Structural Effects of Spray-Applied Polyurethane Foam Insulation

Within a Wood Framed Wall Section

Applied Research Project

A paper submitted in partial fulfillment of the course requirements of RSR 2265

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Word count: 4264

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31st March, 2021

ACKNOWLEDGEMENTS

We would like to thank Dr. Sampath and Mark Bohnert for their advice throughout the duration of this research. We would also like to thank the facilities which allowed us to conduct this research. Thank you to Haul-All for allowing us to use their equipment to construct the sections, and thank you to the Lethbridge College and Teresa Nihill for conducting the testing necessary to write this report.

ABSTRACT

Advancements in the construction industry have led to the development of building materials that are both economical and functional. Spray applied polyurethane insulation (SPF) is one product, which manufacturers claim to not only have insulating properties but also increase wall strength. These claims were tested by compressing scaled-down wall sections in a hydraulic press to determine if wall strength was increased with the use of SPF compared to wall sections filled with traditional BATT insulation and control sections with no insulation. The findings showed that the SPF material provided only a marginal increase the compressive strength of the wall system. However, it was observed that wall systems containing SPF as an insulation were more consistent in their compressive resistance before the point of failure. Larger test groups at full scale are recommended for future research as scaling down wall systems amplifies natural impurities within the wood and human errors in construction, resulting in highly varied test results.

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1 INTRODUCTION

1.1 Background

Spray-applied Polyurethane Foam (SPF) insulation was first developed to be used in military airplanes in the 1940s and was introduced to residential building construction in the 1970s (Khazabi, 2015). Original SPF insulation contained isocyanate; a toxic substance discovered to cause health complications. Khazabi (2015) goes on to say that after several years of research, companies found out a non-toxic variant, which helped reinstate its usage. For those unfamiliar with SPF insulation, it is an expanding foam that hardens after a short passage of time. It is very lightweight and quite a tough material once it has been allowed to set. Due to its resistive properties, it is easy to see without experimentation that it will increase the strength of a ¡timber wall system. It is, however, so far unknown to what degree the strength of typical North American wall systems will be increased.

1.2 Purpose Statement

The purpose of this research is to quantify the strength increase present within standard North American timber wall sections resulting from the use of SPF insulation instead of other traditional insulation materials available on the market. This investigation will test three differing wall sections as follows: wall cavity devoid of insulation, wall cavity with fiberglass BATT insulation, and finally a wall cavity with SPF insulation. We will complete this research using a MODEL ADMET eXpert 1658 600kN Servo-Hydraulic Testing System. (also known as a Universal Testing Machine) and the software used is MTEST Quattro.

This hydraulic press equipped with the ability to measure stress versus position via the application of a uniformly distributed load (UDL) until specimen failure. To draw our conclusions we will compare stress (PSI) and compression (inches) at the moment of failure for each section. In addition, we will take note of any significant differences in the failure mode of each section.

1.3 Research Questions

If it is discovered that SPF provides a substantial increase in strength, it may be possible to negate standard timber sheathing and instead rely on the SPF to provide resistance to lateral loads. Another option if SPF proves to be quite strong is further spacing of timber members, such as studs at 14” increments instead of 12”. Thus, our primary research question is if the use of SPF foam within timber construction allows for a reduction in other construction materials while still producing a structure able to safely withstand factored loads.

2 LITERATURE REVIEW

To stay at the forefront of innovation, and push the boundaries of the trade, the construction industry faces many challenges. One notable challenge is meeting increasing demands for energy efficiency while also meeting the economic demands for cost effectiveness. This is seen specifically in demands for buildings that have a high insulating capacity contrasted with the desire to use cheaper building materials and methods to reduce overall cost (Mohareb & Row, 2014). In residential homes, when the demand for cost effectiveness outweighs the desire for energy efficiency, the results are to build prefabricated, mass-produced homes. Mass production often comes with a sacrifice in building material quality (Wells, n.d.). The trade off to using cheaper materials does however come at a cost to the homeowner. Increased heat loss in the winter and reduced retention of cool air in the summer results in higher costs to both heat and cool the home. Prospective homeowners rarely consider this when deciding on which home to buy (Myers, 2017). One other trade off seen while using lower quality materials is the increased environmental wear from both wind and snow loads resulting in more deterioration and damage than would be seen with higher quality materials. Another downside of using cheaper building materials is reduced resilience to environmental factors such as wind or snow. This means that the lifespan of the building will be reduced, which is a significant consideration given the Southern Alberta climate.

Numerous studies have investigated the effects of spray foam insulation (SPF) when applied into the stud cavities of wood framed wall systems. Many of these studies have findings which show an increase in lateral, and compressive strengths of the wall system when the wall is subject to a uniformly distributed load (Kakroodi et al., 2015). In fact, current research supports that the increase in strength output of the wall systems with SPF applied to the stud cavities was 30%-50% higher when considering racking and lateral forces than those wall systems, which relied solely on the exterior sheathing for support (Dodge & Chadwell, 2008; Khazabi, 2015; Kakroodi et al., 2015). In addition to increasing the overall strength of a wall system, the inclusion of SPF is also suggested to lower the cost of building materials by requiring fewer additional building materials. Grin & Lstiburek (2012) have suggested that the inclusion of SPF in a wall system no longer necessitates exterior sheathing for lateral support, and they also suggest that an interior vapor barrier is no longer required.

Following a comprehensive review of the literature two notable limitations became apparent. The first is due to the novelty of the SPF product in the construction industry. Most of the standard materials used in the construction industry have been in use for many decades, perhaps even centuries (Wang, 2013). This is a direct contrast to SPF materials, which were only developed within the last 50 years. This recent development, along with the specialized installation process, have resulted in SPF use being primarily limited to high-end construction projects. With an industry that is conservative or slow to adapt and incorporate newer methods, this means that little attention and resources have been put towards the exploration of this breakthrough building material, resulting in little research on the product. In addition, existing research on SPF products have not included an examination of the effect of time on material strength. All of the literature reviewed in preparation of this report has consistently suggested that SPF provides a substantial increase in strength to whatever system it is applied. However, many of these studies were completed by companies that either produce or sell the SPF product, which is the second limitation to the known research. This research is then subject to a great deal of bias in the conduction of the research as well as the presentation of the findings, which limits confidence in the reliability of corporate-funded findings.

To maintain a competitive edge in a fast paced and ever-expanding market, the construction industry must meet the lofty demands of building high performance structures while also keeping costs to a minimum (DeWitt, 2017). Meeting both these consumer demands is impossible without innovation and adaptation due to their inverse relationship. Building a higher quality structure requires expensive building materials, while using cheaper materials sacrifices structure quality and durability. One product that has revolutionized the construction industry is spray foam insulation. This product is supported by research with findings that it not only increases the strength of wall systems, but also takes the place of other traditionally required materials such as a vapor barrier or wall system sheathing (Grin & Lstiburek, 2012). The results are stronger walls, which cost less to build due to savings on other materials. Although the few studies completed on this product have consistently supported the strengthening effect SPF has on wall systems, companies that stand to make a profit from the sale of SPF product have completed the research, which suggests a heavy bias. This calls for the need for further research to be conducted on the product for accurate and reliable results on the ability of SPF to increase wall system strength.

3 RESEARCH DESIGN

3.1 Methodology

For this experiment, twelve wall sections were prepared, and using a hydraulic press, were compressed so that compressive load and compression distance could be measured. Seven, eight-foot-long boards of Spruce-Pine-Fir no.1 were obtained from a local hardware store. These boards were then cut into 1.5 X 0.75-inch pieces. These pieces were then trimmed in length to result in 24 pieces measuring 11.5 inches long, and 30 pieces measuring 15.5 inches long. These pieces were then used to assemble 12 standard timber wall sections with a top and bottom plate (using the 11.5-inch lumber), with 6 wall sections having two studs and 6 wall sections having 3 studs. Studs were made using the timber measuring 15.5 inches. The wall sections were held together using staples from a pneumatic stapler that were 2 inches long with a 0.62- inch crown. The necessity of scaling down the wall sections was due to the limitation by the hydraulic press. The hydraulic press was ultimately able to fit a wall section measuring 11.5 X 17 inches, and so the decision was made to scale down the wall size by a ratio of 40% to fit into a press.

Figure 1

Assembly of a Wall Section

Figure 2

Installation of SPF

As such, the decision was made to exclude sheathing from the walls as it is not sold commercially in a scaled-down version, and inclusion could produce skewed results. Both types of wall (two and three stud) were filled with one of three mediums, resulting in two tests of each wall type with each insulating material for a total of twelve tests. Figure 3 pictures an extra three-stud SPF section which was constructed due to extra material. The aforementioned extra section was held as a backup and is not included in the testing data. The control for the study was a wall filled with air. The two test wall types contained either fiberglass BATT or spray-applied polyurethane foam. The fiberglass BATT was held in place by construction plastic wrapping stapled to the studs. The SPF insulation held itself in place due to its own adhesive properties. All test specimens used to conduct this research are pictured in Figure 3.

Figure 3

All Test Sections Used for Data Collection

Each wall section was loaded in turn into a hydraulic press for testing. When placing each wall section, it was attempted that each section be loaded into the hydraulic press as plumb, square and flush with the press as possible without actual measurement. At Lethbridge College, the press model used for testing was the ADMET Expert 1658 600kN Servo-Hydraulic Testing System (also known as a Universal Testing Machine) in conjunction with MTEST Quattro software which is an advance PC based testing system that offers a wide range of flexibility in control, specimen data analysis and reporting.

Once the section was loaded, the hydraulic press was turned on and a monotonic compressive force load was applied until wall failure was achieved. Wall failure was defined as either breaking of any one stud of the assembled specimens, a wall plate being compromised resulting in a loss of wall strength, or the wall section twisted out of the press. Both the compressive force at the point of wall failure and the travel distance of the press arm were measured to determine the load (pounds) and compression (inches) of each wall section. Prior to testing, we are able to input the dimensions of the contact face into the press, which allows it to calculate pounds per square inch (PSI) as the load divided by the area of the contact face.

Figure 4 illustrates the wall dimensions as discussed above, along with contrasting the structure of the two versus three-stud wall structure. In addition, the figure shows how each wall section was loaded in the hydraulic press for compressive load testing.

Figure 4

Wall Section and Hydraulic Press Configuration

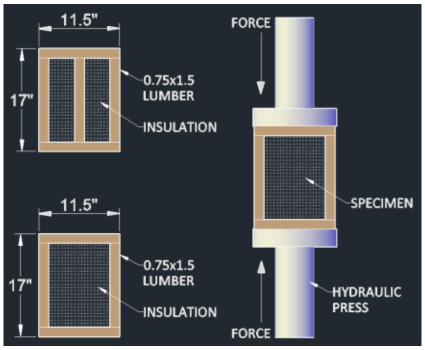


Figure 5

DMET Expert 1658 600kN Servo-Hydraulic Testing System A.K.A UTM

3.2 Data Collection

Data collected from the application of a uniformly distributed compressive monotonic load to two of each wall sections built using either two or three studs and with differing insulating materials is summarized in Table 1.

Table 1

Test Subject Maximum Stress and Compression at Loss of Load

	2 Studs		3 studs	
Insulation Type	Stress (PSI)	Compression (in)	Stress (PSI)	Compression (in)
Empty (1)	19	0.31	29	0.28
Empty (2)	19	0.37	45	0.91
BATT (1)	19	0.36	27	0.32
BATT (2)	20	0.71	34	0.59
SPF (1)	22	0.33	40	0.86
SPF (2)	19	0.33	38	0.78

For completeness, the slenderness ratio was also calculated, as seen in Table 2 below. First, both moment of inertia and the area are calculated for a rectangle. Then, the radius of gyration is calculated by taking the square root of the moment of inertia over the area. Finally the slenderness ratio is calculated by dividing the effective length by the radius of gyration.

Table 2

Slenderness Ratio Calculation

	Variables		Result	Units
	Base	Height		
Moment of Inertia	1.5	17	614.125	in^3
Area	1.5	17	25.5	in^2
	Inertia	Area		
Radius of Gyration	614.125	25.5	4.907	in
	Length	Radius of Gyration		
Slenderness Ratio	17	4.907	3.464	no units

3.3 Data Analysis

Upon completion of the wall section testing, stress output curves detailing the maximum PSI each wall section withstood against the position of the press cylinder were obtained using MTEST Quattro software. Stress output curves were created showing the vertical force being applied to the wall section in pounds per square inch (PSI) on the y-axis and the position change (compression), in inches, of the press cylinder relative to the starting position of the cylinder on the x-axis. Failure of each wall section was defined as the moment where a significant drop in vertical force and increase in position of the cylinder was observed. The specific points of failure from all the strength curves were then plotted on a scatter plot diagram, which allows observation of the variance of force resistance immediately prior to structural failure of each wall section. With this scatter plot, stress output differences can then be compared, contrasting both the differing stud cavity fill types as well as the difference between the wall sections with two or three studs.

Figure 6

Stress vs. Compression at point of failure in sections with three studs

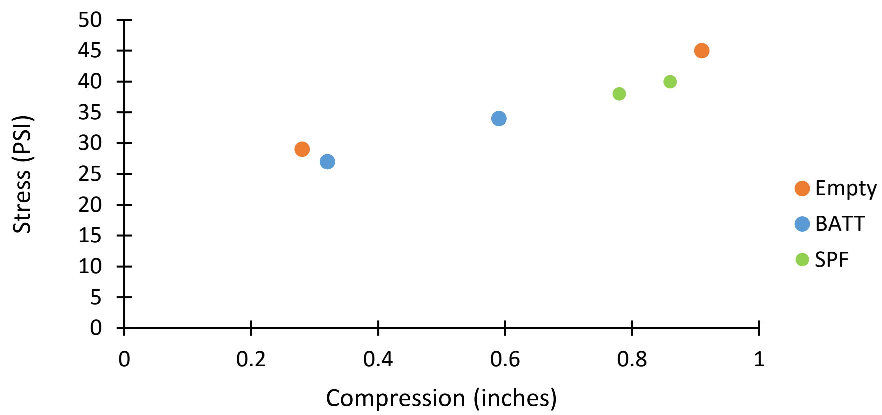
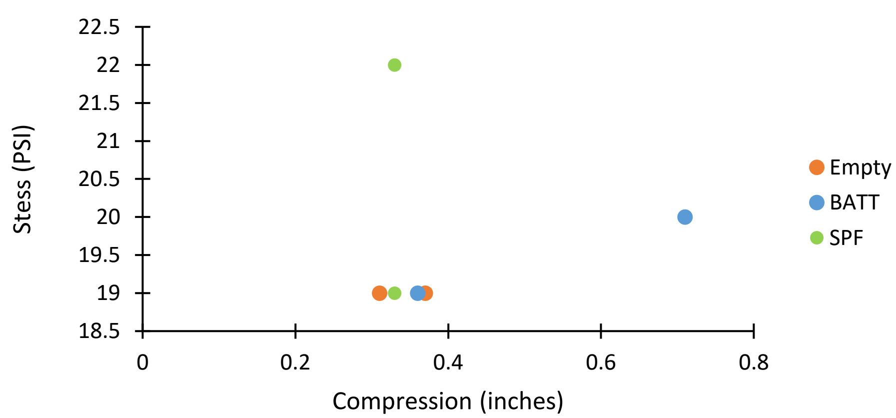


Figure 7

Stress vs. Compression at point of failure in sections with two studs



In addition to the direct comparison of maximum stress, it is interesting to see the full graphical representation of each test throughout their entire durations. While the ADMET Expert Hydraulic Testing System automatically creates a Stress/Position graph, it is unable to overlay past test results. Therefore, to generate a graph of combined full test results the raw data was extracted for each test and processed using Microsoft Excel. Resulting from this process are figures 7 and 8 for three and two stud sections, respectively.

Figure 8

Full test progression - three studs

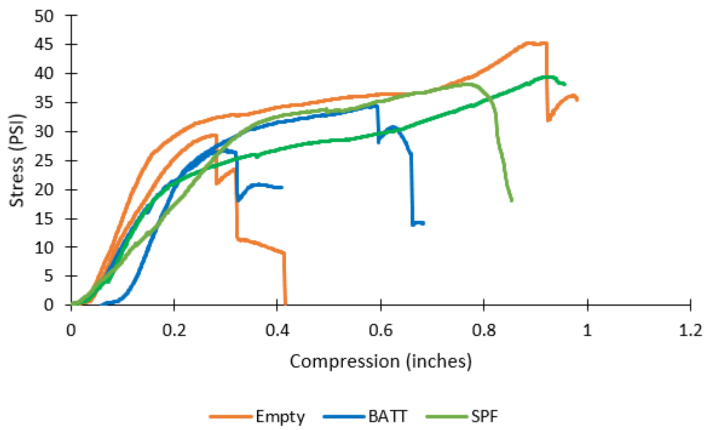
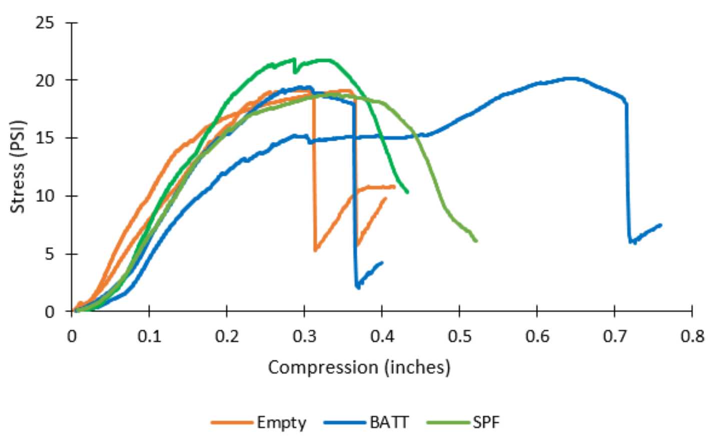


Figure 9

Full test progression - two stud sections



4 RESULTS AND DISCUSSION

4.1 Results

As can be seen in Table 1, the three stud wall sections were consistently able to withstand higher compressive forces than the two stud wall sections, as is expected. Within the three-stud wall section one control wall (no insulation) withstood the highest compressive force before stud fracture. The second and third strongest walls within the three-stud test group were the walls with SPF insulation, followed by one batt insulated wall, the remaining control wall and the final batt wall. Analysis of the maximum stress of the three-stud sections without SPF (empty and BATT) results in an average maximum stress of 33.75PSI, while the SPF sections resulted in an average maximum stress of 39.0PSI. This means that the three-stud sections with SPF insulation exhibited an average 13.5% strength increase over those sections with only air and BATT insulation.

Within the two-stud test group, strengths of the wall sections showed much less deviation. The strongest wall within this test group was one of the SPF insulated walls, followed by one BATT insulated wall. All remaining wall sections showed uniform fracture at the pressure of 19PSI. Generally, as can be seen in Figure 6, the section which withstood the highest PSI also underwent the greatest compression. The behavior of two-stud sections in Figure 7 is not as consistent as the three-stud sections. A two-stud SPF section withstood the highest PSI (among the two-stud sections) but underwent the third least amount of compression. Analysis of the maximum stress of the two-stud sections without SPF (empty and BATT) results in an average maximum stress of 19.25PSI, while the SPF sections gave an average maximum stress of 20.5PSI. This means that two sections with SPF insulation exhibited an average 6% strength increase over those sections with only air and BATT insulation.

A notable observation was made during the testing of the three studded SPF wall sections is that these sections did not fail in the same manner as the wall sections with the batt insulation or the empty sections. A limitation of our hydraulic press was that the bottom cylinder was able to rotate, something that we did not know would happen before beginning testing. The SPF sections, instead of failing due to a buckling stud or failed plate, consistently caused the bottom cylinder of the platform to twist out of position, as show in Figure 10 below. It was upon observation of this twisting motion of the wall section that the test section had to be considered to have failed, due to overall deformation.

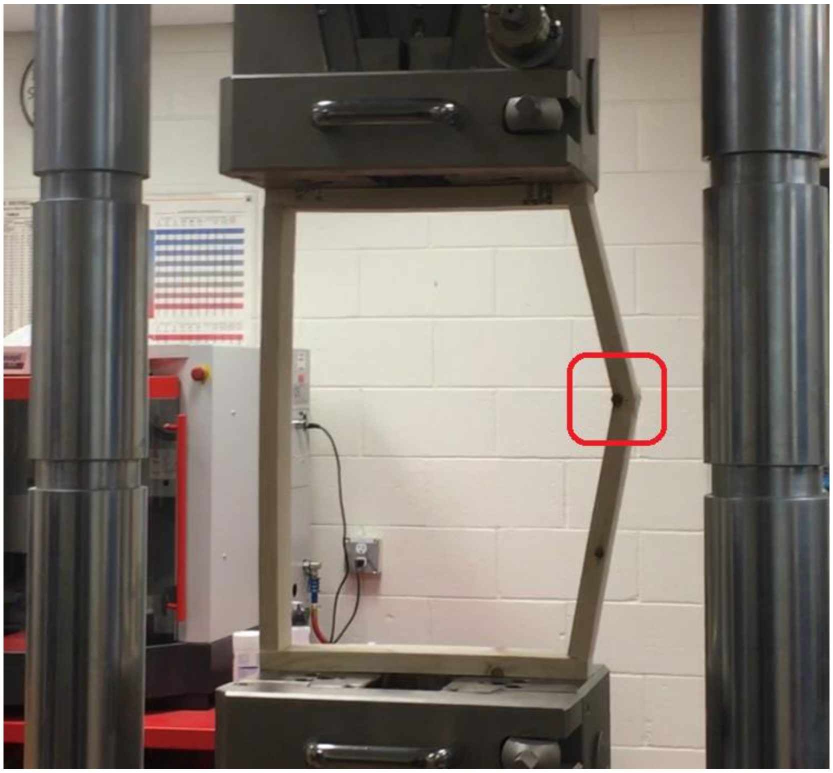
Figure 10

Typical twisting failure mode of section with SPF

Looking at Table 1 we can see that the section that withstood the highest stress was a three-stud empty section. Ultimately an outside stud buckled on this section after the plates had failed, but it was one of only three sections that did not have any significant knots on its studs. It may be interesting to note that each section with knots present in the studs always failed on or around the knot, as can be seen in Figure 11 below.

Figure 11

Typical failure mode of sections with knotted studs



4.2 Discussion

Based on the results of the test, the hypothesis that the SPF insulated walls would display a significant increase in compressive stress resistance is rejected. While the sections containing SPF were not always able to withstand the most stress, their stress resistance was consistently among the highest. Also, while it seems obvious to some, it is now proven that fiberglass BATT insulation possesses no strength properties whatsoever. Thus, both empty and BATT sections have been grouped together as the control.

Timber construction members are highly variant in their actual strength, even though they may be sold as the same type of member. Due to this, timber construction is typically based around 5% confidence intervals of member strength. In other words, timber structures are designed to be built using the bottom 5% of wooden members. This allows for one – or several – of the bottom 5% of timber members to be installed within a structure without becoming structurally unsafe. SPF insulation seems to, in some capacity, “fill in” the gaps left in member strength due the naturally present inconsistencies within timber construction members. In addition, it is possible that the SPF possesses enough strength to effectively act as continuous lateral support for the section studs, preventing them from buckling about their weakest axis. It is possible that the SPF sections’ studs would have eventually buckled about their stronger axis had the bottom arm of the hydraulic press not been able to rotate.

The scaling down of the wall sections and each of the wall members could account for some of the variation in test results and may be a limitation to the experiment. As the walls themselves were scaled to fit in the hydraulic press, any deformity or imperfection in the lumber would play a larger role in the strength of the entire wall system. A particular deformity which would have great impact are the knots in the lumber. This means that when we went through the size reduction process on the table saw, whatever knots were present in the material before, now took up a larger portion of the member’s cross-sectional area than when it was a full sized 2x4. Selection and placement of material with and without knots could account for the anomalous strength values in the wall section testing. This possible limitation is very difficult to overcome in any instance where a wall system must be scaled down. When lumber is scored for quality, it is done so to reflect the quality of the entire board. Although the boards may be scored as an equal quality overall, the area of the board used in the scaled down wall may contain more imperfections than in other sections of the board. A larger sample group may overcome this limitation in future experiments as each wall system has an equal chance to be impacted by this limitation as the others, and the effect would likely be cancelled out by larger sample averages.

A notable observation made during the testing of the SPF walls sections was that prior to stud failure the wall plate of each section experienced considerable damage due to a crushing of the plate member. One possible explanation for this is that the SPF insulation was able to hold the studs in a more stable position than was offered by the BATT insulation and lack of insulation. The result in the SPF wall sections being that the plate material took on higher compressive forces than the studs. In the batt insulation and empty wall sections, the forces applied would transfer more readily to the studs rather than the plates due to their more vulnerable position within the wall system.

From our data we know that, on average, the three-stud SPF sections were 13.5% stronger in compressive resistance than that control sections. Therefore, it is interesting to consider why the absolute highest stress withstood was exhibited by a control section. There were a couple differences between each wall section besides the type of insulating material. First, there were differences in member quality. Many members had large knots or chipped edges (members were too small to exhibit warping), both of which reduce strength. The other main difference was the dimensions. Due to our test sections being constructed by hand, human error was incorporated into all members that needed to be sawed, cut, or stapled. That would mean an indeterminable of the members had variance in their dimensions, which was clearly visible upon loading the test sections into the press. Upon video review of testing, it can be seen that the section which withstood the absolute highest stress had optimum properties for both aforementioned variables: the studs and plates were nearly completely devoid of any defects, and the section was just about perfectly symmetrical. This means that any stresses induced by natural member defects or human error were minimized, and the true strength of the wood's compressive resistance parallel to grain shone through.

5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Conclusion

Further to the purpose of the research, we can define the performance of SPF insulation as being consistently better than traditionally available insulation materials; it is apparent that SPF is better choice against factored load bearing situations based on the research data analysis. The purely compressive strength resistance of SPF insulated specimens was increased by a mere average of 10%. However, the test as mentioned does not guarantee similar results for the full-scale wall sections. In a fully scaled wall section the compressive resistance of the studs would likely be much lower due to a properly proportioned length, and plate failure would be more uncommon.

Finally, we can make a firm statement that SPF is proven to have an impact on a timber construction building's structural strength based on our small-scale research. That is to say that it does indeed consistently improve the compressive resistance of any standard shaped wall section it is installed within. The potential for this product to save on structural material volumes is reasonable, beven considering only a 10% reduction of material. In addition, even without material reduction, use of SPF may suit those who wish to have a solid timber construction with reduced risk of structural failure.

5.2 Recommendations

To properly conduct this experiment and recognize the true potential of SPF within timber construction, it is recommended that this type of research be conducted with full scale wall sections. In addition, it would be beneficial to test a wall section with SPF's lateral strength compared to a wall with sheathing. Moreover, a researcher could consider using rigid insulation instead of BATT to draw a more meaningful comparison of the structural properties of insulating materials. It would be interesting to investigate the strength increase due to SPF in differing timber construction sections such as window sills or floors. Finally, the inclusion of environmental factors such as weather or time may be beneficial information for accurate inclusion in long-term design projects.

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7 DECLARATION OF AUTHORSHIP

The following declaration is to be signed by the applicant, and countersigned by a sponsor who should be an immediate advisor or manager of the applicant. Self-employed applicants will require the signature of a recognized professional. This declaration of authorship must be submitted with your technical report.

I /We, Harrison Hadford, Jordan Dyck, Sishminder Singh, hereby affirm that the enclosed manuscript entitled, Structural Effects of Spray-Applied Polyurethane Foam Insulation Within a Wood Framed Wall Section, is our own composition. We declare that We have personal knowledge of the facts and conclusions set out therein, except where I have stated otherwise, and have in no degree committed plagiarism. On this basis I agree to have the report judged.

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Signature of Applicant(s)

Sponsor's Declaration

I have taken all fair precautions necessary to enable me to assure the Registration Board of The Association of Science and Engineering Technology Professionals of Alberta that the above statement is true.

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Position

8 CONTRIBUTION (%) FROM GROUP MEMBERS

CTAC Learning Outcome Indicators	Harrison	Sishminder	Jordan
1.1 Determine a research area where practical technical investigation is warranted and define research goals and objectives.	100	100	100
1.2 Compile and integrate a wide range of research resources, including professionally published or peer reviewed literature, online tools, and interviews.	100	100	100
1.3 Integrate use of technologies to investigate procedures and analyze issues.	100	100	100
1.4 Assemble, analyze, and appropriately apply technical data to create graphics, reports, and other documents to support the Technology Report.	100	100	100
1.5 Integrate the processing, analysis, and interpretation of technical data to conclude the Technology Report.	100	100	100
1.6 Compile information effectively and accurately by analysing, translating, and producing the Technology Report.	100	100	100
1.7 Justify conclusions and make recommendations.	100	100	100
1.8 Create the Technology Report in professional format using accepted principles of documentation, grammar, writing style, graphics and design.	100	100	100
1.9 Present the Technology Report and respond effectively to questions defending project conclusions.	100	100	100