIOUR OF COMPOSITE WALL SYSTEM

Chapter 2 presented the evolution of the modular building construction around the globe. This chapter also highlighted the benefits and limitations of conventional construction materials used for modular construction, and the high potential of glass fibre reinforced polymer (GFRP) composites. Manuscript 1 in Chapter 3 addressed the first objective of the research by investigating the performance of all composite wall system for modular building construction under axial compression load. Along with the material characterisation of constituent materials, seven full scale (2400 mm high) made of GFRP rectangular hollow section (RHS) extended top and bottom plate supported with studs are fabricated. GFRP sheathing (6.5mm thick) is adhesively bonded to three wall panels with different panel width such as 300 mm, 450mm and 600 mm to investigate the effect of panel width. Whereas one 600mm wide panel is assembled with riveted GFRP boards to evaluate the effect of type of sheathing connection. Moreover, the effect of sheathing thickness and absence of GFRP sheathing was evaluated. The experimental results are presented in terms of load deflection behaviour, loading capacity, panel axial stiffness, failure behaviour and load strain behaviour. FE analysis is then conducted and validated from full scale experimental results and to predict failure behaviour of full-scale wall panels with extended studs.

The experimental tests indicate that the behaviour of full-scale GFRP wall panels is governed by the behaviour of their constituents' material. The walls with extended plates failed at the web-junction of the GFRP RHS profile. The presence of GFRP sheathing significantly improved the loading capacity and stiffness of the wall panel with the panel width has no effect on panel stiffness. Adhesively bonded sheathing to the GFRP RHS profile provided continuous connection between sheathing and performed better than riveted panel. Moreover, a significant increase of 8 and 15 times in panel stiffness and strength can be achieved by extending the RHS studs. The FE analysis further confirmed the benefits of extending stud to the wall panel. The behaviour of optimal panel design in compression is investigated under flexural and in-plane shear loads, and the significant findings are presented in Chapters 4 and 5.

CHAPTER 4: FLEXURAL BEHAVIOUR OF COMPOSITE WALL SYSTEM

Chapter 2 identified the importance of testing load bearing composite wall system in various loading conditions and analysing the effect of important wall parameters. Chapter 3 demonstrated that the benefits of extended stud configuration to improve the strength and stiffness of composite wall system under axial compression. In this chapter, the second research objective is addressed by investigating the performance of eight composite wall panel under different flexural loading conditions, and the significant findings are reported in Manuscript 2. Two panels (2400mm x 600mm) were analysed under four-point (4P) flexural load with and without sheathing. Panels with adhesively bonded GFRP sheathing are tested under uniformly distributed load (UDL) and 4P loading conditions. Another two panels (2400mm x 600mm) with either riveted or bonded GFRP sheathing are tested under UDL. Two adhesively bonded GFRP sheathed double wall panels (2400mm x 450mm) assembled with M12 bolts or adhesively bonded together are tested for point load at inter panel joint location in longitudinal and transverse directions. The experimental results are discussed in terms of strength, flexural stiffness, and failure behaviour. Analytical equation is introduced to describe the loss of flexural stiffness in sheathing wall panel and loading capacity.

The experimental results showed that sheathing significantly enhanced the flexural stiffness and loading capacity of wall panel. However, local bucking at very low 4P load on the top sheet reduced the overall panel stiffness and with the behaviour is reliably predicted by applying a local bucking factor to the sheathing material stiffness. The loading capacity of panel under UDL is significantly higher than 4P load due to the local interlaminar delamination of RHS studs under loading point. Similar to axial compression load, riveted sheathing panel has lower loading capacity and flexural stiffness than panel with adhesively bonded sheets due to partial composite action. Bolted inter-panel connection is 1.4 times stronger than adhesive and exhibited pseudo ductile failure behaviour. Finally, the capacity and stiffness of panel in longitudinal direction is significantly higher than transverse direction. Additional FE results are highlighted in Appendix-C. Investigation onto its behaviour under in-plane shear is presented in Chapter 5.

CHAPTER 5: IN-PLANE SHEAR BEHAVIOUR OF COMPOSITE WALL SYSTEM

Chapter 3 showed that the panel configuration, type of material and their physical properties have significant effect on the performance of wall panel under axial compression. Chapter 4 showed the importance of connection type between the frame and sheathing, and the inter-panel connection hon the flexural behaviour of composite wall system. In this chapter, the final objective of this research is achieved by investigating the performance of wall panel under in-plane shear load. As presented in manuscript 3, six full scale composite wall panels (2400mm x 600mm) similar to those tested in Chapters 3 and 4 are tested under in-plane shear load to evaluate the effect of sheathing height offset, wall opening, type of angle brackets and number of wall panels. The experimental results are discussed in terms of strength, shear stiffness and failure behaviour. Moreover, analytical calculations are presented to demonstrate effect of various parameters on panel stiffness and strength.

The results showed that 10 mm offset from the bottom of the GFRP sheathing significantly increased the loading capacity as it changed the failure behaviour from inter laminar delamination to transverse splitting of bottom GFRP rectangular hollow section (RHS) plate. The presence of wall opening reduce the shear stiffness of the wall panel, with the percentage reduction directly correlated to the ratio of area of the wall opening to the total area of wall. The two customised angle brackets attached at the diagonal corners made the wall panel stiffer and stronger but providing brackets in all corners will not increase further the loading capacity and stiffness. The normalised loading capacity per unit width in single and double frame wall panel is almost similar, however stiffness of single wall panel is significantly lower than double wall panel due the higher 4:1 height to width aspect ratio. Additional FE results are highlighted in Appendix-C. The overall knowledge gained by experimentally testing the composite wall panels under different loading conditions, FE validation and prediction and analytical analysis is highlighted in the following Chapter 6. This chapter also provided recommendations for further studies to have a complete understanding on the structural behaviour of composite wall systems under combined loading conditions.

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Case study

In-plane shear behaviour of prefabricated modular wall system assembled of fibre reinforced polymer composites

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ABSTRACT

Fibre reinforced polymer (FRP) composites could be an alternative of traditional materials for modular construction due to their superior strength to weight ratio, corrosion resistance and immunity from biological degradation. This paper investigates the in-plane shearing behaviour of full-scale modular wall system made from all glass FRP (GFRP) rectangular hollow section (RHS) frames and GFRP sheathing. Monotonic in-plane shear load was applied to understand the effect of important parameters such as sheathing height offset from bottom of wall panel, wall opening, customised angle brackets for additional shear resistance, and comparison between single and double frame wall system. The results show that the wall panel with 10 mm sheathing offset from bottom deformed under shear and avoided high compression stress with significant higher loading capacity than panel with full sheathing. The stiffness of wall panel with opening can be estimated from the wall opening ratio of opening to total wall area. Furthermore, the installation of customised angle brackets can improve the loading capacity and stiffness of the wall panel. Finally, high height-to-width panel aspect ratio increased the loading capacity but reduced the overall panel stiffness in both single and double wall panels. Overall, this study presented that the structural parameters alter the ultimate failure modes which increased the overall loading capacity and impacted the panel stiffness.

1. Introduction

Modular construction is increasingly adopted in industry nowadays, with a few major benefits of high quality, quick construction, and lower cost of construction over traditional on-site constructions [1–5]. Ferdous et al. [1] presented a number of examples of modular systems for two- to 44-storeys high buildings, wherein timber, steel, concrete and their hybrid materials are used as

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Table 1
Mechanical properties of the GFRP sheeting and M20 Bolts.

Properties	Test Standard	GFRP Sheet		RHS Profile [37]		M20 Bolts [37]
		Avg. Value	Avg. SD	Avg. Value	Avg. SD	Avg. Value
Longitudinal tensile strength (MPa)	ISO 527–1:1995 [38]	568	1.9	686	44.2	-
Longitudinal tensile elastic modulus (GPa)		33.8	1.9	42.9	2.2	-
Longitudinal Poisson's ratio		0.27	0.01	0.30	0.02	-
Transverse tensile strength (MPa)		42	1.2	47	3.9	-
Transverse tensile elastic modulus (GPa)		11.7	0.3	12.1	1.1	-
Transverse Poisson ratio		0.13	0.03	0.15	0.07	-
Longitudinal flexural strength (MPa)	ISO 14125:199 [39]	689	0.4	-	-	-
Longitudinal flexural elastic modulus (GPa)		26.4	1.1	-	-	-
Transverse flexural strength (MPa)		61	2.1	-	-	-
Transverse flexural elastic modulus (GPa)		9.1	0.1	-	-	-
In-plane shear strength (MPa)	ASTM D5379:1993 [40]	69	2.5	89	14.6	-
Longitudinal interlaminar shear strength (MPa)	ASTM D2344–16 [41]	37	0.9	-	-	-
Transverse interlaminar shear strength (MPa)		9	0.6	-	-	-
Minimum tensile strength (MPa)	Property class: 8.8, M20, Pitch 2.5 mm, Minor diameter 19.67 mm	-	-	-	-	830
Proof strength (MPa)		-	-	-	-	600
Minimum yield strength (MPa)		-	-	-	-	660
Minimum shear strength (MPa)		-	-	-	-	514.6

construction material. Whereas, researchers proposed to utilise the glass fibre reinforced polymer (GFRP) composites over the conventional construction material due to the superior physical properties such as high strength to weight ratio, immunity to corrosion, immunity to pest decay and biological decay [6,7]. The applications of GFRP as reinforcement in concrete [8,9], strengthening of masonry walls [10,11] and repairing of existing structures [12,13] are widely investigated. In building construction, walls may be subjected to compression, bending and in-plane shear load for example caused by dead load and wind. While the applications of GFRP panels under axial compression [14,15] and flexural loading are explored in literature [16–19], the effect of in-plane shear load on all composite wall panels is not well understood and requires more investigations for their potential and safe application.

The behaviour of modular composite wall systems under in-plane shear was studied in [20], where adhesively bonded frames were developed for in-plane shear load, with full length sheathing composite panel connected from bottom plate or full height tie down bolts. It was found that the failure was initiated by the diagonal cracking in magnesium oxide (MgO) board in both panels. Under shear load, the far side of panel sheathing experienced compression load due to the ground contact. This phenomenon may intensify the stress in sheathing to cause earlier cracking in sheathing. Similar phenomenon may cause the earlier fastener bending and fastener pull off under in plane shear load for timber walls [21–23], tearing thin plate around fasteners [24] and local sheet buckling near to compression stud in steel concrete walls [25–27]. This type of failure can be avoided by shortening the length of sheathing from the bottom in composite shear wall. It is important therefore to understand the effect of sheathing height offset from the bottom of wall panel under in-plane shear load.

Wall openings are found as an important feature in building structures and also reduces the stiffness and introduces stress concentration at edges [28]. A number of studies has been conducted on in-plane shear behaviour on traditional wall panels with openings, where it is reported that inclined shear cracking at corner is a common failure behaviour in timber [29,30] and concrete [31,32] shear walls due to high stress concentration at opening corners. However, Husain [33] mentioned that use of fibre composites in retrofitting at wall openings helps to increase the loading capacity of the wall panel but has a minor effect on the wall stiffness. Very few studies were conducted for in-plane shear behaviour on composite wall systems manufactured by full pultruded panel section [34]. This can limit the development of such composite wall system for modular construction. Therefore, wall systems made of assembly of multiaxial pultruded GFRP rectangular hollow section (RHS) adhesively bonded to GFRP sheathing may be of interest and their performances under in-plane shear load with and without wall openings need to be understood.

In modular structures, connections between structural members ensure the overall structural integrity. Several studies have been conducted on the connections between composite frame and sheathing [14–18,35] and their failure mechanisms are explored. Under in-plane shear loading, however, the connection between composite wall frame members and connection between frame with other module or ground is very important. Angle brackets [36] and hold-down [30] are commonly used to resist shearing and uplift during in-plane loading respectively for timber shear walls. Application of nails in wooden wall panels also ease the fabrication and installation of angel brackets and hold downs. In all composite wall panels, however, nail application is difficult to implement and therefore angle brackets and hold downs are usually riveted with the frame member. In a previous study of all composite wall panels [14] under axial compression, it was highlighted that failure was mainly governed by the delamination of sheathing and had a minimal or negligible effect on riveted angle brackets because overall load was carried by the frame and sheathing. This indicates the potential

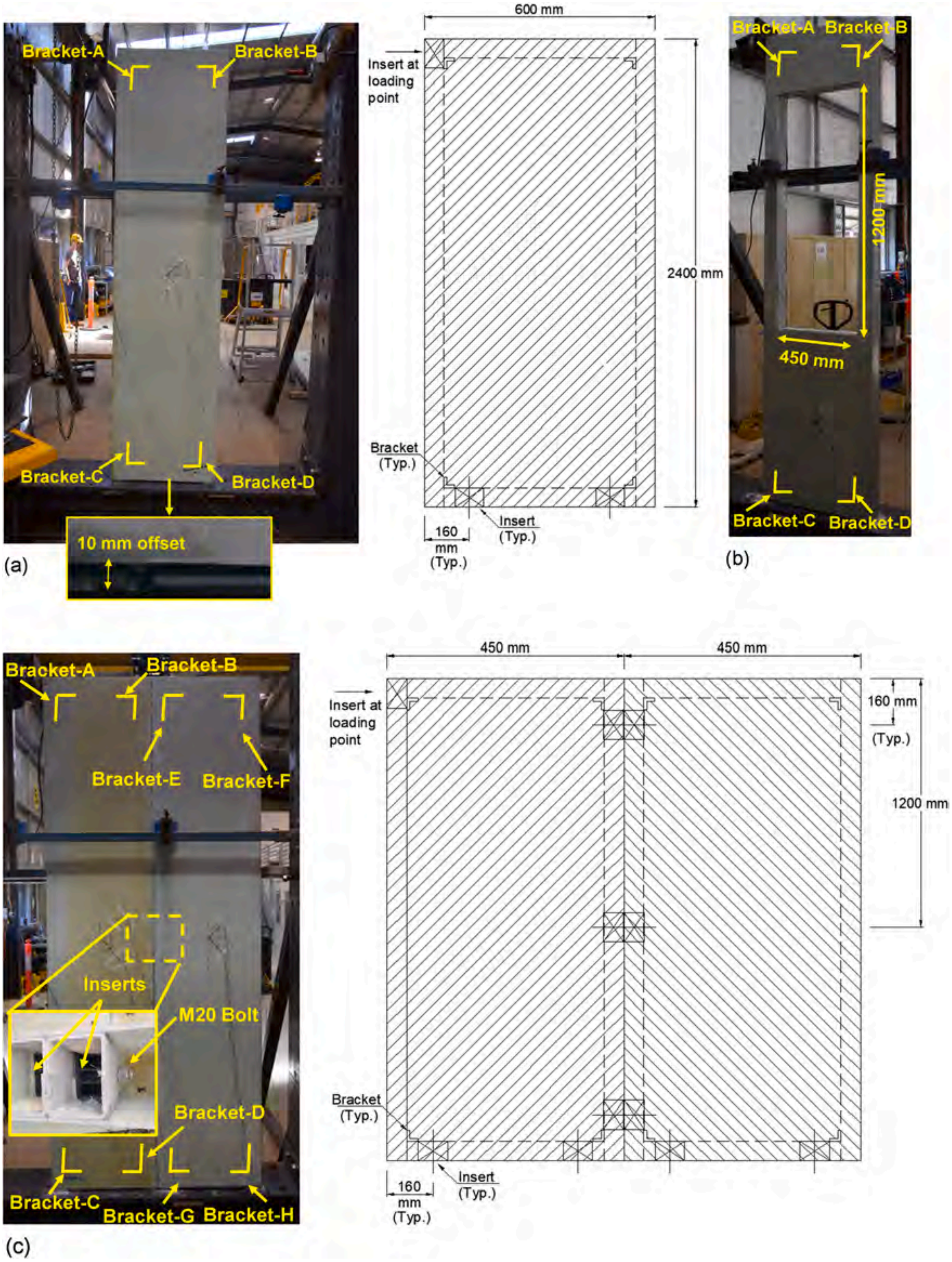


Fig. 1. (a) Single frame (b) Panel with opening (c) Double wall frame.

usage of riveted angle bracket for composite wall system under compression. The applications of riveted angle brackets and hold-down under in-plane shear load are however not explored for shear resistance and therefore further investigation is required. Manalo [20] tested a double frame composite wall panels connected with shear key that helps to transfer the load from one panel to another, hence double frame achieved twice stiffness and loading capacity of single frame. In addition, bolted joints are convenient to join two wall

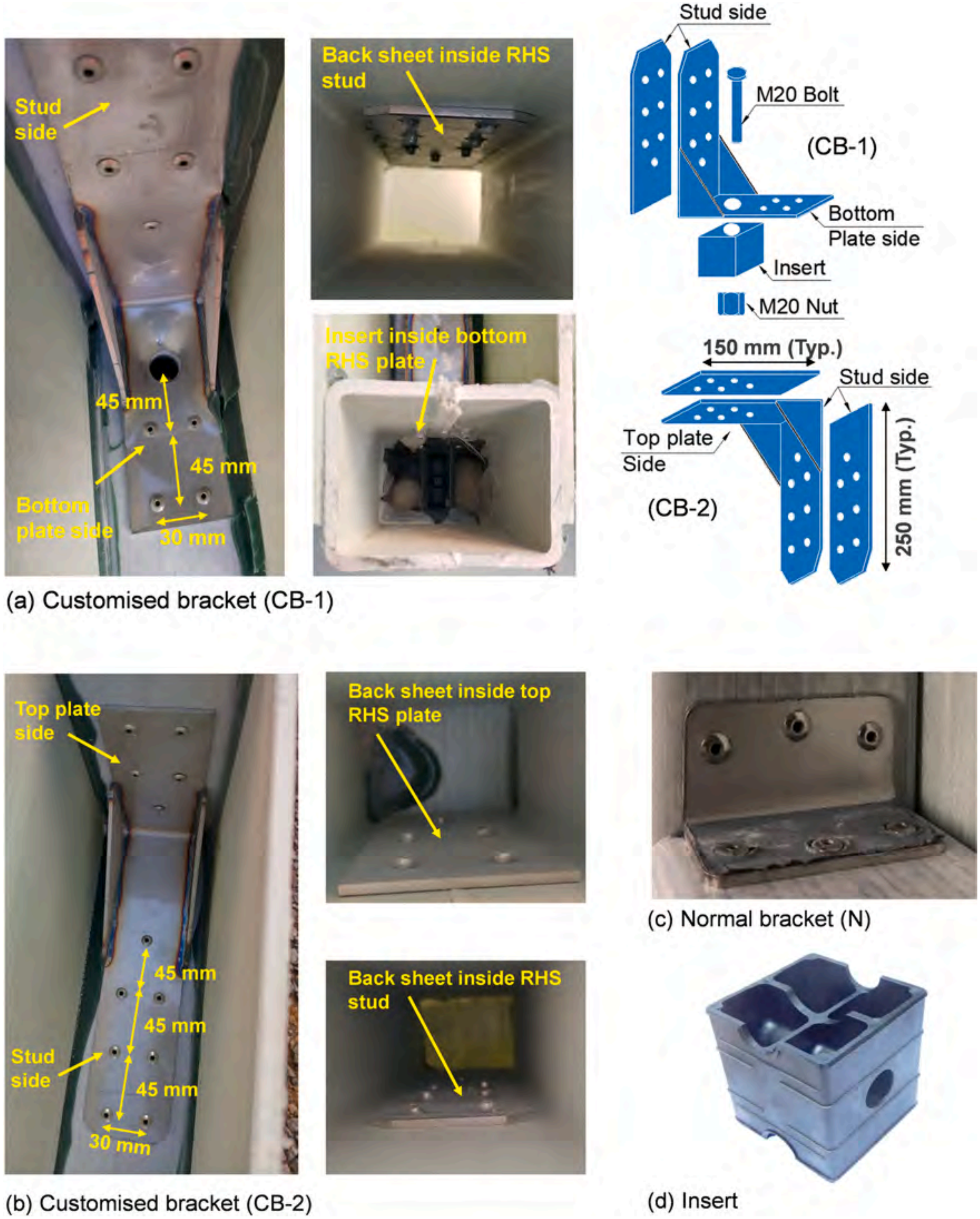


Fig. 2. (a), (b) and (c) Details of angle brackets used in composite wall panels (d) Anti-crush insert [43].

panels together but their performance and behaviour under in-plane shear load needs to be investigated.

In this study, GFRP composite wall panels were manufactured and tested under in-plane shear load. The novelty of this study is that it analyses the behaviour of key design parameters, such as effect of sheathing height from the bottom of wall panel, effect of wall opening in composite wall, effect of angle brackets and comparison of single and double frame composite wall under in-plane shear load. The results of this study may provide a better understanding of in-plane shear behaviour of modular composite wall systems with these key parameters for their reliable design and application.

2. Experimental programme

2.1. Materials

A pultruded GFRP rectangular hollow section (RHS) of 100 × 75 × 5 mm was used to fabricate the main frame of the wall panels. The material properties of the RHS profile were taken from past research [37] where the same materials were evaluated as used in this study, and are listed in Table 1. Multiaxial 6 mm thick GFRP sheet was used on both sides as a sheathing for all the wall panels. The relevant ASTM and ISO test standards using coupon specimens were followed to evaluate the mechanical properties of the sheathing material and are summarised with standard deviation (SD) in Table 1.

2.2. Specimen details

Six full-scale wall panels were fabricated by industrial partner to maintain high quality fabrication and tested under in-plane shear. Stainless-steel (SS) angle brackets measuring 35 × 35 × 70 mm were used to connect the RHS studs and plates to form a main frame for the panels; the sheathing was adhesively bonded to the frames similar to that in Fig. 1(a) and in [14]. All wall panels were 2400 mm in height and single frame panels were 600 mm wide. One panel with window opening 450 mm x 1200 mm was fabricated to compare with full sheathed panel in Fig. 1(b). Two 450 mm wide single-frame panels were connected with M20 bolts to fabricate the double-frame wall panels shown in Fig. 1(c). Customised angle brackets in Fig. 2(a) and (b) are used in three wall panels as in Table 2. Inserts in Fig. 2(d) were provided at loading point, bolted inter-panel and bottom connections to prevent any stress concentration; the bolts were tightened to a torque of 20 N-m as recommended by Manalo et al. [42]. The panels are designated according to the number of panels (F for single frame and DF for double walls), effect of sheet offset from the bottom (S_0 and S_{10} for full sheet and 10 mm short from the bottom respectively), effect of window opening (O) and effect of customised angle brackets (B_2 and B_4, for two or four angle brackets respectively). For example, specimen $FS_{10}O$ is a single wall with the sheathing 10 mm short from the bottom with window opening, while specimen $FS_{10}B_2$ is a single wall panel with the sheathing 10 mm short from the bottom with two customised angle brackets.

2.3. Test setup and instrumentation

All wall panels are installed upright on the UB460 steel beam by using M20 bolts and tested under monotonic in-plane shear load applied by 100 kN hydraulic jack from the top left corner according to the procedure in ASTM E72–05 [44] and in Fig. 3(a). Axial load is not considered as recommended by [45]. One full scale wall panel per parameter was tested similar to previous research [15,18,35], however, this may limit the repeatability of the results. Therefore, variety of instruments were attached to capture data from critical locations. 20 mm uniaxial strain gauges (SG) capacity were used to measure strains at the locations (see Section 3). As shown in Fig. 3 (a), string pot is connected to the right top corner to measure lateral deflection, 30-ton capacity of load cell was attached to hydraulic jack to record applied load and digital image correlation (DIC) camera was used to record lateral deflection at various points of wall panel along the height in Fig. 3(b). Strain, load, and deflection data were recorded in a SmartStrain data logger system. Roller supports on both sides were provided to avoid falling and maintain the vertical alignment.

3. Experimental results and discussion

Failure modes of all wall panels are summarised in Fig. 4 and summary of experimental results is summarised in Table 3. In general, failure originated at the bottom plate with longitudinal cracking in the RHS section or delamination between the sheathing and bottom plate. The effects of various parameters are discussed in below sections.

3.1. Effect of sheet offset

The effect of sheathing offset was evaluated by comparing the FS_{10} (10 mm short sheathing length from the bottom plate) and FS_0 (Full panel height sheathing length). The overall results show that a higher in-plane shear capacity can be achieved by shortening the

Table 2
Angle bracket details.

Panel Label	Bracket-A	Bracket-B	Bracket-C	Bracket-D
FS_0	N	N	N	N
FS_{10}	N	N	N	N
$FS_{10}O$	N	N	N	N
$FS_{10}B_2$	N	CB-2	CB-1	N
$FS_{10}B_4$	CB-2	CB-2	CB-1	CB-1
DFS_{10}	N	CB-2	CB-1	N
	Bracket-E	Bracket-F	Bracket-G	Bracket-H
DFS_{10}	N	N	N	N

(N = Normal bracket), (CB-1 Customised bracket-1), (CB-2 Customised bracket-2), For more details see Fig. 2.

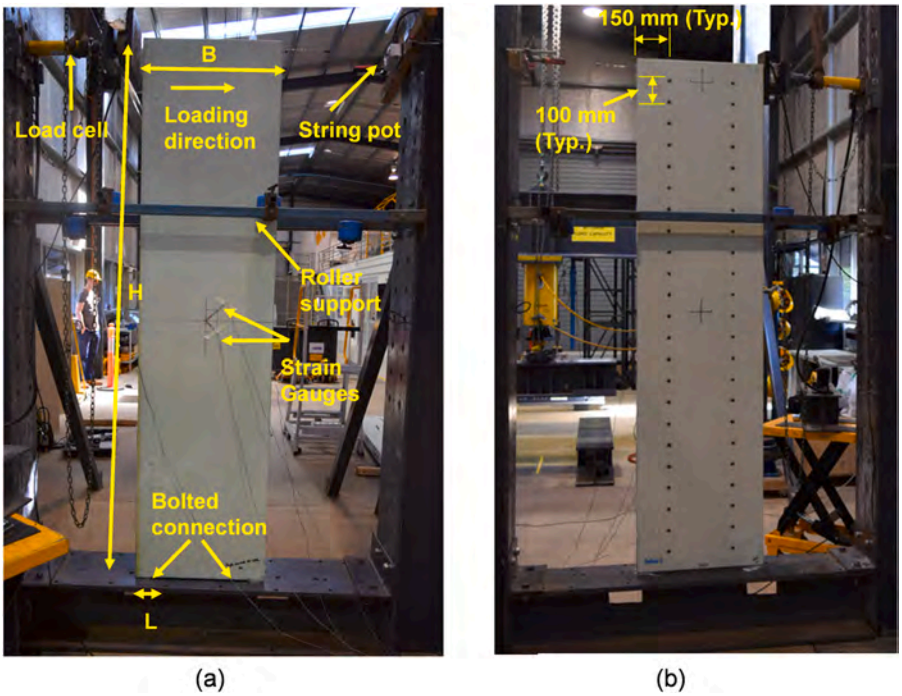


Fig. 3. (a) Test setup (b) Marking for DIC measurement.

sheathing length in the wall panel at the bottom as it changed the failure behaviour of the panel. The effect of sheet offset on load deflection, failure behaviour and load strain behaviour are discussed in the following sections.

3.1.1. Load deflection behaviour

Fig. 5 shows the load deflection behaviour of FS_{10} and FS_0 panels. The experimental results indicate that both composite panels exhibit similar shear stiffness but a significant difference in loading capacity can be observed. This is because the shortening of the sheathing height by 10 mm from bottom has a very minimal effect on the lateral stiffness of panel. Whereas it alters the failure mechanism from inter laminar delamination of sheet to transverse splitting of bottom RHS plate as explained in Section 3.1.3 that helps to eliminate premature delamination failure and consequently increase the loading capacity of wall panel. Experimental panel stiffness (K) is calculated by the ratio of linear portion of load deflection curve in Fig. 5 and recorded as 229 N/mm and 233 N/mm for FS_0 and FS_{10} respectively. By considering wall panel as a cantilever under point load, the experimental flexural stiffness of 1.05×10^{12} N/mm^2 for both panels can be calculated by Eq. (1). However, the calculated panel flexural stiffness is 1.19×10^{12} N/mm^2 by Eq. (2) and material properties in Table 1 corresponding 13.7% higher than experimental stiffness. This could be due to the theoretical analysis did not consider fabrication imperfection tolerance and/or the SD of 6–8% in material properties listed in Table 1 may have some influence. The 10 mm sheathing offset from the bottom plate in FS_{10} increased 1.71 times loading capacity than panel FS_0. The maximum loading capacity of FS_0 was 6.84 kN with horizontal deflection of 30.1 mm. Thereafter, no increment in load was observed and panel failed at 6.01 kN. Whereas FS_{10} reached to 11.6 kN loading capacity with horizontal deflection of 79.8 mm. Thereafter, a significant drop in the load can be observed. Before reaching to the peak load, both panel shows nonlinear behaviour until ultimate failure and this is explained in the following section.

$$EI = \frac{H^3 m}{3} \tag{1}$$

$$EI = 2E\left(I + Ad^2\right) \tag{2}$$

where E is the longitudinal modulus of elasticity in the longitudinal direction, I is the second moment of inertia in the direction of the applied load, H is the height of the wall panel, m is the ratio of load and deflection of linear portion of load deflection curve, A is the cross sectional area of RHS stud and d is the distance from centre of bottom bolt and the centroid of the RHS.

3.1.2. Failure behaviour

FS_0 exhibits a linear elastic behaviour until 6.1 kN load and then a loud sound was heard with a minor load drop at 6.1 and 6.3 kN. This could be due to the initiation of delamination between bottom plate and sheathing. Upon the load was reaching at 6.8 kN, a loud sound was heard followed by major delamination between sheathing and bottom RHS plate as shown in Fig. 4(a) and this caused a sudden loss of 29% load in Fig. 5. Thereafter, the panel regains 18% load because of the load transferred between angle bracket (N) and bottom plate. Upon increasing the load, a continuous creaking sound was heard that could be due to the corner splitting of RHS bottom plate in Fig. 4(b) followed by the crushing of insert in Fig. 4(c) but finally at 6.0 kN the panel failed due to the rivets pull off from bottom plate in Fig. 4(d). On the other hand, FS_{10} exhibits a linear elastic behaviour until 6.9 kN load and then a cracking sound was heard that could be due to the initiation of cracking of insert in the bottom plate in Fig. 4(I). Thereafter decrease in the shear stiffness can be observed in the panel. At 8.7 kN a sudden 6.7% load drop was observed that could be due to the major crushing of insert, because no delamination between bottom plate and sheathing was observed similar to $FS_{0.}$ Then a minor increment in panel stiffness was observed but at 11.6 kN sudden drop in load with loud sound can be attributed by the splitting of bottom RHS plate in Fig. 4(g). After major crushing of the insert at 8.7 kN, the load was mainly carried by the bottom RHS plate that can be explained by the inundation of washer in Fig. 4(f). A minor crushing of vertical stud was also observed as shown in Fig. 4(h).

3.1.3. *Load strain behaviour*

Fig. 6(a), shows the load strain behaviour of FS_{10} and FS_0 wall panels. SG-1 and SG-2 of both panels are attached on the vertical studs and exhibit a linear behaviour in tension and compression. Similar load strain slopes of SG-1 and SG-2 in both panels indicate that sheathing offset does not have much impact on the load distribution on vertical studs. Similarly, SG-3 and SG-4 also exhibit linear load strain behaviour in both panels. Whereas a minor fluctuation in SG-4 of FS_{10} can be seen at 8.7 kN, which could be due to the major cracking in inserts in Fig. 4(e), because no delamination similar to FS_0 was observed. On contrary to this, SG-3 and SG-4 of FS_0 show 2.3 and 1.4 times higher strain than $FS_{10,}$ respectively. This indicates that in FS_{10} sheathing exhibits complete shear behaviour and deformed along with panel in Fig. 6(b). Hence, strain in SG-3 and SG-4 is recorded less than SG-1 and SG-2 due to closer location to the neutral axis. Whereas, in FS_0 sheathing experienced combination of shear and high compression stress concentration at compression side bottom corner, due to contact between sheathing and UB460 in Fig. 6(c). Hence the strain in SG-3 and SG-4 of FS_0 is recorded higher than SG-1 & SG-2. During loading, the bottom plate moved upward along with frame while the sheathing under compression remains stationary, therefore this phenomenon caused high shear stress concentration between the sheathing and bottom plate and that caused the delamination between bottom plate and sheathing in Fig. 4(a). On the other hand, in FS_{10} due to the stress concentration at anchor bolts, the bottom of RHS plate deformed into transverse splitting of matrix as shown in Fig. 4(g). Overall, reduction in the sheathing length significantly improved the in-plane shear performance of the panel by avoiding premature failure.

3.2. *Effect of wall openings*

The effect of wall opening is evaluated by comparing the FS_{10} (without opening) and $FS_{10}O$ (with opening). The overall results show that the shear stiffness can be estimated from the percentage area removed for the wall opening. The effects of wall opening on load deflection, failure behaviour and load strain behaviour are discussed in the following sections.

3.2.1. *Load deflection behaviour*

In Fig. 7, panels FS_{10} and $FS_{10}O$ exhibit linear behaviour until 6.7 kN and 5.8 kN respectively. The shear stiffness of FS_{10} and $FS_{10}O$ is calculated as 233 N/mm and 152 N/mm respectively from the linear portion of the curves. The 34.7% lower value of experimental shear stiffness of FS_{10} can be explained by the removal of 37.5% area due to the opening in the wall panels, similar reduction is also observed by [28]. However, Shahnewaz et al. [46] proposed that reduction on shear stiffness by wall openings can be calculated by Eq. (3) and the calculated stiffness of $FS_{10}O$ is 177 N/mm which is 14.12% over estimated. This imperfection could be due to the local rotation at wall opening area of panel $FS_{10}O$ in Fig. 7(b), which is also observed in [46,47]. Fig. 7(b) shows linear deflection behaviour of wall panel along panel height until 2100 mm. Thereafter, even at very low load a reduction in deflection can be observed. This indicates that overall panel did not deform uniformly but a local deformation around wall opening area occurred. A linear relation can be observed FS_{10} exhibited a maximum load at 11.6 kN with horizontal deflection of 79.8 mm and $FS_{10}O$ reached at 9.83 kN with horizontal deflection of 105 mm. Both panels exhibit similar linear and non-linear behaviours which are further explained in the following section.

$$K_{Opening} = K_{Full}\left[1 - \frac{r_{o/w}\left(A_o/A_w\right)}{\sqrt{r_{o/w} + r_o\left(A_o/A_w\right)}}\right] \tag{3}$$

where $K_{opening}$ is the shear stiffness of $FS_{10}O$, K_{Full} is the shear stiffness of FS_{10}, r_o is aspect ratio of opening, $r_{o/w}$ is aspect ratio of opening to wall (max. of opening width/wall width or opening height/wall height), A_0 area of opening and A_w area of wall.

3.2.2. *Failure behaviour*

The removal of sheathing area from the panel did not affect the failure behaviour because failure is governed by the bottom plate as discussed in Section 3.1.3. Panel $FS_{10}O$ exhibits a linear elastic behaviour until 5.5 kN load compared with 6.9 kN in FS_{10} and then a cracking sound was heard that could be due to the initiation of cracking of insert in the bottom plate in Fig. 4(i). Thereafter decrease in the shear stiffness can be observed in the panel. At 6.7 kN, a load drop was observed that could be due to the further crushing of insert along with washer inundation in Fig. 4(j). Thereafter the panel sustain the shear stiffness until final failure at 9.8 kN with sudden drop in load and that can be explained by the splitting of bottom RHS plate in Fig. 4(j). The inundation of washer damaged the top portion of

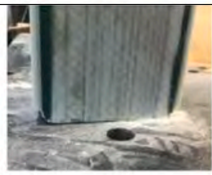
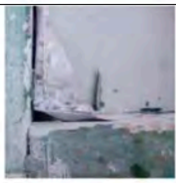
Panel Name	Failure bahaviour of wall panels			
FS_0	 (a) Delamination of sheathing at 6.84 kN	 (b) Corner splitting at 5.66 kN	 (c) Insert crushing at 5.66 kN	 (d) Rivets pull off at 6.01 kN
FS_{10}	 (e) Insert crushing at 6.91 kN and 8.7kN	 (f) Washer inundation at 8.7 kN	 (g) Transverse splitting at 11.66 kN	 (h) End crushing at 11.66 kN
$FS_{10}O$	 (i) Insert crushing at 5.5 kN	 (j) Washer inundation at 6.7 kN	 (k) Transverse splitting at 9.8 kN	 (l) End crushing at 9.8 kN
$FS_{10}B_2$	 (m) Enlargement of bolt hole at 14.6 kN	 (n) Bending of angle bracket at 14.6 kN	 (o) Isometric view of (n)	 (p) Delamination of sheathing at 14.1 kN
$FS_{10}B_4$	 (q) Enlargement of bolt hole at 13.9 kN	 (r) Bending of angle bracket at 13.9 kN	 (s) Isometric view of (n)	 (t) Delamination of sheathing at 15.43 kN
DFS_{10}	 (u) Delamination of sheathing at 20.5 kN	 (v) Bending of angle bracket at 19.5 kN	 (w) Rivets pull off at 19.5 kN	 (y) Rivets pull off at 19.5 kN

Fig. 4. Failure behaviour of wall panels.

Table 3
Summary of the full-scale test of composite wall panels.

Wall panel	Failure load (kN)	Stiffness (N/mm) $K = \frac{\Delta F}{\Delta \delta}$	% Stiffness of panels to FS_{10}	Final failure
FS_0	6.84	229	98.28	Delamination in sheathing at bottom plate
FS_{10}	11.66	233	100	Bottom plate transverse splitting
$FS_{10}O$	9.80	152	65.30	Bottom plate transverse splitting
$FS_{10}B_2$	14.60	392	168.24	Delamination in sheathing at bottom plate
$FS_{10}B_4$	15.43	386	165.66	Delamination in sheathing at bottom plate
DFS_{10}	19.50	1359	583.26	Delamination in sheathing at bottom plate

Specimen designation system.
F (Single frame), DF (Double frame), Sx ($_0$ = full sheathing, $_{10}$ = 10 mm sheathing offset from bottom) O (Window opening), Bx ($_2$ = two customised angle brackets, $_4$ = four customised angle brackets).

bottom RHS plate and intensified the crushing of insert. Thereafter concentrated load is transferred to the bottom portion of RHS plate

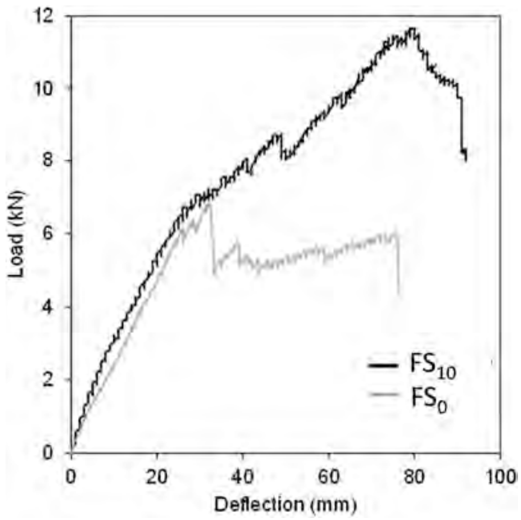


Fig. 5. Load deflection for sheathed wall panels FS_{10} and FS_0.

which caused the final transverse splitting failure. A minor crushing of vertical stud like FS_{10} can also be observed in the panel $FS_{10}O$ in Fig. 4(l). Furthermore, Fig. 7(b) depicts the lateral deflection of wall panel along the height starting from the base of window opening to full height. A drop in deflection at 2100 mm indicates the local deformation in panel explained in Section 3.2.1.

3.2.3. Load strain behaviour

Fig. 8 shows the load strain behaviour of FS_{10} and $FS_{10}O$ wall panels. SG-1 and SG-2 of both panels exhibits linear tensile and compression strain behaviour until the ultimate failure respectively. A significant higher strain in FS_0O indicates that reduction of the sheathing area exerted higher axial strain on the vertical studs. SG-3 and SG-4 of FS_{10} exhibit linear load strain behaviour until the failure with minor fluctuation of SG-4 at 8.1 kN due to the major crushing of insert as explained in Section 3.1.3. Whereas, SG-3 and SG-4 of $FS_{10}O$ are attached near to the bottom plate, therefore strain fluctuations after 5.7 kN can be observed due to the initiation of crushing of inserts. Strain in SG-3 of FS_{10} is recorded higher than $FS_{10}O$, because SG-3 in FS_{10} is placed in the middle of wall panel where the diagonal strain is maximum in sheathing under in-plane shear load. However, RHS studs in FS_0O experienced higher strain compared with $FS_{10,}$ indicating that lower sheathing area provide lower resistance to in-plane shear load. Overall, reduction of sheathing decreases the panel stiffness and loading capacity of the composite wall panel, but with similar failure behaviour, due to the significant lower transverse strength of RHS bottom plate.

3.3. Effect of type of angle brackets

The effect of angle brackets is evaluated by comparing the FS_{10} (with normal brackets), $FS_{10}B_2$ (with two customised brackets) and $FS_{10}B_4$ (with four customised brackets). The overall results show that the customised brackets increased the loading capacity and shear

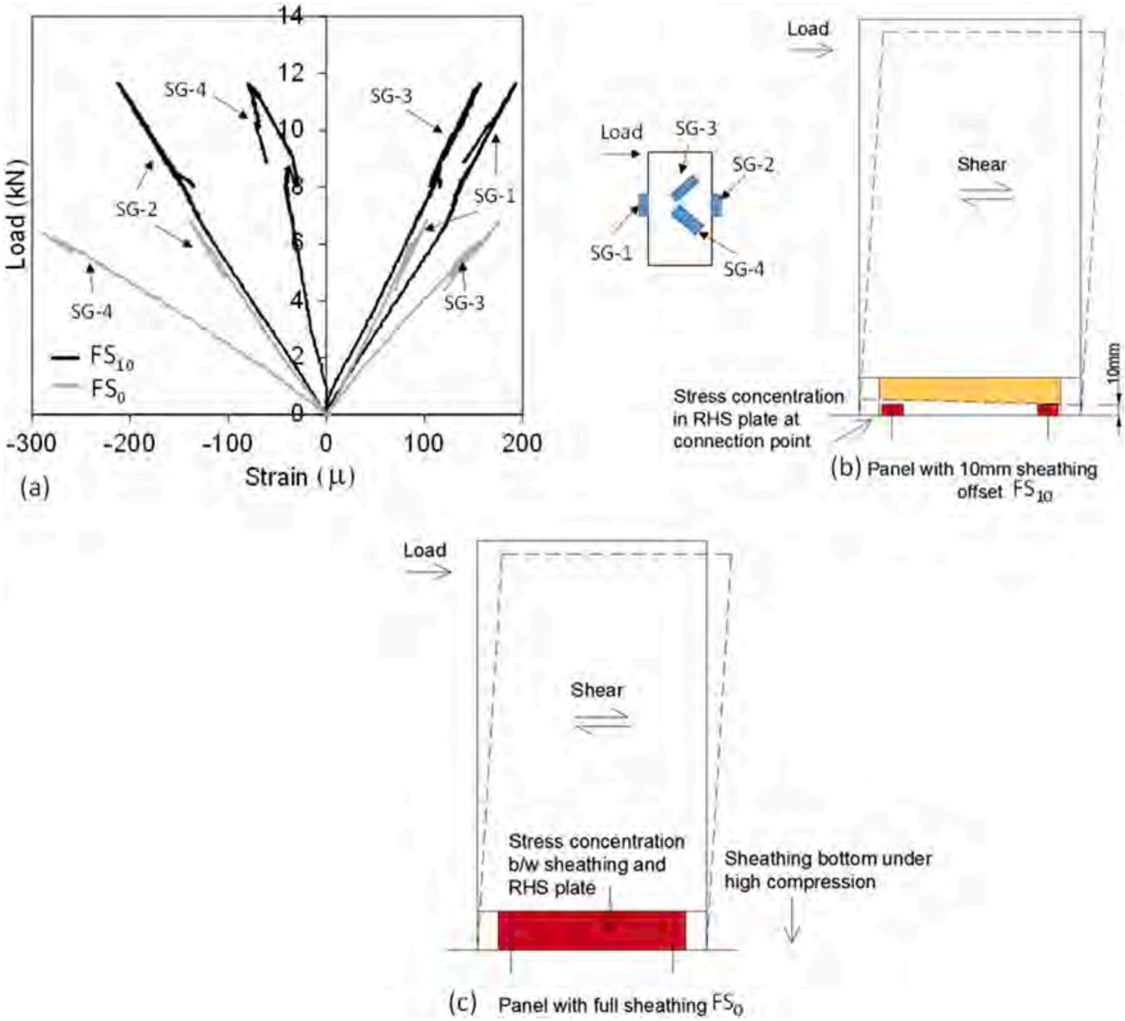


Fig. 6. (a) Load strain behaviour of sheathed wall panels FS_{10} and FS_0 (b) FS_{10} failure mechanism (c) FS_0 failure mechanism.

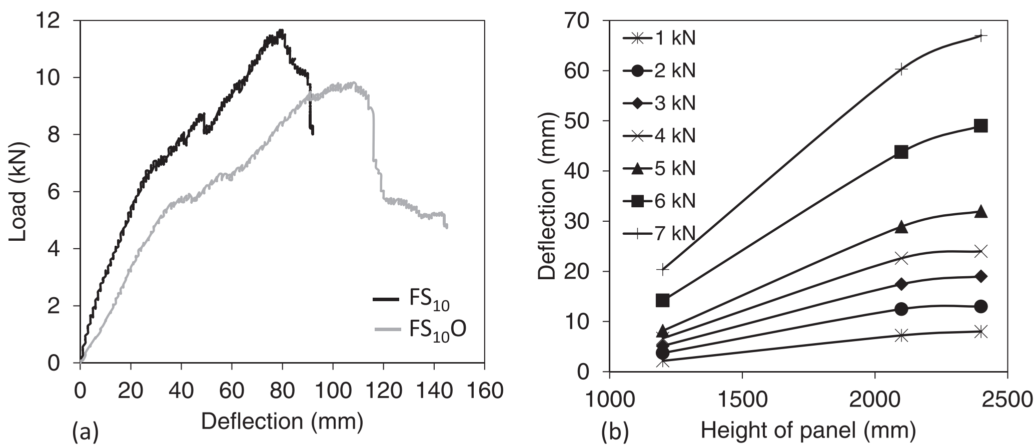


Fig. 7. (a) Load deflection behaviour of FS_{10} and FS_0O wall panels (b) DIC lateral displacement around window opening.

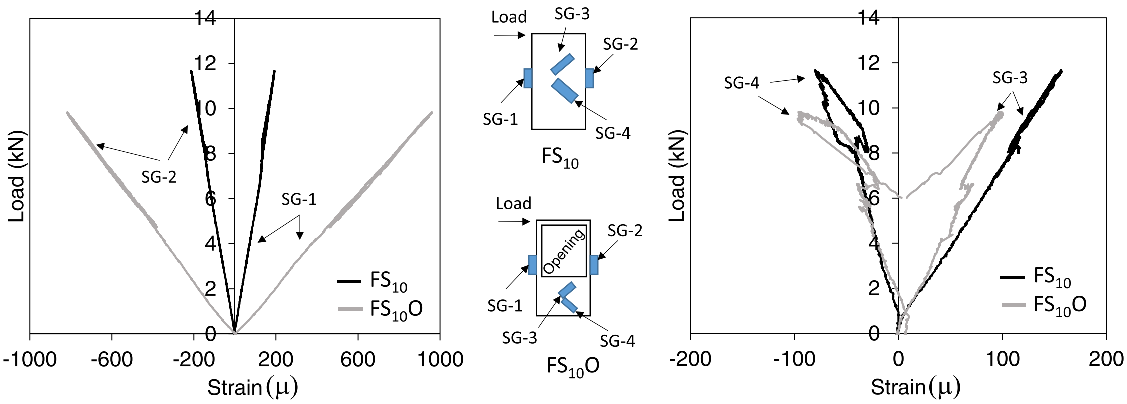


Fig. 8. Load strain behaviour of FS_{10} and FS_0O wall panels.

resistance of the wall panel due to the yielding of bracket before final failure. Whereas, no significant variation is observed by increase of the number of customised brackets, because of the failure behaviour of $FS_{10}B_2$ and $FS_{10}B_4$ governed by bottom load side angle bracket. The effects of fittings on load deflection, failure behaviour and load strain behaviour are discussed in the following sections.

3.3.1. Load deflection behaviour

Fig. 9 shows the load deflection behaviour of panels FS_{10}, $FS_{10}B_2$ and $FS_{10}B_4$. Panels $FS_{10}B_2$ and $FS_{10}B_4$ exhibit linear behaviour until 14.6 kN and 15.43 kN, also with similar shear stiffness of 391 N/mm and 386 N/mm respectively based on the linear portion of the curves. Both panels exhibit similar stiffness and loading capacity but with 1.52 and 1.29 times higher stiffness and loading capacity than FS_{10}, respectively. This indicates that the addition of customised angle brackets can contribute to the overall panel stiffness and loading capacity. However, similar stiffness of $FS_{10}B_2$ and $FS_{10}B_4$ panel can be due to the stiffness provided by only the load side bottom customised bracket. The load on loading side anchor bolt can be calculated by Eq. (4) with the consideration of the rotation of panel at the bottom left corner of the panel in Fig. 3(a). Bottom load side anchor bolt always experiences high reaction due to the applied load and the resulting high stress concentration. Therefore FS_{10}, $FS_{10}B_2$ and $FS_{10}B_4$ panels had similar failure behaviour as further explained in further section.

$$PxH = pxL \tag{4}$$

where P is the load applied, H is the height of the wall panel, p is load on anchor bolt and L is the distance of bolt from edge of wall panel.

3.3.2. Failure behaviour

Panel $FS_{10}B_2$ follows a linear behaviour until 14.6 kN thereafter, a drop in the load can be observed. This could be due to the enlargement of the bolt hole and bending of the angle bracket as shown in Fig. 4(m) and (n) respectively. Upon further loading, the continuous deformation in brackets transferred the load between sheathing and bottom RHS plate. Hence, an instant delamination can be observed in Fig. 4(p) at 14.1 kN. Similarly, for panel $FS_{10}B_4$, a load drop at 13.9 kN was observed and similar failures such as enlargement of bolt hole and bending of angle bracket was observed in Fig. 4(q) and (r) respectively. Finally, the panel $FS_{10}B_4$ failed due to the delamination of bottom plate in Fig. 4(t) at 15.43 kN. Whereas, in contrary to these failures, panel FS_{10} failed due to the transverse cracking in the bottom RHS in Fig. 4(h) plate as discussed in Section 3.1.2. Therefore, the addition of angle brackets in $FS_{10}B_2$ and $FS_{10}B_4$ panels altered the failure behaviour from transverse cracking of the bottom plate to the delamination of sheathing at bottom plate location. This indicates that the addition of angle brackets and insert at hold down location could increase the loading capacity through different failure mechanism. However, failure occurred at the bottom load side anchor bolt as shown in Fig. 4(e), (i), (m) and (q) in all panels. The strain behaviour of $FS_{10}B_2$ and $FS_{10}B_4$ panels are explored further and compared with FS_{10} in following section.

3.3.3. Load strain behaviour

Fig. 10 (a) shows the load strain behaviour of SG-1 and SG-3 of FS_{10}, $FS_{10}B_2$ and $FS_{10}B_4$ panels. SG-1 is attached to the load side of the vertical stud, showing linear tensile behaviour. Similarly, SG-3 is attached on the sheathing, with linear tensile behaviour until final failure. Thereafter, reversion in strain can be observed with decrease in load. The minor strain fluctuations in SG-1 and SG-3 in FS_{10} were due to the local failures as explained in Section 3.1.2. In Fig. 10 (b), SG-2 is attached to the compression studs and follows a linear compression behaviour. Similarly, SG-4 is attached on the sheathing and showed linear compression behaviour until the final failure. Overall, the load strain behaviour indicates that regardless the type and quantity of angle brackets, FS_{10}, $FS_{10}B_2$ and $FS_{10}B_4$ panels have similar trends in terms of stain. $FS_{10}B_2$ and $FS_{10}B_4$ present similar strain level, loading capacity and failure behaviour, highlighting the possibility of use one set of customised angle bracket to achieve high loading capacity.

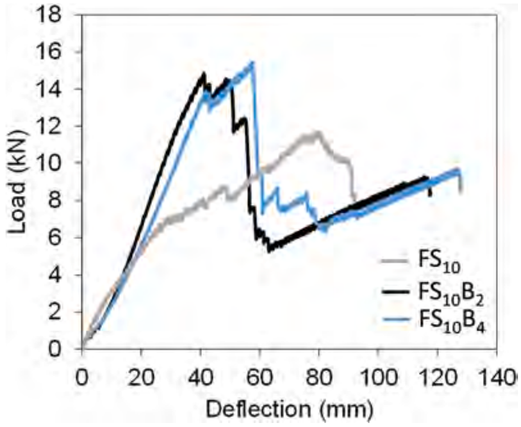


Fig. 9. Load deflection behaviour of FS_{10}, $FS_{10}B_2$ and $FS_{10}B_4$ wall panels.

3.4. Double wall and single wall panel

The effect of wall width is evaluated by comparing DFS_{10} (double wall panel) and $FS_{10}B_2$ (Single wall panel with two customised brackets). The overall results show that double frame has higher panel stiffness but lower loading capacity per unit width. This is due to the high load transfer on load side anchor bolt due to the wider panel.

3.4.1. Load deflection behaviour

In Fig. 11 (a), panels DFS_{10} exhibits linear behaviour until 20.5 kN corresponding to a horizontal deflection of 19.8 mm. Then a sudden drop of 67% load was observed due to the initial failure explained in following section. Thereafter a linear increment in load was observed due to the load carried by angle brackets until final failure at 19.5 kN and 92 mm horizontal deflection. Whereas, $FS_{10}B_2$ presents loading capacity of 15.2 kN with a horizontal deflection of 58.1 mm. Fig. 11 (b) shows the normalised loading capacity of both panels by dividing the width of the wall panel. It is clear from the graph that the normalised loading capacity of single wall panel is higher than the double wall because higher panel width exerts higher load on the load side hold-down bolt. Whereas, double panel exhibits 2.6 times higher shear stiffness than single panel as shown in Fig. 11 (b). Because single panel $FS_{10}B_2$ has high aspect ratio of 4:1 (height:width ratio) and has a tendency to deform under the rigid body rotation as explained by [48]. The failure behaviour of such panels is further explained in the following sections.

3.4.2. Failure behaviour

Panel DFS_{10} follows a linear behaviour until 20.5 kN; thereafter, a significant drop in the load can be observed. This was due to the delamination of bottom RHS plate in Fig. 4(u). At 26 mm deflection, the panel started regaining the load because even after the delamination of bottom plate in Fig. 4(u), the hold-down contributed in carrying the load until reaching 19.5 kN load with lateral deflection of 75 mm. Thereafter until 92 mm no load increment was observed, indicating the yielding in rivets, and causing the final failure due to the rivets pulled off from the vertical plate in loading side and from the bottom of normal bracket in compression side of panel (as shown in Fig. 4(w) and (y) respectively). $FS_{10}B_2$ also shows the similar failure behaviour except of rivet pull off as discussed in Section 3.3.2. The load strain behaviour of both panels is discussed in the following section.

3.4.3. Load strain behaviour

Fig. 12, presented the load strain behaviour of DFS_{10} and $FS_{10}B_2$ wall panels. SG-1, SG-3 and SG-5 presented linear tensile behaviour and SG-2, SG-4 and SG-6 presented linear compression behaviour until final failure. SG-1 shows 2.7 times higher tensile strain in $FS_{10}B_2$ than DFS_{10}, supporting the reduction of stiffness at similar level of 2.6 times as discussed in Section 3.4.1. Whereas SG-2, SG-3 and SG-4 showed 1.6, 1.9 and 2.9 times higher strain in $FS_{10}B_2$ than DFS_{10}. Such variations could be due to the location of strain measurements as a result of variation in width of both panels. However, in panel DFS_{10} higher strain in SG-5 than SG-3 can be explained as the second panel P-2 in Fig. 12 provided lateral movement resistance to first panel P-1. Therefore, lower displacement exhibits lower strain in SG-3 of P-1. Similarly, SG-4 recorded lower strain than SG-6 in panel DFS_{10}.

4. Conclusion

The structural performance of composite wall panels under in-plane shear load was evaluated in this paper. The effects of sheathing height offset, presence of wall opening, types of angle brackets at frame corners and number of wall panel (single and double) were clarified. Based on the experimental investigation, the following conclusions can be drawn.

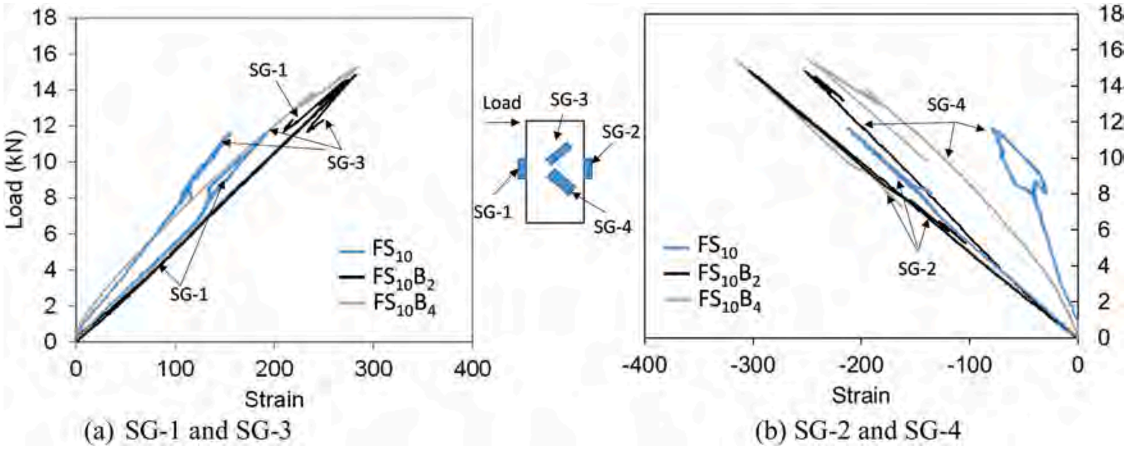


Fig. 10. Load strain behaviour of FS_{10}, $FS_{10}B_2$ and $FS_{10}B_4$ wall panels.

- The sheathing offset (10 mm from the bottom) enhanced the loading capacity of the composite wall panel as it avoided the additional compression stress in the sheathing and transferred most of the load to the pultruded FRP sections. Panels with full sheathing experienced stress concentration resulting in premature delamination failure at the bottom plate. No variation on shear stiffness was observed in both sheathing configuration.
- The presence of window opening reduced the loading capacity and shear stiffness of the composite wall panel. The decrease in strength and stiffness is directly proportional to the ratio of wall opening to total area of the wall. This can be reliably calculated by the empirical formula considering the aspect ratio of window opening to wall modules.
- The provision of customised angle brackets at the corners of FRP frame increased the loading capacity and stiffness of composite wall systems. However, the number of customised brackets has insignificant effect on the loading capacity, stiffness and failure behaviour. Two customised brackets provided in diagonal corners are sufficient in improving the in-plane shear behaviour.
- The loading capacity per unit width of single panel is marginally higher than the double wall panel. The stiffness of double wall is 2.6 times higher than the single wall panel, because of its tendency to deflect with higher deflection caused by rigid body rotation.

The experimental results obtained from this study indicates that composite wall system may be considered as an alternative material for modular construction. However, a detailed comparative study between GFRP composite and other conventional material wall system should be considered for future research. A careful attention should however be given to the fabrication of wall panels and connection details to maximise the utilisation of high strength properties of the GFRP materials.

CRediT authorship contribution statement

Arvind Sharda: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Validation, Writing – original draft. **Allan Manalo:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Wahid Ferdous:** Supervision, Methodology, Writing – review & editing. **Yu Bai:** Methodology, Writing – review & editing. **Lachlan Nicol:** Writing – review &

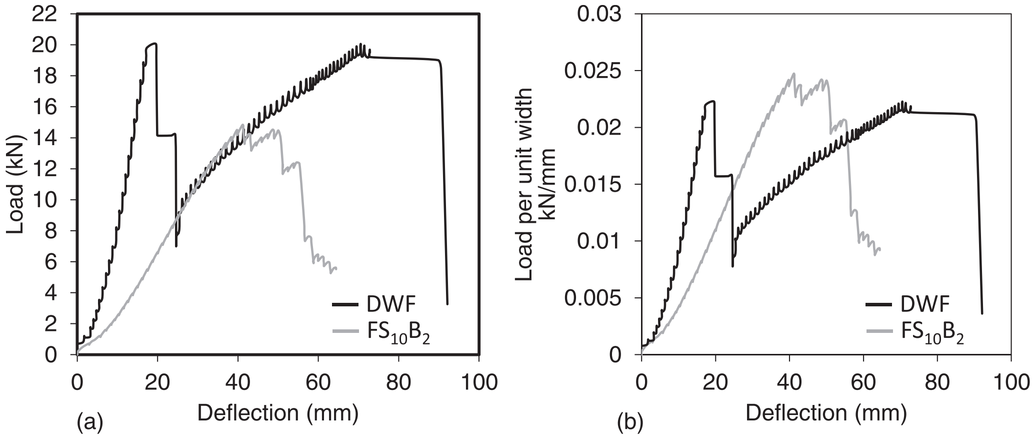


Fig. 11. DWF and $FS_{10}B_2$ wall panels (a) Load deflection behaviour (b) Normalised load with panel width vs deflection of panel.

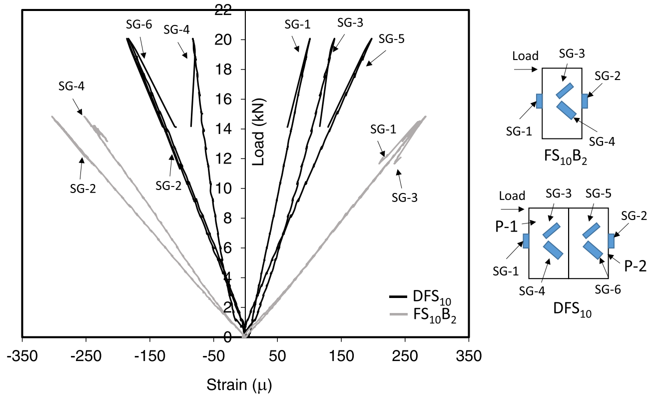


Fig. 12. Load strain behaviour of DFS_{10} and $FS_{10}B_2$ wall panels.

editing. **Ali Mohammed:** Writing – review & editing. **Brahim Benmokrane**: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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CHAPTER 6: CONCLUSION

Glass fibre reinforced polymer (GFRP) composite material has emerged as a promising alternative to conventional construction materials for modular building construction due to their lightweight, high-strength, high durability and speed of construction. However, the limited understanding on their structural performance against different loading actions limits the confidence of engineers and contractors to adopt composite wall system as main material for modular construction. Therefore, this study scientifically investigated the performance of GFRP composite wall system under axial compression, bending and in-plane shear through experiment, FE analysis and analytical investigations. The major findings of this research are stated below:

6.1 State-of-the-art review on the modular composite wall system

The review of literature on the advantages to use fibre reinforced polymer (FRP) as a construction material for modular wall systems highlighted that its behaviour may be affected by different design parameters under different loading conditions. There are also a number of challenges and opportunities in utilising fibre composites for modular building construction. From the systematic review, the major findings are drawn below:

- The high strength-to-weight ratio of FRP than conventional materials such as steel, concrete and timber highlighted its potential for modular construction. Additionally, immunity to corrosion, no pest and biological decays and lower embodied energy of FRP than conventional material make them greener and more economical due to low maintenance.
- Integrity of composite wall system highly depends upon the connection between frame and sheathing, and inter-panel connection. The behaviour of the inter-panel connection of composite wall system is hardly explored with some exception of adhesive lap joints.
- Load bearing wall system needs to withstand compression, flexural and in-plane shear load due to live and static gravitational loads and wind. Wall height to width ratio plays an important role in performance of wall system under compression load and in-plane sheer load.
- Wind loading caused uniformly distributed load (UDL) on walls perpendicular to its direction. Flexural behaviour of FRP under point load is widely explored and web-flange shear and local bucking in sheathing is commonly observed due to the stress

concentration at loading points. However, understanding of the behaviour of composite wall system under UDL is limited.

- The Finite Element Analysis (FEA) is an effective method to analyse the failure behaviour of composite structures. FEA modelling and analytical analysis can help to validate, analyse and to predict the expensive experimental results.

This state-of-the-art review highlighted that FRP composites are an effective alternative to conventional construction materials. In order to raise awareness and build the confidence of designers, engineers and researchers, it is necessary to understand behaviour of composite wall system under different load actions with different design parameters.

6.2 Axial compression behaviour of composite wall system

Load bearing wall systems carry dead load and live load, which subject it under axial compression. In this study, the effect of presence of sheathing, type of sheathing material, sheathing thickness, connections between sheathing and wall studs, and stud configuration on the axial compressive behaviour of composite wall system was investigated. The following conclusions can be drawn out from this study.

- The material properties of sheathing and the structural frames which are used in the fabrication of the composite wall systems provided a very good correlation between the strength and failure behaviour under axial compression.
- Composite wall panels under axial compression mostly failed by the web-flange junction failure of top or bottom RHS plate. This failure behaviour is due to the low mechanical properties of the pultruded GFRP sections in the transverse direction.
- The type of sheathing has a significant effect on the axial stiffness and strength of the composite wall system. GFRP sheathing provided more than 1.62 and 2.54 times axial stiffness and strength than fibre cement sheathing due to their superior mechanical properties. The GFRP sheathing also provides structural stabilisation by distributing the load to all components of wall system.
- Axial stiffness is independent of panel width because failure was governed by top or bottom RHS plate. However, local sheet bucking in 600 mm wide panel leads to premature failure and a lower compression capacity per unit width than 300 mm wide panel.

- Adhesive bonding can provide a better composite action than rivets due to the continuity of connection between frame and sheathing. The unsupported length of the riveted sheathing experienced sheet wrinkling causing premature failure of the wall system.
- An improvement in panel stiffness and increased in capacity by 8 and 15 times, respectively were observed in extended stud configuration than extended plate wall panel. The change of failure behaviour from inter-laminar delamination to end crushing in extended stud panel utilised up to 70% axial compression strength of RHS section.
- FE analysis showed that at least 10 times panel stiffness and strength can be increased by extending the wall studs. The predicted failure of this composite wall system is by local buckling of the GFRP sheets due to the high level of load to fail the RHS section in the longitudinal direction.

The results of the axial compression study showed that extended stud configuration in composite wall system can eliminate the premature web-flange junction failure of top or bottom RHS plate. However, it may induce local sheet buckling which can be controlled by introducing the nogging between vertical studs. Finally, adhesively bonded connection has more composite action than riveted and that helps to transfer the load among all member of wall panel.

6.3 Flexural behaviour of composite wall system

Wind actions normal to the surface will cause bending to the composite wall system. In this study, the effect of the presence of sheathing , type of loading (uniform, UDL or four-point), connections between the sheet and frame (adhesive or riveted), inter-panel connections (bonded or bolted) and loading direction on the flexural behaviour of full-scale composite wall panels is evaluated. The following conclusions can be drawn out from this study.

- The addition of GFRP sheet increased the flexural loading capacity and stiffness by 1.75 and 2.34 times, respectively compared to the frame only. It also changed the failure behaviour from web-flange shear of the RHS studs to interlaminar delamination in the top sheet.
- The moment capacity of panel under UDL is 2.12 times higher than four-point loading. Under four-point loading, the panel failed due to the interlaminar delamination of the RHS under the loading point whereas UDL caused splitting of RHS studs.
- Under UDL, adhesively bonded frame exhibits 2.31 times higher loading capacity than riveted panel due to the high composite action provided by adhesive connection. Slippage between the sheathing and frame results into the web-shear failure of RHS stud, whereas sheet shearing and RHS was observed in bonded panel.

- The flexural capacity and failure behaviour of the composite wall panels are affected by the inter-panel connections. The bolted panel has 1.4 times higher loading capacity than adhesively bonded panel. The adhesive connection experienced brittle delamination failure, while yielding of the bolts combined with insert crushing and RHS splitting produced pseudo ductile failure in bonded connection.
- The loading direction significantly affected bending capacity and stiffness. In the longitudinal direction of the panels showed at least 1.6 times higher strength and stiffness than in the transverse direction due to the higher strength and stiffness in longitudinal direction than in the transverse direction.

The results of both compression and flexural investigations showed that adhesive bonding can provide a good composite action between the frame and sheathing, and an overall good structural performance of the individual composite wall panel. However, it is better to connect the wall panels together using bolts than adhesive for a more reliable and easier assembly composite wall systems. Moreover, the bending strength measured from four-point loading is very conservative compared to UDL as the latter eliminates the stress concentration on the loading points resulting in better utilisation of the high strength of FRP composite materials.

6.4 In-plane shear behaviour of composite wall system

The wind acting parallel to the direction of the walls create in-plane shear. In this study, in-plane shear behaviour of composite wall system was evaluated. The effect of sheathing height, wall opening, addition of customised angle brackets and number of wall panels was determined by testing full-scale wall panels under in-plane shear. The following conclusions can be drawn out from this study.

- The in-plane shear capacity of composite wall panels is enhanced by 1.71 times by offsetting the sheathing 10 mm from the bottom plate. This is due to that sheathing offset eliminate any additional compression stress in the sheathing, thereby avoiding premature delamination failure at the bottom plate.
- Wall openings reduces the loading capacity and shear stiffness of composite wall panel. The stiffness reduction is directly proportional to the ratio of wall opening to total area of the wall.

- Loading capacity and shear stiffness of composite wall panel can be enhanced by 1.52 and 1.29 times respectively with addition of customised angle brackets. However, two customised angle brackets are sufficient than four angle brackets.
- The loading capacity per unit width of single panel is slightly higher than the double wall panel but the stiffness is 2.6 times lower than the double wall. This is due to the single panel deflects at higher deflection caused by rigid body rotation.

The results indicates that sheathing offset from bottom is an appropriate alternative to increase the panel stiffness and loading capacity of composite wall panel in addition of two customised angle brackets. Moreover, a good structural performance of composite wall systems under different loading actions and effective utilisation of their high strength material properties can be achieved with proper design of material components and connections between them.

6.5 Contribution of the study

The results obtained from this research discovered the important parameters that predominantly affect the performance of composite wall panels under different loading actions. This research generated numerous experimental data from full-scale tests that can be further researched for individual parametric studies to build failure graphs and can be utilised to perform FE analysis of combined loading conditions. The significant contribution of this study are the followings:

- Demonstrated the performance and benefits of all composites wall systems for modular building and construction.
- Understood the structural performance of modular composite wall system under axial compression, flexural and in-plane shear load. The important parameters under different loading conditions are also highlighted.
- Understood and developed FE model and validated through full-scale compression test of wall panels. Hence predictions of failure load with changed configuration of wall panel are presented. Similarly, FE analysis, validating the flexural and in-plane shear test results can be seen in Appendix-A
- Developing new stiffness equation will help to predict the panel stiffness of thin wall composite wall system and predict the failure behaviour accurately.

6.6 New opportunities and future research

This thesis assured the performance of modular composite wall system that can be utilised for real world civil applications. The repeatability achieved through experimental works validated by FE analysis and predicting the failure behaviour through analytical analysis increase the confidence in adopting GFRP for modular construction. Based on the significant outcomes of this study, new potential research areas are available to further understand the critical parameters that influence the performance of composite wall system as follows:

- A full axial compression test for extended stud with sheathing should be conducted to understand the effect of local sheet bucking on the performance of wall panel. Additionally, a progressive non-linear failure FE analysis will help to provide and capture all possible failures of composite material including connections between them.
- UDL caused premature failure on the bottom sheet that is in contact with airbags. Composite panel with solid core simulating the insulation material for thermal or acoustic application should be tested for UDL.
- Nogging provides lateral support to vertical studs and can be utilised to eliminate the local sheet buckling under compression and inward buckling under UDL.
- The effect of other environmental parameters such as temperature, moisture and ultraviolet (UV) radiations on the performance of composite wall system under different loading conditions need to be investigated.

It is important to understand the behaviour of composite wall system under the combined actions of compression, bending and in-plane shear. The current study evaluated in detail the behaviour of composite wall system under one loading condition, which can be used to validate the results of the FE simulation on the combined load actions. FE analysis of combined loading conditions will help better understand the real-world behaviour of such composite wall system.

APPENDIX-A

CONFERENCE PAPER-1

COMPARATIVE EVALUATION OF COMPOSITE WALL PANELS UNDER UNIFORMLY DISTRIBUTED LOAD AND 4 POINT FLEXURAL LOAD
(2021 National Symposium on Advanced Materials and Sustainable Technologies)
(AMST2021)

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Modular construction is growing rapidly in the developed countries because of its faster construction, better quality and lower construction waste compared to the conventional construction. Fibre composites such as glass fibre reinforced polymer (GFRP) provides higher strength to weight ratio and is anticipated as an alternative to conventional construction material. The wall system of modular buildings are highly prone to wind load, especially in Australia where majority of population is living near to the coastal areas.The flexural properties of fibre composite sandwich panels are generally explored under three or four point flexural loading conditions. Whereas, wind tend to induce uniformly distributed load (UDL) on the wall system.

Therefore, in this study full scale 2400 mm x 600 mm all composite wall panels are analysed under four point flexural load and uniformly distributed load applied by two spreader beams and inflatable air bags respectively. Pultruded GFRP rectangular hollow section (RHS) 100mmx 75mmx 5mm profiles are used as studs and plates of the structural frame and 6 mm thick GFRP sheets are adhesively bonded with frame as a sheathing materials. Under the four point flexural loading, local buckling on the top sheet is initiated with initial load and propagated upon increasing the load. This caused the inter laminar delamination in the top sheet and finally panel failed due to the web buckling in RHS studs at the loading points. Whereas, uniform loading caused the shear failure in sheet along with the RHS studs and finally the panel failed due to the corner splitting of RHS studs at supporting point of the panel. The simulated wind effect by UDL, changed the failure behavior of composite wall panels compared to the four point loading. Moreover, under UDL composite panel effectively utilize the high flexural strength and failed at more than twice bending stress than the four point flexural load.

This study demonstrated the change in failure behavior of composite materials under different loading conditions and demonstrated the potential to properly utilize the available material properties by considering the most relevant loading condition.

CONFERENCE PAPER-2

COMPARATIVE EVALUATION OF THE COMPRESSIVE BEHAVIOR OF MODULAR COMPOSITE WALL WITH AND WITHOUT SHEATHING

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Keywords: *Modular wall system, Compression behavior, GFRP panels*

1 Introduction

A boom in the modular construction (MC) has been seen in many developed countries due to their high quality, fast construction speed and low waste [1]. In MC, load bearing walls modules can help to reduce dead load by eliminating if not minimizing beams and columns. The high strength-to-weight ratio of glass fibre reinforced polymer (GFRP) composites are anticipated to further reduce the dead load of modular construction for easy handling, transporting and installation as well as providing a highly durable infrastructure [2]. This study comparatively evaluate the compressive behavior of a new composite wall system made from multi-directional pultruded sections with and without GFRP sheathing. Finite element analysis was also implemented to understand in detail the failure mechanisms and overall behavior of this load bearing modular wall system.

2 Experimental program

2.1 Materials

Pultruded GFRP rectangular hollow section (RHS) 100 mm x75 mm with 5mm thickness and GFRP 6.5 mm thick sheet was used as structural frame and sheathing for wall panel, respectively. The mechanical properties of the RHS section and the GFRP sheets are listed in Table 1.

2.2 Specimen preparation and details

Typical top and bottom plates with vertical studs configuration was considered to fabricate two 600mm x 2400mm wall panels. The GFRP RHS was assembled together using riveted angle brackets. GFRP sheathing was adhesively bonded on both sides in one panel and referred as frame with sheets (FWS). Whereas, second panel was tested without sheathing and referred as frame only (FO)

2.3 Test Setup

An axial compression load was applied by 500 kN hydraulic jack through spreader beam on both wall panels as shown in Fig.3.

3 Experimental Results and Discussion

In Fig.3, load increased linearly with axial deformation until 42kN in FO wall panel. Whereas, a minor drop in load was observed due to the initiation of horizontal cracking in top RHS plate shown in Fig. 1(a) and the wall panel failed at 47kN due to the web-flange junction failure shown in Fig.1 (b). Whereas, in FWS wall panel, initial inter-laminar delamination at junction of top RHS plate and vertical studs can be observed at 105kN. The progression of delamination increased the lateral deformation of top RHS plate and caused major delamination at 165kN. But one sheet remained intact with top RHS plate from one side until final failure and the lateral deformation of top RHS plate stretched this sheet which caused a quick debonding as shown in Fig. 1(d). This was immediately followed by the final failure of web-flange junction as shown in Fig. 1(c). The failure behavior of FWS wall panel indicates that sheathing largely helped to provide a composite action by distributing the load to all structural members of the frame. Whereas, FO wall panel failed pre-maturely because of top RHS plate section deformation. Therefore, GFRP sheets significantly enhanced the loading capacity and overall panel stiffness of FWS by 6.2 and 9 times than FO respectively, by providing additional material stiffness and majorly altering the panel failure behavior.

4 Finite Element Analysis

4.1 FEA modelling

The FEA was implemented using Abaqus CAE 2019. 3D deformable shell with S4R mesh was used to model RHS frame and GFRP sheathing. Wall panel assembly, load and boundary conditions were considered similar to the full scale wall testing.

4.2 FEA Results

Fig.3 presented a good correlation between FEA and experimental load deflection behavior. From Fig.2 (a), upon loading the FO wall panel with 47kN, angle brackets caused the stress concentration at bottom web-flange junction area of top RHS plate and reached to the failure transverse stress of RHS section. Therefore, failure initiated with horizontal cracking at bottom part of RHS plate and final failure caused due to the web-flange junction failure in Fig. 1(a) and (b) respectively. Additionally, the deformation in top RHS plate also caused the lateral global buckling in frame. On the other hand, in Fig. 2(b), upon loading FWS wall panel with 165kN, top RHS plate reached to failure stress range and initiated the web buckling and that caused the major delamination in the GFRP sheet. But overall, sheathing distributed the stresses in top plate and vertical studs and prevented the pre-mature failure similar to FO wall panels. Therefore, stress distribution by sheathing in panel members increased the loading capacity and overall stiffness of wall panel and also prevented the global buckling but local sheet buckling can be observed in wall panel.

The FEA results indicates that behavior of full scale composite wall system can be predicted accurately until the initiation of failure in the top plate.

Table-1: Material properties

Material	Direction	Elastic modulus (GPa)	Ultimate strength (MPa)
GFRP RHS	Axial	42.63	309
	Transverse	13.24	47
GFRP sheet	Longitudinal	8.70	299
	Transverse	1.63	80

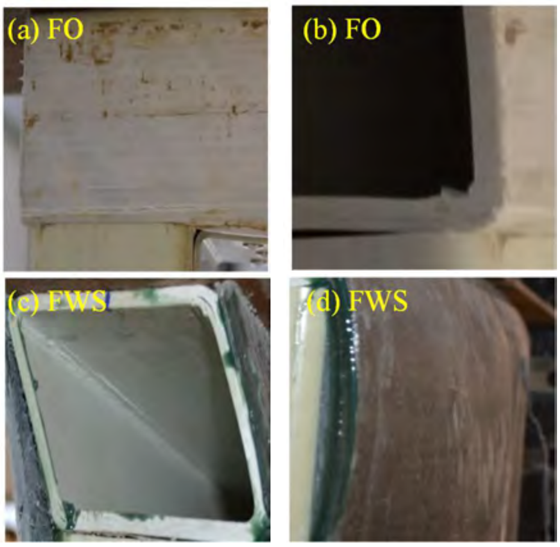

Fig.1. Failure modes of walls (a) Horizontal cracking (b) & (c) Junction failure (d) Sheet debonding

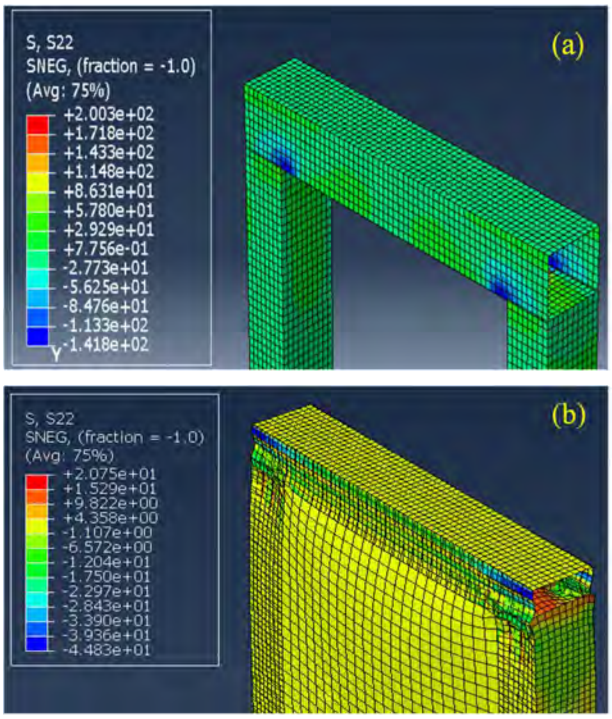

Fig.2. FEA longitudinal stress plots for panels (a) FO (b) FWS

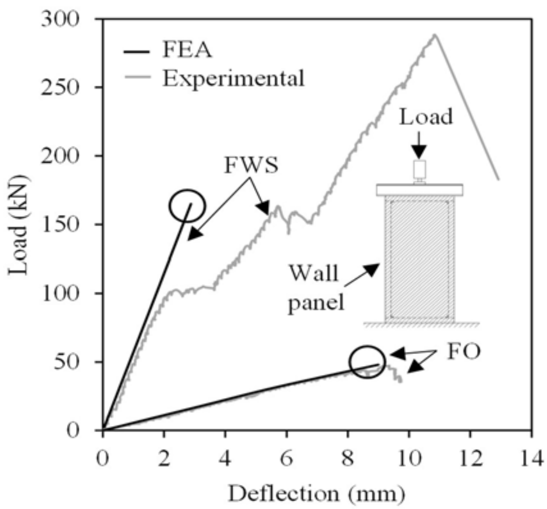

Fig.3. FEA and experimental load-deflection behavior of FO and FWS wall panels

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APPENDIX-B

CHAPTER TITLE: Construction Industry Transformation through Modular Methods

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CHAPTER SUMMARY (250 - 500 WORDS):

Modular building construction has attracted significant attention from the construction industry in recent years. This type of construction system has been reasonably used in the Sweden, United Kingdom, United States and Japan, whilst becoming popular in Australia, China, Netherlands, Germany, and Hong Kong. This chapter presents the benefits of modular construction over conventional construction systems such as high-quality control, rapid construction, risk minimisation, trades availability in adverse weather conditions, waste minimisation and mechanisation of the manufacturing process to overcome the current challenges. The design requirements of modular buildings for hydraulics, electrical, mechanical, heating ventilation and air conditioning (HVAC), fire, acoustics, and thermal are briefly presented. The growth of modular construction market by region and application is reviewed and the future global growth forecast is also presented. A comparative analysis of the cost involved in site-intensive and modular constructions are discussed to assist in understanding the wider benefits of modular systems. A number of case studies ranging from residential to commercial building projects using modular construction are presented. Finally, the potential of fibre composite materials to fabricate innovative construction modules is discussed. At the end of this chapter, readers will gain understanding on the benefits of modular construction and new innovations for transforming the construction industry.

TABLE OF CONTENTS:

1. Introduction

Modular construction is an off-site construction process in which the building components are manufactured/fabricated in controlled factory environment. The prefabricated building components, also known as modules are transferred to the construction site using flatbed truck and trailer. The modules are then assembled with suitable connection systems to form modular buildings. Depending on the degree of fabrication, the prefabricated modules are classified into three categories: 1D single element (2 points connection e.g., beams or columns), 2D panelised system (4 points connection e.g., walls and floors) and 3D volumetric component (8 points connection e.g., pods). This component based design (splitting a product into smaller, more manageable parts) offers significant savings in the component production cost and the speed of assembly. Modular construction is primarily focused on the panelised and volumetric construction as they encompassed 70% to 95% of a building. Design using modular construction requires proper understanding of modular production and installation. The chapter discuss the fundamental aspects of modular construction system.

2. Benefits of modular construction

Modular buildings are greener, faster and smarter over conventionally constructed buildings. This construction process is revolutionising the method that the world builds [1]. A brief overview on the three major beneficial aspects are discussed.

Greener: The factory-controlled manufacturing process produces less amount of waste and creates fewer disturbances at construction site. Buildings constructed by modular construction can be disassembled and their used modules can be refurbished for another application. The reuse of modules can possibly minimise the demand for raw materials and that helps to reduce the total energy utilisation. The recycling process in factory environment is reducing waste generation and saving the building materials. Moreover, the possibility of moisture absorption by the modules in conventional construction can be eliminated as the building components are substantially manufactured in a controlled environment (i.e., without weather exposure) using higher quality materials [2].

Faster: The manufacturing of modules and site work occurs simultaneously, allowing 20% to 50% faster completion of the project work compare to traditional construction. The risk of weather delays can also be mitigated as approximately 60% - 90% of the construction work is completed inside the factory. The faster delivery of buildings is offering a quicker return on investment. Modular construction follows the same building codes and standards as conventionally constructed structures and can utilise the same traditional construction materials such as timber, concrete and steel. To ensure that fabrication, transportation, storage, and installation occurs in a timely and cohesive manner, the contractors or suppliers should be involved during the design phase [3]. Fig. 1 compares the completion time between traditional construction and 3D volumetric modular construction, which shows that an offsite manufacturing can reduce 20-50% construction time.

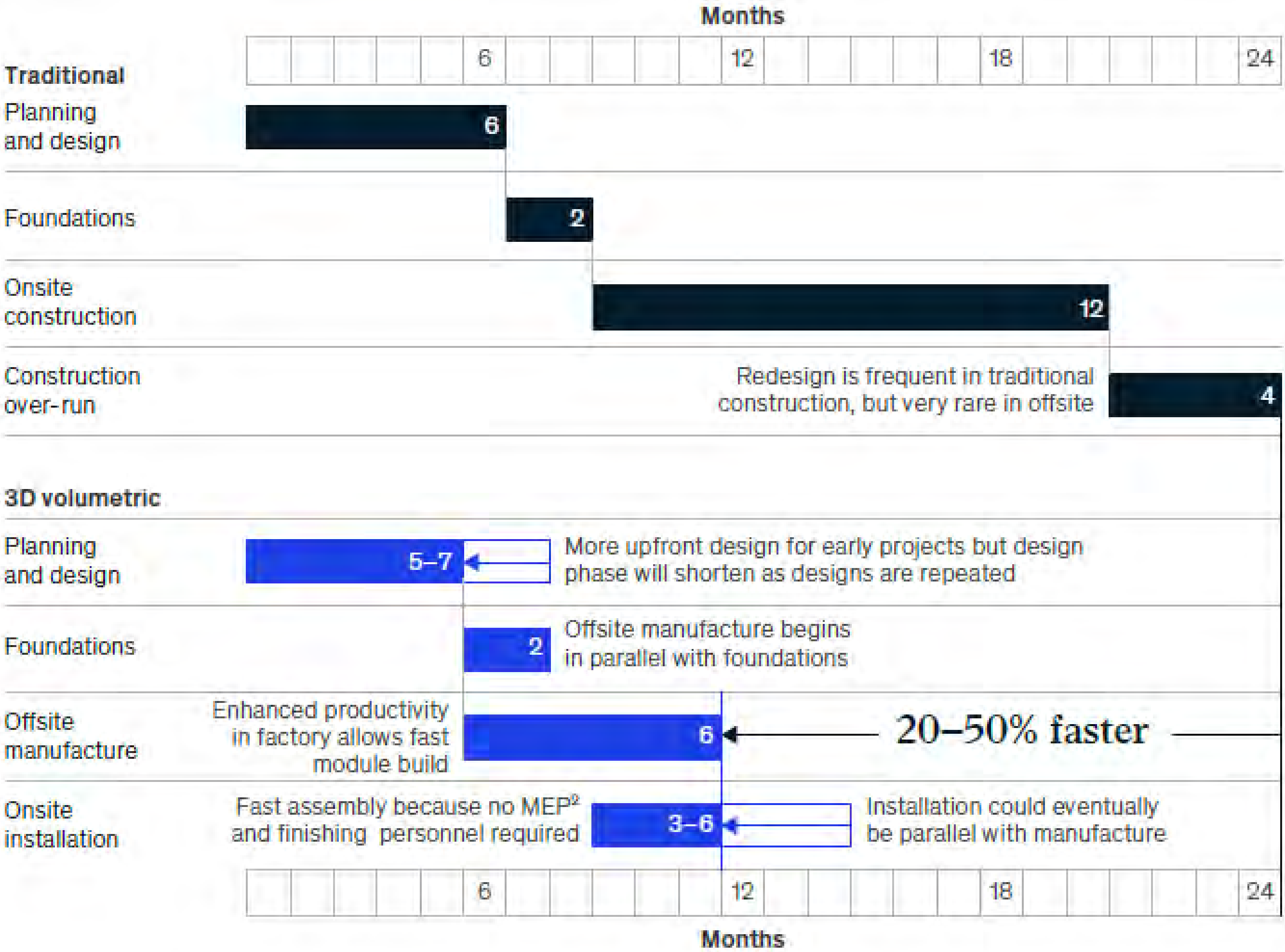

Fig. 1: Project construction duration: traditional vs modular [4]

Smarter: The risks of accidents and associated liabilities for workers can be minimised by the indoor construction facilities and automation. The implementation of health and safety policies, procedures and risk assessment of standard manufacturing process is much easier than construction site. The quality of prefabricated modules is verified through non-destructive testing in a factory setting to prove that they pass and being certified for their design and performance requirements. Other than superior durability and higher quality, off-site construction greatly reduces on-site logistic volume, noise and overall local disruption. Only a limited number of workers are required on-site that reduces the project cost since a major part of the construction is completed off-site. The consideration of high-performance design features, energy modelling and incorporation of solar or wind power can help to achieve net zero [5].

In addition, the modular method of construction are often considered as safer (by relocating most jobs into a sheltered/controlled factory environment and eliminating most work at height) and of higher quality (better quality control of a production line). There also can be societal benefits of changing jobs from needing travelling worked temporarily on site to being close to home.

3. Design requirements of modular buildings

A reliable design guideline for modular structure is necessary to further reduce the overall project cost and completion time [6]. In modular construction, typically two design approaches such as load bearing wall modules and corner supported modules are followed for concrete and steel respectively. The current design approach is considered traditional limit state design criteria based on strength and serviceability. When introducing new materials in modular construction, the overall public perception is that the modular components do not satisfy the minimum standard requirements as their long term performance is still unclear. To ensure a safe design, all possible loading circumstances should be considered. The short-term loading generated during manufacturing, assembling and transporting modules may affect load-transfer mechanisms, the unavoidable fact which is different from the traditional construction.

Moreover, a different set of equipment is required for on-site assembling when compared with traditional construction method. The influence of on-site installation must be taken into consideration. Because of this variability, the design guidelines for traditional construction might not be the best option for modular buildings. Therefore, developing suitable design strategies for modular structures is essential as the 80% of the building operational costs is dependent on the design stage [7]. Handbooks were developed for the design of modular structures around the world [5, 8-10]. These handbooks are intended to provide technical guidance for modular construction and design to meet the expectation for different stakeholders. Although it is promoting the uptake of safe and high quality modular structures, the design and selection of materials need to comply relevant standards and industry best-practice. Table 1 summarised relevant guidelines and standards that are currently being used around the world.

Table 1: Relevant technical guidance and standards used for modular construction

Regulations	Services	Relevant codes/standards used in Australia
Design	Handbook, UK	The modular housing handbook – Bayliss and Bergin, 2020, UK
	Book, UK	Design in modular construction – Lawson et al, 2014, UK
	Handbook, USA	Prefab architecture: A guide to modular design and construction – Ryan E. Smith, 2011, USA
	Handbook, Australia	Handbook for the design of modular structures - Murray-Parkes et al., 2017, Australia

The design of structure in a particular region is highly dependent on their temperature and moisture. To ensure efficiency and longevity of the structures, different building techniques including safe materials selection, cost effective and energy efficient design approach need to be considered for different temperatures, moisture and extreme weather. Understanding the climate zone map is therefore important. Fig. 2 is showing an example of the climate zone map for Australia while the design requirements for different climate zone is provided in Table 2.

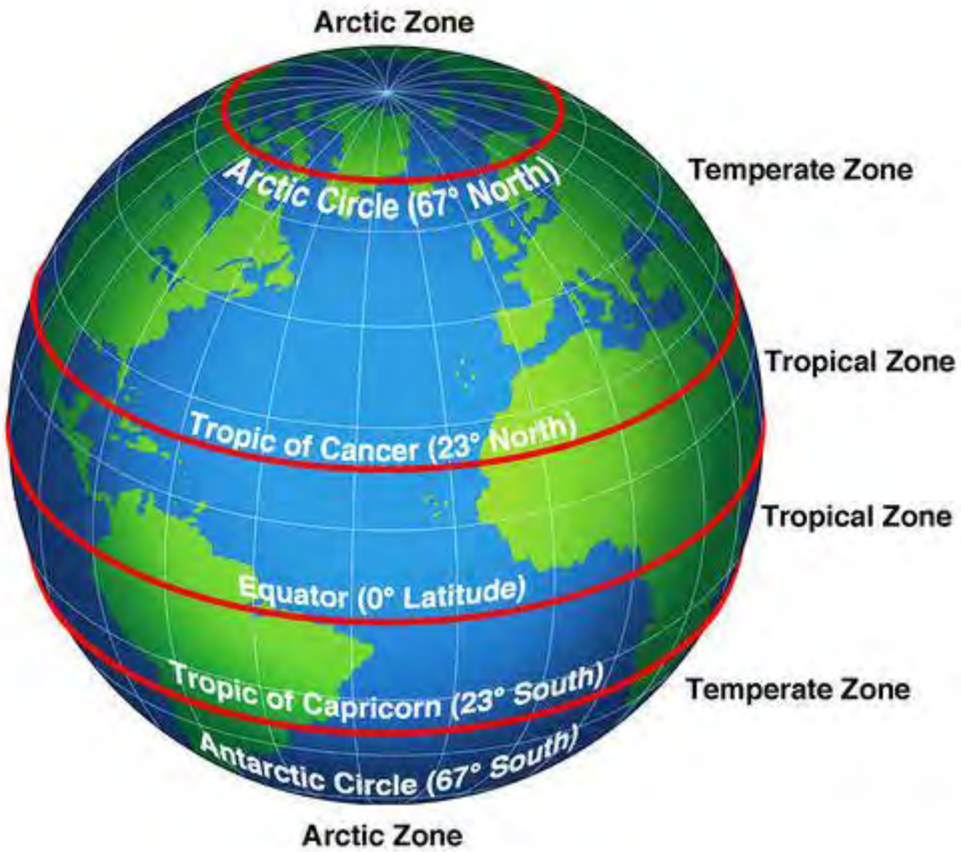

Fig. 2: An example climate zone map [11]

Table 2: Design requirements for different climate zone [12]

Climate zone	Tropical	Sub-tropical	Hot arid	Warm	Cold
Description	Warm winters, hot humid summers, and high summer rainfall	Mild winters and warm humid summers	Cold winter nights and hot dry summers	Cool winters and warm summers	Mostly cold temperature during the whole year
Average Temperature, ^{o}C	25 to 32	22 to 30	20 to 35	16 to 30	-3 to 10
Design aim	Cool the interior all year round	Provide some warmth for winter and cool the interior for summer	Complex design issues due to the seasonal extremes	Warm in winter	Warm in the whole year
Building materials	Lighter materials, such as metal and timber	Combination of lighter and denser building materials	Combination of lighter and denser building materials	Denser materials, such as brick and concrete	Denser and high insulation materials
Design consideration	Allow for good ventilation, high ceilings, well-insulated and ventilated roof	Allow for good ventilation, high ceilings, insulate walls	Allow for good ventilation, high ceilings, light-coloured walls and roof, reduce east and west facing windows and walls	Allow for good ventilation, high ceilings	Slippery and sloped roofs, right number of windows, lower ceilings, darker colour of roofs and walls

4. The future of modular construction

4.1. Modular construction market

The global market size of modular construction is projected to increase to US$108.8 billion at a compound annual growth rate (CAGR) of 5.75% from 2020 to 2025 (Fig. 3) [13]. The North America, Europe and Asia-Pacific regions will continue to dominate modular construction market while the interest will grow in South America, Middle East and Africa. The cheap labour and acceptance of lower quality buildings providing an effective barrier to entry in these markets. Modular construction can claim $130 billion of the market by 2030 in USA/Europe, bringing an annual cost savings of $22 billion that would help fill a productivity gap of $1.6 trillion reported in 2017 [4].

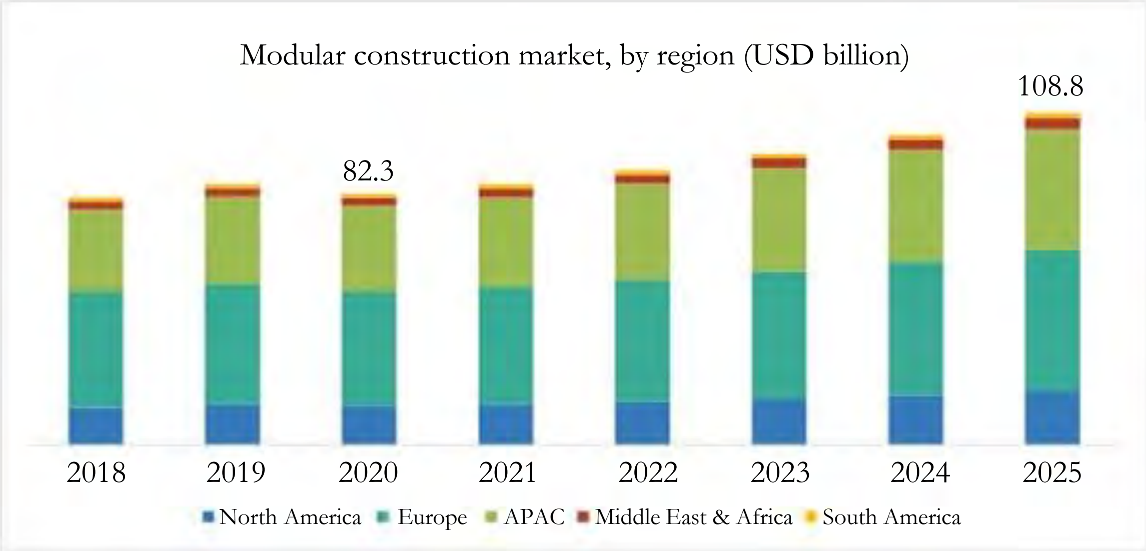

Fig. 3: Prediction of modular construction market by region [13]

The sustainable modular construction is estimated to dominate the market in near future [13]. Currently, steel holds the largest share in modular construction market due to its design flexibility, high strength, structural integrity and fire resistance that minimising maintenance cost. Moreover, steel frames are easier and safer over timber-framed relocatable buildings due to their superior structural integrity. The United Kingdom is one of the leading markets for modular construction that is projected to increase twice by 2025 compared to 2014 (Fig. 4). The largest application of modular buildings is within the residential sector followed by commercial, industrial, healthcare and educational sectors as shown in Fig. 5. However, the healthcare sector is predicted to be the fastest-growing modular construction market for the next few years [13]. The transportation route and method can play an important role for future growth of modular construction market.

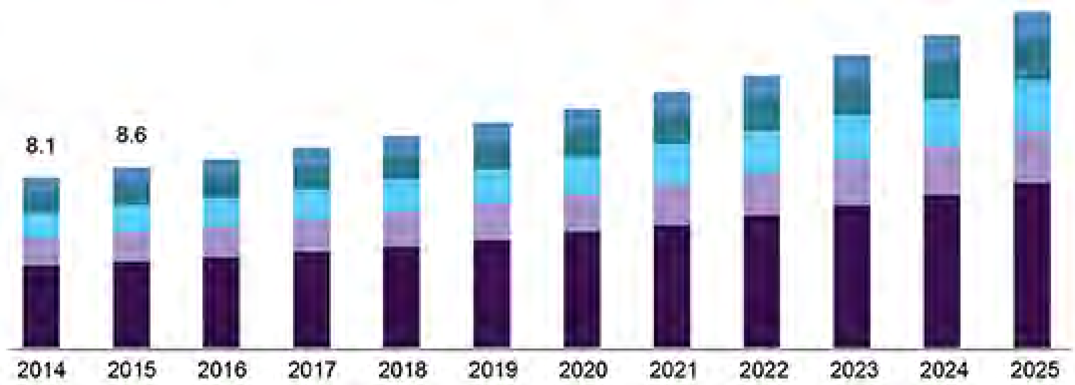

Fig. 4: Modular construction market size in the United Kingdom by application (USD billion) [14]

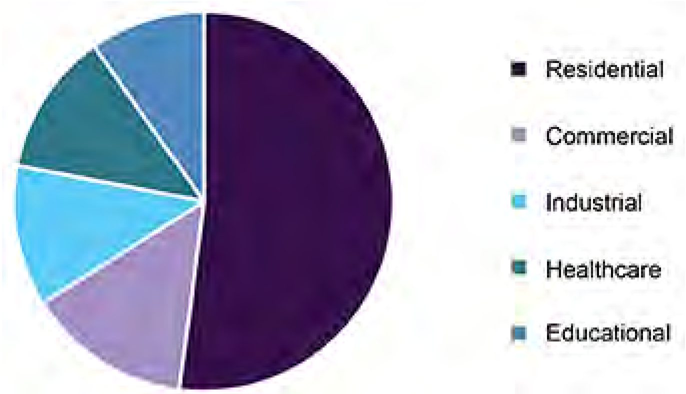

Fig. 5: Global modular construction by application, 2018 [14]

4.2. Cost analysis

High initial cost is required to establish manufacturing plant for prefabricated modules [15, 16]. Based on the opinion from 100 UK house-builders regarding modular construction, Pan et al. [17] reported that the high initial cost is one of the challenges to promote modular construction. For example, Laing O'Rourke has invested 104 million pounds on a modular construction facilities while L&G spent 55 million pounds for setting up a factory [18]. Jaillon and Poon [19] mentioned that the high initial capital is a major barrier to prefabrication in a dense urban area. Mao et al. [20] indicated high initial cost is one of the top three major challenges for modular construction.

A proper planning, economic design process and advanced manufacturing can reduce the total cost of modular buildings. For example, automated manufacturing process for fabricating numerous modules simultaneously can save on materials, labour and transportation costs [21, 22]. The operational costs of a building can be minimised by microgrid integration and thermal comfort [23]. In addition, the low interest on borrowed capital, savings on consultants' charges because of standard modules, quick start-up of the owner's business are also expected to reduce the high initial cost of modular construction. Most importantly, the faster construction and lower on-site labour costs than conventional construction method can offset the high initial cost of modular construction. A comparative analysis between traditional and modular construction costs in different construction phases are illustrated in Fig. 6. This analysis showed that there is an opportunity to save up to 20% project cost if conventional construction is replaced by modular construction. On the other hand, the modular construction project cost may increase up to 10% if savings from labour cost are outweighed by materials or logistics costs. Another breakdown cost comparison between site-intensive and modular constructions based on the different activities is shown in Fig. 7. Depending on the design, materials and custom features, the cost of modular buildings can be approximately $2500 to $3000 per square meter [24].

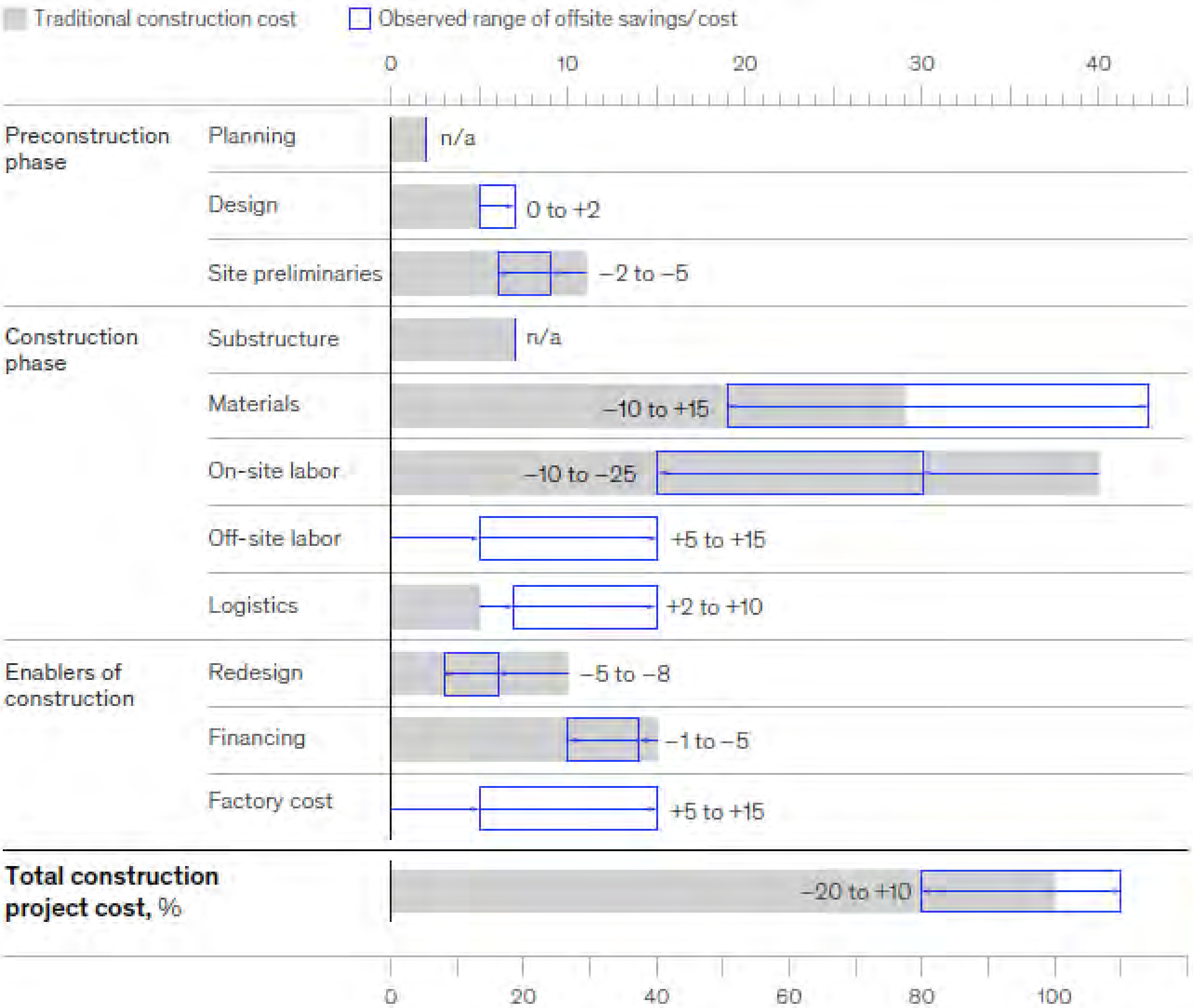

Fig. 6: Project construction cost: traditional vs modular [4]

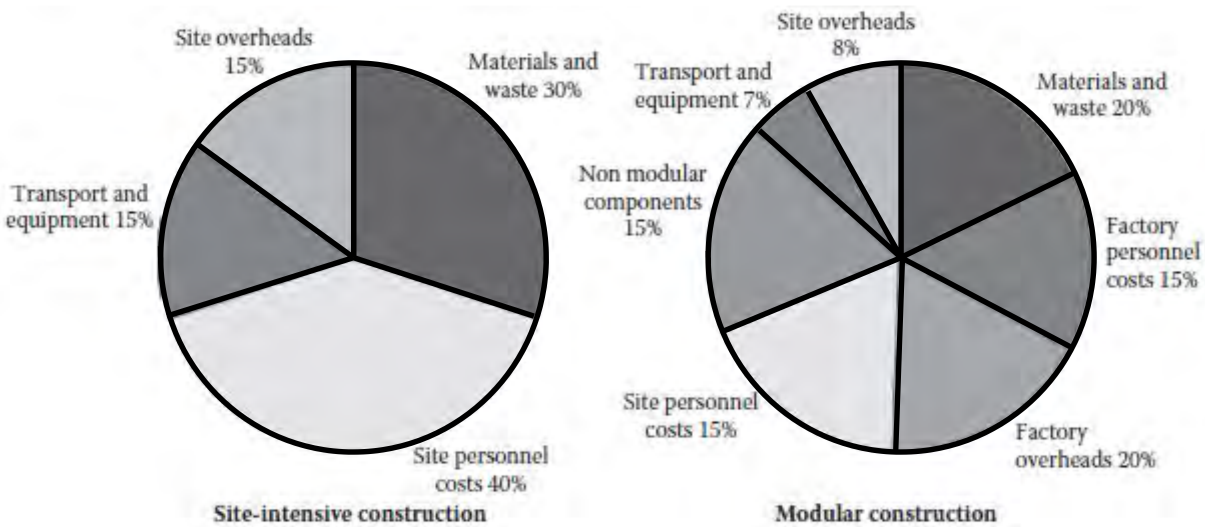

Fig. 7: Breakdown cost comparison: traditional site-intensive vs modular construction [5]

5. Case studies of modular constructions

Currently, the modular housing is sharing 45% in Finland, Norway and Sweden, 15% in Japan, 10% in Germany, 6% in China, 5% in Australia, 5% in UK and 3% in US of the total new building construction [4]. Fig. 8 illustrates the position of different countries in terms of supply and demand of modular structures. The both supply and demand for modular structures are increasing in Australia due to their high construction cost and great unmet demand for buildings. Similarly, the raising construction wages in skilled labours have driven a recent shift towards modular construction in the western United States. Approximately 20 to 30 thousands units per year were built in Singapore while 15 thousands new homes were constructed in 2018 using modular construction in UK [4]. With an increased housing demand and labour shortages in the construction trade, modular construction gains traction in markets with higher housing demands and labour shortages. To meet the UK's housing needs, another 300,000 units must be built every year. Surprisingly, the current supply and demand in Germany is appearing low. This is perhaps due to their construction strategy where the buildings are mostly constructed by private households that can make a difference in the dynamics of construction market. Technology advancements such as robotisation and 3D-printing make modular construction more productive and environmentally friendly. By reusing and controlling construction space, modular construction reduces wastage of raw materials without compromising the integrity of the building. The growth of the market is driven mainly by infrastructure investments and government initiatives; however, the rising offset manufacturing investment and financial crisis may be challenges.

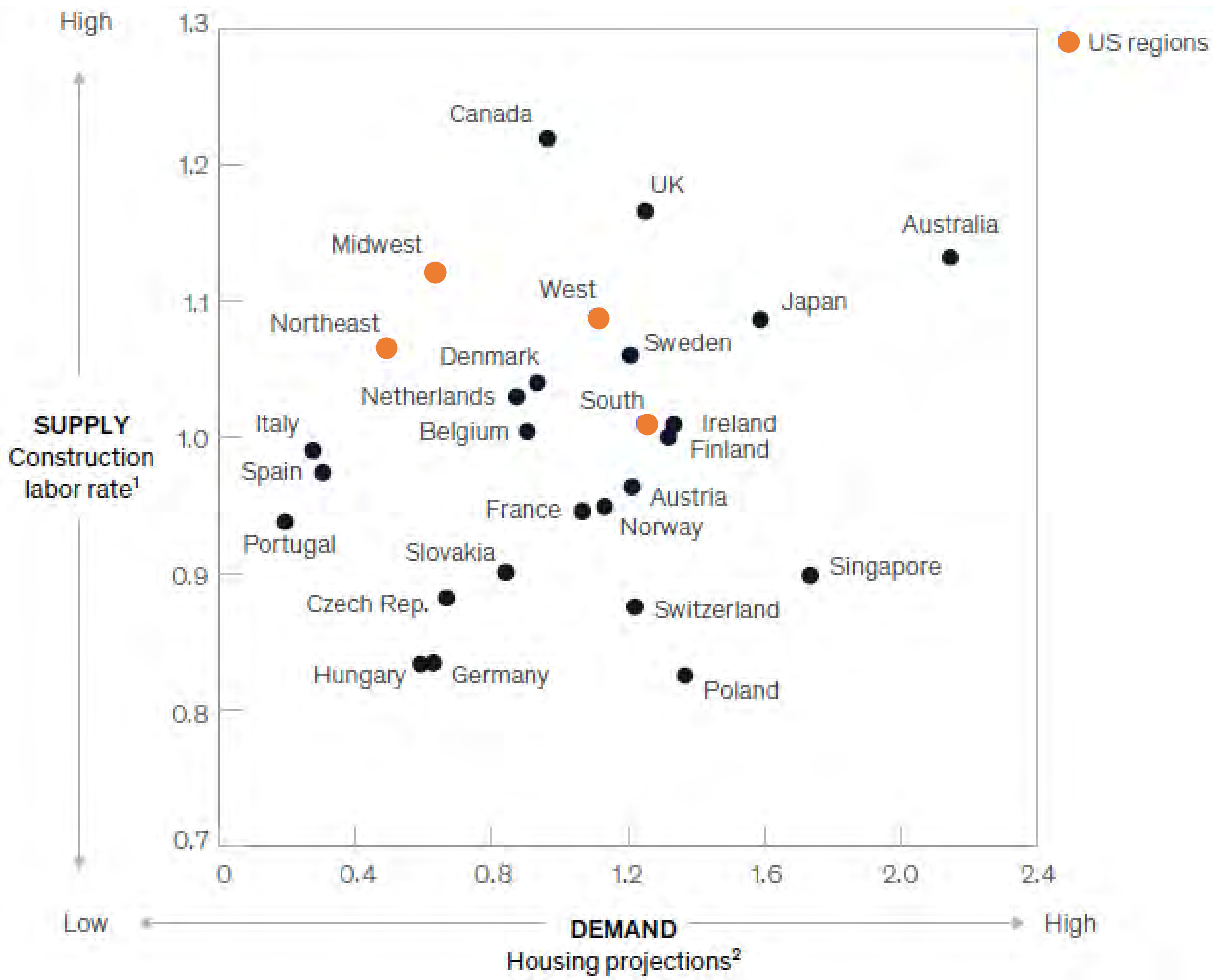

Fig. 8: Construction labour supply vs near future demand for new housing [4]. [1]Construction wage-to-national median wage and [2]2017–20 average housing projection as a percentage of national housing stock

Residential and commercial are the two broad categories of buildings. The key difference between these two categories are provided in Table 3. A high number of residential and commercial buildings are constructed around the world using modular construction. The case studies for residential houses and commercial buildings are discussed in the following subsections.

Table 3: difference between residential and commercial buildings

Key differences	**Residential**	**Commercial**
Purpose of construction	Designed to be lived in	Used for business activities
Building materials	Generally, timber frame construction	Generally, steel frame construction
Codes	Simpler and easier regulations than commercial	Stricter regulations than residential
Cost	More expensive due to the increase of overhead, labour, and equipment cost	Less expensive due to bidding process and the use of specialised equipment
Example property	Living houses	Office buildings, apartment complex

5.1. Case studies for residential houses

Residential houses are generally low-rise buildings. Sometimes they can be constructed to fulfil different objectives. Marmol Radziner constructed a house in Desert Hot Springs, California using modular construction [25]. This building was constructed on a five-acre land that includes two-bedroom, two-bath and capture the natural views of San Jacinto peak and the nearby mountains. The additional covered outdoor areas provided extra living spaces and a separate modular carport allows the residents to leave the car behind as they approach into the building.

Atelier Tekuto designed the A-ring house in Kanazawa, Japan with the aim to reduce energy costs [26]. To achieve this goal the builders used special aluminium components that can reflect lights, enhance energy efficiency and reduced energy costs. The water pipes are installed through the interior that is not only providing structural support but also acting as a temperature control system for heating and cooling.

Archipelontwepers designed the Steel Study House II in Leeuwarden, The Netherlands [27]. The design concept of this building is based on the lightweight modular components that combines modern urban design with simplicity to build a cost effective prefab housing project. This type of design generates less waste and represents the high potential of modular construction project.

The innovative floating home in Seattle was constructed in a nearby shipping yard before it placed permanently in Lake Union [28]. This type of arrangements is offering unparalleled views for the residents. The lower level is constructed with ceramic panels and frosted glass, while ceramic surfaces and teak wood were selected for the upper level. The exterior materials were selected in such a way that ensures longevity and ease of maintenance.

Portable modular homes or relocatable homes are also available for supporting the needs for urban, rural and regional housing. This type of buildings are compact, cheap and lightweight [29]. Some special features such as overhead cupboards in kitchen, full carpet throughout, built in robes and stainless steel appliances are also available. A brief summary of the different types of modular residential houses are provided in Table 4.

Table 4: Summary of the case studies for residential houses

Objectives	**Location**	**Special features**	**Example houses**	**Ref**
House in desert	Desert hot springs, California, USA	Outdoor in-ground pool, fireplace, solar panels and sustainable design solutions		[25]
Reduce energy costs	Kanazawa, Japan	Aluminium components to enhance energy efficiency by reflecting LED lights, interior water pipes offer a thermal radiation system for cooling and heating		[26]
Lightweight house	Leeuwarden, Friesland, The Netherlands	Built with lightweight components, generate less waste and are easier to construct than traditional homes		[27]
Floating house	Lake Union, Seattle, Washington, USA	Offering unparalleled views		[28]

Portable house	UK	Compact living spaces, low cost, lightweight, and portable		[29]

5.2. Case studies for commercial buildings

Modular construction is the most suitable construction method for structures with repeated units such as apartments, offices, hotels dormitories, hospitals and schools [30]. A large number of tall modular buildings are constructed around the world in the past decade. The 57-storeyed J57 Mini Sky City was constructed in just 19 days in China [31]. The modular construction method for J57 eliminated the use of up to 15,000 concrete trucks that reduced a significant volume of construction dust associated with traditional construction processes. Moreover, it has been claimed that the construction method also saved 12,000 metric tonnes of carbon-dioxide emissions. The 208m tall building was fabricated using steel due to the design flexibility, strength, rapid construction and accuracy.

In Singapore, the Clement Canopy is a prominent modular building completed in 2019 [32]. Approximately 85% work of each module was completed off-site before assembled onsite. This includes such as doors, window frames and glazing, painting, wardrobes and MEP (mechanical, electrical and plumbing) including sanitary and water pipes, which all are totally completed before bringing them on site. This construction process reduced onsite waste by 70% and offsite waste approximately 30%.

In UK, the modular construction is becoming popular and currently more than 7.5% of the new homes are constructed using this method. The noticeable modular buildings are Croydon Tower in London [33], Apex House in Wembley [34] and Victoria Hall in Wolverhampton [35]. The pre-fitted, pre-wired and pre-plumbed modules (i.e., around 95% completed modules) were installed in Croydon Tower immediately after finishing concrete core. The lifting and placing of prefabricated modules in Apex House took only 10 minutes per unit. The rapid construction process saved the project completion time by 50%, compared to the equivalent steel-framed or concrete-framed tower. Instead, the ground floor of the Victoria Hall was site built and the remaining floors being assembled using prefabricated modules.

In Australia, the Collins House [36] and La Trobe Tower [37] are the significant prefabricated buildings. Each storey of Collins House contains a 150 mm thick floor, precast post-tension beams and a prefabricated facade. Precast stairs were also built in factory. To avoid the usual disruption during day-time, the construction of the 3D volumetric components with integrated facades for La Trobe Tower organised at night while the internal fittings were completed during day-time. This system reduced the construction time by 9 months.

In USA, the Tower B2 in Brooklyn [38] and AC NoMad in New York [39] are the two significant modular constructions. Tower B2 was constructed with 930 prefabricated steel modules with 17% lower cost compared to conventional construction. Similarly, each steel module in AC NoMad comprised with guest room, flooring, bedding, even toiletries and the rooftop bar is also concepted using prefabricated modules. However, the public areas, such as the lobby and restaurant are constructed using conventional construction methods. A summary of the notable commercial modular buildings is provided in Table 5.

Table 5: Notable commercial modular buildings around the world

Height, (m)	**No. of storey**	**Name and location**	**Year completed**	**Completion time**	**Service**	**Ref**
208	57	J57 Mini Sky City, Changsha, China	2015	19 days	Atriums, apartments and office space	[31]
184	60	Collins House, Melbourne, Australia	2019	30 Months	Residential tower	[36]
140	40	The Clement Canopy, Singapore	2019	30 Months	Commercial flat for residents	[32]
135	44	Croydon Tower, London, UK	2018	35 weeks	Commercial flat for residents	[33]
133	44	La Trobe Tower, Melbourne, Australia	2016	16 months	Residential tower	[37]

109	32	Tower B2, Brooklyn, USA	2015	-	Commercial flat for residents	[38]
109	26	AC NoMad, New York, USA	2020	-	Hotel	[39]
83	29	Apex House, Wembley, UK	2017	12 months	Student accommodation	[34]
77	24	Victoria Hall, Wolverhampton, UK	2009	27 weeks	Student accommodation	[35]

6. Innovations in modular construction

6.1. Opportunities with composite materials

Researchers around the world are now exploring the acceptability of fibre reinforced polymer (FRP) composites and laminated veneer lumber (LVL) as alternative materials to replace timber, concrete and steels in modular building applications [40-44]. Griffith [45] indicated that the lack of knowledge on the behaviour of new materials is responsible for underestimating their properties in prefabricated building components. However, in one particular example FRP was used to construct a 5 story office building justified the credibility of FRP composites for low-medium rise buildings [46]. FRP modular buildings are expected to design by considering the load bearing wall module system. Therefore, the mechanical performance of a modular composite wall system ensures the suitability of this technology in modular building construction [47]. An investigation on the static performance of a modular FRP sandwich slab system showed that the bending stiffness can be engineered as per design requirements [41]. The post-fire mechanical performance of prefabricated fire-resistant panels has indicated that the modular composite slabs are able to sustain around 50% of the structural stiffness and strength after 90 minutes of fire exposure [48]. FRP composites has also shown great potential to resist impact loads and corrosion [49, 50]. These are some of the evidence that the FRP will take the lead for future materials in modular constructions.

6.2. Future opportunities

FRP composites and laminated timbers are offering several advantages over the traditional construction materials. The challenges of using FRP and laminated timbers in construction need to be addressed that might open the door for future research opportunities. The long term behaviour of composite modular structures under extreme loading conditions need to be investigated to ensure reliability and safety during the design lives. The short-term (e.g., transportation and handling) and long-term (e.g., fatigue and durability) imposed action need to be considered for the design of modules.

The sustainability of modular structures and life cycle cost analysis are the two major areas where only limited information are available. The expected lower life cycle cost due to the use of FRP that requires less maintenance than traditional constructional materials may offset the high initial investment cost of modular constructions. The brittleness or low ductility of the FRP materials can be a challenge for utilising composite materials in construction, however, a suitable design guideline may overcome this issue. Modular building's structural integrity and performance is highly dependent on the inter-module connections. Some potential connections systems are exist but developing a reliable connection system is still a challenge [2]. The limited information on fire performance of the composite materials are also restricting their reliable application. In addition, the manufacturing of lightweight and durable modular units, smart connection system, suitable computational tools and reliable design provisions are the key challenges for next generation modular buildings.

Summary

Offsite modular construction has demonstrated several advantages over the traditional onsite construction in terms of minimising construction time, reducing construction wastes, improving quality within reasonable price and more importantly minimising negative environmental impacts. Despite having significant benefits of modular construction, the private companies still relies comprehensively on the traditional on-site construction method due to limited variety of design, complex approval processes, transportation difficulties, higher upfront costs and difficult financing. However, the modular construction increased significantly all over the world in the last few years. The acceptance and application of modular construction can be increased further with the development of design provisions and in using new generation materials that can exploit the many benefits of this type of construction system. Obviously, the shorter the construction period, the less the developer's carrying costs and the quicker the project will return a profit.

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APPENDIX-C

1. FINITE ELEMENT (FE) ANALYSIS OF FLEXURAL BEHAVIOUR OF COMPOSITE WALL SYSTEM

In chapater-4, composite wall panels SF4L (without sheathing) and SA4L (with GFRP sheathing) were analysed experimentally and analytically under four-point load. In addition to that FE analysis by considering the maximum linear load was performed and it was in a good agreement with experimental results in Fig-1. FE results predict the maximum deflection of 20.80 mm at 125kN at loading points in SA4L wall panel. Whereas experimentally 23.66 mm at 125kN was recorded in SA4L. Similarly, FE results predicts the maximum deflection of 33.31 mm at 79 kN at loading points in SF4L wall panel. Whereas 39 mm at 79kN was recorded during the experiment. Fig 2 and 3 shows the FE analysis results highlighting the maximum deflections at loading points for SA4L and SF4L panels respectively.

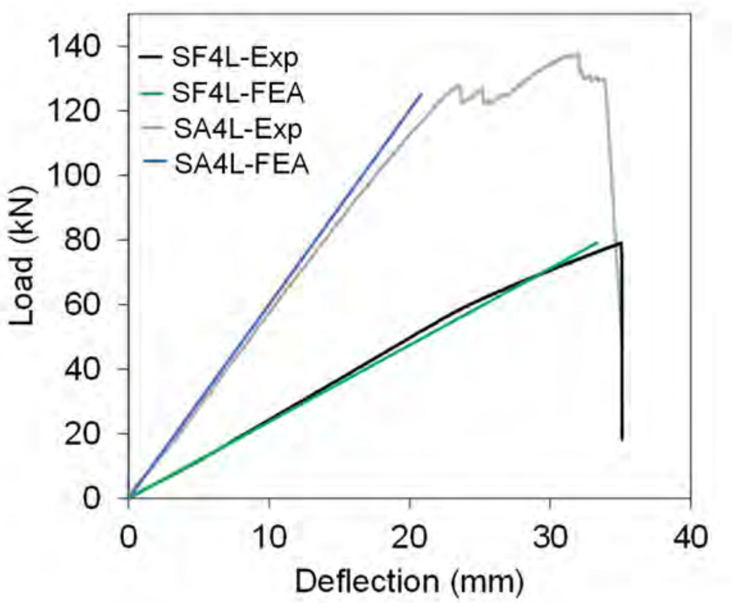

Figure 1: Load deflection behaviour of SF4L (without sheathing) and SA4L (with GFRP sheet) panels

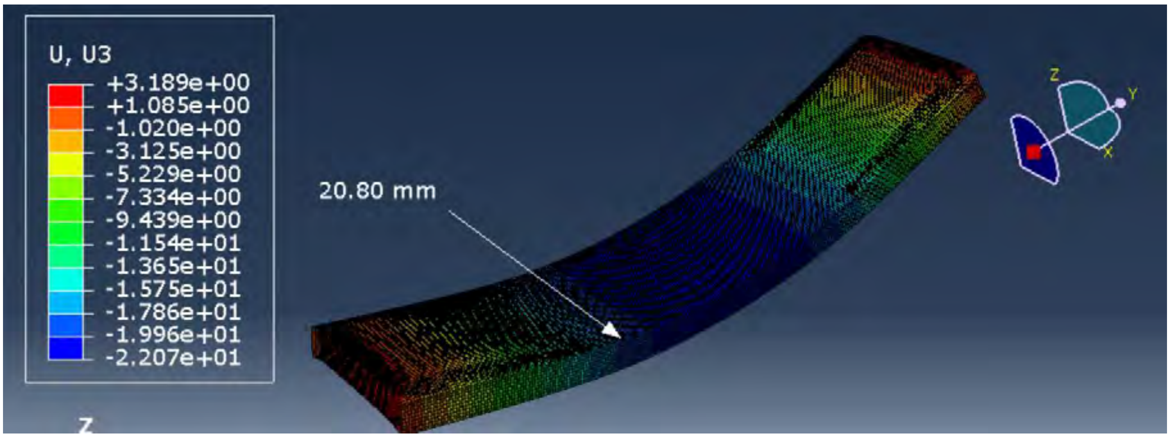

Figure 2: Deflection of SA4L at 125 kN load.

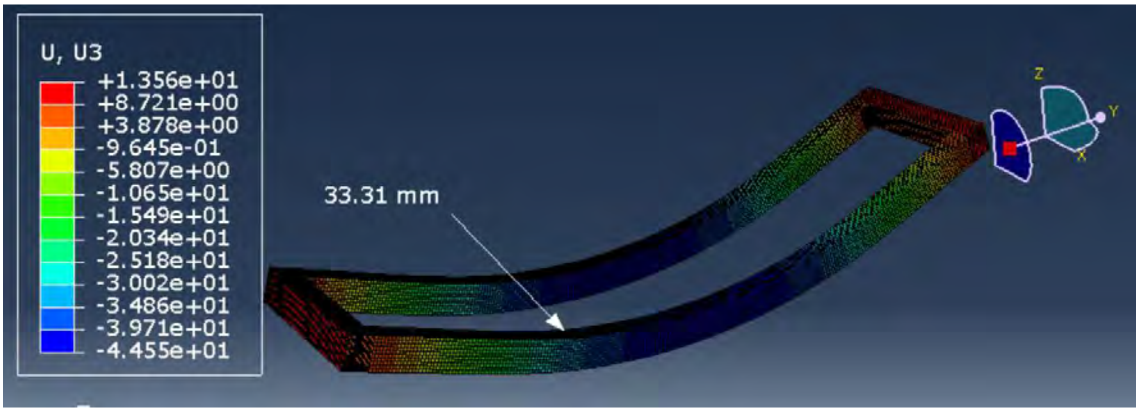

Figure 3: Deflection in SF4L at 79 kN load.

2. FINITE ELEMENT (FE) ANALYSIS OF IN-PLANE SHEAR BEHAVIOUR OF COMPOSITE WALL SYSTEM

In chapater-5, in-plane shear behaviour of wall panel $FS_{10}O$ (with opening) is analysed experimentally. The analytical equation predicted the loss of shear stiffness of wall panel due to the removal of sheathing area by opening. Fig 4 shows the experimental and FE load deflection behaviour of $FS_{10}O$ panel and has a good agreement with experimental result. Fig 5 shows the comparison of lateral deflection data captured from digital image correlation (DIC) camera and FE analysis. At 5kN experimental and FE deflection curves have good agreement and local deformation at opening can also be seen in Fig 6.

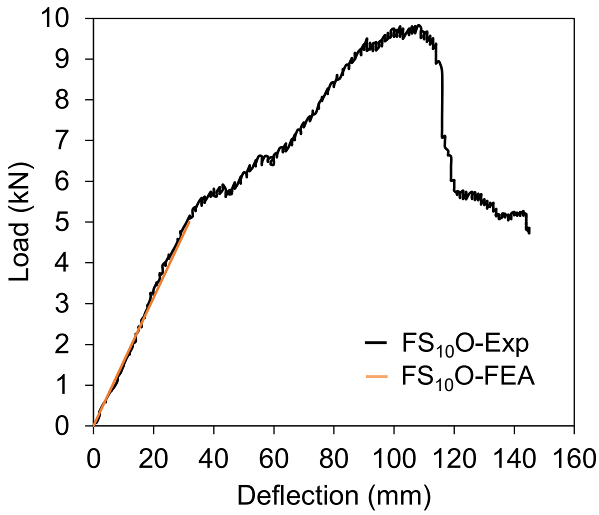

Figure 4: Load deflection behaviour of $FS_{10}O$ (with opening)

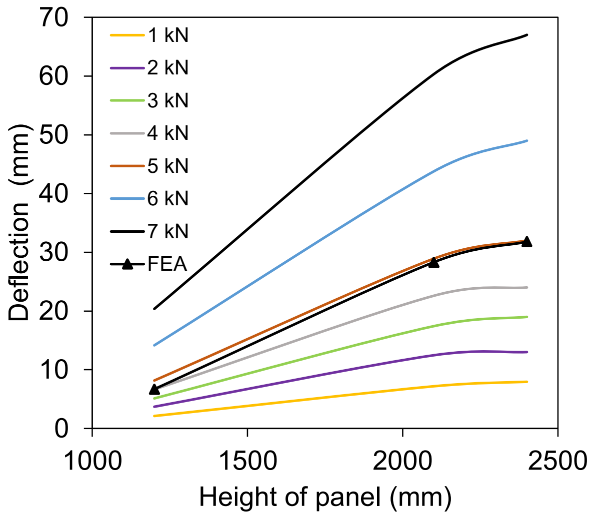

Figure 5: Lateral deformation along the height of $FS_{10}O$ panel from DIC and FE analysis

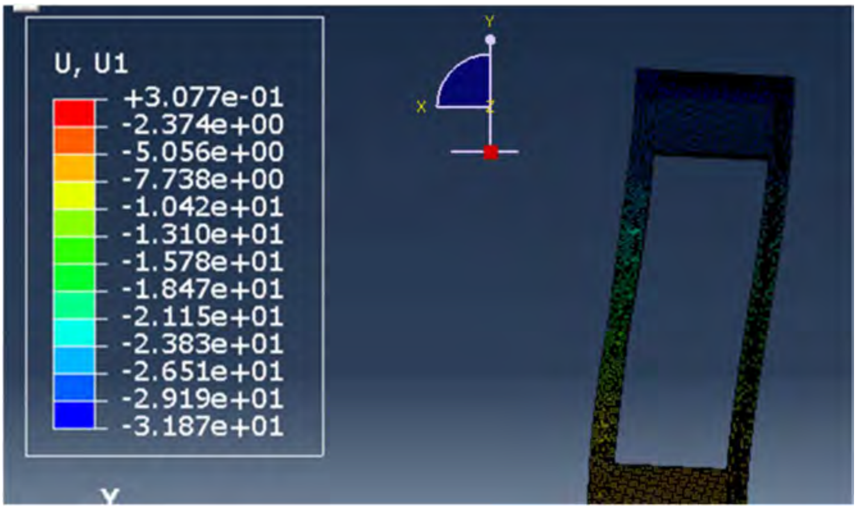

Figure 6: Lateral deformation at 5kN

Overall, linear analysis was considered in current approach, and it shows a good correlation in all loading conditions. However, a non-linear progressive failure analysis needs to be investigated further to capture the failure behaviour and predict the local failures in composite wall system.

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