Evaluation of Recycled Short Glass Fibre HDPE for Residential Structural Walls

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Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged. I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Abstract

Australia's transition to a circular economy lags behind many first-world nations, highlighting the pressing need for innovative solutions in recycling and sustainable material usage, particularly in the plastics industry. Meanwhile, the construction sector grapples with supply shortages of traditional material such as timber, driving the pursuit of alternative materials. This thesis addresses this dual challenge by evaluating the viability of recycled high-density polyethylene (HDPE) reinforced with short glass fibres (SGF-HDPE) as a substitute for timber in residential structural wall stud applications.

The suitability of SGF-HDPE in conjunction with sheathing materials, in a residential structural wall stud application was evaluated using finite element analysis (FEA) in order to:

1) reduce material from the framing material without significantly compromising the composite wall performance and
2) explore the feasibility of incorporating perforations in the web structure to accommodate water, electrical, and communication services and evaluates its performance.

It analyses the use of SGF-HDPE as a framing component in conjunction with two types of sheathing material; oriented strand board (OSB) and fibre cement. Three distinct stud profiles are investigated to enhance structural characteristics under different loading conditions, with a particular emphasis on flexural behaviour. Moreover, it evaluates the performance of the composite wall in three load scenarios; axial longitudinal direction, flexural in the sagittal direction and in-plane shear in the transversal direction.

The results of the analyses showed that the strategic positioning of perforations in the stud web can be achieved with minimal structural performance compromise. This innovation opens the door to manufacturing walls from SGF-HDPE with ample provisions for essential services such as water pipes and electrical cables. Furthermore, the contribution of sheathing to the overall performance of the wall is profound. The study also demonstrates more complex geometry can be effectively leveraged to reduce material consumption without significantly compromising performance.

This thesis provides valuable insights into the use of SGF-HDPE as a sustainable timber substitute in the Australian construction sector. By addressing resource scarcity and waste management it contributes to the domain of sustainable construction practise. The findings propose a framework for further research and development in this area and help set a course for a more resource efficient future.

1 Introduction

1.1 Background

Plastics have become an integral part of our modern society and are widely used in various applications. However, the increasing use of plastics has resulted in a surge in plastic waste, which has detrimental effects on the environment (Al-Salem, Lettieri, & Baeyens, 2009). With estimated recycling rates in Australia of plastics at 8%, a monumental increase in our recycling capacity is therefore necessary to reduce the impact of plastic waste on the environment (Ferdous et al., 2021). In addition to environmental benefits, recycling plastics also has potential economic advantages, including the creation of jobs and the reduction of raw material costs.

Civil engineers play a vital role in the development of sustainable infrastructure. The use of recycled plastics in civil engineering applications can provide a sustainable solution to the challenges posed by plastic waste. Recycled plastics have already been successfully used in several civil engineering applications, including road construction, bridge building, and wastewater treatment (Alyousef et al., 2021; Chmielowski et al., 2023; Colangelo, De Luca, Ferone, & Mauro, 2013; Enfrin & Giustozzi, 2022; Skoratko & Katzer, 2021; Zhao & Zhang, 2007).

Recycled plastics are already being used in civil engineering application, for instance; in the construction of roads. Recycled plastics can be mixed with asphalt to create a more durable and long-lasting road surface. This can result in cost savings and environmental benefits as the use of recycled plastics can reduce the amount of virgin asphalt required, which reduces carbon emissions associated with the production of asphalt (Bell, 2019).

A closer example is the use of recycled plastics in the construction of bridges. Recycled plastic timber can be used as a substitute for traditional timber in bridge construction and railway sleepers. This has several advantages, including reduced maintenance costs, increased lifespan, and improved resistance to weathering and degradation (Ferdous et al., 2015; Gou, Al-Tabbaa, & & Evans, 2019). This type of application usually utilises continuously reinforced glass fibre plastic and is manufactured using pultrusion as opposed to a short glass fibre matrix proposed by this study.

The use of recycled plastics in civil engineering applications presents significant opportunities for sustainable infrastructure development. Civil engineers can play a significant role in promoting the use of recycled plastics in civil engineering applications, resulting in both economic and environmental benefits. As such, it is essential to continue exploring the use of recycled plastics in civil engineering and promoting their adoption in infrastructure development (Jones, 2019). Residential timber stud frames are a seemingly good avenue to explore as they address current and impending issues within the construction market.

During 2017-18, Australia constructed 32,320 houses using timber as the framing material (F. W. P. Australia, n.d.). The timber frame market is subjugated to ongoing challenges with only some issues resolvable in the near term (Riddle, 2016). Specifically, the supply of timber frames is increasingly strained leading to higher prices. Ongoing concerns about durability has also led to the introduction of H2 as a minimum standard also inflating the price of the material. A larger range of viable alternatives is a desirable outcome for consumers.

There are currently challenges with this SGF-HDPE in the given application. The typical modulus of elasticity of HDPE materials can be as little as 1 GPa, while a combining this with 30-40% short glass fibre is found to increase the modulus of elasticity to approximately 3GPa at room temperature (Bajracharya, Manalo, Karunasena, & Lau, 2014). This is significantly lower than timber used for wall systems. As most composite wall designs are normally governed by serviceability limits such as deformation and not strength, it is important that the behaviour of wall systems made from this emerging material is evaluated.

This study will seek to determine potential combination of system components that can be utilised under typical loading conditions. The system of components will be limited to the configurations of studs, top and bottom plates as well as sheathing materials to improve the strength characteristics.

In addition to the optimisation of the configuration of the wall structure, the study also aims to optimise the cross-sectional profile of the stud elements of the wall structure to minimise material while maintaining performance under expected loads. It also aims to consider the ability to run serves through the walls without reducing structural performance.

1.2 Project Significance

Recycled short glass fibre composite plastic provide a relatively low cost and sustainable alternative to traditional framing materials. It will consume a material that is in oversupply throughout the world and put it into an application that is intended to be in place for a minimum of 25 years. There are sociological benefits to a material such as this being suitable for the given application.

There has been some amount of research into the construction of modular walls using similar materials such as; rigid polyurethane foam for the framing and Magnesium Oxide for the sheathing (Manalo, 2013). As well as, continuously reinforced glass fibre plastics (GFRP) as the frame and sheathing (Xeros, 2021). However, many of these material combinations exhibit the same recyclability issues. They are either not easily recyclable, or the material strength characteristics are significantly reduced from their pre to post recycled states.

Short glass fibre reinforced plastics are able to be granulated and reused with only minor variation to critical material strength properties (Bajracharya et al., 2014; Bernasconi, Rossin, & Armanni, 2007). This is significant, as in theory, materials can be taken from an end-of-life project, granulated and turned back into new material with approximately equivalent material strength properties, thus being ideal for a circular economy future. The result of this project will help shape further studies into the use of short glass fibre plastics in a circular economy building materials future.

1.3 Aims and Objectives

This research aims to evaluate the structural behaviour of a wall frame systems comprising of two different types of sheathed material; orientated strand board (OSB) and fibre cement. Using finite element analysis, it will evaluate the following behaviours:

- The buckling behaviour when subjected to uniformly distributed load in the longitudinal direction,

- The flexural behaviour when subjected to a uniformly distributed load in the sagittal direction,
- The in-plane shear behaviour when subjected to a uniformly point load in the transversal direction.

It seeks to determine the extent of the SGF-HDPE material, that constitutes the frame, that can be minimised without significantly reducing the composite wall performance. It explores more complex stud geometry with three stud profiles and determines the effectiveness of each section under the three loading conditions. It then seeks to allow services to run through the stud sections by incorporating penetrations to the web of the stud, without significantly compromising performance through an iterative process.

1.4 Expected Outcomes and Benefits

A number of research gaps exists in determining the limits of recycled short glass fibre composite in combination with a sheathing material. The gaps include; the effects of different types of sheathing material on the overall performance of the wall, how material can be limited from construction without effecting performance and how to improve the functionality of the design.

Most studies that are conducted give little consideration to the usability and cost of the type of wall construction that is being considered. While cost is difficult to evaluate due to the many factors that make it up, reducing the material required to produce a similar outcome will typically reduce cost. In addition, other studies give little consideration, if any, to the requirement to run services such as water and electricity through the wall structure and how this might impact the performance of the wall.

The expected outcomes of this research, using finite element analysis, are to determine:

- the impact on wall behaviour of OSB and fibre cement sheathing on wall system comprising of solid (78x45mm) SGF-HDPE,
- a profile of the glass fibre reinforced studs that reduces the mass of the material used and only has limited effect on the wall behaviour, or improves the behaviour,

- a perforation pattern of the web of the short glass fibre reinforced stud that only has limited effect on the behaviour of the wall.

1.5 Limitations

The finite element analysis has proved to be a valuable tool int the assessment of the structural performance of the composite wall system. However, limitation of the analysis and therefore this thesis should be considered. To mitigate these limitations this research should be complimented with physical testing and field observations during future research stages.

1.5.1 Idealised Connection Between Framing and Sheathing

The most notable of limitation exists between the idealisation of the framing members to the sheathing material, and the connection between members during the FEA simulations. In reality the connections between the aforementioned items are dependent on a number of real-world constraints. These include factors such as; workmanship, type of adhesives, fastener method and quantity etc. These complexities can lead to discrepancies between the FEA simulation and actual performance.

1.5.2 Inability to Predict Bolt Pull-Through on Foundation

Another notable limitation, particularly in the model validation section of the study, was the interaction of the foundation bolt with the bottom plate. The FEA ability to dynamically adjust material properties based on a material being crushed is non-existent using Solidworks. During the in-plane shear simulations, the foundation bolt would pull through the bottom plate and effect the deflection of the wall structure. It is postulated that this contributed to the uncertainties between the FEA and empirical studies of Manalo (2013) under in-plane shear behaviour.

1.6 Summary

The increasing use of plastics in our society has led to a rise in plastic waste, which has negative environmental impacts. Recycling plastics is necessary to mitigate these effects and offers economic advantages. Civil engineers can contribute to sustainable infrastructure development by incorporating recycled plastics in various applications, such as road construction and bridge building. For example, recycled plastics can be mixed with asphalt to create durable roads, reducing the need for virgin asphalt and lowering carbon emissions (Ma, Nawarathna, & Hesp, 2022; White, 2020; Willis, Yin, & Moraes, 2020). Additionally, using recycled plastic timber in bridge construction improves longevity and resistance to weathering (Al-Salem et al., 2009; Chandra & Kim, 2012; Jackson, Solutions, & Nosker, 2009; Nosker, Lynch, & Lampo, 2012).

Despite challenges, such as reduced elasticity at high temperatures, exploring the use of recycled plastics in civil engineering can lead to economic and environmental benefits (Shojaei, Yousefian, & Saharkhiz, 2007). The present study focuses on optimising the configuration and profile of wall structures using recycled short glass fibre composite plastic, aiming to minimise material consumption while maintaining performance. The project's significance lies in providing a low-cost and sustainable alternative to traditional framing materials, utilising oversupplied materials and promoting circular economy practices.

The research aims to evaluate the structural behaviour of wall frame systems with different sheathed materials and determine the extent to which the glass fibre reinforced plastic frame can be reduced without significant performance reduction. The expected outcomes include understanding the impact of sheathing materials on wall performance, reducing material usage, and considering the functionality of wall designs, including the ability to accommodate services. The research employs finite element analysis to achieve these goals.

2 Literature Review

2.1 Supply and Demand of Resources

As indicated in Figure 1 turnover of Australia manufacturing production has been increasing over the decades, its proportion of the national gross domestic profit (GDP) has been in steady decline (Macrotrends, 2022). Australia does not manufacture as many materials locally as it once did, and instead, like many other first world countries is becoming more reliant on low-cost labour abroad to produce its consumer goods. Without this industry, Australia lacks the facilities to efficiently reprocess recovered resources into new materials. Australia has a dismal average recycling rate of 8% for HDPE with targets to increase this number to 20% by 2025 (Government, 2021). There is a great need for innovation of the market to close this gap in the recycling rate.

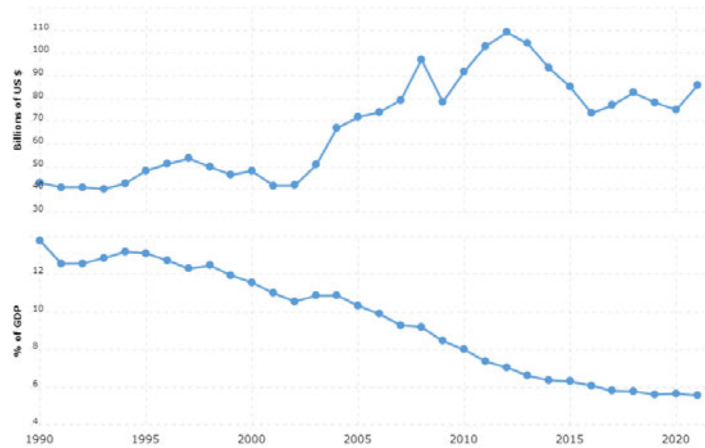


Figure 1 – Australia Manufacturing Output 1990-2022

According to Timber and Forestry News (News, 2022) there will be a timber shortage in Australia until at least 2035. Recently the Australian Government has made the largest investment of $86 million in 30 years into the timber plantation market (Duniam, 2022). However, this investment will not come to fruition for at least another 25 years. To compound matters, the invasion of Ukraine by Russia and subsequent sanctions and other difficulties associated with war will further the short supply of timber. As Russia, Ukraine and Belarus account for a quarter of the world's timber exports (Times, 2022). Furthermore, Australia is predicted to have a housing shortage for at least the next 10 years (Corporation, 2022). These coinciding factors make for a perfect storm for framing elements for a house being in short supply.

With this oversupply of recovered HDPE's and an undersupply of timber forecast for decades to come, this obvious question should be asked; what timber products could be replaced with recycled plastics? The purpose of the proposed research project is to determine the suitability, both economically and structurally of a composite HDPE material as a replacement to timber stud frames in a residential application.

2.2 Timber as a Building Material

Given the intent of this study is to determine the viability of recycled short glass fibre composite plastics in a wall stud application in a residential housing application, it is useful to consider the status quo material; softwood timber. Timber has a long history in Australia as both a structural and non-structural material. Although it took some twenty years for the first settlers of Australia to realise the timber species found in Australia were more useful than 'of little use, not fit for building either houses or boats' (Melbourne, n.d.). Timber has been used to build houses in Australia for over 200 years now.

Typical grades used in Australian residential timber frame applications are machine grade pine (MGP) 10 and MGP 12. These grades have specific minimum performance characters as classed by Table H3.1 of Australian Standards AS 1170.1-2010. The two attributes this study will focus on are:

- The modulus of elasticity (parallel to the grain for timber)
- Tension parallel to grain

When considering the MGP 10 for 70-140mm timber respectively these figures from Table 1 are:

- 10 GPa
- 7.7 MPa

While for MGP 12 these figures are:

- 12.7GPa
- 12MPa

As a more general comparison it will also be useful to determine the weight per linear meter of timber compared to the final proposal. While not a critical attribute, weight does play an important factor in the possible acceptable of such a material in the marketplace. If the final proposal is much heavier than softwood timber, this may be seen as burdensome and is noteworthy at a minimum.

TABLE H3.1

CHARACTERISTIC VALUES FOR DESIGN—MGP10, MGP12, MGP15 & A17 STRESS GRADES

Stress grade	Section size		Characteristic values, MPa										Design density	Joint group
	Depth	Breadth	Bending	Tension parallel to grain	Compression parallel to grain	Shear in beams	Average modulus of elasticity (see Note1) parallel to grain	Average modulus of rigidity	Bearing: Perpendicular to grain	Bearing: Parallel to grain	Shear at joint details	Tension perpendicular to grain		
	mm	mm	(f'_b)	(f'_t)	(f'_c)	(f'_s)	(E)	(G)	(f'_p)	(f'_l)	(f'_{sj})	(f'_{tp})	(kg/m^3)	
MGP 10	70 to 140	35 and 45	17	7.7	18	2.6	10 000	670	10	30	4.2	0.5	500	JD5 (see Note 2)
	190		16	7.1	18	2.5								
	240		15	6.6	17	2.4								
	290		14	6.1	16	2.3								
MGP 12	70 to 140	35 and 45	28	12	24	3.5	12 700	850	10	30	4.2	0.5	540	JD4
	190		25	12	23	3.3								
	240		24	11	22	3.2								
	290		22	9.9	22	3.1								
MGP 15	70 to 140	35 and 45	39	18	30	4.3	15 200	1 010	10	30	4.2	0.5	570	JD4
	190		36	17	29	4.1								
	240		33	16	28	4.0								
	290		31	14	27	3.8								
A17	70 to 120	35	45	26	40	5.1	16 000	930	17	50	6.0	0.6	650	JD3
		45	40	24	35	4.5								
	140, 190	35	45	24	35	4.5								
		45	40	21	32	4.0								
	240, 290	35	40	18	27	3.6								
		45	40	17	25	3.3								

NOTES:

1 The average modulus of elasticity includes an allowance for shear deformation and is for short duration loading.

2 For MGP 10 grade, JD4 may be used where heart-in material is excluded.

3 The modulus of rigidity (estimated as one-fifteenth of the average modulus of elasticity) is included for the estimation of torsional rigidity.

4 Interpolation may be used to obtain properties for depths not listed.

Table 1- Table H3.1 of AS 1720.1 (S. Australia, 2010)

2.3 Material Properties and Strength Characteristics

This section aims to identify appropriate academic studies or other suitable literature that explore the mechanical attributes of differing composition of recycled plastics and short glass fibre composites. It seeks to determine a range of mechanical attributes that might be achieved in commercial application.

There are a number of studies that explore the mechanical properties of different types of plastics combined with a short glass fibre matrix of chopped strand (AlMaadeed, Ouederni, & Khanam, 2013; Bajracharya et al., 2014; Bajracharya, Manalo, Karunasena, & Lau, 2017; Ucar, 2016; Yadav, 2021). Most of these studies tend to explore the effects of increasing the amount of glass fibre content within the matrix structure in relationship to various mechanical attributes such as Youngs Modulus and tensile strength. In all of these studies, there is common agreement the more glass fibre that is incorporated into the material the more strength it inherits. These studies tend to agree that the ideal percentage of glass fibre to plastic tends to be in the 30-40% region.

One such study reviews low density polyethylene (LDPE), medium density (MDPE) and high-density polyethylene (HDPE) before and after the introduction of 20% by weight short glass fibre (AlMaadeed et al., 2013). In this study, the HDPE+GF provided superior mechanical attributes when compared to the LDPE and MDPE with the Elastic Modulus being an approximately 1.4 GPa with a standard deviation of +/- 0.1 GPa. However, this is a significantly lower Elastic Modulus of both MGP 10 and MPG 12 timbers. The tensile strength of the SGF-HDPE is just as interesting with the measured value being approximately 42 MPa as compared to about 7MPa for timber parallel to the grain. Similar results have been achieved in studies by (Somnuk, Yanumet, Ellis, Grady, & O'Rear, 2003).

Other studies explore using different plastics as the binder material. Studies were discovered that used Acrylonitrile butadiene styrene (ABS) (Yadav, 2021) as the binder as well as recycled PolyEthylene Terephthalate (rPET) (Ucar, 2016). These various studies have found variation between not only the binder material, but the glass content percentage. This part is unsurprising, however where there is a little more of an unknown factor is the fact that even studies with the same binder and glass fibre variables, there is significant variation in the material properties.

A potential manufacturing technique that could be used to form the framing members in this study is injection moulding. Injection moulding produces favourable fibre orientation and predictability of material strength. Tensile, compression and flexural modulus have been found to be 3.07, 2.48 and 3.3 GPa respectively when injection moulding 30% by weight short glass fibre with HDPE (Bajracharya, Manalo, Karunasena, & Lau, 2016b).

Composite materials like these, particularly without years or decades long testing and manufacturing development, will be prone to mechanical attribute testing variability outcomes. This can be largely attributed to the unknown variability in manufacturing and it would be assumed in a large-scale manufacturing environment that this variability of the material would be reduced over time.

To the same degree as the variability, the research type testing that has occurred on the materials is not subject to significant optimisation and improvement regimes. Therefore, it's reasonable to assume not the lowest of available figures when it comes the analysis of this study. With this consideration, the following ranges will be considered as part of the analysis:

- Elastic Modulus
  - 1.4-8.5 GPa
- Tensile Strength
  - 25-75 MPa

2.4 Deformation Due to Web Perforation

Studies have existed over recent history on the effects of web perforations primarily on steel. Due to the isotropic nature of the proposed material, steel is considered an appropriate comparison when trying to determine a suitable web perforation pattern. Web perforations are particular useful in reducing material consumption and increasing the ability to run services through the material. The waste from any holes punched into the web can be refed into the melt hopper without notable degradation of the material characteristics (Bernasconi et al., 2007).

Studies such as (Schuster, Rogers, & Celli, 1995) explored how different types of holes such as; diamond, elliptic and circular influence the shear capacity of the beams under loading conditions. For the purpose of this dissertation, only simple circular hole configurations will be considered as part of the analysis.

Having simplified the type of web opening to a circle, the magnitude of the penetration when compared to the web depth has significant impact. Previous research has indicated that when considering mid span deflection that a hole diameter to web depth ratio of less than 0.2 will yield comparable results top one without any penetration (Wang, Li, Luo, Cao, & Wang, 2022). This study did only consider penetrations at a fixed axis from the mid-point, therefore there is some scope within this research to determine if larger holes places further from the midpoint will allow for more favourable deration of deflection.

2.5 I-Beam Optimisation

The optimisation of the I-beam will be a critical component of this dissertation. A number of studies exist in exploring the optimisation of thin-walled I-beam sections, usually in respect to steel. However, the approaches used in the optimisation problem and the results found for various loading cases can be utilised for this study. For instance, Ozbasaran (2018) used the crow search method to obtain an optimal geometry given some constrains, albeit that the constraints used are not all applicable to this problem. In this method, the web depth was constrained within bounds, however with a stud wall, the web depth will need to be constrained at 70 an 90mm to fit convention. A research gap exists in determining the optimal I-beam profile of the given material to suit the expected loading conditions of a residential wall.

Ozbasaran (2018) explored optimal I-section beam design, concluding that a stress constraint is possible to be the dominating factor of a cantilever beam under distributed force (Ozbasaran, 2018). This is a of particular interest because of the low yield strength of the nominated material may show a dominant buckling mode of failure. A research gap exists in the knowledge of the suspected mode of failure under the loading conditions expected of the SGF-HDPE.

2.6 Sheathing Materials

Sheathing can have significant effect on increasing the flexural capacity of a wall system. According to (Sharda et al., 2023a) when sheathing a GFRP wall with GFRP sheathing the flexural modulus increased by more than double. However, the study also concluded the sheathing has little effect on the flexural stiffness. This is likely attributed to the fact that both the sheathing and GFRP were made of the same material. Therefore, there was no increase of the modulus of elasticity of the material and due to the material being relatively thin, there was little increase of the moment of inertia to be considered significant.

While studies exist for comparing the effects of sheathing materials in seismic areas and illustrates the improvements to design that are possible with different sheathing products (Accorti, Baldassino, Zandonini, Scavazza, & Rogers, 2016). There is a research gap in determining the impact of high strength sheathing materials in comparison to a framing material with a relatively low modulus of elasticity. There is a lack of understanding as to what degree the sheathing material can be used to improve the performance of the wall structure under loads considered in this study.

2.7 Recyclability of Materials

Although the intended application of the framing material is one that should have relatively long in service life span, it's end of life reusability is a factor that needs consideration. The most ideal scenario for this type of material at the end of life is that it could be granulated, remelted and injected to form a new product. However, this process will degrade the material to an extent (Kudrathaya, 1996). Diluting the material that has been recycled multiple times with virgin materials will limit these degradation effects (Bajracharya, Manalo, Karunasena, & Lau, 2016a).

Other studies have found have limited degradation effects via the process of granulating and remelting glass fibre reinforced with different types of plastics (Bajracharya et al., 2014; Bernasconi et al., 2007). The main limiting factor would seem to be how the glass fibre length is shortened during the granulation process, monitoring the composition of fibre length can lead to more certain outcomes of strength characteristics. While the end of use is not a primary focus of this study, these studies do show promise for the potential for true circular economy type of products. More research is required in this area to develop this potential fully.

OSB as a sheathing material has a particular advantage as it can be manufactured from other end of life timber product that are chipped and used for the manufacture of the OSB (Nguyen, Luedtke, Nopens, & Krause, 2023). Moreover, other waste stream materials can be incorporated into the manufacturing process to improve other properties such as hydrophobic allowing for an even more sustainable product (Ayrilmis, Buyuksari, & Avci, 2009).

2.8 Degradation

SGF-HDPE can undergo a number of temporary or permanent degradations under certain conditions (Bajracharya et al., 2017). These conditions include:

- elevated temperatures,
- UV radiation,
- hydrothermal.

Of particular concern to this study is the effect of degradation under heat. With the instances of ambient temperatures exceeding 40°C expected to increase in coming decades the considerations of the effects of heat in the mechanical strength of the framing material is critical (LittleShrub, 2019; Melville-Rea & Verschuer, 2022). The other effects of UV and hydrothermal are considered less impactful in the scope of this study as the framing material will be concealed and in a relatively dry environment.

The tensile modulus of HDPE reinforced with 30% short glass fibre sees a decrease of 35% at 60°C and 45% at 80°C (Bajracharya et al., 2017). Therefore, consideration of the material strength characterises at elevated temperatures will be undertaken during this study as it is more representative of the operating environment of the materials. This study will use the material properties as indicated in Figure 2 for an elevated temperature of 60°C.

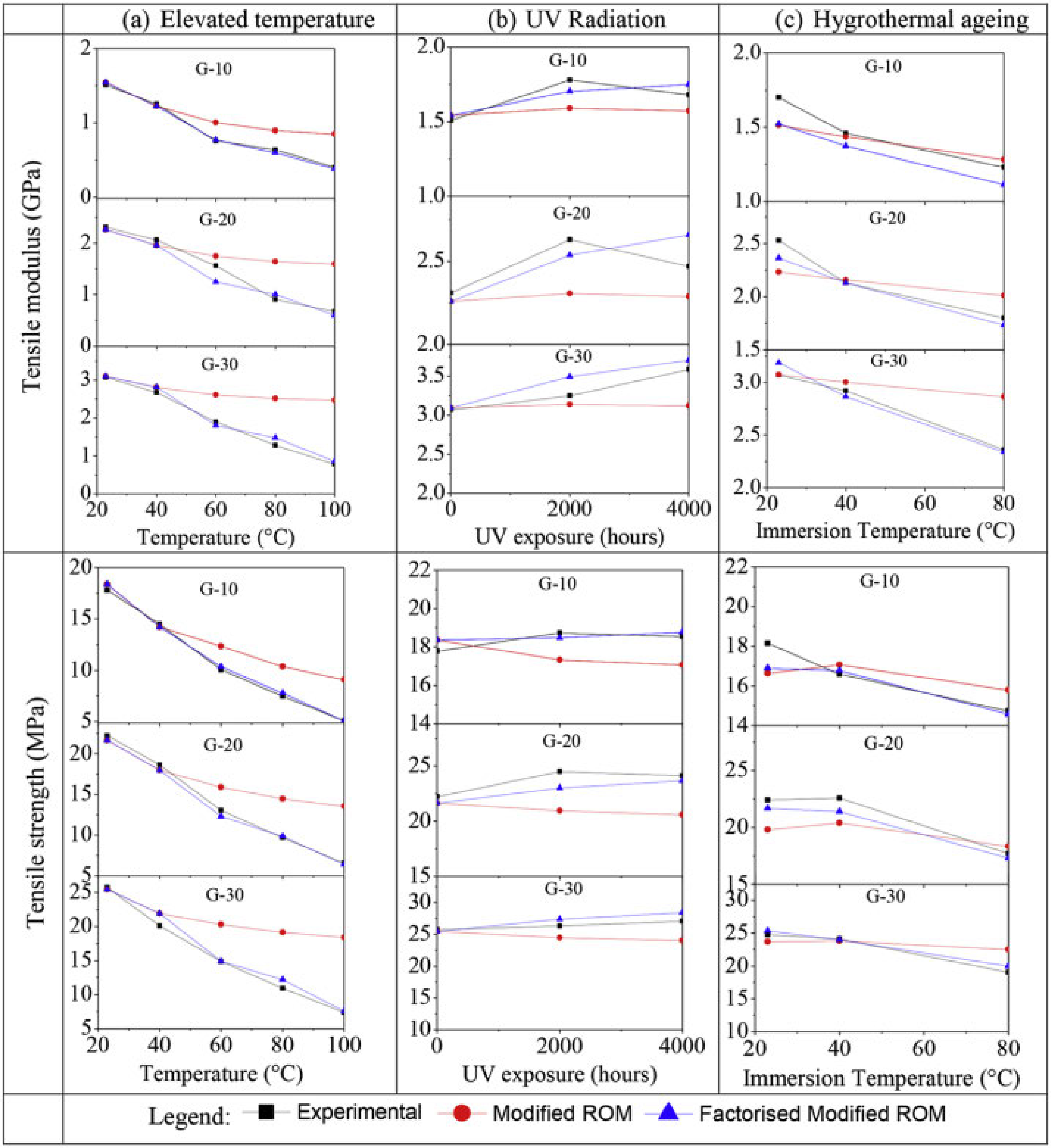


Fig. 14. Comparison of experimental and modified ROM peak tensile stress.

Figure 2 – Material Strength Properties Under Different Forms of Degradation (Bajracharya et al., 2017)

2.9 Finite Element Analysis of Modular Walls

This section looks at existing finite element analysis of modular walls in each of the expected loading conditions under analysis.

2.9.1 FEA of Axial Capacity in the Longitudinal Direction

Similar to this study, the effects of fibre cement sheathing of 6mm were considered under axial load in the longitudinal direction have been considered by other studies (Sharda et al., 2021). In this study, the studs used continuous glass fibre reinforced rectangular (GFRP) hollow section (RHS) as the framing material as well as top and bottom plate. The main failure mode was due to the collapse of the RHS that included horizontal cracking of the fibre cement sheet as indicated by Figure 3

This study plans to use solid units of short glass fibre reinforced HDPE for the top and bottom plate as indicated by Figure 4. This type of top and bottom plate is unlikely to be subject to the same failure mode found by Sharda et al (2021) and is more likely subject to column buckling given the low modulus of elasticity.

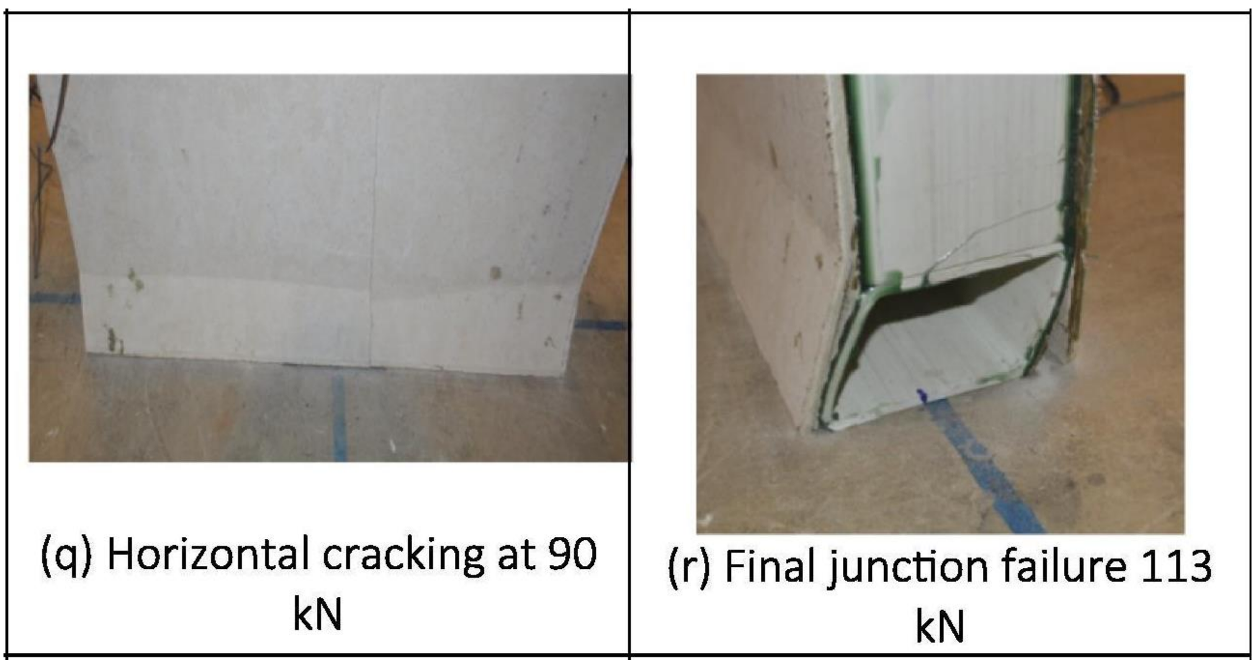


Figure 3 – Failure Mode of Fibre Cement Sheathed Wall with GFRP RHS as Framing Materials (Sharda et al., 2021)

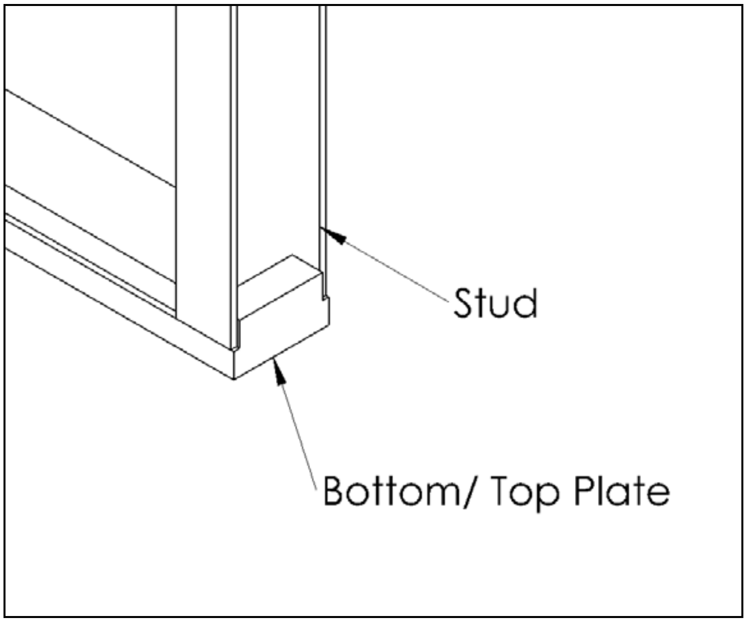


Figure 4 – Proposed Top and Bottom Plate

2.9.2 Flexural Capacity in the Sagittal Direction

Sharda et al (2023) explored the flexural behaviour of composite walls with GFRP sheathing and RHS as the framing materials through empirical experimentation. Important learning can be drawn from this research. The connection method between the sheathing and the framing material made a profound impact on the flexural capacity. An adhesive connection indicated a flexural capacity of 2.31x higher than a rivet connection (Sharda et al., 2023a). As a result, the FEA that will be conducted during the course of this study will consider an ideal bonded connection between the sheathing and proposed framing material. This will also serve as a limitation of this study as future research would be required to determine if this idealised connection is representative.

2.9.3 In-Plane Shear Behaviour in the Transversal Direction

The effectiveness of modular walls as a shear wall have studied and are considered to be dependent on a number of factors. All of the research that was considered as part of this thesis reviewed GFRP RHS used in combination with various sheathing materials.

Of particular interest to this thesis, the offset of the sheathing board 10mm from the bottom edge avoided additional compression stress in the sheathing, avoiding premature delamination failure (Sharda et al., 2023b).

2.10 Typical Services Through Walls

2.10.1 Background

The framing material of a wall has a number of functions. Other than supporting the structure and providing a structure for finishing products to be attached to such as plasterboard or cladding, the frame also needs to be conducive to the provision of services such as plumbing, electrical and communications. Any proposed framing material should have the ability to cater for services in some manner. This study will explore if perforations can be added to the web of the framing material without a significant performance degradation.

2.10.2 Electrical and Communication Provisions

Typical residential housing circuits will consist of three main types of wiring, one for lighting, one for higher amperage appliances such as cookers, and one for general purpose outlets (GPO's). Lighting will typically assume 1.5mm^2 wiring, GPO's will be 2.5mm^2 and heavy-duty appliances will be 4mm^2. Given that the higher amp appliances are only located in specific locations, the fewer provisions that are made for plumbing can be reutilised for this type of service. Therefore, general provisions for 2.5mm^2 wire would be made in more abundance, this will accommodate both 1.5mm^2 for lighting as well and for GPO's and other general comms (Pro, n.d.).

To allow for these common and abundant types of services, a minimum of 10.3mm will be required (Quickbit, 2021). Given these services need to be pulled through, friction needs to be kept to a minimum and therefore sufficient clearance for these services is required. Expanding the clearance to 13mm, or slightly greater than half inch, will reduce the friction when the wires are being pulled through during construction, but will also allow for any other half inch service to be accommodated. This diameter will also be less than the 0.2 ratio previously discussed for a typical 70mm stud.

2.10.3 Plumbing Services

The types of plumbing pipes for residential developments within Australia have evolved over the years particularly for pressure systems. Historically combinations of lead, steel, copper have been used and now increasingly plastic pipes are being used (Heathcote, 2009; Parkinson, nd). This results in their being a spectrum of pipe sizes that service a residential dwelling.

Common pressure pipes found within a residential development change based on a number of factors however, are typically in the range of 16-40mm. While waste pipes will typically be either DN 40 or DN 50 depending on application (S. Australia, 2021). Therefore, with respect to plumbing pipes, holes of up to 50mm may need to be considered for drainage.

2.11 Research Gap

While GFRP is a relatively well researched material as the framing material of a modular wall, little research exists into the performance of a wall with SGF-HDPE. Furthermore, research into the effects of using a material with and I-beam shape with a low modulus of elasticity are virtually non-existent in a composite wall system. This study aims to explore the use of the combination of these materials under three different loading conditions using FEA.

Unlike other studies of this nature, this framing material is likely to be subject to localised web failure under buckling when subjected to axial and normal forces. It is unclear how profound this mode of failure will be on the wall system performance. Furthermore, it is also unclear if adding perforations to the web will exacerbate this potential for localised failure. This thesis aims to explore these attributes.

3 Methodology

3.1 Wall Systems

The wall system's structure will closely replicate the dimensions of a traditional 90mm timber stud wall commonly used in Australian construction. Other than where required for bracing, timber frames in Australia do not typically have sheathing material attached (Timber). To ensure compatibility with other building materials such as window frames and timber trimmings, the overall thickness of the wall structure at 90mm will be maintained.

For this study, the use of 6mm OSB or fibre cement sheeting, one layer to each side, a 78mm stud structure will be considered (Figure 5). A standard typical wall height of 2400mm will be assumed including top and bottom plates. Nogs, which are often used for lateral restraint in timber stud walls, will be excluded. The sheathing is expected to act as sufficient lateral restraint in longitudinal direction.

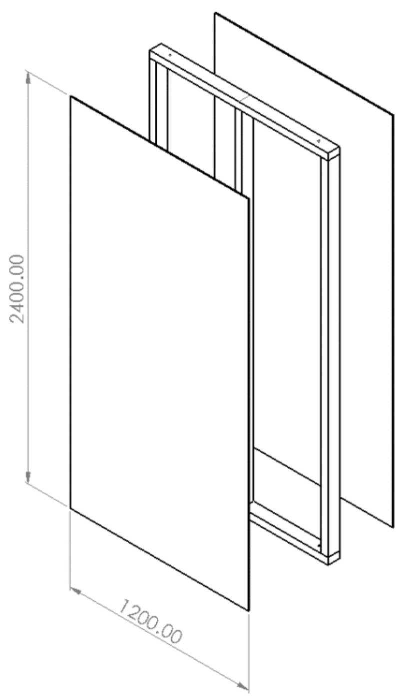


Figure 5- General Wall Configuration

3.2 Analysis Staging

The analysis of this will be broken into three stages:

1. Baseline design
2. Stud section optimisation
3. Web perforation optimisation

3.2.1 Baseline Design

Stage 1 will consider a base line substitution of materials given a similar application. It will consider the studs, top and bottom plate as if they were substituted in the place of timber studs. This will include a single top and bottom plate of 78x45mm SGF-HDPE, with 78 x 45mm SGF-HDPE studs at even centres. The frame will then be sheathed with 6mm OSB or 6mm fibre cement and analysed. This analysis will serve as the comparison to further material reduction of the stud design.

3.2.2 Stud Section Optimisation

Stage 2 will begin to reduce the material required to produce the stud sections by exploring the use of an I beam profile. It will determine is the material can be reduced for this component without significantly reducing the capacity of the wall when applied to any given load scenario. In the first instance, the I-beam shape will be determined using empirical calculations to determine the best moment of inertia for a limited volume of material. The shape will then be verified using FEA to determine any deficiencies of the design.

3.2.3 Web Perforation Optimisation

Stage 3 will explore the size and concentration of service perforations that can be assumed by the web structure of the stud section without significant deration of the capacity of the wall when applied to any given load scenario. It will take the best performing stud section from the stud section optimisation stage and then introduce web perforations to analyse the effects.

3.3 Systems Under Analysis

As discussed in the previous section, there will be a staged approach to the analysis of the wall systems. The most favourable result of the stud section optimisation will be used to move into the web perforation optimisation section.

Name	Frame	Sheathing (both sides)
Baseline O	Solid 78x45mm	6mm OSB
Baseline F	Solid 78x45mm	6mm Fibre Cement
SS1O	I beam profile 1	6mm OSB
SS1F	I beam profile 1	6mm Fibre Cement
SS2O	I beam profile 2	6mm OSB
SS2F	I beam profile 2	6mm Fibre Cement
SS3O	I beam profile 3	6mm OSB
SS3F	I beam profile 3	6mm Fibre Cement
SP1O	Profile 3 web perforation pattern 1	6mm OSB
SP2O	Profile 3 web perforation pattern 2	6mm OSB
SP3O	Profile 3 web perforation pattern 3	6mm OSB
SP4O	Profile 3 web perforation pattern 4	6mm OSB
SP5O	Profile 3 web perforation pattern 5	6mm OSB
SP6O	Profile 3 web perforation pattern 6	6mm OSB

Table 2 - Test Plan

3.4 Material Properties Used for Analysis

3.4.1 Short Glass Fibre Reinforced HDPE

Given that the material properties are bound to the temperature, a derated set of material properties will be considered for this study. The properties listed in Table 3 are approximated figures for the SGF-HDPE at 60°C and consistent with a material that has ~60-70% HDPE and ~30-40% short glass fibre by weight.

While the literature research could not find any information on the reduction of compressive or flexural strength at elevated temperatures, Bajracharya et al (2016) determined these values for 30% by weight SGF-HDPE. Where flexural strength was determined to be 48.3MPa and compressive strength 36.7MPa. An estimate deration factor of 45% was applied to both of these values for use in this study to represent material properties at elevated temperatures.

3.4.2 SGF-HDPE

Property	Value
Tensile Modulus	1.9 GPa
Tensile Strength	15 MPa
Yield Strength	10 MPa
Compressive Strength	20.2 MPa
Flexural Strength	26.6 MPa

Table 3 – Short Glass Fibre Reinforced HDPE properties

3.4.3 Oriented Strand Board (OSB)

Property	Value
Tensile Modulus – Transverse	3.2 GPa
Tensile Strength – Transverse	12.51 MPa
Tensile Modulus – Longitudinal	5.7 GPa
Tensile Strength – Longitudinal	16.8 MPa

Table 4 – OSB Properties (Islam, Islam, & Alam, 2017)

3.4.4 Fibre Cement

Property	Value
Tensile longitudinal, Ultimate stress	2.12 MPa
Tensile longitudinal, Elastic modulus	3.05 GPa
Poisson ratio, longitudinal	0.38
Tensile transverse, Ultimate stress	2.06 MPa
Tensile transverse, Elastic modulus	3.03 GPa
Poisson ratio, transverse	0.36
Compressive longitudinal, Ultimate stress	37 MPa
Compressive longitudinal, Elastic modulus	2.38 GPa
Compressive transverse, Ultimate stress	36 MPa
Compressive transverse, Elastic modulus	1.92 GPa
In-plane shear, Ultimate stress	7.70 MPa
In-plane shear, Elastic modulus	1.85 GPa

Table 5 – 6mm Fibre Cement Properties (Sharda et al., 2021)

3.5 Connections

This thesis will consider the connection between the sheathing material and framing material to use an ideal adhesive. The connection to the floor will be M20 class 8.8 high-tensile SS shanked bolts at 100mm from each end. The bolt is to have a 36mm head to the bolt.

Items	Specification
Property class:	8.8 (M20)
Minor diameter, Dc:	19.67 mm
Area of root of thread:	225 mm^2
Pitch, P:	2.50 mm
Minimum tensile strength:	830 MPa
Proof strength:	600 MPa
Minimum yield strength:	660 MPa
Minimum shear stress[a]:	514.6 MPa
Min. breaking load in single shear (Thread):	117 kN
Minimum bolt tension[b]:	145 kN

[a] Ultimate shear stress equals 62% of ultimate tensile strength.
[b] Full tightening.

Table 6 – M20 class 8.8 Stainless Steel Bolts Properties (Hizam, Karunasena, & Manalo, 2013)

3.5.1 Limitations

It is outside the scope of this thesis to conduct any further analysis the effects of an unideal connection between the sheathing and the framing members might cause. This may limit the actual performance of the wall and further analysis is needed in this respect.

3.6 Expected Loading Conditions of Wall

Three independent loading conditions will be analysed as part of this study. The loading conditions that will be analysed will simulate the expected loading directions of a typical residential wall application. This thesis does not consider in detail, combined loadings of the wall structure due to the varied nature of the combined loading, instead it sets out to find the critical load of a given condition.

3.6.1 Axial Behaviour When Subjected to Uniformly Distributed Load in the Longitudinal Direction

3.6.1.1 General

Given the composite nature of the wall structure and the reliance for the resistance to buckling and compression being a product of the sheathing and framing, empirical calculations such as Euler's buckling formula has limited applicability. While studies have shown the tendency to undergo Eulers buckling mode for composite systems similar to the proposed, the calculation of the effective moment of inertia is not without its challenges (Eyvazian et al., 2021). FEA is the preferred mode of analysis for this loading criteria.

3.6.1.2 Buckling Analysis

Using FEA, linear buckling analysis will be performed using Solidworks software. This analysis will calculate the critical buckling load, eigenmodes, and eigenvalues of the structure. The eigenmode associated with the lowest eigenvalue represents the buckling mode of interest in this case, Euler buckling.

3.6.2 The Flexural Behaviour When Subjected to a Uniformly Distributed Load in the Sagittal Direction

3.6.2.1 General

Similar to the buckling analysis, the various connections of the composite wall make this behaviour difficult to analyse using empirical calculations. Furthermore, FEA is more adept to identifying web buckling of the stud section given the low modulus of elasticity of the material.

3.6.2.2 Flexural Analysis

Keeping to maximum serviceability limits of stud height/150 but not greater than 20mm (S. Australia, 1999). Given that the smallest typical wall is 2400mm, then maximum deflection will be limited to 16mm. However, the found point bending test method has a span of 2000mm between supports, under these conditions the serviceability is limited to 13.33mm.

3.6.3 The In-Plane Shear Behaviour When Subjected to a Concentrated Load in the Transversal Direction

3.6.3.1 General

Studies that were reviewed in the course of the literature review revealed a sometimes-complicated failure mode of in-plane shear walls (Priebbenow, 2021; Xeros, 2021). FEA serves as appropriate means of evaluation of this behaviour.

3.6.3.2 In-Plane Shear Analysis

Using the mounting method described in 3.5 Connections of the in-plane shear will be analysed for the ultimate strength. The deflection of the wall will also be reviewed and compared with the baseline analysis.

3.7 Consequential Effects/ Ethics

Generally speaking, the concept of the design is to take material that is otherwise being sent to landfill and repurpose it into long standing construction projects. As the types of plastics that are being considered as binders use fossil fuels to develop them as a virgin product, the fact they are being put into projects with typical life expectancies of >25years, means that carbon is not being emitted into the atmosphere and therefore is locked in for a least this period of time. Generally, this type of proposed product would be considered a beneficial in most regards, however it is not completely void of consequential effects.

3.7.1 Fire

Fire is the most obvious consequential effect of this type of product. The National Construction Code of Australia 2019 does provision for how to design a building for certain types of fire events (Board, 2019). The first common example fire events would be inter-tenancy, or where the boundary is close to the neighbouring building. In this instance a fire resistance level (FRL) is required of the given wall. The other common type of fire event that is designed for is in a bushfire zone. These are building that are usually in a more rural setting, therefore only applicable to a small fraction of the total building stock. AS 3959 sets out the parameters for consideration and design in these areas (S. Australia, 2018).

It is important to note the consideration of fire on this type of material in the given application as a number of consequential effects will be resultant from a fire event. When considering the use of the material in a wall that requires a FRL, unlike timber of metal, recycled plastics reinforced with short glass fibres have a lower decomposition point. AS 1530.4 has an explicit set of criteria for both load bearing and non-load bearing walls (S. Australia, 2014). Although it is not within the scope of this document to explore the suitability of this type of material for use in residential walls that require an FRL, it is important to consider the consequential effects at a later date.

As AS 1530.4 provides clear definitions about what is acceptable for use in an application that requires an FRL, this standard can be used to determine the combinations of materials that might be acceptable for an FRL of a certain criterion. However, failure to achieve even the lowest level of FRL doesn’t mean the demise of the potential of the application. Many walls within the scope of residential application require no FRL whatsoever. In fact, in the typical detached house that is not close to a boundary, most of the internal and external walls will require no FRL, therefore there is still scope for the application.

There is however one significant consequential effect with relation to a combustion event. This is within the confines of the toxic fumes emitted from the material burning. When compared to untreated timber, HDPE gives off many more toxic fumes than timber does (Estrellan & Iino, 2010). While houses aren’t meant to burn, it’s still a common occurrence and therefore must be considered.

Houses consist of a vast number of materials, some worse than others when burning. For instance, a common material in houses is carpets, which is often recycled PET or nylon, which are similar in composition of toxic emissions when burning. It is reasonable to deduce that the use of this type of material in itself is not a reason a certain toxic gas would be emitted in a fire scenario. However, it may be reasonable to conclude that the concentration or quantity of toxic fumes would be increase during a fire event. There has the potential to be an ethical concern into the future.

3.7.2 Recyclability

In the current market there is little secondary market for recycled plastics reinforced with short glass fibres post their initial life. While residential buildings are built to serve its purpose for decades, even buildings can have a useful life expectancy. While there is significant and growing recycled market for HDPE, ABS and glass, when combining these materials, there is no commercially available mechanism to easily separate these materials back to their individual components. Therefore, the ability to remould the product so it maintains reasonable strength characteristics for reuse is important. Bernasconi et al (2007) suggest that this type of product is able to be ground and remoulded whilst keeping favourable strength characteristics. This demonstrates that the material, in theory, can be recovered and reused into the future.

It's worth noting that currently treated timber is not able to be recycled and is currently sent to landfill. While it is not preferable that any material is simply sent to landfill at the end of its life. In the event there is not an industry for the collection and reuse of recycled plastics reinforced with short glass fibres, it can be argued that it is no worse than many current building and construction materials. The ethics of this may be considered relative. Ultimately a non-landfill product is better, but one that is no worse than the existing may be ethically adequate until further advances are made in material recovery and manufacturing.

3.7.3 Degradation

While it's not within the scope of this document to consider the effects of degradation, it can be said that the material is subject to negative degradation potential. According to (Bajracharya et al., 2017) HDPE when impregnated with short glass fibre undergoes a number of modes of degradation when exposed heat, moisture and UV. Further research will be required to determine the applicability of these forms of degradation for the given application and climatic conditions.

These degradations effects may have unintended consequential effects post construction. It's possible that while the building may meet the structural adequacy requirements when built, over the years or decades the material may become less performant and therefore structural adequacy could be compromised in certain environmental conditions or emergency situations such as fire. There is an ethical consideration to ensure the product is fit for purpose for the life of the building, not just the end of the warranty period, which in most states is 7 years.

3.7.4 Heat

Heat while a form of degradation, is deserving of a specific study into the potential implications of elevated heat conditions of the material in the given application. According to (Bajracharya et al., 2017) elevated temperatures of 60°C when compared to ambient 23°C temperatures can have profound effects on the strength characteristics of the material.

Ambient temperatures in most states of Australia are seasonally found to be above 40°C. It is reasonable to postulate that under certain conditions, such as a darkly painted wall, that the internal wall temperature of a house may be expected to reach 60°C during a hot day. Under these conditions is will be critical to evaluate the effects of a significantly depreciated tensile strength of the material. Studies have found the tensile modulus to reduce by almost half under these conditions. This poor performance under such conditions may need to limit the application of the material to specific wall applications such as internally between two conditioned spaces.

3.7.5 Safety

Some potential safety issues have already identified in this section regarding toxicity during a combustion event as the degradation of the material. Future exploration of this application would need to consider the failure modes in the given application with expected sub optimal conditioning. For instance, during a fire event, how does the material behave and are there any design alterations that need to occur away from typical design to accommodate the specific behaviour of this material? Further consideration might need to include the applicably of this type of material in the application for high wind areas such as the tropical coastal regions of Australia that are subject to cyclones.

4 Finite Element Analysis

4.1 Introduction

Using SolidWorks, this section evaluates the structural performance of a composite wall that incorporates SGF-HDPE framing materials with either OSB or fibre cement sheathing. The FEA is first validated against an existing empirical study by Manalo (2013) before it examines the performance under three types of loading conditions.

4.2 Model Development

4.2.1 Components

4.2.1.1 Sheathing

The sheathing consists of 6mm x 2400mm x 1200mm sheet of the designated material. Both OSB and fibre cement considered Mohr-Columb stress criterion using a linear elastic orthotropic model.

4.2.1.2 Framing

The framing, include studs and top n bottom plate, considered a linear elastic isotropic model using Mohr-Columb stress criterion.

4.2.1.3 Connections

The connections between all components were considered to be ideal adhesion. Under flexural conditions, the bottom side was connected by a hinge to one end and a roller at the other. In-plane shear considered a virtual wall to the bottom plate with foundation bolts pre-loaded with 150N axial force. Compression considered the bottom plate fixed in three planes.

4.2.1.4 Load Application

Under flexural loading, two steel bars, 100mm x 50mm, comprising of ANSI 1020 cold rolled steel were introduced at 1000mm centres to distribute the flexural load. In-plane shear, a 100mm x 100mm x 10mm ANSI 1020 cold rolled steel was used to distribute the load 50mm from the top edge. Compression a 100mm x 50mm ANSI 1020 cold rolled steel was mounted to the top surface of the top plate to distribute the load of the compression force. Self-weight was not considered for any material.

4.3 Model Validation

4.3.1 Comparison Study

To validate the model, previous research that did not undertake FEA was modelled and compared with the results from that study (Manalo, 2013). This study was selected as it had a number of similarities with the materials being selected as part of this dissertation. Manalo (2013) study used a framing material of polyurethane foam (PUF) in combination with 10mm magnesium oxide sheathing.

Unlike other studies that used continuously glass fibre reinforced HDPE which generally has material strengths greater than the sheathing material, Manalo (2013) used a framing material that generally had material strength characteristics approximately equal or less than the sheathing material. This is significant, as the sheathing contributes a significant part of the wall's overall strength.

Properties (MPa)	Glass fibre reinforced rigid PUF	SGF- HDPE
Modulus of elasticity	843	1900
Flexural strength	11.60	26.6
Tensile strength	2.54	15
Compressive strength	13.42	20.2
Shear strength	5.56	unknown

Table 7- Material Properties from Manalo (2013) study compared to SGF-HDPE

4.3.2 Flexural Behaviour

Using Solidworks the flexural behaviour was modelled mimicking the Manalo (2013) study. In this study, flexural behaviour was determined using a four-point bending method. Specimen CT- 1 of Manalo's testing specimens was used as a comparison (Table 7).

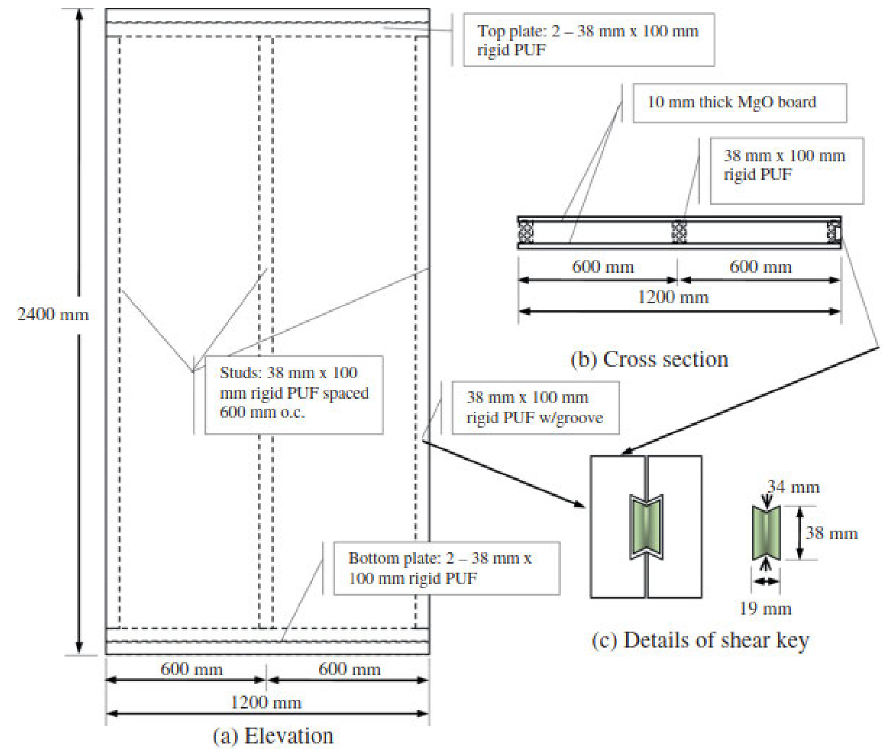


Fig. 2. Details of the prefabricated composite walls made from rigid PUF and MgO board.

Table 2
Details of the prefabricated composite wall specimens.

Specimen name	Type of test	Description
BT-1	Flexure (transverse)	Composite walls with rigid PUF frames and MgO board on two sides
BT-2	Flexure (transverse)	Same as BT-1
CT-1	Compression	MgO board is continuous from top plate to the bottom plate, with all panel edges over framing
CT-2	Compression	MgO board is offset 10 mm from the edge of the bottom stud
CT-3	Compression	Same as CT-1 but with a hole of 150 mm diameter in the MgO board
RT-1	In-plane shear	Single wall which is connected to the steel base using bolts at the bottom plates only
RT-2	In-plane shear	Single wall which is connected to the steel base with tie-down bolts in the full height of the wall
RT-3	In-plane shear	Two wall panels which are connected to the steel base using bolts at the bottom plates only
RT-4	In-plane shear	Two wall panels which are connected to the steel base with tie-down bolts in the full height of the wall

Figure 6 – Configuration of Specimens in Manalo (2013) Testing

As indicated in section 2.3.1 of Manalo (2013) study, the four-point bending test was set up with supports at 2000mm centres with load point at 1000mm centres (Figure 7). This same scenario was modelled in Solidworks as indicated by Figure 7 to determine the validity of the model.

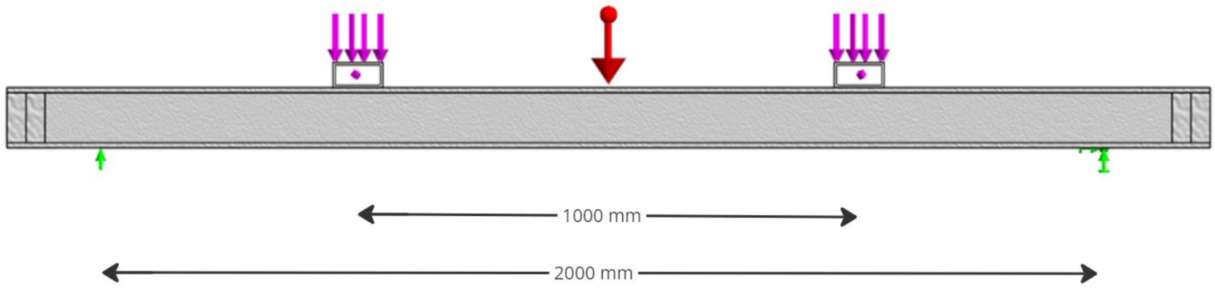


Figure 7 - Four-Point Bending Configuration

4.3.2.1 Observations

The flexural behaviour of the model displayed a compelling resemblance to the Manalo's study as demonstrated in Figure 8. The bending stiffness of the model was determined to be 1.2505kN/mm whereas BT-1 and BT-2 were 1.2876 and 1.2507 kN/mm respectively. This is equivalent to a standard deviation of between 0.0174 based on the available data from the study. Noting that the exact y intercept of Manalo study was not determinable from the graph, therefore was simply assumed to be 0 for this comparison.

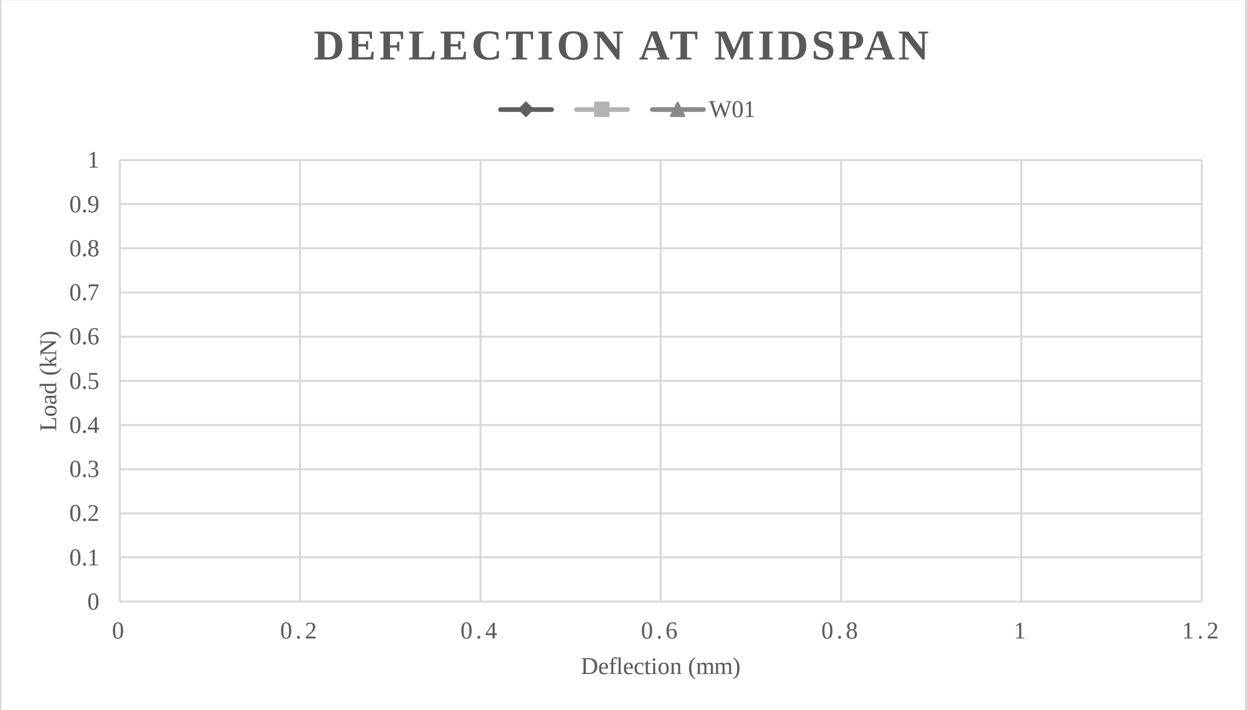


Figure 8 – Flexural Behaviour Plot Comparison

Figure 9 – FEA of Deflection in the Z Direction Under a Total Load of 24.03kN

The mode of failure found in the empirical study was flexural tensile cracking of the MgO board and these failures occurred at 24.03 and 20.86kN. The under FEA indicated that the MgO board would have a safety factor of 1 at a load of at 15.29 kN on the outside face on the support side. The location of the least safety of factor was consistent with the location of failure in the empirical study.

Given the low sample size of the testing in flexural behaviour and the relatively high standard deviation of the load at failure, it's difficult to comment on the reliability of the FEA analysis as compared to the tested values. The FEA seems to predict the location of the failure well, but is also probably conservative in its assessment of the load at failure.

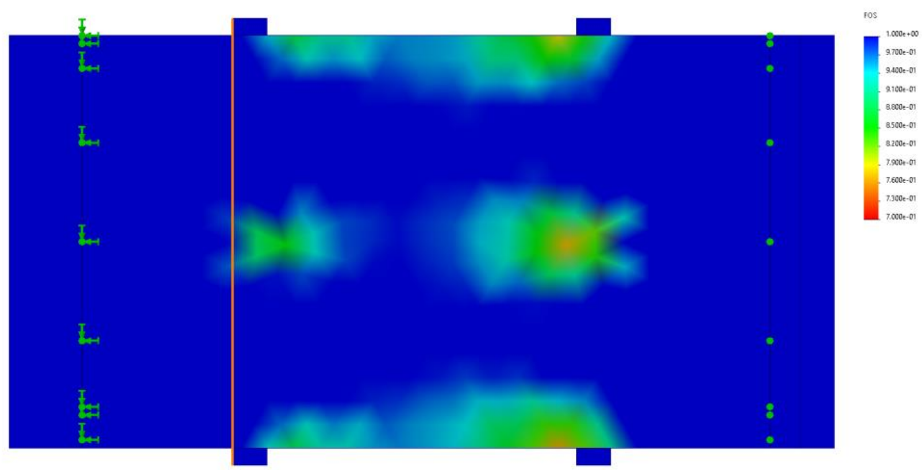
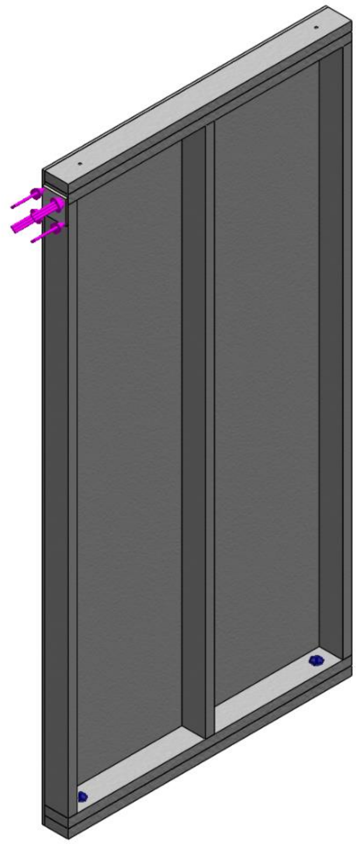


Figure 10 – Factor of Safety Under 20kN Load on the Tensile Side of the MgO Board of the Support Side

Overall then FEA appears to a suitable means of predicting the flexural behaviour and a reasonable means, perhaps even a conservative, of predicting flexural failure of brittle assemblies.



4.3.3 In-Plane Shear

In plane was modelled in a close approximation to the study of Manalo (2013). The empirical study did not precisely identify the location of the hydraulic ram. Therefore, some discrepancy is likely to occur between the model and the FEA due to the potential for a larger or lesser moment arm. The FEA considered a 100mm x 100mm spreader plate centred 100mm from the top face (Figure 11).

The FEA considered RT-1 from the empirical study, which consider the wall being restrained the foundation by two 20mm bolts with 36mm washers 100mm from the edges (Figure 12). The FEA considered a virtual wall (immovable surface) to the base of the wall.

Figure 11- In-Plane Shear Configuration (with MgO Board Removed for Visibility)

4.3.3.1 Deflection

The FEA demonstrated good resemblance to the empirical study at low loads. However, as the load increases beyond 20kN an ever-increasing deviation is evident. This deviation suggests a secondary effect that is not properly accounted by for by the modelling. Given the PUR's relatively low compressive strength, the pull through of the 20mm bolts is the likely culprit.

Both the empirical study and the FEA demonstrate that the 36mm washers compresses the PUR beneath it and the washers begin to pull through the material. This type of failure is difficult to analyse accurately through FEA.

In the empirical study, as the 36mm washer compresses the PUR, this is likely to increase the compressive strength of the material under it while the shear capacity of the material has an ever-decreasing capacity. This transition of modes of failure is something that the FEA is unlikely to be able to determine accurately and explains the deviation in higher load states.

Overall, the FEA is relatively reliable and prediction the in-plane shear deflection.

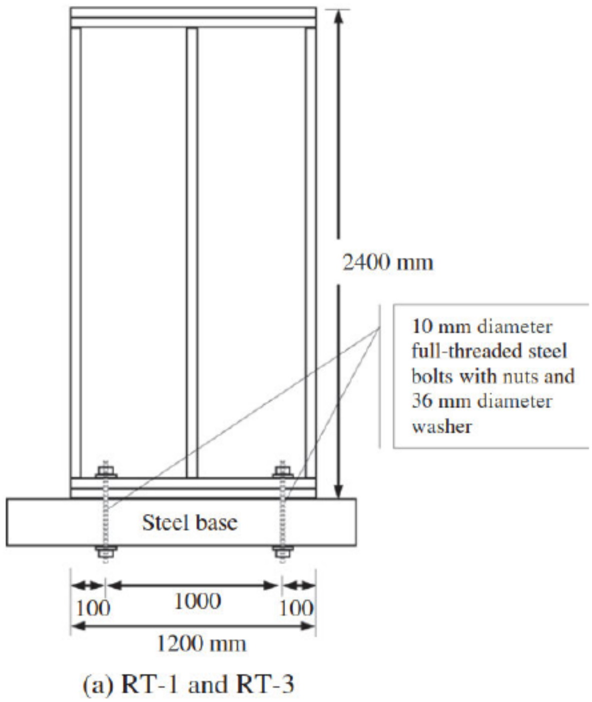


Figure 12 - Arrangement from Manalo (2013) Empirical Study

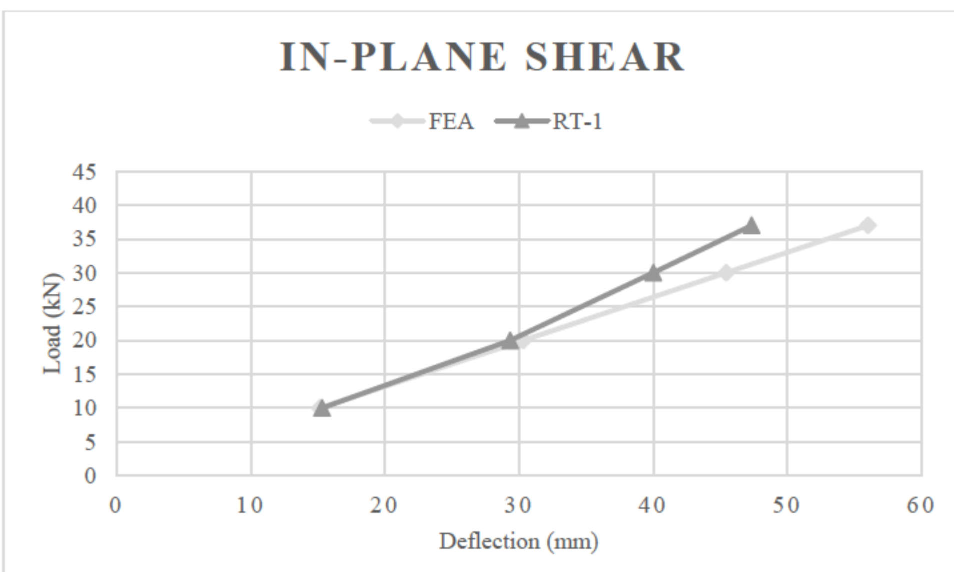


Figure 13 – In-Plane Shear Plot Comparison

4.3.3.2 Mode of Failure

While the FEA was able to predict the deflection relatively well under a transversal load, the mode of failure was less reliable. Using the Mohr-Coulomb Stress criteria the FEA showed a concentration of stress around the bolt closest to the side of the applied load. While the stress plot on the surface of the MgO board is indicative of the shear cracking shown in the empirical study, the magnitude of force at failure is considered to be significantly lower than the empirical study. The FEA indicates that failure might be induced as 6.8kN as compare to the 39kN experienced in the testing (Figure 14).

The use of FEA for brittle materials in this thesis for determining the failure point of in-plane shear will need to be correlated with empirical tests to determine the validity. However, this may mean that any results determined as part of this study would serve as a conservative estimate of the actual results.

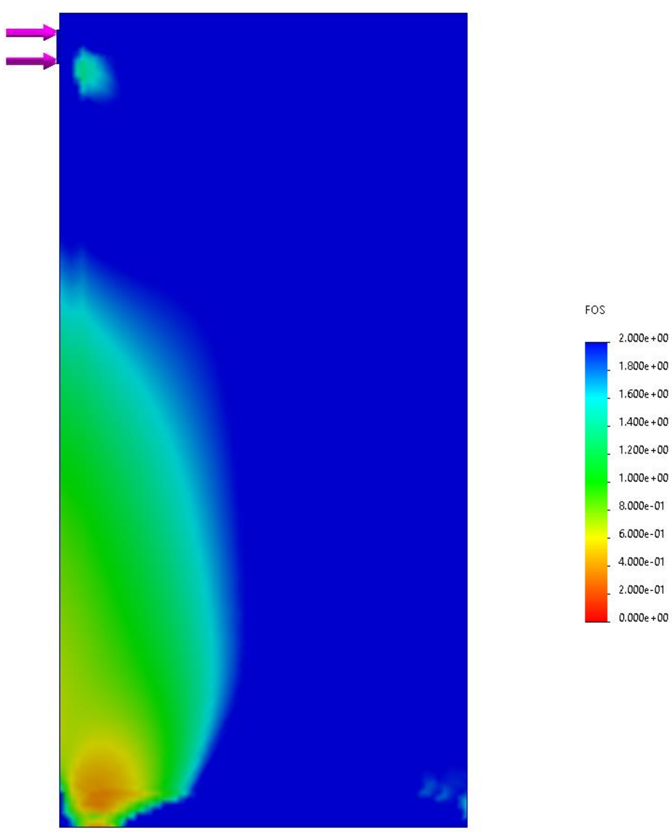


Figure 14 – Factor of Safety Plot, In-Plane Shear

4.3.4 Axial Compression

Like with the other scenarios, a Solidworks simulation was defined to mimic the characteristics of the Manalo (2013) study.

4.3.4.1 Deformation

The deformation of the FEA was within reasonable approximation of the Manalo (2013) study with plot convergence at approximately the 175kN mark (Figure 15). It is uncertain why there are deviation between methods, however the non-linear nature of the Manalo study would suggest some non-ideal factor within the empirical study. However, the difference between methods is within a reasonable approximation and therefore conclusions can be drawn from the FEA.

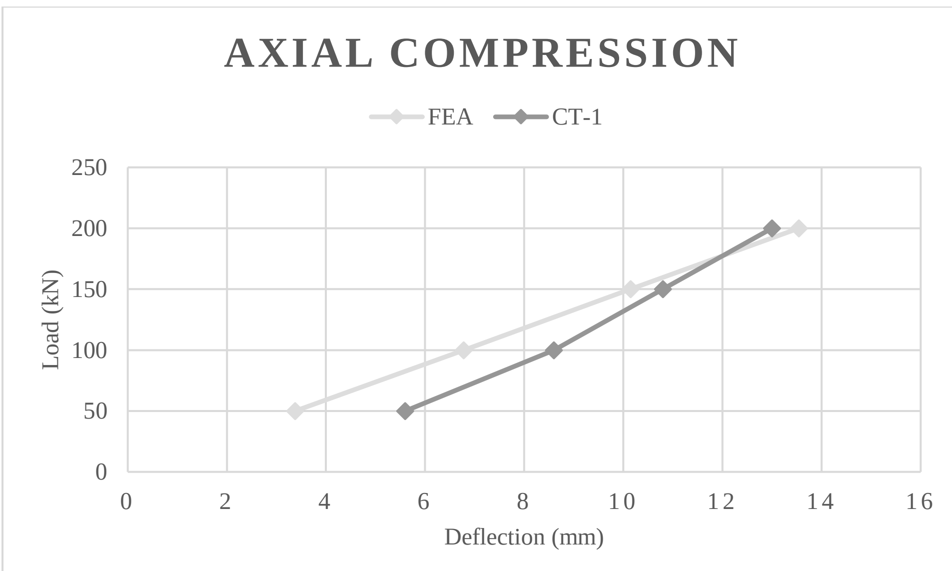


Figure 15 -Axial Compression Plot Comparison

4.3.4.2 Mode of Failure

Like with the empirical study, the FEA indicates high concentrations of stress around the MgO board where it connects to the studs. The FEA indicates a failure at 150kN around these junctions. As with the in-plane shear failure, the FEA indicates failure at a lower threshold and therefore may be seen as slightly conservative of the empirical study of 206kN.

4.4 Contribution of Sheathing

4.4.1 General

Consideration of the contributions made from the sheathing materials are considered in this section. While not a focus of this study, the contribution of the increase of performance due to the sheathing would make an interesting focus for further studies of this kind of framing material.

4.4.2 Flexural contribution

The sheathing of the wall construction has a significant effect on the flexural stiffness of the wall construction. As a comparison this study compared the flexural stiffness of the baseline stud components and SS1. When comparing the baseline or SS1 stud section with fibre cement sheathing to that without sheathing, the wall with the sheathing experience approximately a 7.5x increase in flexural stiffness. In the case of OSB the flexural stiffness increased by approximately 13x.

The area of stress concentration also moved from the web of the stud structure to the flange of the structure (Figure 16). This redistribution of stresses from the flange to the sheathing is of critical importance when considering the overall capacity of the wall structure and underscores the importance of the sheathing. It also demonstrates the ability to considerably improve the performance of the wall by changing the characteristics of the sheathing, which is potentially an avenue for future research.

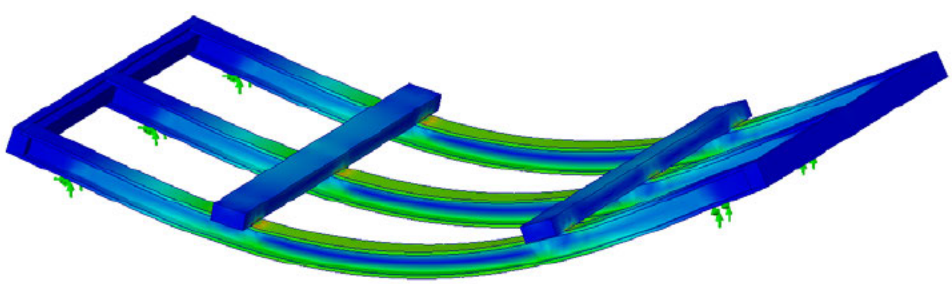


Figure 16 - Stress Plot of SS1 Without Sheathing

4.4.3 In-Plane Shear Contribution

The contribution of the sheathing to in-plane shear cannot be overstated. This analysis of this thesis considered in-plane shear at a minimum magnitude of 5kN. Without sheathing the analysis of in-plane shear failed due to too large of deflections even at only 5kN. Concluding that where in-plane shear is required to be resisted against, a sheathing, or other form of restraint, would be required to facilitate it and the framing materials alone could not be relied upon.

4.4.4 Compression Contribution

The contribution of sheathing to the compression behaviour is mainly attributed to the restraint along the minor axis. Sheathing acts as a continual restraint along the minor axis and prevents particularly the outer studs from deflecting outwards under compression. The analysis indicated the resistance to axial compression could be improved 3.5-9x based on a combination of the stud profile and sheathing type.

As indicated in Figure 17, the outside studs were able to deflect in the x-direction more freely without sheathing which enabled more translation in the y-direction for any given load. While not a focus of this study, this significant variation on the improvement factor due to the use of sheathing is a promising avenue for further improving the compression resistance of the wall structure in future studies.

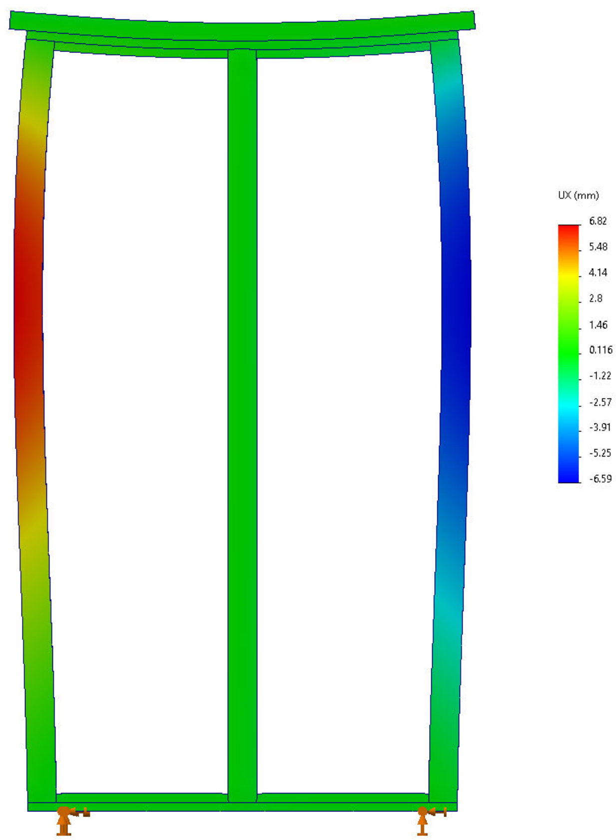


Figure 17- Deflection in the X Plane Without Sheathing

4.5 Component Design

4.5.1 General

In addition to the 78x45mm baseline design, three other configurations of stud assembly we devised and FEA undertaken.

4.5.2 Stud design

The stud design in the first stage compared three designs against the baseline 78x45mm solid stud section (Figure 18). The aim was to improve the moment of inertia around the two axes, while minimising the cross-sectional area of the material, the relative improvement as compared the baseline can be seen in Table 8.

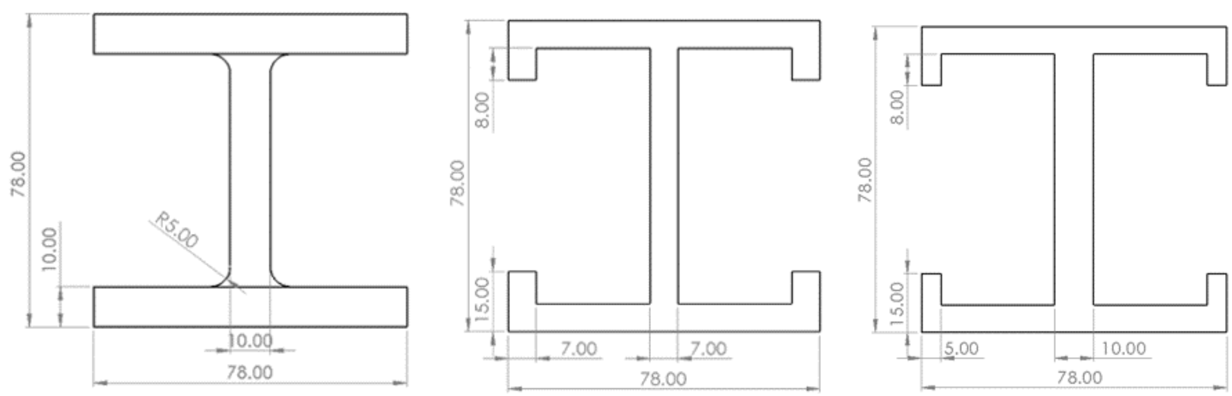


Figure 18 – Stud Cross Section Profile, left: SS1, middle: SS2, right: SS3

Property	Baseline	SS1	SS2	SS3
Area (mm^2)	3510	2161	1764	1892
Area % of baseline	-	62%	50%	54%
Moment of inertia x (mm^4)	592312	1067884	838684	772470
Ix compared to baseline	-	180%	142%	130%
Moment of inertia y (mm^4)	1779570	2266966	1710380	1725398
Iy compared to baseline	-	127%	96%	97%

Table 8 – Area and moment of inertia comparison to baseline

4.5.3 Top and Bottom Plate Design

The top and bottom plate consisted of a 1200mm long bar profiled to accept the stud shape of each of the variations. Generally, it has a 7mm recessed edge along the front and rear with perpendicular slots to accommodate the stud web and flange turnovers. The top and bottom plate were also modelled to be the short glass fibre reinforced HDPE consistent with the specifications set out in Table 3. Two 20mm holes were formed throughout the thickness of the material 100mm from the ends to accommodate the foundation bolts with 36mm heads.

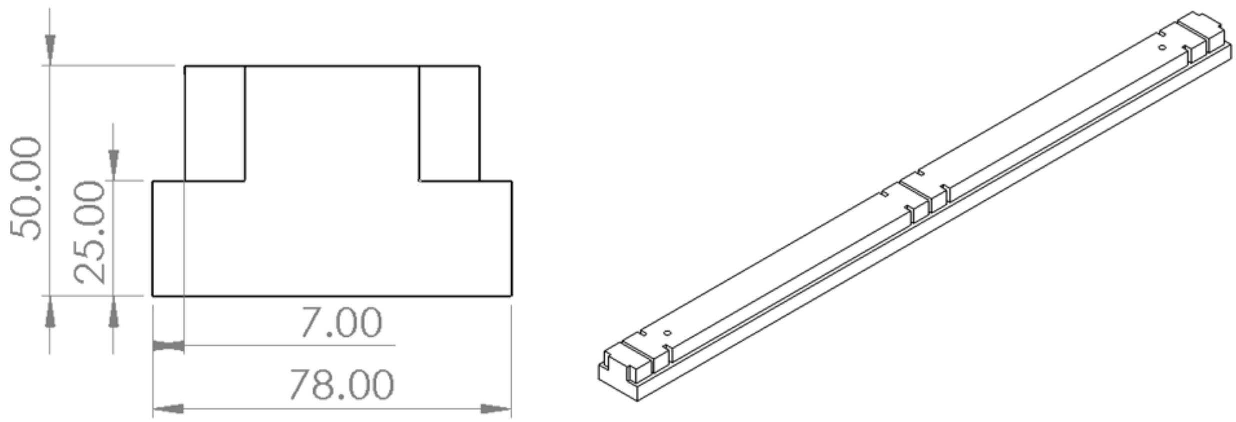


Figure 19 – Top and Bottom Plates, left: End Profile, right: Isometric Line Drawing

4.5.4 Assembly

The 1200 x 2400 x 6mm sheathing panel, both fibre cement and OSB was mounted to both sides flush with all edges. The model assumes ideal connection with all components including adhesions of sheathing to the framing materials.

4.6 Stud Section Optimisation and Behaviour

4.6.1 Flexural

4.6.1.1 General

Like in the Manalo (2013) study, the flexural behaviour of the baseline composite made from a construction of; 78x45mm solid studs of short glass fibre HDPE and a sheathing material of either 6mm OSB or fibre cement, was analysed under a simulated four-point bending test. The simulation assumed two solid steel bars of 100x50 at 1000mm centres. The FEA assumed no self-weight of any of the materials. As stipulated by AS 1720.3 the flexural deflection of the wall cannot exceed span/150 or 20mm. As the 2400mm high is placed over supports at 2000mm wall this means the wall cannot deflect more than 13.33mm.

The flexural behaviour across all configurations experience linear profiles when plotting the relationship of load vs deflection. Therefore, the stiffness in kN/mm was used as the comparison point for all configurations as show in Figure 20.

4.6.1.2 Baseline F and Baseline O

The baseline study using fibre cement were studied using FEA for the flexural behaviour. The baseline analysis of the fibre cement and OSB revealed that the flexural stiffness was primarily governed by the sheathing type. The maximum deflection of 13.33mm being exceeded fibre cement and OSB at 11.3kN and 18.8kN respectively (Table 9)

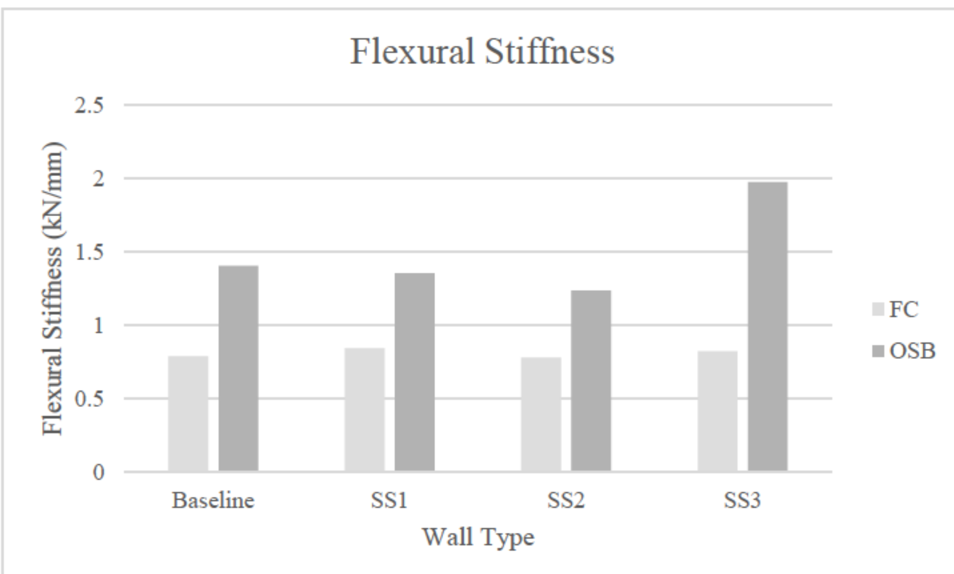


Figure 20 – Flexural Stiffness (kN/mm) of Each Wall Type Under Four-Point Bending

However, the FEA indicated that the serviceability limits of the composite wall was unlikely to be the limiting factor. Considering a minimum safety factor of 1, the fibre cement on the compression side exceeded the safety factor at an applied load of only 3.2kN. This would most likely result in a compression buckling of the fibre cement. However, with reflection of the model validation in mind, this is likely a conservative estimate of the actual applied load at failure.

Whereas the limiting factor of the OSB was the maximum deflection limit of 13.33mm as the minimum safety factor at an applied load of ~18.8kN was 1.07. Given the deflection was the limiting factor, the OSB presented as a more reliable candidate than the fibre cement for further analysis as the flexural behaviour was better estimate by the FEA than the ultimate load capacity.

The higher flexural stiffness of the OSB composite wall can be owed to the disparity between the tensile modulus in the longitudinal direction. OSB exhibits 3.05 GPa whereas fibre cement exhibits 5.7GPa in the longitudinal direction (Table 5). Given its location at the point of maximum moment arm from the centroid, the compounding effect of this increased modulus is evident in Figure 20. This underscores the opportunity of future studies to explore the potential to leverage this component to increase flexural characteristics.

4.6.1.3 SS1F and SS1O

With a 38% reduction in material, and moment of inertia around the y axis of the stud increased by 27%, the deflection of SS1 was approximately equivalent to baseline for both fibre cement and OSB (Figure 20). The FEA also revealed this configuration was limited by high strain of the web in the middle stud (Figure 21, left). This high strain led to more pronounced deflection and became a target of improvement for SS2 and SS3.

4.6.1.4 SS2F and SS2O

SS2 introduced ribs to the flange (Figure 19) to redistribute the strain from the central section. As compared to the baseline, SS1 experienced peak stress of 159%, SS2 was 163% (Figure 21, right). This iteration was able to reduce the material further from SS1, however was not able to effectively redistribute the internal stresses away from the web of the stud.

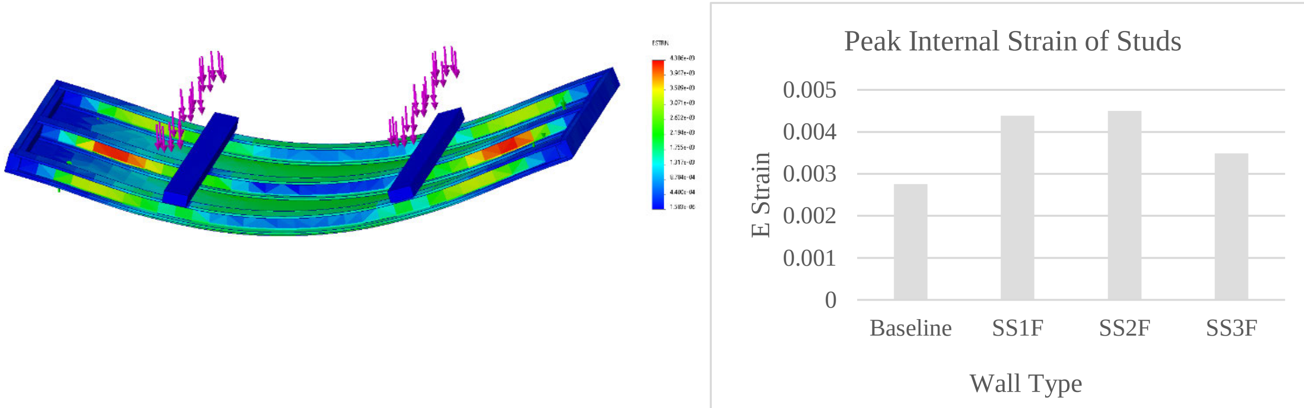


Figure 21 – Left: Strain Concentration of Studs, right: e-Strain of Each Stud Configuration Under Flexural Loading

	BL O	BL F	SS1F	SS1O	SS2F	SS2O	SS3F	SS3O
Load at serviceability (kN)	11.3	18.8	11.2	18.0	10.4	16.4	10.9	25.6
Safety Factor = 1 (kN)	3.2	20.0	4.8	30.0	4.9	23.0	4.9	29.0
SF at serviceability	0.28	1.07	0.43	1.67	0.47	1.40	0.45	1.13

Table 9 – Comparison of Load and Safety Factor of Wall Types

4.6.1.5 SS3F and SS3O

With the flexural stiffness of the composite able to be maintained with the introduction of the ribs to the flange, attention was redirected to decreasing the internal strain of the studs and improving the flexural stiffness. To do so, the web was thickened to 10mm, while the flange ribs were thinned to 5mm (Figure 18). While this did increase the cross-section area overall to 54% that of baseline (Table 8), the internal strain decreased from 163% to 126% (Figure 21) of baseline resulting with an improved flexural stiffness (Figure 20). SS3 was able to assume 25.6kN before the serviceability limit of 13.33mm was exceeded with a safety factor of 1.13 at that point.

Strain redistribution was the key to more efficient load transfer within the structure. By optimising the distribution of material, the internal stress paths are aligned more effectively. Although there was a decreased moment of inertia from SS2 to SS3 (Table 8), the FEA would indicate that efficiencies of the load redistribution were enough to see a performance improvement under flexural behaviour in the four-point bending test. Indeed, as indicated in Figure 20, this was the most critical factor in improving the flexural stiffness.

4.6.1.6 Summary

Figure 22 indicates the safety factor at a load the serviceability limit of 13.33mm that would be reached. This allows determination of the limiting factor of the composite wall. The fibre cement variant of the composite wall would be limited by the ultimate load capacity of the wall. Although the model validation indicated the FEA would likely yield a conservative result of the load at failure of the wall, the load at failure of all the fibre cement components were far less than desirable and it would fail at approximately 4.9kN.

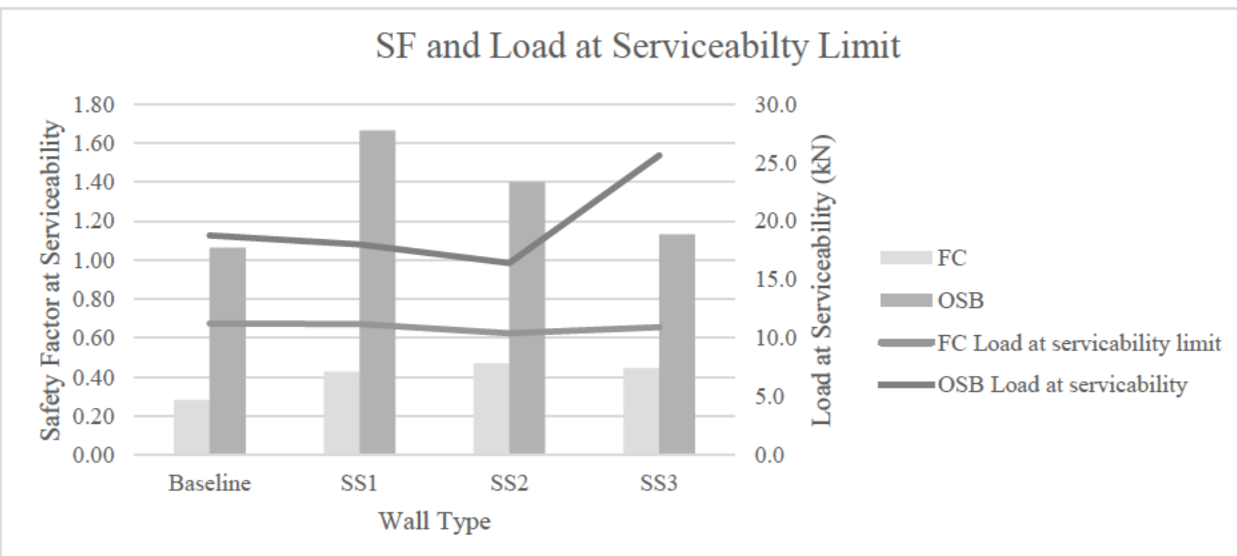


Figure 22 – Safety Factor and Load at Maximum Serviceability Deflection

Whereas the OSB variant of the modular wall was deemed to be the most reliable according to the FEA. Not only did it demonstrate the highest flexural stiffness (Figure 20), but it also exhibited has a respectable safety factor of 1.13 at the serviceability limit.

4.6.2 In-Plane Shear

4.6.2.1 General

The in-plane shear simulation was undertaken by modelling the composite wall in a manner consistent with the Manalo study as indicated by 4.3.3. Unlike the flexural behaviour, and given the ideal connection assumption between materials, the in-plane shear behaviour was governed by two main items. The most prominent of which being the sheathing material, and the second being the connection to the foundation.

4.6.2.2 Load-Deflection Behaviour

Both the OSB and the fibre cement exhibited good resistance to shear in terms of deflection of the wall. As the resistance to shear of the walls were primarily governed by the sheathing material, Equation 1 was used to determine the global stiffness or each variant (ASTM International, 2015). On average, the fibre cement experienced a global stiffness of approximately 2450kN/m across the range whereas the OSB was approximately 3200kN/m (Figure 23).

$$G' = \frac{P}{\Delta} * \frac{a}{b}$$

Equation 1 – Global Stiffness

Where: P = applied load (kN)

Δ = horizontal deflection or displacement of the top of the wall (m)

a = height of the panel (m)

b = width of the panel (m)

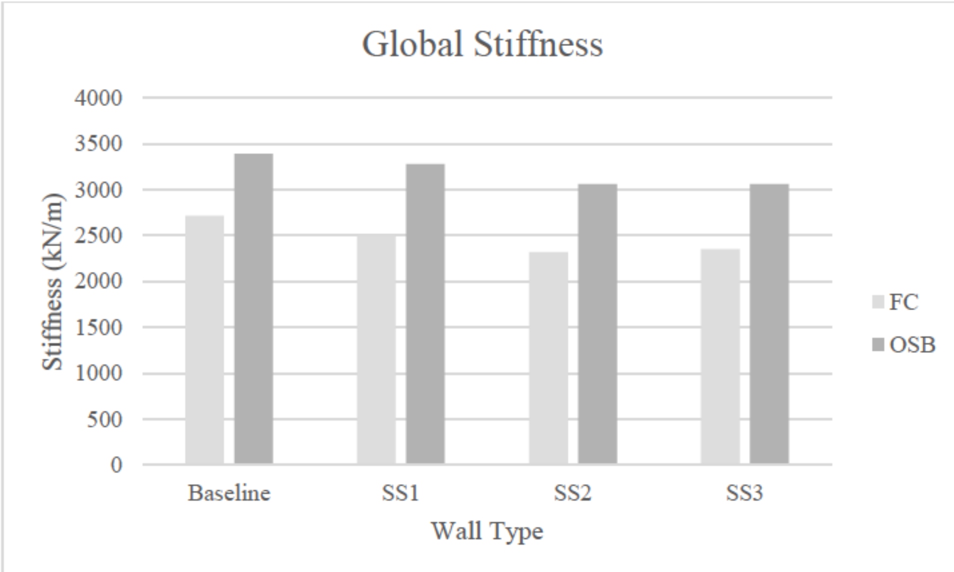


Figure 23 – Global Stiffness of Walls

According to the FEA, all walls experienced linear deformation with respect to the applied loads suggesting there was a lack of secondary effects. However, simple racking deflection of the wall was not the only effects observed. A significant contribution to deflection was attributed to the pull through of the foundation bolts with the 36mm head. This analysis does only consider the wall on a rigid foundation and future consideration would need to be considered using this type of wall construction on a flexible foundation such as on timber joists (Gates, 1997).

4.6.2.3 Failure behaviour

The limiting factor of the in-plane shear was the safety factor of the materials. As with the global stiffness, the biggest influence of the ultimate load capacity of the wall was the type of sheathing material. Given this, amongst the three variants, SS1-SS3 the variation between the ultimate load capacity of the wall structure varied only slightly in magnitude.

As indicated in Figure 24the failure of the sheathing material and the rest of the wall were determined separately. It is the bottom plate that experienced excessive stress at the lowest applied force. This was due to the foundation bolt pulling through the material. It was not the intent of this study to improve this component and future studies could look to improve this part. For this reason, the failure of the sheathing material was analysed separately as other studies of a similar nature have indicated this criticality of the design (Anil, Togay, Işleyen, Söğütlü, & Döngel, 2016; Dujič, Klobčar, & Žarnić, 2008; Grossi, Sartori, & Tomasi, 2015a, 2015b; Togay, Anil, Karagöz Işleyen, Ediz, & Durucan, 2017).

While not a subject of intense scrutiny of this study, it was evident a lower force could be applied to the baseline wall type to induce failure of the sheathing. This was thought to be due a combination of two factors. The first being the proximity of the foundation bolt to the stud. This study consistently placed the centre of the foundation bolt 100mm from each end of the wall. Given the width of the baseline stud was 35mm verses the 78mm of SS1-SS3, this meant the hole of this bolt was closer to the centre of mass of the stud for SS1-SS3.

As the reaction forces of the applied load were being directed into the location of the foundation bolts, the narrower stud of the baseline lead to a less effective redistribution of stress into the wall system. In the case of the narrower stud, more of the stress redistribution was forced through the sheathing in higher concentration leading to a more premature failure of this component.

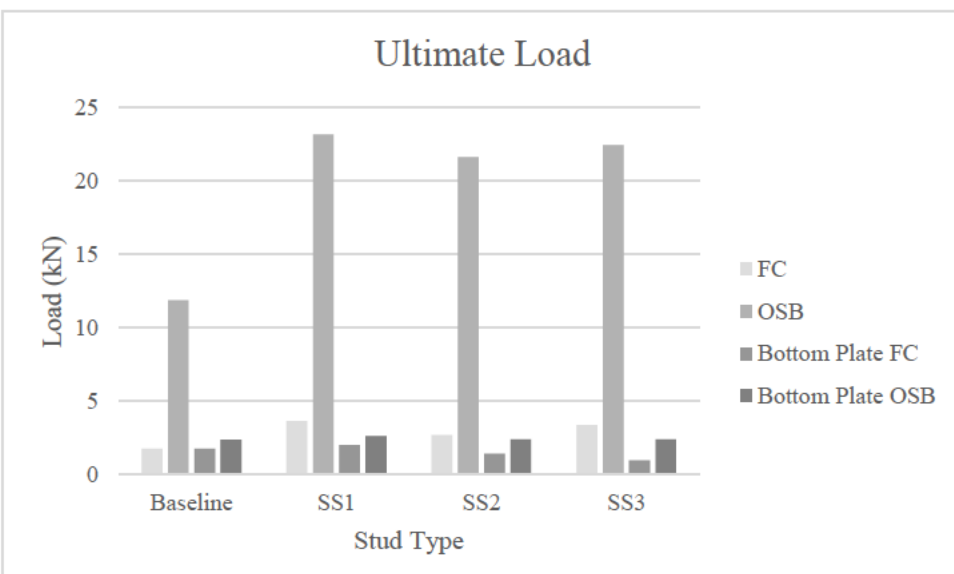


Figure 24 – Ultimate Load Capacity in Shear of Sheathing and Bottom Plate

Owed to the more performant material characteristics of the OSB, predicably the OSB was able to resist shear at higher magnitudes before failure. However, this does consider ideal connections between the materials and empirical investigation is required to validate the FEA.

4.6.3 Compression

4.6.3.1 General

The FEA model for this section was set up in a manner consistent with 4.3.4. Like with the in-plane shear behaviour, the behaviour under compression was mainly governed by the type of sheathing present.

4.6.3.2 Load-deflection behaviour

The compressive strength of the wall is primarily governed by the sheathing material with a minor secondary effect related to the cross-sectional area of the stud relative to the direction of applied force.

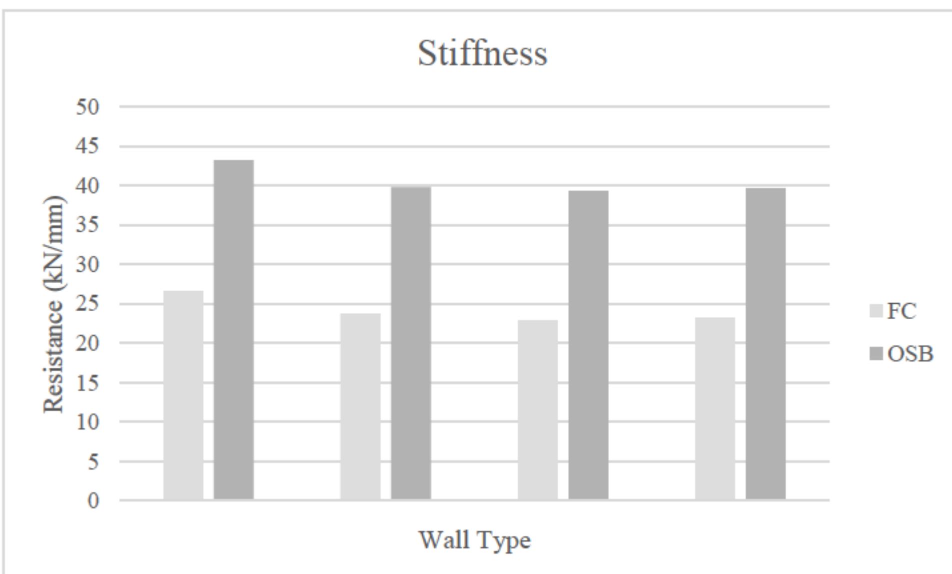


Figure 25 – Stiffness Under Compression

4.6.3.3 Failure behaviour

Given the sheathing was designed to run the full length of the wall, therefore the sheathing will be in contact with the foundation and the top load plate in the analysis. With respect to the fibre cement the FEA indicated the sheathing would undergo failure under compression at approximate 20-30kN (Figure 26: right). In all instances this was due to the studs deflecting in the lateral direction under the compression load leading to tensile failure of the fibre cement in the lateral direction as indicated in Figure 26: left.

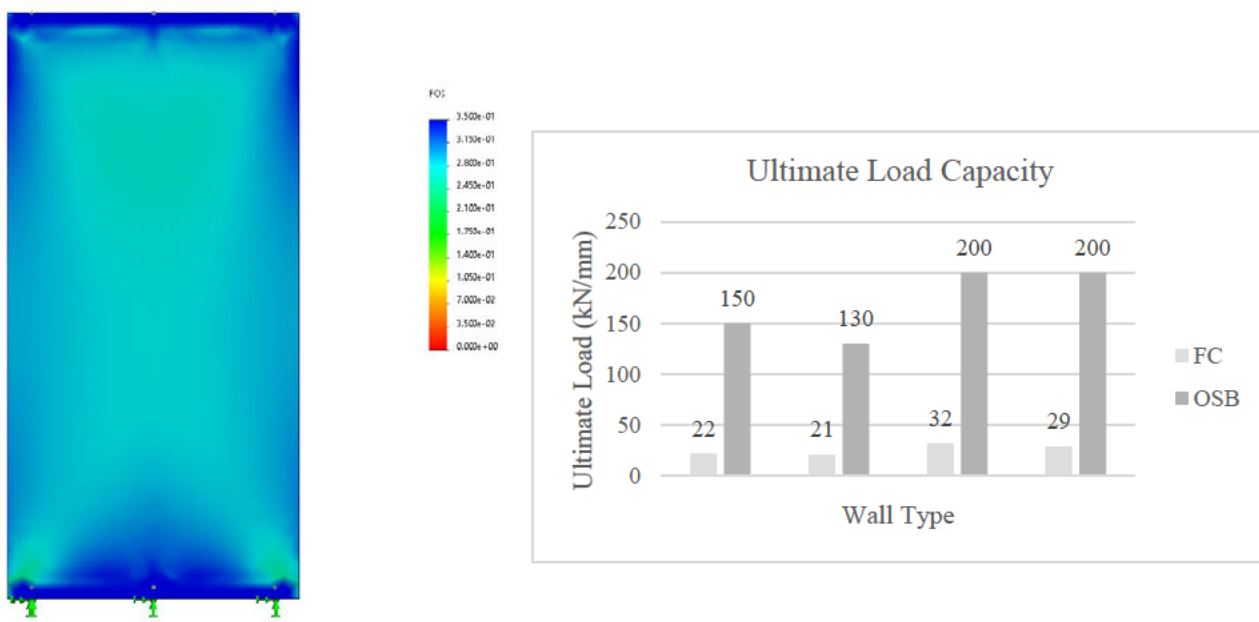


Figure 26 – left: Compression Buckling of Sheathing, right: Ultimate Load Capacity of Wall Types

The OSB on the other hand was able to observe some modest gains in the ultimate load capacity due to the stud member design owed to the dispersion of a particular concentration of stress. As indicate by Figure 27, a concentration of stress was observed between the sheathing and the bottom of the bottom plate. It is assumed the I-shaped section without the ribs on the flange in combination with the sheathing lead to a point load condition of the bottom plate. In the opposite view, the ribs of the flange were able to dissipate the concentration of stresses in SS2 and SS3 leading the modest gains in ultimate load capacity (Figure 26, right).

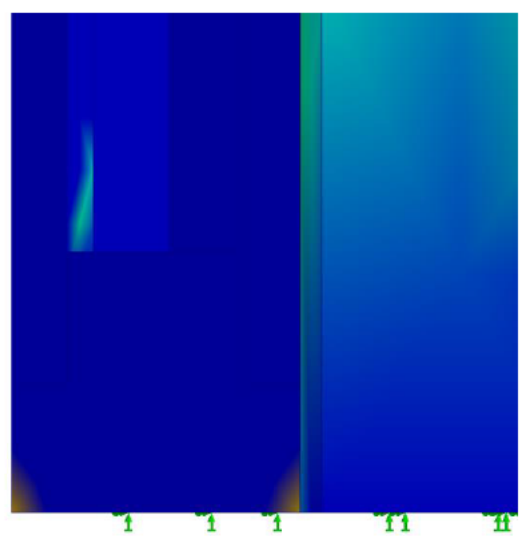


Figure 27 – Concentration of Stress to Bottom Plate of SS1

4.7 Web Perforation

4.7.1 General

Given the in-plane shear behaviour is governed by the sheathing material, the introduction of modest perforations into web of the stud will have little effect on the behaviour under an applied load in this direction (Degtyareva et al., 2019; Togay et al., 2017; Vasconcelos et al., 2013). Because of this, the in-plane shear behaviour will not be considered during the analysis of this section.

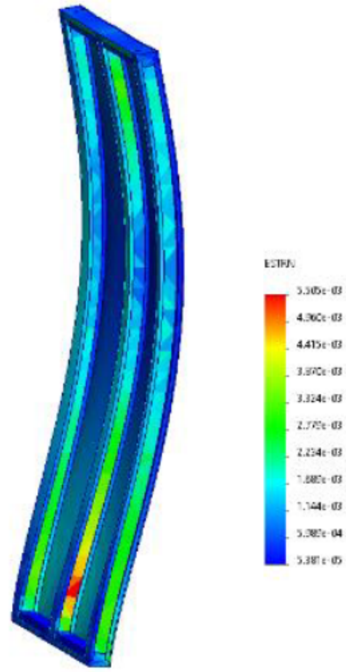


Figure 28- Strain Concentration

Unlike the simulated four-point bending associated with the flexural strength in earlier parts of this dissertation, the restraints of the web perforation and applied loads were simulated more in line with expected forces of an external wall. This includes; a 10kN (3.47kPa) applied force to the entire surface of one side of the sheathing to simulate wind load. The bottom plate being connected to the ground in three planes and the top plate being restrained in the x plane with 5mm allowable deflection to simulate restraint from the roof trusses. There was an applied load of 50kN in the y direction to the top plane, and with the 5mm deflection in the x plane, this allowed for some amount of eccentricity.

As the fibre cement sheathed walls were limited by the sheathing, they are inappropriate to model the determine the impact of the perforations to the web design. In the case of the fibre cement, the ultimate load capacity of the sheathing will be exceeded prior to the internal shear force of the web becoming detrimental. For this reason, fibre cement is excluded from the remained of the analysis.

4.7.2 Stress Concentration

Given the specific nature of the design, the perforations being introduced into the web can be strategically located to penetrate in the areas where the shear force is at its minima. As indicated in Figure 28 the shear force is at a minimum at about 0.6 the length of the stud from the bottom, or at 1.5m. It is at this location that holes in the web suitable for plumbing as well as electrical are to be introduced to allow for services.

Given plumbing pipes require larger hole than electrical for typical residential houses the hole for the plumbing are to be located as close the expected shear force minima as possible with the smaller electrical holes to the exterior.

4.7.3 Perforation Analysis

The baseline FEA considered a wall under a single set of loading conditions described in 4.7.1 without any perforation of the web. In this scenario the wall span is now 2400mm as compared to the simulated four-point bending which was 2000mm, therefore a new serviceability threshold of 16mm is observable for flexural deflection. Noting that the intent of this section to analyse the impact of service penetration to the web and is not attempting to determine any limit of loading conditions.

The FEA indicated that any penetration of the web would lead to a redistribution of stresses within the structure which would increase deflection by 2% and reduce the safety factor by 8%. These results are comparable with the finding of other studies than analysed perforation of the web structure at the point of lowest internal shear forces (Schuster et al., 1995; Wang et al., 2022). However, unlike what was indicated in Wang et al (2022) the penetrations opening size could be increase significantly from the 0.2 ratio of the web depth. Indeed, the FEA analysis of this study indicates that significant increase of penetration aperture around the minima of the internal shear force is possible without effect (Figure 29).

Figure 29 – Deflection and Safety Factor of Web Perforation Variants.

During the analysis, the perforations aperture was increase through SP1O to SP4O. SP4O indicated that the hole diameter of 48mm could not be extended beyond 100mm from the centre of the minimum shear force without an increase of deflection and a reduction of safety factor as with SS4O (Figure 31). The 20mm hole of SP5O was determined to be the largest hole possible at that location before a degradation of wall performance was observed. SP6O then included two more 13mm hole at another increment of 100mm that indicated that no adverse performance would be observed.

A further analysis was undertaken to consider the effects of a drainage hole being drilled. Drainage holes might be drilled into the lower part of the studs by plumbers to accommodate concealed drains of basins by plumbers. Given the placement of these holes will be depended on the required slope of the drainage pipe, the exact location, or provisioning for these services is not possible at the manufacturing stage. Typical sizes for these types or services are DN 40 (S. Australia, 2021) which would typically be drilled out with a 44mm hole saw (Bunnings). The hole last located 250mm from the base of the stud at the area of highest concentration of stresses.

The FEA indicated only marginal deflection change increasing by 3% from baseline however, a significant deration of the safety factor was observed, decreasing 25% from the baseline. The highest stress on this wall was concentrated around the hole made to facilitate drainage pipes. This is unlike the wall without these holes were the stresses we able to distribute at a lower magnitude evenly throughout the web (Figure 30).

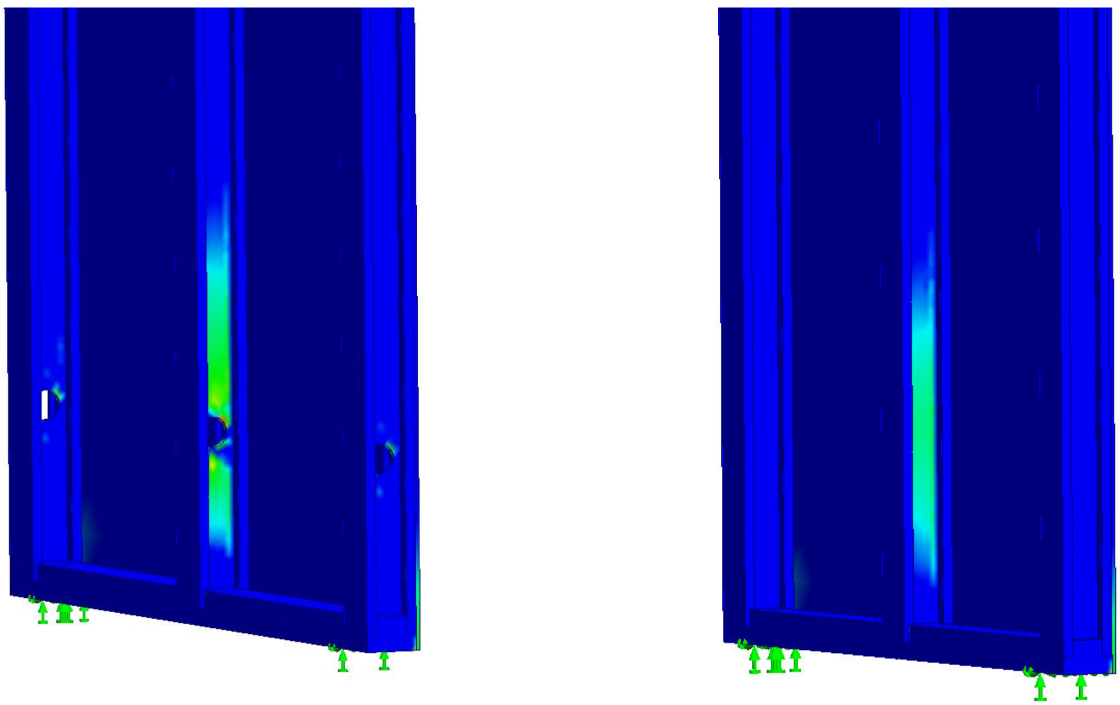


Figure 30 – left: Concentration of Stress Around Lower Hold for Plumbing Drainage right: Distributed Stress Through Standard Web

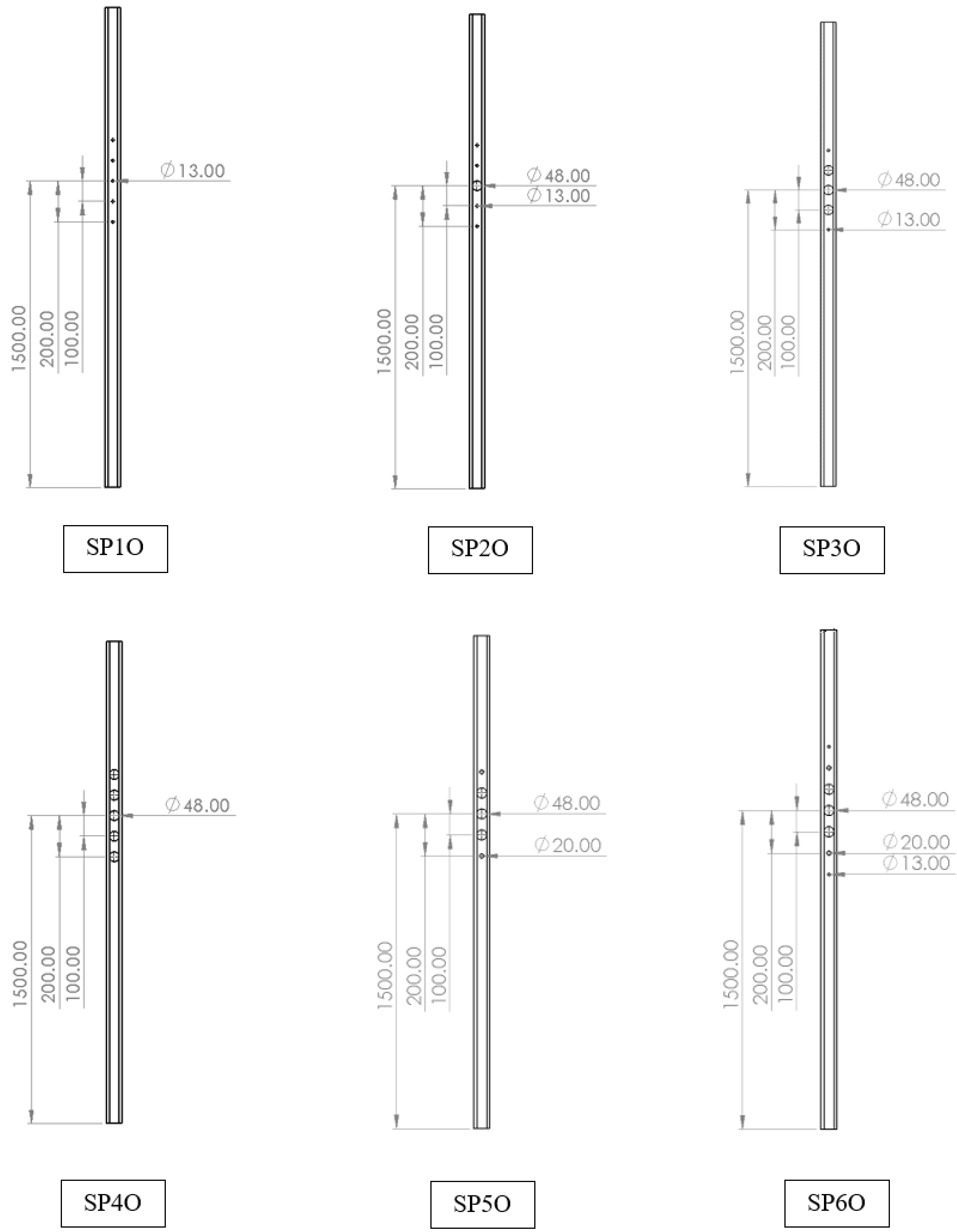


Figure 31 – Stud Perforation Patterns

4.8 Summary

In this section, the validity of the model was established through a comparison with prior research by Manalo (2013). The objective of the study was to explore the model's prognosis of the structural mechanics in; flexural behaviour, in-plane shear, axial compression. The model was varied and analysed through different stud cross sectional profiles and an optimised design was then analysed further with web penetrations. The intent was to determine if penetrations of the web could be included to facilitate the addition of services such as electrical, plumbing and HVAC without significantly compromising performance.

The flexural analysis revealed that the wall response characteristics could be significantly improved by the selection of sheathing material. The OSB was the more reliable of sheathing material than fibre cement, where the serviceability limit would be exceeded before the safety factor of the materials were. However, in this study, the safety factor of the materials was not significant enough that this would be acceptable in a building and construction environment.

The in-plane shear behaviour was governed by the sheathing material and the contribution of the stud to the shear resistance was only minor. Like with flexural behaviour, the FEA considers ideal connection between the sheathing frame members, empirical validation will be required to ensure accuracy. While there are no serviceability limits for in-plane shear, a statistically significant understanding of the wall behaviour in this loading scenario would be required for adoption.

The resistance to compressive forces was not affected by the stud design in a significant way, however was affected by sheathing type. The stiffness in compression of OSB and fibre cement was approximately 40kN/mm and 22.5kN/mm respectively. However, the design on the stud did have a significant impact on the ultimate load capacity. Avoidance of the concentration of stresses on the bottom plate prove crucial in improving the safety factor of the wall structure. Should the walls load bearing capacity need to be improved in the future, the shape of the stud to reduce stress concentrations on the bottom plate could be an area of focus for future research.

The analysis into the web perforations to accommodate services revealed that ample provisions for services could be added to the upper section of the studs with only minor detrimental effect. However, any introduction of services to the bottom third could induce stress concentrations and lead to reduced loading capacity of the structure.

Overall, the material showed promise for the application of a residential stud wall. It should be reiterated that this analysis was conducted at a reduced strength of the material properties to characterise a worst-case scenario. Further empirical analysis will be required to validate the concept further accounting for the unknowns and variability discussed within this study.

5 Conclusion and Recommendations

As our economy changes and moves towards a circular economy, traditional building practises will need to evolve to meet these new market requirements. Simply relying on traditional building practises won't help this transition nor will it continue to be sustainable in the long term. The global economy has an oversupply of waste plastics and an undersupply of solid timber materials that typically need to be sourced from virgin supplies.

The research evaluates the viability of SGF-HDPE in association with sheathing materials within the realm of residential structural wall stud application. Using FEA to pursue two central objectives:

- limit the framing material while maintaining the composite wall's performance
- to investigate the practicability of integrating perforations in the web structure, thereby facilitating the accommodation of water, electrical, and communication services.

The study uses SGF-HDPE as a foundation element paired with two types of sheathing materials; OSB and fibre cement. Furthermore, it examines three discrete stud profiles, tailored to augment structural attributes under varying loading conditions, with an emphasis on flexural behaviour. It does so by evaluating the composite wall across three distinct load scenarios: axial longitudinal direction, flexural in the sagittal orientation, and in-plane shear in the transversal plane.

5.1 Validation of the FEA Model

The successful validation of the FEA against Manalo's (2013) empirical study with respect to the behaviour of the structure was a crucial milestone of this study. The demonstration of a close correlation between the empirical study and FEA, fortifies the credibility of the FEA as a predictive tool. The validation of the FEA demonstrates that the software can be used confidentially as a predictable tool of the behaviour of the wall under the loading conditions. The software's ability to predict ultimate strength of the material under a loading condition and the point of failure is less reliable however, it is the assumption of this study that the limits stated within this study are likely conservative. Ultimately empirical testing will be required to validate the model and further analysis may be require based on these results.

The validation of the model demonstrates that FEA can be used to make informed design decisions. This study only explored some of the aspects that could be altered to streamline the construction process. As industry strives for more environmentally friendly solutions, the ability to explore novel materials and construction practises at low cost and risk become more important. This study has demonstrated that FEA can be used further to optimise design prior to more expensive empirical testing.

5.2 Flexural

The FEA of the flexural behaviour of the composite wall system utilising SGF-HDPE studs and either OSB or fibre cement sheathing revealed the following:

- When considering fibre cement flexural stiffness only deviated a minor amount due to the composite wall being governed by the critical strength of the sheathing material.
- When considering OSB flexural stiffness could be improved by up to 1.4x with SS3 while decrease the material used as compared to the baseline by 46%.
- OSB was considered to be a more reliable sheathing material as it had a safety factor of more than 1 at the load required to deflect the wall to the serviceability limit.
- The presence of sheathing increases the flexural stiffness by:
    - ~7.5x for fibre cement
    - ~13x for OSB

  This suggests more research could be undertaken in the future to determine the most optimal sheathing configuration for the material.
- When considering a sheathing with a stronger elastic modulus such as OSB, while the overall performance of the wall is improved, this does lead to a higher concentration of stress in the web of the stud. This suggests studs need to be optimised to suit a sheathing type.

- Adding ribs to the flange improves stress distribution, increasing flexural rigidity and safety factor.

5.3 In-Plane Shear

The FEA of the in-plane shear behaviour of the composite wall system utilising SGF-HDPE studs and either OSB or fibre cement sheathing revealed the following:

- Sheathing is critical to the walls ability to resist in-plane shear, without sheathing walls did not perform.
- Stud design only had a minor effect on the performance of the wall under in-plane shear loading conditions.
- The OSB was approximately 1.3x stiffer than the fibre cement. This suggests strategic selection of sheathing materials is possible to improve characteristics under these loading conditions.
- The ability to resist in-plane shear was depended not only on the sheathing materials, but the foundation bolt pulling through the bottom plate. This suggests better mechanisms of load distributions could be utilised to improve this performance further.

5.4 Compressive

- Behaviour under compression influenced by sheathing type, with secondary effect from cross-sectional area/materials in the applied force direction.
- Fibre cement sheathing is vulnerable to compression-induced failure (around 20-30kN).
    - Failure attributed to lateral deflection of studs, resulting in tensile failure of fibre cement.
- OSB sheathed wall limited by SGF-HDPE material properties, stud design optimisation has modest effect.
    - SS1 and SS2 stud designs redistribute stress concentration effectively to bottom plate, leading to more stable design.

- Further research could explore stud footprint optimisation to limit stress concentration.

5.5 Web Perforations

- Analysis of SS3O with web perforations for impact on structural behaviour under combined loading conditions.
  - FEA showed a slight increase in deflection and minor decrease in safety factor compared to SS3O without perforations.
  - Perforations should be strategically located around area of least internal shear force (about 0.6 length from bottom).
  - Seven perforations were able to be introduced (3 at 48mm, 2 at 20mm, 2 at 13mm) without further deterioration.
- Evaluation of holes for plumbing drainage closer to point of maximum internal stress.
  - FEA indicated a marginal deflection increase (3%), but safety factor deteriorated by about 25%. Thus, indicating that specific consideration would be needed on site for walls that require hole at lower portions of the stud.
  - Caution is needed for using this type of wall with perforations in lower third of stud construction.

5.6 Areas of Further Research

As commonly themed throughout this thesis, the analysis found within is purely theoretical and does not take into account the variability associated with construction of actual specimens. The study uses idealised connection design of both the sheathing to studs, and between the members themselves. There is a significant degree of uncertainty surrounding these idealisations.

With respect to the inter-member connectivity, further FEA should be conducted on fixing designs to connect the members to each other. Owed to the potential manufacturing techniques of SGF-HDPE, complex shapes can be manufactured and potentially interlocking without the need for traditional fasters like screws or nails. The effects on these connection design needs further analysis to determine the most efficient way of combining the members.

Furthermore, the interaction between the SGF-HDPE and the sheathing material is still unknown. Further studies could be undertaken to determine if a mechanical or adhesive bond it optimal for the design and the effects of either compared to this study.

Appendix A- Risk Management

This research project is entirely desktop based and therefore the risk factors involved are limited. While various studies do acknowledge the presence of eye strain injuries conducting desktop research, simple strategies can be adopted to reduce these risks.

These risk management strategies can be broadly categorised into good ergonomics and good environment. For instance, the screen completed during this study is centred at the height of vision. Using a large format screen without bezels allows for the centring of main piece of work to avoid unnecessary rotation of the neck while leaving the peripheral positions for secondary reference material.

Other environmental factors are considered such as lighting conditions and appropriate ventilation and environmental conditioned contribute to reducing the potential health related issues (Bergefurt, Weijs-Perrée, Appel-Meulenbroek, & Arentze, 2022). Appropriate ventilation and background lighting conditioned have been optimised to reduce eye strain and improve general wellbeing.

Appendix B – Resource Planning

The resource planning of this undertaking is mainly limited to computation power and software to complete the finite element analysis. To complete the finite element analysis Solidworks will become the main provision required. A student licence of this has been obtained for this purpose. To run this software a business computer with suitable processing power has also been obtained (Solidworks, 2022).

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