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QUANTIFICATION OF THERMAL BRIDGING EFFECTS IN COLD-FORMED STEEL WALL ASSEMBLIES

Divyansh Kapoor
University of Massachusetts Amherst

QUANTIFICATION OF THERMAL BRIDGING EFFECTS IN COLD-FORMED STEEL WALL ASSEMBLIES

A Thesis Presented

by

DIVYANSH R. KAPOOR

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Approved as to style and content by:

____
Kara D. Peterman, Chair

____
Sergio F. Breña, Member

____
John E. Tobiason, Department Head
Civil and Environmental Engineering

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ABSTRACT

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February 2020

DIVYANSH R. KAPOOR, B.S., UNIVERSITY OF MASSACHUSETTS, AMHERST

M.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Kara D. Peterman

Thermal bridging can be defined as the phenomenon where a structural element spanning the building envelope acts like a thermal pathway which collects and moves energy (heat) from the interior to the exterior of the structure. CFS construction, due to the high thermal conductivity of steel with respect to its surrounding structural components and repetitive nature of framing, is highly prone to thermal bridging. The high relative difference in material conductivity causes CFS members to provide a path of least resistance for heat flow, thereby significantly altering the thermal performance of wall assemblies. Existing literature in the field of thermal bridging with a focus on CFS wall assemblies discuss mitigation strategies and overall performance but rarely focus on quantifying individual member contributions.

Hence, the objective of this research project was to quantify the magnitude of energy loss through cold-formed steel (CFS) stud wall assemblies at a component level to lay the groundwork for future works that promote sustainable, energy efficient, and improved building design recommendations.

Therefore, a parametric evaluation was performed using ISO 10211:2007, Annex A, conforming specialty heat transfer software Blocon Heat3 version 8 to generate the data required for analysis. 80 unique wall assemblies and the impact of selected parameters on

the overall thermal transmittance of the wall assembly were studied as part of the parametric evaluation. The key variables of the study are steel thickness, stud depth, stud spacing, cavity insulation R-value, external insulation thickness (R-value), and fastener diameter and length.

Based on the results of the analysis, effects of increasing stud and track thickness, depth, and stud spacing have been discussed in the form of trends in overall heat flow and linear thermal transmittance coefficient values. Similarly effects of increasing fastener diameter and penetration have been discussed in the form of trends in overall heat flow and point thermal transmittance coefficient values. Additionaly, effects of increasing external insulation have been discussed by addressing changes in heat flow.

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CHAPTER 1

INTRODUCTION

1.1 Motivation for study

Cold-Formed Steel (CFS) construction has become increasingly popular in the United States due to benefits such as increased sustainability, durability, non-combustibility, resiliency, cost-effectiveness and constructability (Buildsteel.org 2018). However, CFS construction is prone to thermal bridging due to the high thermal conductivity of steel components with respect to their surrounding components. The high relative difference in material conductivity causes CFS members to provide a path of least resistance for heat flow, thereby significantly altering the thermal performance of wall assemblies. Hence, there exists the need to quantify these effects to provide practicing engineers and designers with accurate and reliable information to promote efficient and code compliant design solutions.

1.2 Research objective

The objective of this research work is to provide in-depth information on thermal performance of typical CFS wall assemblies with a focus on overall heat flow. This has been done by addressing trends observed in insulation effectiveness and individual component contribution as the thermal transmittance coefficient of the component.

1.3 Scope of work

The scope of this research work is limited to quantifying heat flows and thermal bridging effects for CFS wall assemblies with framing factors in the range of 11% to 14%

which corresponds to 24 inches to 16 inches on center CFS stud spacing. Analysis of the wall assemblies was carried out using ISO 10211:2007, Annex A, conforming specialty heat transfer software Blocon Heat3 (Blocon 2018). Additionally, insulation selection is based on ASHRAE 90.1 climate zones and hence is limited by the respective minimum required insulation values for the zone (ASHRAE 90.1).

1.4 Thesis organization

This Master's thesis comprises of six chapters. The first chapter serves as an introduction into the research objectives, motivations, and scope of work. The second chapter, "Literature Review", aims provide the reader with necessary context to the problem being studies by providing summaries of recent works in the field. The next chapter, 3-D Steady State Thermal Analysis, Model Validation, and Parametric Evaluations, provides detailed information about the analysis and validation methods, typical wall geometry, and parametric evaluation of wall assemblies. Chapter 4 discusses how the results were generated and interpreted to quantify thermal performance. Finally, Chapters 5 and 6, provides conclusions and discussions of the results along with a direction of future research.

Additionally, detailed breakdown of material properties, parametric evaluation wall assemblies, heat flow and transmittance results, can be found in Appendix A through C. Appendix C provides further information on fastener modelling simplification used during the finite element analysis phase of the project.

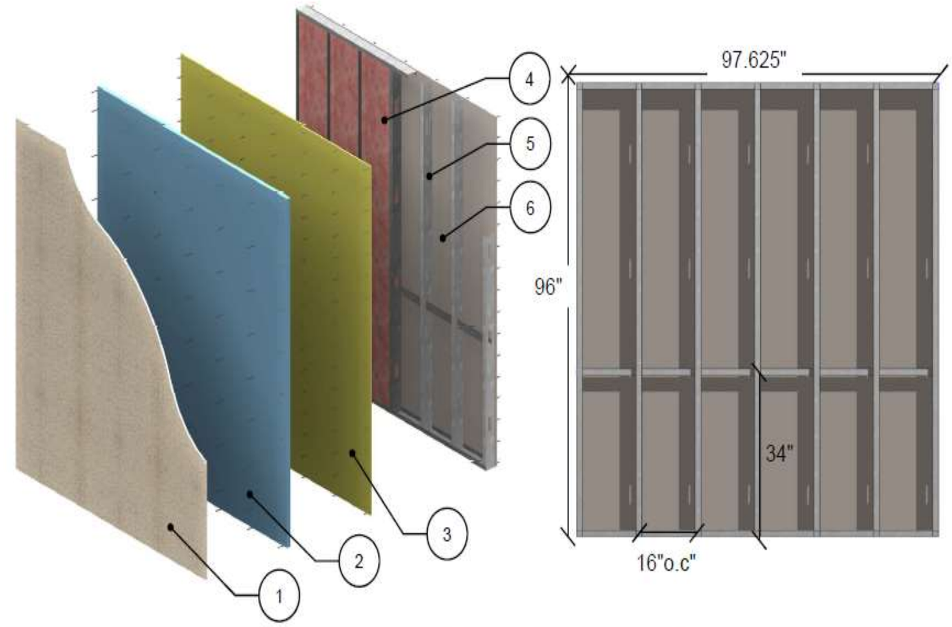
CHAPTER 2

LITERATURE REVIEW

This section provides a summary of some of the most recent or relevant works that served as a background to this project. Extensive work has been done in this field by Morrison Hershfield Ltd. and Martins et al. 2016 who have performed parametric studies to assess the overall heat flow and impact of mitigation strategies respectively. Additionally, a study conducted by NAHB Research Center, which compares the annual performance of identical steel framed and wood framed construction houses has also been included to serve as a comparison between the two construction materials.

2.1 Thermal analysis of cold-formed steel wall assemblies (AISI RP 18-1 2018)

To assist with the development of a simplified calculation methodology for determining the thermal performance of generic CFS wall assemblies, Morrison Hershfield Ltd. was contracted by the American Iron and Steel Institute (AISI) to perform this study. The thermal performance of 27 steel stud assemblies, which resulted in an overall 90 project models, was analyzed using Siemens NX modelling software and TMG thermal Solver. The key variables were insulation thickness, insulation placement, steel stud depth, and varying fastener patterns. The project assemblies comprised of stucco, exterior rigid board insulation, gypsum sheathing layers, cavity insulation, CFS member, and fasteners and can be seen in Figure 1.



1	2	3	4	5	6
¾ Stucco	Exterior Rigid Board Insulation	5/8" Gypsum Sheathing	Cavity Insulation	Steel Studs, Tracks and C-Channel	5/8" Gypsum Interior Drywall

Figure 1: Basic configuration of the project assemblies (AISI RP 18-1, 2018)

The modeling procedure and material properties were validated against the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) research projects 1365 RP and 785 RP in addition to the Oak Ridge National Laboratory (ORNL) hotbox compilation study. The modelling approach provided simulated assembly surface to surface R-values that were within -1.4% to +2.5% and -7.1% and +8.4% to surface to surface R-values obtained from ASHRAE 785-RP and ORNL Compilation study respectively.

Table 1 summarizes the modelling matrix and material properties used for this study. Three different 43 mil CFS studs were utilized, namely 350S162, 1000S162, and 1200S162. The results of the parametric evaluation and detailed results for the 1000S162 - 43 mil wall assemblies have been summarized in Table 2.

Table 1: Summary of material properties and modelling matrix (AISI RP 18-1, 2018)

ID	Material	Validation Assembly	Thickness (In)	Conductivity K-Value (BTU-In/hr ft^2 °F)	R-Value (hr ft^2 °F/BTU)
1	Stucco	All	3/4"	9.375	0.08
2	1.5" XPS	2, 5, 8, 11, 14, 16, 20, 23, 26	1.5"	0.200	7.5
	3" XPS	3, 6, 9, 12, 15, 18, 21, 24, 27	3"	0.200	15.0
3	Fasteners 6" or 12"o.c.	All	#6	346	-
4	Gypsum Sheathing	All	5/8"	1.11	0.56
5	3 5/8" x 1 5/8" Steel Stud	1-9	0.0428" (43 Mil)	495	-
	10" x 1 5/8" Steel Stud	10-18	0.0428" (43 Mil)	495	-
	12" x 1 5/8" Steel Stud	19-27	0.0428" (43 Mil)	495	-
6	3 5/8" x 1 1/4" Steel Tracks	1-9	0.0428" (43 Mil)	495	-
	10" x 1 1/4" Steel Tracks	10-18	0.0428" (43 Mil)	495	-
	12" x 1 1/4" Steel Tracks	19-27	0.0428" (43 Mil)	495	-
7	1 1/2" x 1 1/2" C-Channel	All	0.0428" (43 Mil)	495	-
8	Air Cavity	1-3	3 5/8"	4.0	0.9
	R-19 Insulation	4-6	3 5/8"	0.191	19
	R-38 Insulation	7-9	3 5/8"	0.095	38
	Air Cavity	10-12	10"	11.1	0.9
	R-19 Insulation	13-15	10"	0.526	19
	R-38 Insulation	16-18	10"	0.263	38
	Air Cavity	19-21	12"	13.3	0.9
	R-19 Insulation	22-24	12"	0.632	19
	R-38 Insulation	25-27	12"	0.316	38
9	Gypsum Drywall	All	5/8"	1.11	0.56

The effect of increasing cavity insulation was most noticeable when comparing wall assemblies with air cavity with wall assemblies with R-19 insulation and resulted in an increase of 221% to 245% in the simulated R-value when no external insulation was present. However, diminishing returns were observed when cavity insulation was further increased from R-19 to R38, and the reduction was about 23% to 27%. When external insulation of R-7.5 (1.5-inch XPS) was present, the addition of R-19 insulation in the cavity increased the simulated R-value by about 72-79%. Diminishing returns were again observed when R-19 insulation was replaced with R-38 insulation, and the increase in R-value was 20% to 23% with. Similar results were observed when the assemblies with XPS thickness of 3.00 inches were compared.

It was also observed that stud depth had modest impact on the overall R-value of the wall assembly when comparing 350S162, 1000S162, and 1200S162 models. Varying fastener patterns only impacted the R-value of the assembly when fasteners were present that penetrated the XPS. However, the impact was constant even when comparing assemblies with 6.00 inches on center interior and no exterior wall assemblies with both 6.00 inches on center and 12 inches on center exterior patterns.

Due to the continuous nature of the external insulation, the increase in overall R-value was almost equal to the R-value of the XPS being added. This trend was observed for all air cavity wall assemblies.

Table 2: Summary of results for 1000S162 – 43 mil steel stud wall assemblies (AISI RP 18-1, 2018)

Assembly Ref.	Fastener Pattern	Gypsum Fastener Spacing	Ext. Insul. Fastener Spacing	Framing 16"o.c.	Component R-values hr·ft^2·°F/BTU (m^{2}K/W)							Simulated R-Value	Simulated U-value
					Interior Air Film	Interior Gypsum	Cavity Insulation	Exterior Sheathing	Exterior Insulation	Stucco	Exterior Air Film		
10	1	6" oc	N/A	1000S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.344**
	3	12" oc	N/A	1000S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.344**
11	1	6" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.5**	**0.096**
	2	6" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.3**	**0.097**
	3	12" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.5**	**0.096**
	4	12" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.3**	**0.097**
12	1	6" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**18.0**	**0.056**
	2	6" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.5**	**0.057**
	3	12" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**18.1**	**0.055**
	4	12" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.5**	**0.057**
13	1	6" oc	N/A	1000S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**9.8**	**0.102**
	3	12" oc	N/A	1000S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**9.8**	**0.102**
14	1	6" oc	None	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.4**	**0.054**
	2	6" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.1**	**0.055**
	3	12" oc	None	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.4**	**0.054**
	4	12" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.1**	**0.055**
15	1	6" oc	None	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.0**	**0.038**
	2	6" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.2**	**0.040**
	3	12" oc	None	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.0**	**0.038**
	4	12" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.2**	**0.040**
16	1	6" oc	N/A	1000S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**12.4**	**0.081**
	3	12" oc	N/A	1000S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**12.4**	**0.081**
17	1	6" oc	None	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.3**	**0.045**
	2	6" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.9**	**0.046**
	3	12" oc	None	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.3**	**0.045**
	4	12" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.9**	**0.046**
18	1	6" oc	None	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.1**	**0.033**
	2	6" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.0**	**0.034**
	3	12" oc	None	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.1**	**0.033**
	4	12" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.0**	**0.034**

2.2 Lightweight steel-framed thermal bridges mitigation strategies: A parametric study (Martins et al. 2016)

The authors, Martins et al. (2016), evaluated the performance of thermal break strategies such as thermal break rubber strips, vertical male or female studs, slotted steel studs, and combinations of the same along with different insulations like polyurethane foam, silica aerogel insulation blankets, and vacuum insulated panels (VIPs). The parametric study comprised of single thermal bridge mitigation strategies, combined mitigation strategies, and a parametric study for U-value improvement.

The wall assembly used for analysis can be seen in Figure 2 below, and the most effective single thermal break strategy was found to be the use of slotted steel studs which provided a reduction of U-value of 4.54%. Rubber strips offered a thermal advantage of 1.9% when 5mm rubber strips were used and 3.5% when 10mm rubber strips were used. The use of vertical male and female studs was found to have a negligible thermal advantage of 0.2% to 0.4%.

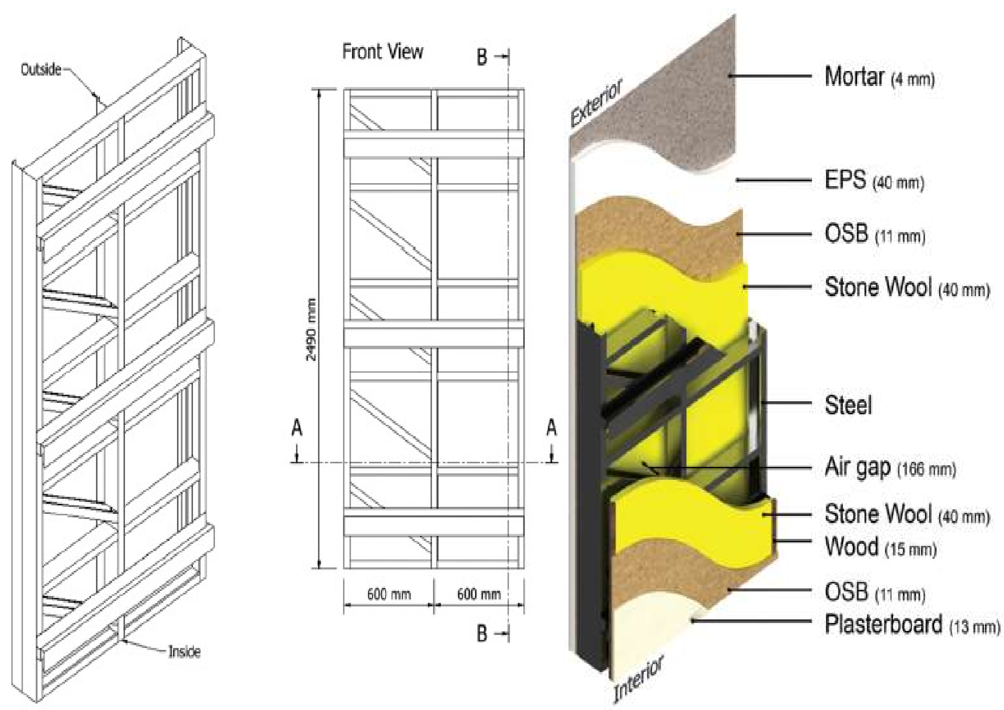


Figure 2: Description of CFS wall assembly and components (Martins et al. 2016)

Combined mitigation strategies such as using rubber strips, slotted steel profiles and bolted connections offered a promising reduction in overall U-value of as high as 8.3%. A summary of these results can be seen in Table 3.

Table 3: Summary of results for different single and combination based thermal break mitigation strategies (Martins et al. 2016)

Model		Model description				U-value (W/(m^2 K)) (ΔU)
		Without horizontal steel connections	Rubber strip	Vertical female or male studs	Slotted steel profiles	
Single strategies	A[a]					0.3011 (–)
	B_1		✓ 5 mm			0.2954 (−1.9%)
	B_2		✓ 10 mm			0.2906 (−3.5%)
	C_1			✓ 15 mm		0.3021 (+0.4%)
	C_2			✓ 25 mm		0.3018 (+0.2%)
	D_1				✓ 14%Only vertical	0.2913 (−3.2%)
	D_2				✓ 28%Only vertical	0.2904 (−3.5%)
	D_3				✓ 28%	0.2874 (−4.5%)
	E	✓ 9 bolts				0.2949 (−2.1%)
Combined strategies	F	✓ 9 bolts	✓ 10 mm		✓ 28%Only vertical	0.2782 (−7.6%)
	G				✓ 28%	0.2762 (−8.3%)

[a]Reference model.

From their parametric study for U-value improvement, Santos et al. concluded that the best single strategy was using VIPs (49% reduction). Also, the most efficient solution was found to be placing 30mm VIPs on both sides in combination with the use of slotted steel profiles, 10mm rubber strips, and bolts. This provided an overall reduction of 68.2% in the calculated U-value. A summary of the results of the parametric evaluation can be seen in Table 4.

Table 4: Summary of parametric study for U-value improvement (Martins et al. 2016)

Model		Model description							U-value (W/(m^2 K)) (ΔU)
		Without horizontal steel connections	Rubber	Slotted steel profiles	Polyurethane foam		Aerogel	VIPs	
					Without air gap and stone wool	With 40-mm air gap and without stone wool			
Single strategies	A[a]								0.3011 (–)
	H				✓				0.1615 (−46.4%)
	I					✓			0.1876 (−37.7%)
	J						✓ Internal side only		0.2295 (−23.8%)
	K						✓ External side only		0.2356 (−21.8%)
	L						✓		0.1889 (−37.3%)
	M							✓ Internal side only	0.2032 (−32.5%)
	N							✓ External side only	0.2048 (−32.0%)
	O							✓	0.1536 (−49.0%)
Combined strategies	P	✓	✓ 10 mm	✓ 28%Only vertical	✓				0.1271 (−57.8%)
	Q					✓		0.1525 (−49.3%)	
	R			✓ 28%	✓				0.1173 (−61.0%)
	S					✓			0.1333 (−55.7%)
	T						✓		0.1406 (−53.3%)
	U							✓	0.0959 (−68.2%)

VIP: vacuum insulation panel.
[a]Reference model.

2.3 The effectiveness of thermal insulation in lightweight steel-framed walls with respect to its position (Roque and Santos, 2017)

Roque and Santos in their paper "The effectiveness of Thermal Insulation in Lightweight Steel-Framed Walls with Respect to Its position", evaluated the performance of cold-formed steel wall assemblies with a focus on the effectiveness of thermal insulation with regards to its position in the wall assembly. Three different insulation locations and the resulting cold, warm, and hybrid frame wall assemblies were studied, and they have been shown in Figure 3.

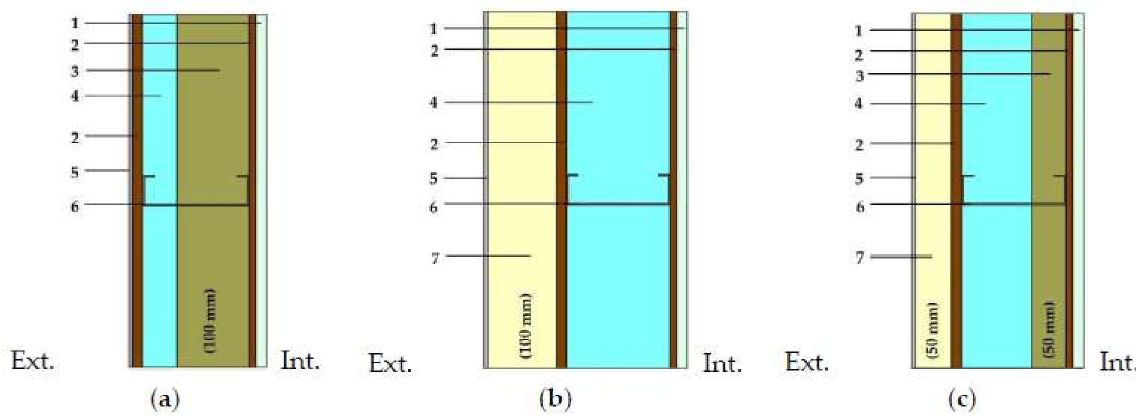


Figure 3: Facade wall assemblies, (a) Warm, (b) Cold, and (c) hybrid frame construction. Materials: 1—Gypsum board; 2—OSB; 3—RW; 4—Air; 5—ETICS finish; 6—LSF; 7—EPS (Roque and Santos, 2017).

The purpose of their numerical study (Refer Table 5) was to evaluate the effectiveness of insulation, study the influence of the thermal bridges formed due to the cold-formed steel construction on overall thermal performance, and analyze the thermal performance in accordance with the Portugal Thermal Regulation for residential buildings.

Table 5: Parametric study on insulation location (Roque and Santos, 2017)

Cold Construction		Warm Construction		Hybrid Construction	
Material [(1)]	*d* (mm)	Material [(1)]	*d* (mm)	Material [(1)]	*d* (mm)
ETICS finish	5	ETICS finish	5	ETICS finish	5
OSB	15	EPS	150 (W1)	EPS	75 (H1)
RW	150 (C1)		125 (W2)		62.5 (H2)
	125 (C2)		100 (W3)		50 (H3)
	100 (C3)		75 (W4)		37.5 (H4)
	75 (C4)		50 (W5)		25 (H5)
	50 (C5)		25 (W6)		12.5 (H6)
	25 (C6)	OSB	15	OSB	15
Steel Studs	150	Steel Studs	150	RW	75 (H1)
OSB	10	OSB	10		62.5 (H2)
Plasterboard	15	Plasterboard	15		50 (H3)
					37.5 (H4)
					25 (H5)
					12.5 (H6)
				Steel Studs	150
				OSB	10
				Plasterboard	15

[(1)] From outer to inner surface.

It was observed that for cold framed construction, neglecting the contribution of the CFS members overestimated the thermal performance of wall assemblies by as much as 94% (Figure 4). It was also observed that there exists a direct correlation in the reduction of insulation effectiveness when steel studs penetrate more of it. This implies that greater thicknesses of insulation in the same cavity have a more reduced effectiveness due to increased CFS stud penetration.

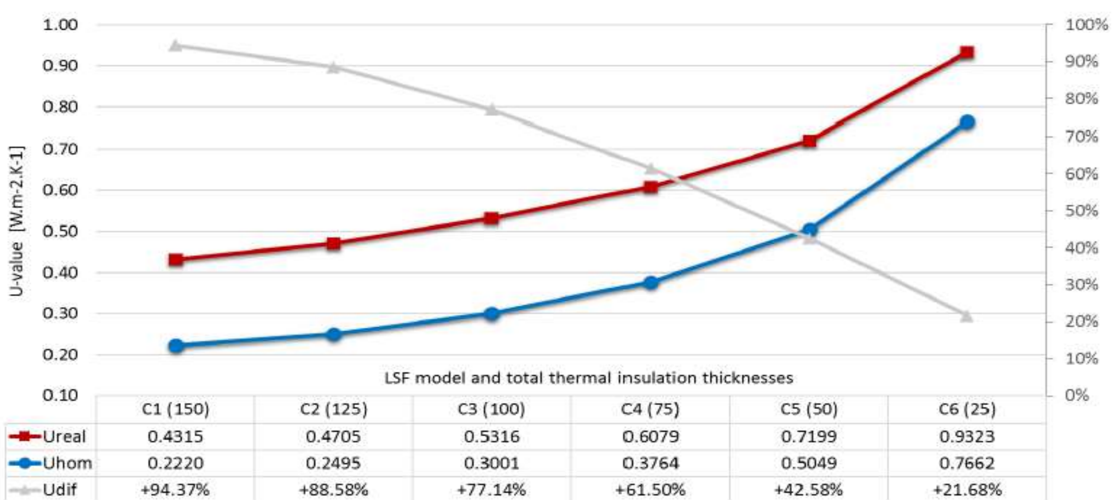
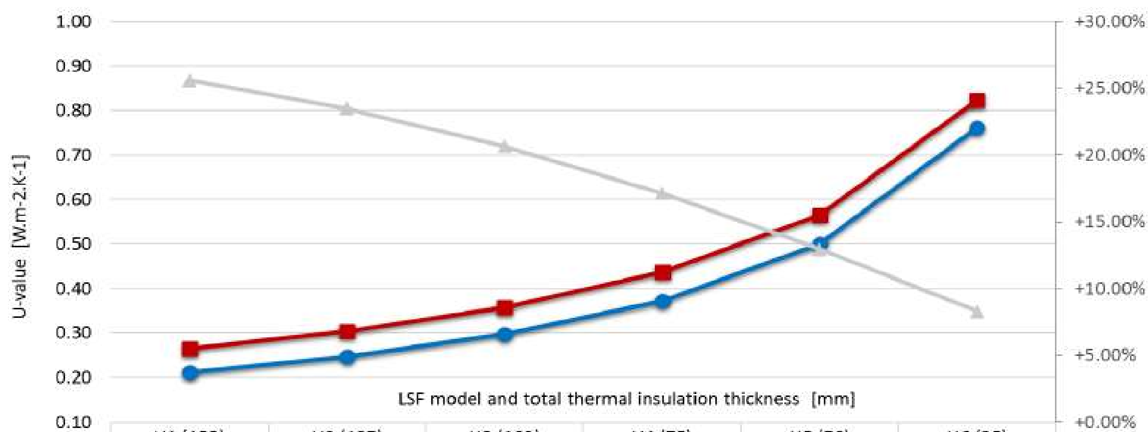


Figure 4: Results of the cold frame construction parametric study (Roque and Santos, 2017)

When all the insulation is placed outside the façade cavity (warm frame construction), the impact of CFS framing was 0.4% to 1.4%. In the case of hybrid frame construction, a similar overestimation of thermal performance as observed in cold frame construction was observed. However, the difference in U value was significantly reduced with a maximum being about 25.6% (Figure 5). They determined that this diminishing effect was due to the presence of external insulation, which reduced the detrimental effect of studs piercing through the internal insulation.



	H1 (150)	H2 (125)	H3 (100)	H4 (75)	H5 (50)	H6 (25)
Ureal	0.2650	0.3045	0.3581	0.4364	0.5648	0.8238
Uhom	0.2110	0.2466	0.2968	0.3725	0.5001	0.7607
Udif	+25.59%	+23.48%	+20.65%	+17.15%	+12.94%	+8.29%

Figure 5: Results of the hybrid frame construction parametric study (Roque and Santos, 2017)

2.4 Steel vs. wood: Long-term thermal performance comparison (NAHB 2002)

In their report to the U.S. Department of Housing and Urban Development (HUD), North American Steel Framing Alliance (NASFA), and National Association of Home Builders (NAHB), the NAHB Research Center compared the thermal performance (energy consumption) of two nearly identical side-by-side unoccupied houses located in Valparaiso, Indiana. One of the houses was built from CFS members and the other was built up of conventional dimensional lumber. The electric use and natural gas use were the key parameters for comparison.

The CFS demonstration home (Figure 6) comprised of wall studs spaced 24 inches on center with loadbearing studs located directly in line with roof rafters and floor joists. The structural steel studs were 550S162-33 mil, and non-structural steel studs were 350S162-27 mil members. The steel framed members were designed using the Prescriptive Method for Residential Cold-Formed Steel-Framing. Exterior wall sheathing was 7/16 inch oriented-strand-board and ¾ inch rigid extruded polystyrene panels were secured to the outside of the OSB with plastic cup nails.

Figure 6: CFS demonstration house (NAHB 2002)

The wood demonstration home (Figure 7) comprised of wall studs spaced 16 inches on center with loadbearing studs located directly in line with roof rafters and floor joists. The structural wood studs were 2x6 Douglas Fir, and non-structural wood studs were 2x4 Douglas Fir. Exterior wall sheathing was 7/16 inch oriented-strand-board.

Figure 7: Wood framed demonstration house (NAHB 2002)

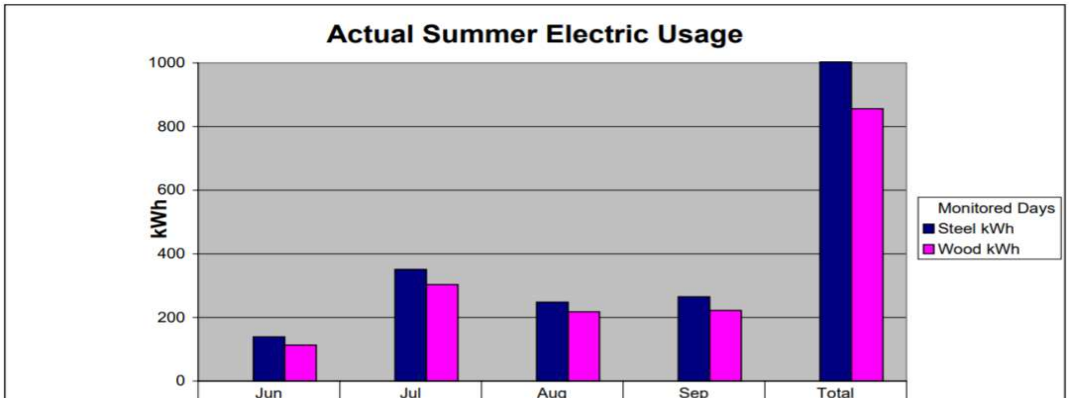
Table 6 provides a detailed comparison of the framing details used in both these demonstration houses.

Table 6: Comparison of framing details for the wood framed and cfs framed demonstration homes (NAHB 2002)

COMPONENT	STEEL HOUSE	WOOD HOUSE
Basement	**Unfinished with Steel stud framing**	**Unfinished with Wood stud framing**
Exterior Walls		
Drywall Size	1/2"x4'x8'/12'	1/2"x4'x8'/12'
Stud Size and Spacing	(2x6x33) Steel @ 24" o.c.	2x6 Wood @ 16" o.c.
Wall Sheathing	7/16"x4'x8' OSB	7/16" x4'x8' OSB
Rigid Foam Material & Thickness	3/4" Tenneco Extruded Polystyrene R-3.8 Rigid Foam Panels	N/A
Siding Material	Vinyl Siding	Vinyl Siding, Partial Brick Front
Ceiling Joists and Roof Rafters		
Joist Size and Spacing	(2x10x43) Steel @ 24"o.c.	2x10 Wood @ 16" o.c.
Drywall Size and Fastening	½"x4'x8'/12' w/Drywall screws	1/2"x4'x8'/12' w/Drywall screws
Rafter Size and Spacing	(2x8x54) Steel @ 24" o.c	2x8 Wood @ 16" o.c.
Roof Sheathing	7/16"x4'x8' Oxboard	7/16" x4'x8' Oxboard

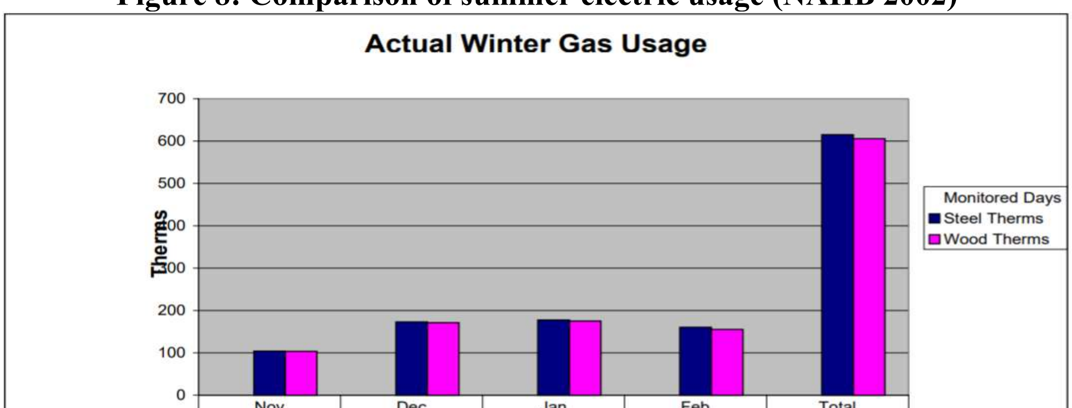
For SI: 1 ft.= 305 mm, 1 inch= 25.4 mm.

It was found that the energy consumption during the summer months (Figure 8) was an average 17.1% higher for the CFS framed house when compared with the wood framed house. In the winter months (Figure 9), the CFS framed house only utilized an average of 1.5% more energy than the wood framed house. The normalized difference between the two houses was found to be 3.9% more natural gas usage and 7.8% more electric usage when comparing the CFS construction with wood construction. This corresponds to an increased annual cost of \$35.69 (Based on NIPSCO April 2001 rates) or an increased cost of \$0.016/ft^2 for the 2,200 ft^2 demonstration houses (NAHB 2002). This unexpectedly low cost indicates the potential for reduction in energy consumption as a wall assembly designed with thermal performance in mind could potentially far exceed the thermal performance of its timber counterparts.



	Jun	Jul	Aug	Sep	Total
Monitored Days	30	33	25	25	113
Steel kWh	139	351	248	265	1003
Wood kWh	113	303	218	222	856

Figure 8: Comparison of summer electric usage (NAHB 2002)



	Nov	Dec	Jan	Feb	Total
Monitored Days	23	23	27	26	99
Steel Therms	104.08641	172.87356	177.64899	160.40355	615.01251
Wood Therms	103.54749	171.36159	175.25379	155.50836	605.67123

Figure 9: Comparison of winter das usage (NAHB 2002)

CHAPTER 3

3-D STEADY STATE THERMAL ANALYSIS, MODEL VALIDATION, AND PARAMETRIC EVALUATIONS

3.1 3-D Steady state thermal analysis

Extensive three-dimensional thermal modelling and analysis of the selected cold-formed steel wall assemblies were performed using ISO 10211:2007, Annex A, conforming specialty heat transfer software Blocon Heat3. The governing differential equation is solved by the software with explicit forward finite differences, and successive over-relaxation technique is used in the steady-state case.

Additionally, Heat3 only accepts input in the International System of Units (SI). Hence, material properties, geometric properties, and boundary conditions were converted from U.S. customary units to SI units both units of measurement have been used in the research project. The following geometric properties, material properties, and boundary conditions were used for the analysis.

3.2 Wall geometry

The wall assemblies used for analysis comprised of cold-formed steel studs, tracks, cavity insulation, external insulation (where applicable), gypsum sheathing, and fasteners. A representative assembly with these components can be seen in Figure 10. A detailed breakdown of individual components can be found in the modelling matrix (Table 14 – Table 29) in Appendix B.

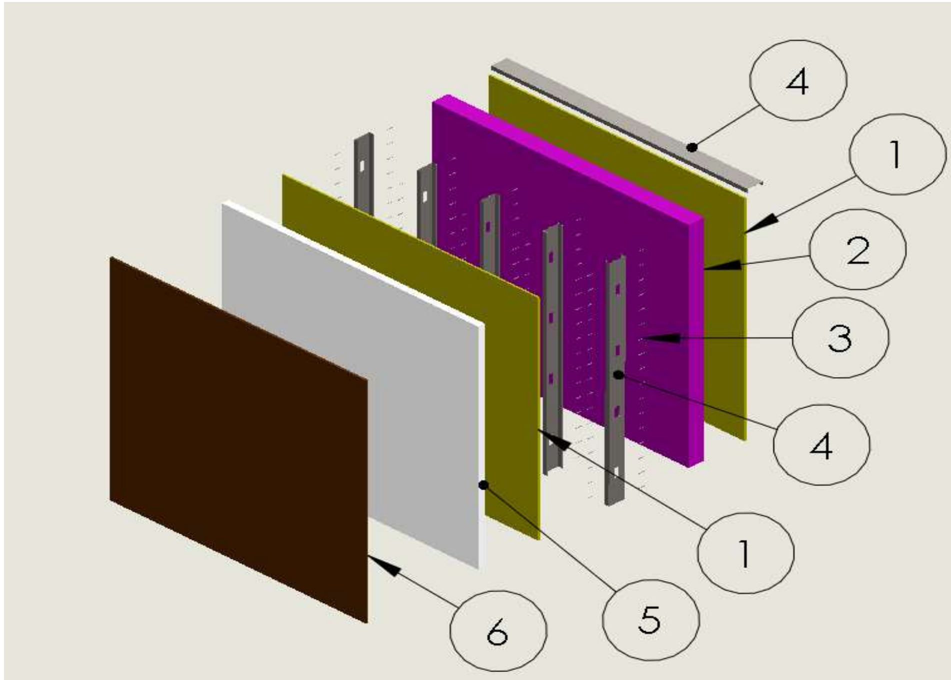


Figure 10: Representative wall assembly components: 1—Gypsum board (Sheathing); 2—Cavity insulation; 3—Fasteners;4—CFS studs and tracks (Bottom track not shown for clarity); 5—XPS; 6—Stucco.

3.3 Material properties and boundary conditions used for analysis

Material properties used for the analysis and validation models were based on previous works by Morrison Hershfield Ltd. for RP18-1 from Appendix D in ASHRAE 765-RP and the ASHRAE HoF and have been summarized in Table 12 in Appendix A.

The boundary conditions used for the analysis of validation and project wall assemblies were based on Table 10, Chapter 26 of the ASHRAE HoF and were kept the same as the values used in RP18-1 to ensure that this work can build upon and have results comparable with existing research. The internal and external surface air film resistances have been summarized in Table 7.

Table 7: Summary of boundary conditions

No	Surface Boundary	Temperature		Film Convective Coefficient	
		°F	°C	BTU/h·ft^2 ·°F	W/m^2·°C
1	Interior	33.8	1	1.46	8.31
2	Exterior	32	0	6.00	34.05

The internal and external temperatures were taken as 1°C and 0°C to obtain a non-dimensionalized temperature index. This allows the results to be applicable to any temperature change provided the other analysis geometric and material properties remain unchanged.

3.4 Solver information, modelling assumptions, and geometry simplifications

The software solves the governing differential equation with explicit forward finite differences, and successive over-relaxation technique is used in the steady-state case to estimate heat flow through the assembly (Blocon 2017). The stopping criteria for the analysis were set to a net error of 0.01% for both the calculated temperatures and heat flow.

Furthermore, the software can only analyze linear geometries hence the following simplifications were made during the modelling process –

3.5 Fastener modelling

Fasteners were modelled as cuboids with equivalent cross-sectional area and length as the chosen fastener's shank's cross-sectional area and total length respectively or from start of sheathing to interior end of CFS stud flange (Refer Figure 11). Fastener head and threads were not modelled for the wall assemblies (Refer Appendix D for detailed discussion of this assumption and further information on fastener modelling)

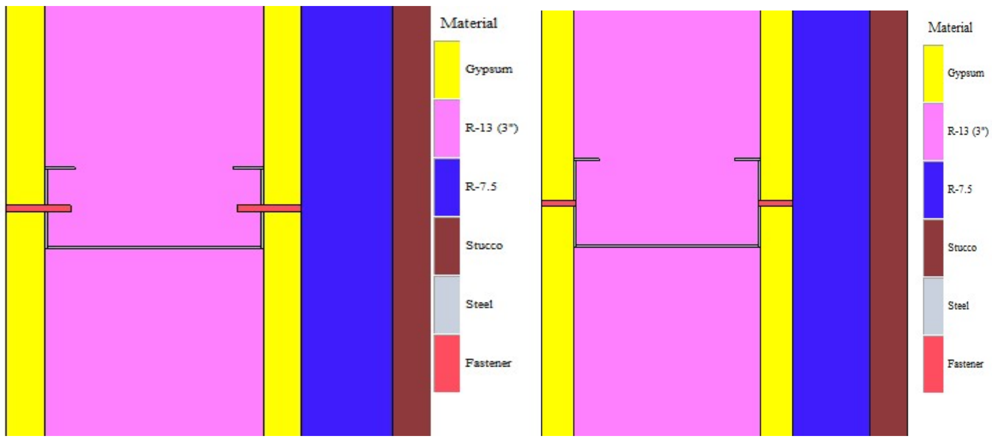


Figure 11: 2-D section cut through wall assembly at fastener locations (Left – Fastener length modelled and Right – Fastener modelled from start of sheathing to interior of Flange)

3.6 Flange-Lip interface and flange-web interface modelling

When modelling CFS studs, tracks, and bridging, corner radii had to be neglected. Flange-web and flange-lip interfaces were modelled as right angles. The same simplifications were made in AISI RP18-1 (2018), thereby making the models consistent with existing research

3.7 Model validation

Validation of selected boundary conditions, material properties, modelling, and analysis procedure was done by comparing simulated overall R-value and U-Value of validation models to values in the report AISI RP18-1 (2018). By comparing Heat3 simulated values with heat flow values obtained in AISI RP18-1, the analysis procedure was validated with RP18-1 and consequentially with ASHRAE 1365-RP (2011), ASHRAE 785-RP (1996), and ORNL hotbox compilation study.

The following four AISI RP18-1 (2018) wall assemblies were modeled in Heat3 for comparison

Table 8: Summary of validation models

Validation Models

Assembly Reference (RP18-1)	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Exterior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
1	Stucco	0.75	--	--	6" o.c	--	Gypsum	0.625
4	Stucco	0.75	--	--	6" o.c	--	Gypsum	0.625
2	Stucco	0.75	R-7.5	1.5	6" o.c	--	Gypsum	0.625
5	Stucco	0.75	R-7.5	1.5	6" o.c	--	Gypsum	0.625
Assembly Reference (RP18-1)	**Outer Sheathing Thickness (in)**	**Steel Stud**	**Steel track**	**Steel Channel**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
1	0.625	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	3.625	Gypsum	0.625
4	0.625	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-19	3.625	Gypsum	0.625
2	0.625	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	3.625	Gypsum	0.625
5	0.625	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-19	3.625	Gypsum	0.625

Table 9 summarizes the results of the validation trials

Table 9: Summary of validation results

Assembly Reference (RP18-1)	Description	Simulated R-Value (RP18-1)	Simulated U-Value (RP18-1)	Simulated R-Value (AISI - SPF)	Simulated U-Value (AISI - SPF)	Δ R-Value	Δ U-Value
		hr·ft²·°F/BTU	BTU/hr·ft²·°F	hr·ft²·°F/BTU	BTU/hr·ft²·°F	%	%
1	No Cavity or Exterior Insulation	2.9	0.345	2.82	0.355	-2.84%	2.92%
4	R-19 Cavity and No Exterior Insulation	9.31	0.107	9.19	0.109	-1.30%	1.32%
2	No Cavity and R-7.5 Exterior Insulation	10.4	0.096	10.35	0.097	-0.53%	0.53%
5	R-19 Cavity and R-7.5 Exterior Insulation	18.6	0.054	18.44	0.054	-0.88%	0.88%

Upon comparing overall R-value and U-value of the selected validation models, a maximum difference of -2.84% and +2.92% was found. This error was deemed acceptable, and the thermal modelling procedure and material properties were validated.

3.8 Parametric evaluation

For the parametric evaluation, 80 unique wall assemblies were created to study the impact of selected parameters on the overall thermal transmittance of the wall assembly, linear transmittance of the CFS studs and tracks, and point transmittance of the fasteners. The key variable parameters of the parametric evaluation were steel thickness, stud depth, stud spacing, cavity insulation R-value, external insulation thickness (R-value), fastener diameter and length. These parameters and their range of values have been summarized in Table 10.

Table 10: Summary of variable parameters

Parameter	**Variable Values**
CFS Member Thickness	33, 43, 54, 68, 97 (mils)
CFS Member Depth	3.625 & 6.000 (inches)
CFS Stud Spacing	16 & 24 inches on center
Cavity Insulation R - Value	Air & R-13 (hr·ft^2 ^{o}F/BTU)
External Insulation R - Value	R-7.5, R-10, R-12.5 (hr·ft^2 ^{o}F/BTU)
Fastener Diameter and Length	#6, #8 1-15/16", #10 2-1/2", #10 3-00"

The CFS stud and track depth, thickness, and spacing for analysis were selected to reflect commonly used values for walls in the framing factor range being studied. Cavity insulation and external insulation combinations were selected based on minimum insulation R-values prescribed by ASHRAE 90.1 2016 to include as many ASHRAE climate zones as possible. Table 11 summarizes the combinations of insulation used for the analysis and the respective climate zone and building type (NR – Non-residential and R-Residential) they represent.

Table 11: Insulation combinations and their representative Climate Zones

Exterior Insulation	Cavity Insulation	ASHRAE 90.1 2016 Climate Zone
N/A (No XPS)	R-13	Zone 0 (NR & R) & 1 (NR & R)
R-7.5 (1.5 inches)	R-13	Zone 4 (NR & R), 3 (R), & 2 (R)
R-10.0 (2.0 inches)	R-13	Zone 5 (NR & R)
R-12.5 (2.5 inches)	R-13	Zone 6 (NR & R) & 7 (NR)

Fastener selection was based on AISI North American Standard for Cold-Formed Steel Structures (S240-2015 edition). This standard requires that the screws be self-drilling and that at least three threads are exposed for proper engagement.

Table 14 through Table 29 in Appendix B summarize the 80 unique wall assemblies analyzed as part of the parametric evaluation.

CHAPTER 4

QUANTIFICATION OF THERMAL TRANSMITTANCE COEFFCIENTS

Thermal transmission coefficients were estimated by comparing the difference in the overall heat flow of the assembly when the anomaly is present with an iteration when the anomaly is removed. For example, to estimate the thermal transmission coefficient of CFS studs, an iteration of the wall assembly with studs (Figure 12 (a)) was run, and then the heat flow value was compared to overall heat flow of the same assembly without the CFS studs (Figure 12 (b)).

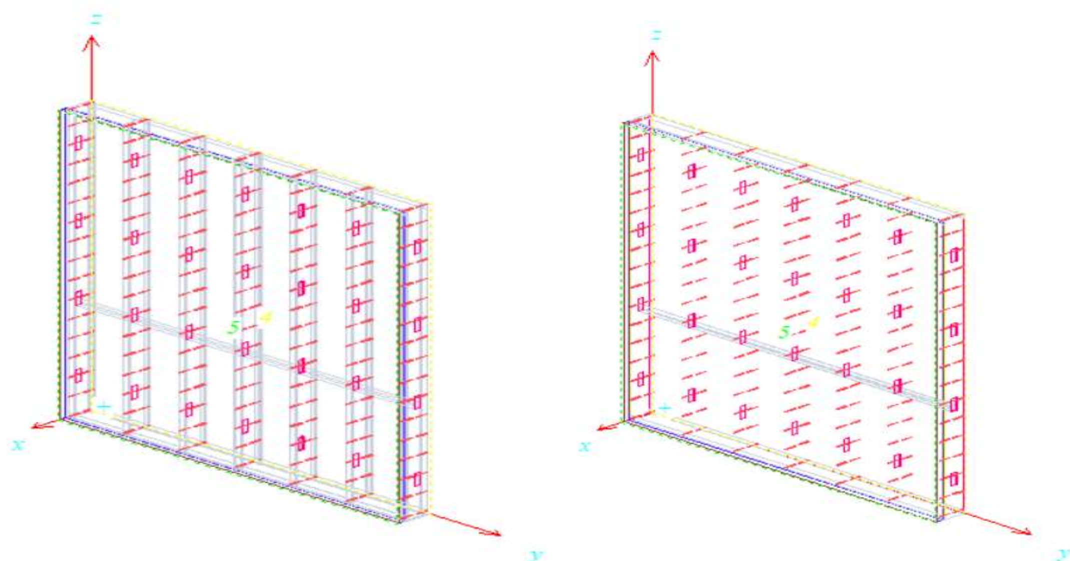


Figure 12: (a) Heat3 model of wall assembly with CFS studs ; (b) Heat3 model of wall assembly without CFS studs

This process was repeated to estimate the thermal transmission coefficients for tracks, fasteners, and no anomalies (homogenous wall), which resulted in 400 iterations of the wall assemblies.

Equation 1 was used to calculating linear transmittance coefficient of studs. Similar equations can be formed for other linear elements such as tracks and bridging.

$$\psi_{Studs} = \frac{Q_{cw} - Q_{No\ Studs}}{L_{Studs}} \tag{1}$$

Similarly, point thermal transmittance coefficients were calculated for non-continuous, non-linear point anomalies like fasteners $\chi_{Fastener}$. This can be calculated using Equation 2.

$$\chi_{Fastener} = \frac{Q_{cw} - Q_{No\ Fastener}}{N_{Fasteners}} \tag{2}$$

The thermal transmission coefficients thus calculated provided excellent agreement with overall heat flow values estimated by 3-D finite element solutions and the heat flow values obtained by using the linear and point transmittance coefficients. The heat flow predicted by thermal transmittance coefficients was within -2.6% to +3.1% of the FEA solutions even though they were obtained from different iterations of the wall assembly.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Effect of increasing stud and track thickness

The dataset indicated that there exists a direct correlation between CFS member thickness and overall heat flow through the assembly. Hence, an empirical relation based on six regression analysis was developed to correlate member thickness and overall heat flow. The coefficient of determination was found to be on average 0.96 which shows high confidence in the trend being presented. The same trend has been represented in graphical form and numerical form in Figure 13 and Equation 3 respectively.

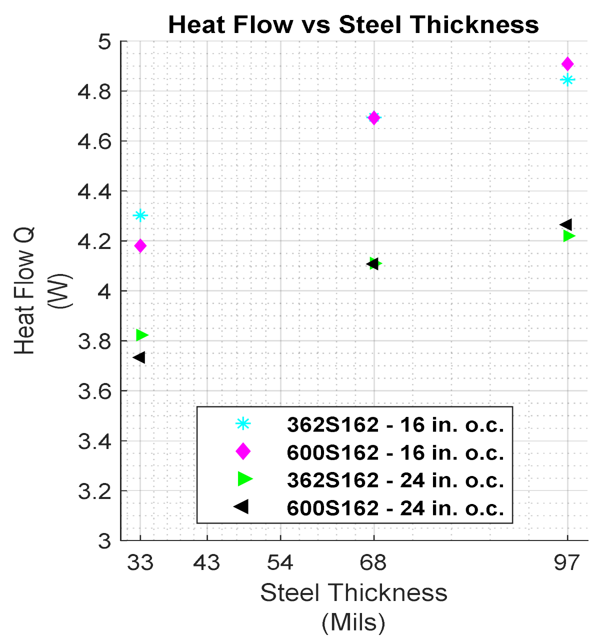


Figure 13: Trend observed in heat flow due to increasing CFS Member Thickness

For a known heat flow value (Q1) from an assembly, additional heat flow value (Q2) can be calculated for similar assemblies differing in gage using equation 3. Here, K is the spacing and stud depth factor based on the regression analysis. Possible values for stud depth and spacing factor K, have been summarized in Table 12.

$$Q_2 = Q_1 (K)^{\left(\frac{T_2}{T_1}\right)} \tag{3}$$

Table 12: Summary of stud spacing and depth factor

	362S162		600S162	
	Spacing (inches on center)			
	16	24	16	24
K	1.038	1.030	1.049	1.040

5.2 Effect of increasing stud and track depth

To study the dependence of thermal transmission coefficients and overall heat flow with CFS member depth, 40 wall assemblies were analyzed for the seven climate zones that are included in the parametric evaluation. Typical 3-5/8" and 6-00" web depth (362S162 and 600S162) CFS member wall assemblies were analyzed.

It was observed that increasing the member depth increased the heat flow and thermal transmittance coefficients of the assemblies located in Zone 2 and higher but decreased the same for assemblies located in Zone 1. The change in heat flow was approximately -2% to +1% and the change in linear thermal transmittance coefficients was approximately -4% to +5% for studs and -4% to +3% for tracks. Tables 29 through Table 32 summarizing the heat flow values, U-values, R-values, and thermal transmittance coefficients can be found in appendix C.1 through C.3. Figure 14 through Figure 17 represent the breakdown of heat flow through different components of the wall assembly for the analyzed models.

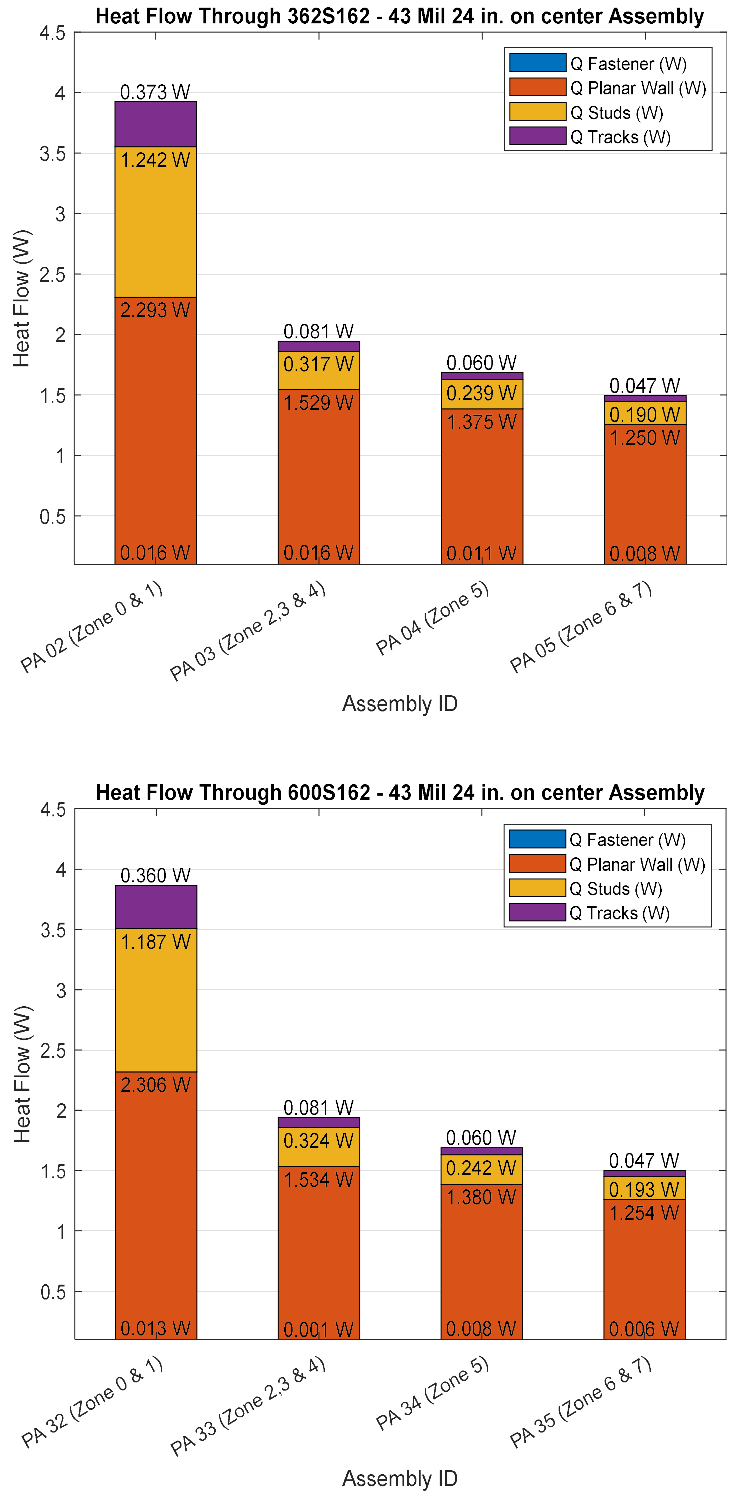


Figure 14: Comparison of heat flow through 362S162 - 43 Mil 24 in. on center and 600S162 - 43 mil 24 in. on center assemblies

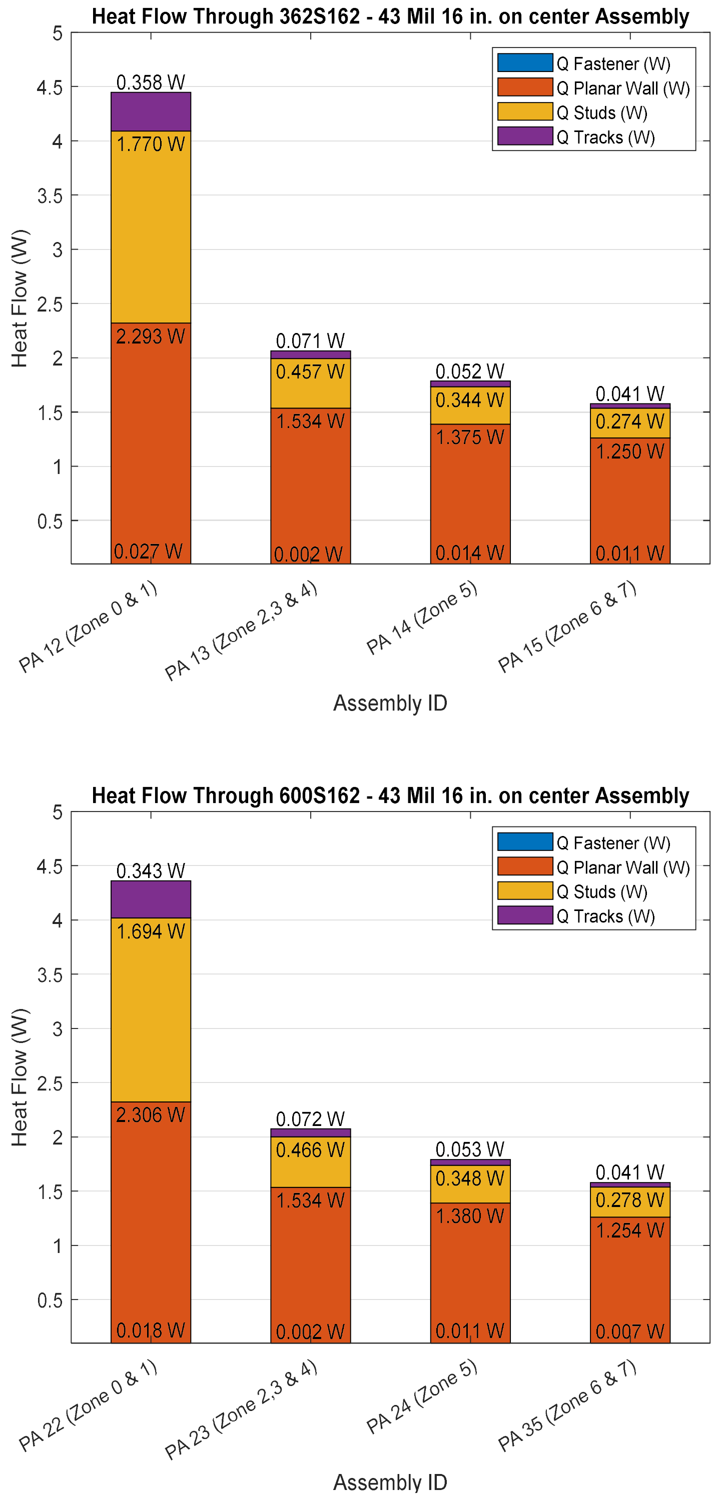
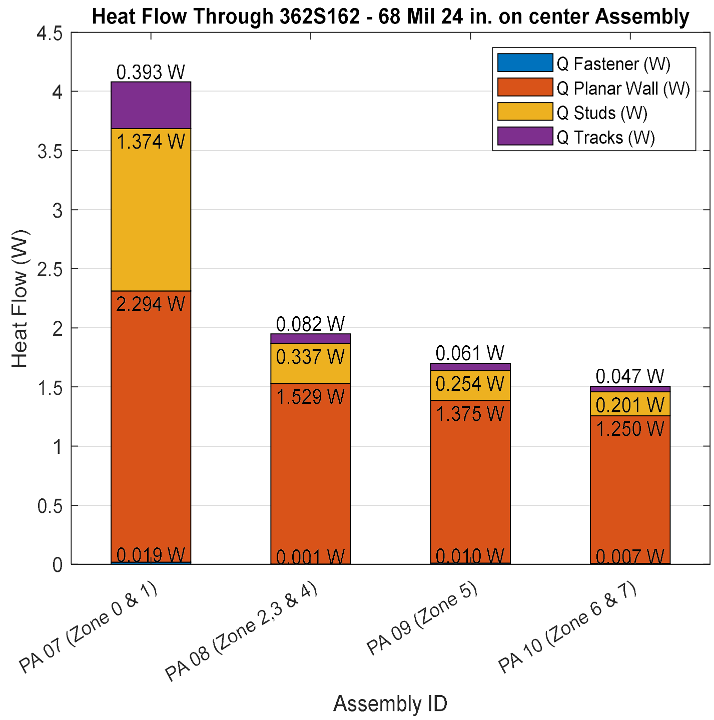


Figure 15: Comparison of heat flow through 362S162 - 43 Mil 16 in. on center and 600S162 - 43 mil 16 in. on center assemblies



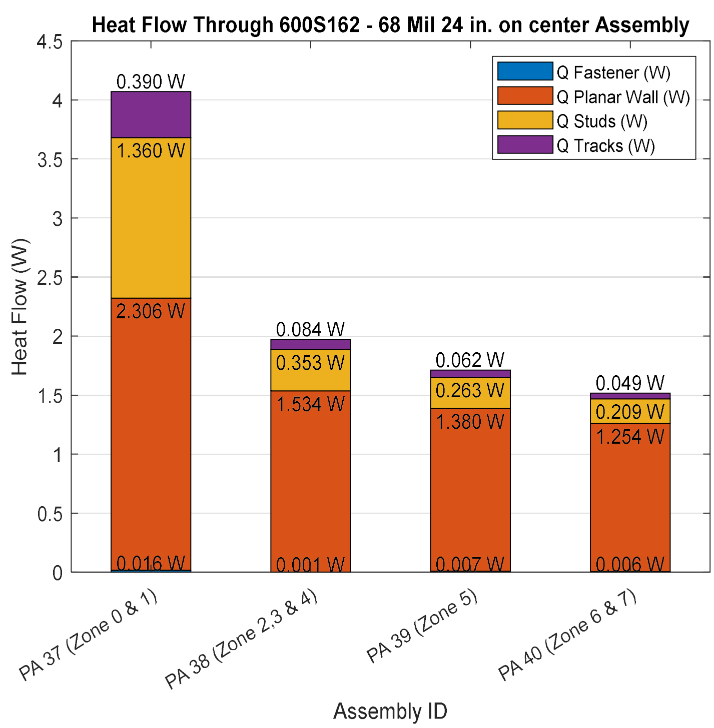
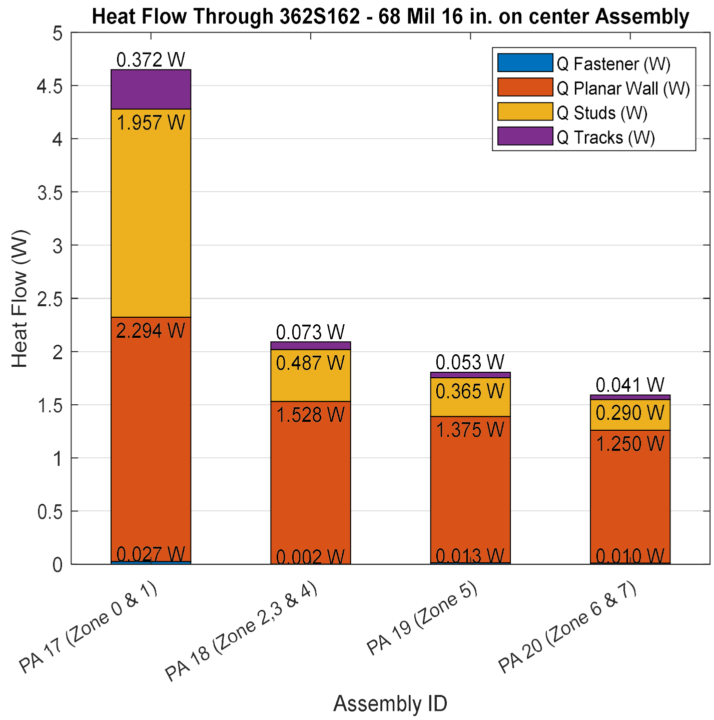


Figure 16: Comparison of heat flow through 362s162 - 68 mil 24 in. on center and 600s162 - 68 mil 24 in. on center assemblies



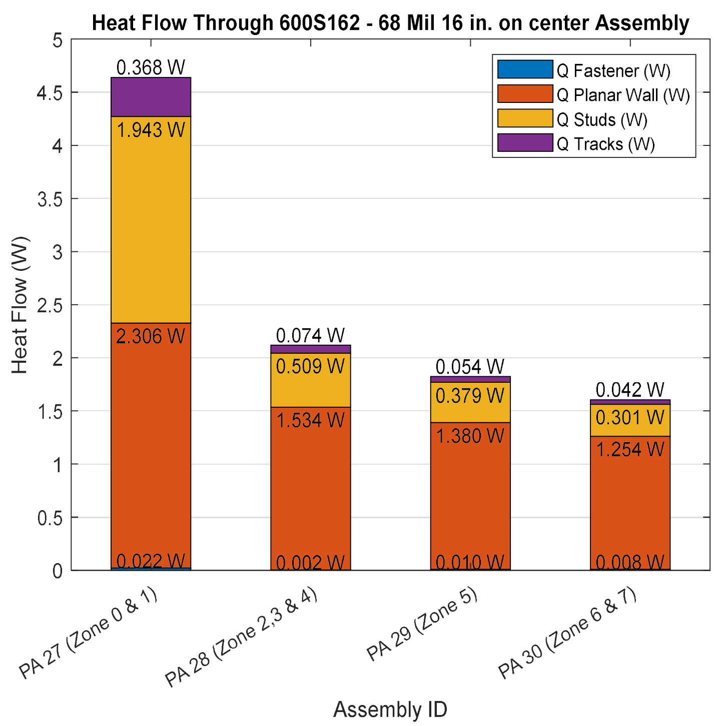
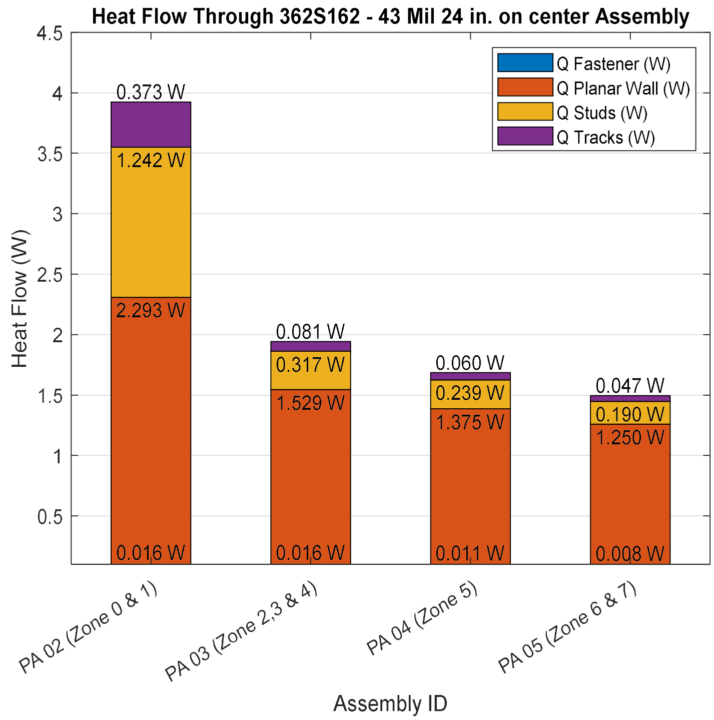


Figure 17: Comparison of heat flow through 362s162 - 68 mil 16 in. on center and 600s162 - 68 mil 16 in. on center assemblies

5.3 Effect of stud spacing

To study the dependence of thermal transmission coefficients and overall heat flow with CFS stud spacing, 40 wall assemblies were analyzed for the seven climate zones that are included in the parametric evaluation. 16 inches on center and 24 inches on center stud spacing wall assemblies were analyzed and compared.

It was observed that decreasing the stud spacing increased the overall heat flow through the assembly and the thermal transmittance coefficient for the studs. However, the thermal transmittance coefficient of the tracks decreased when stud spacing was decreased even though no changes were made to the tracks. This resulted in an overall increase of 6 to 14% in the overall heat flow and an increase of 2 to 3% in the thermal transmittance coefficient of the studs. The thermal transmittance coefficient of the tracks decreased by 4 to 15%. These trends were observed in all the comparison assemblies and Table 29 through Table 32 in Appendix C summarizes the same. Figure 18 through Figure 21 on the next pages represent the breakdown of heat flow through different components of the wall assembly for the analyzed models.



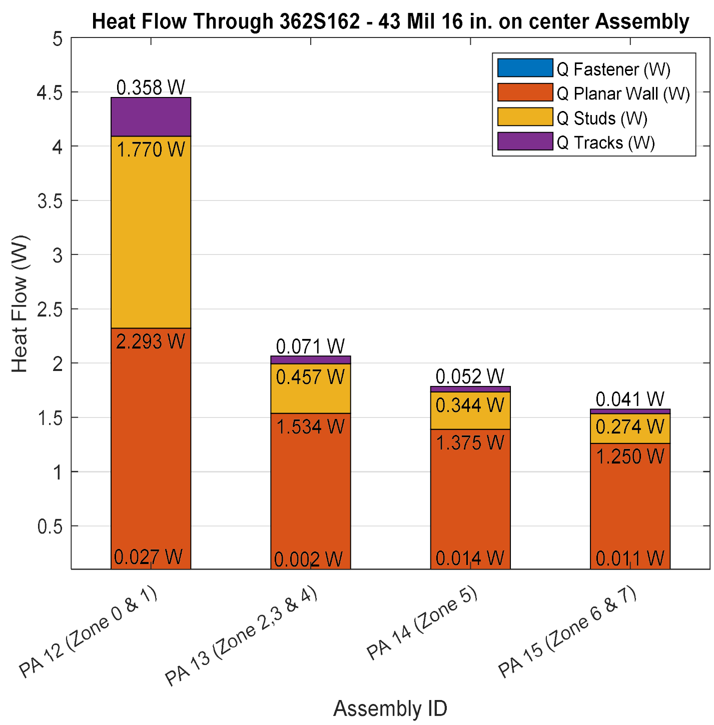


Figure 18: Comparison of heat flow through 362s162 - 43 mil 24 in. on center and 362s162 - 43 mil 16 in. on center assemblies

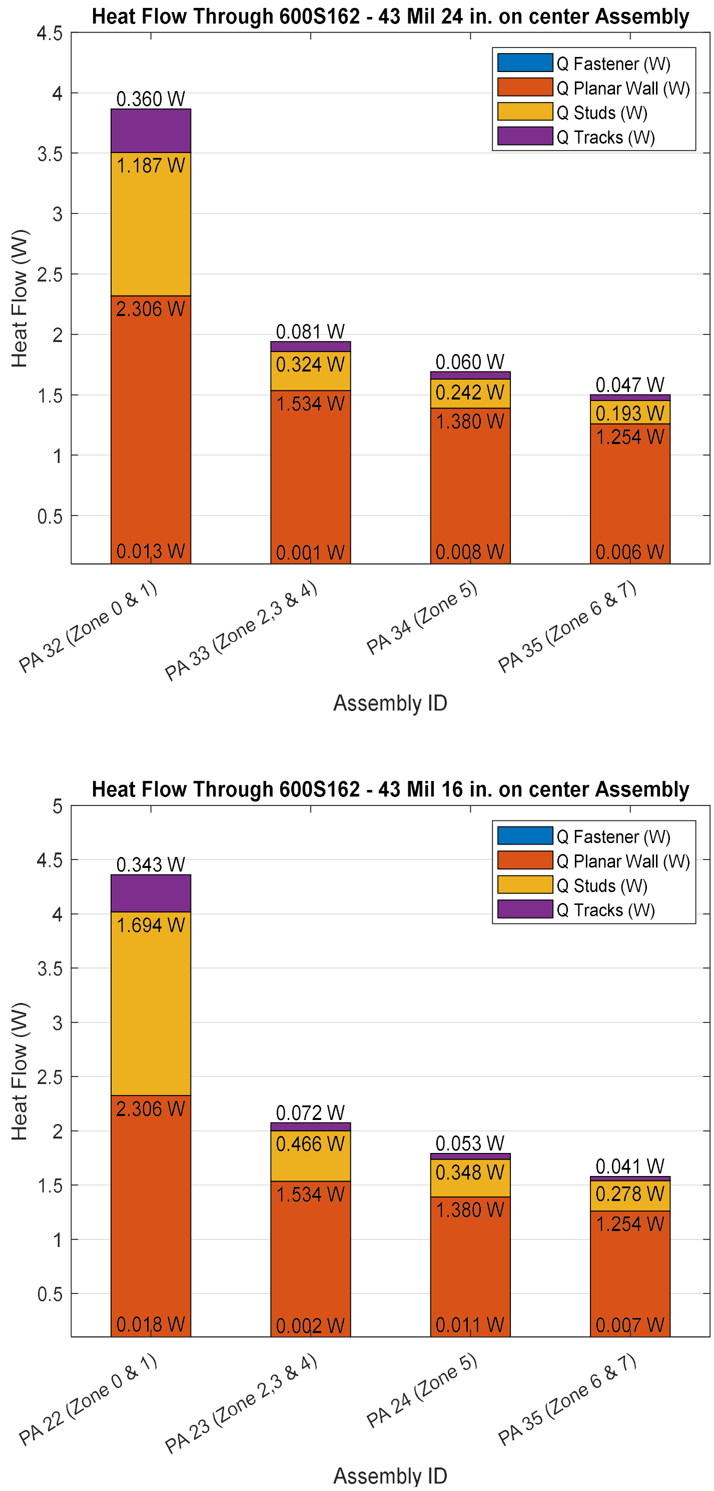


Figure 19: Comparison of heat flow through 600s162 - 43 mil 24 in. on center and 600s162 - 43 mil 16 in. on center assemblies

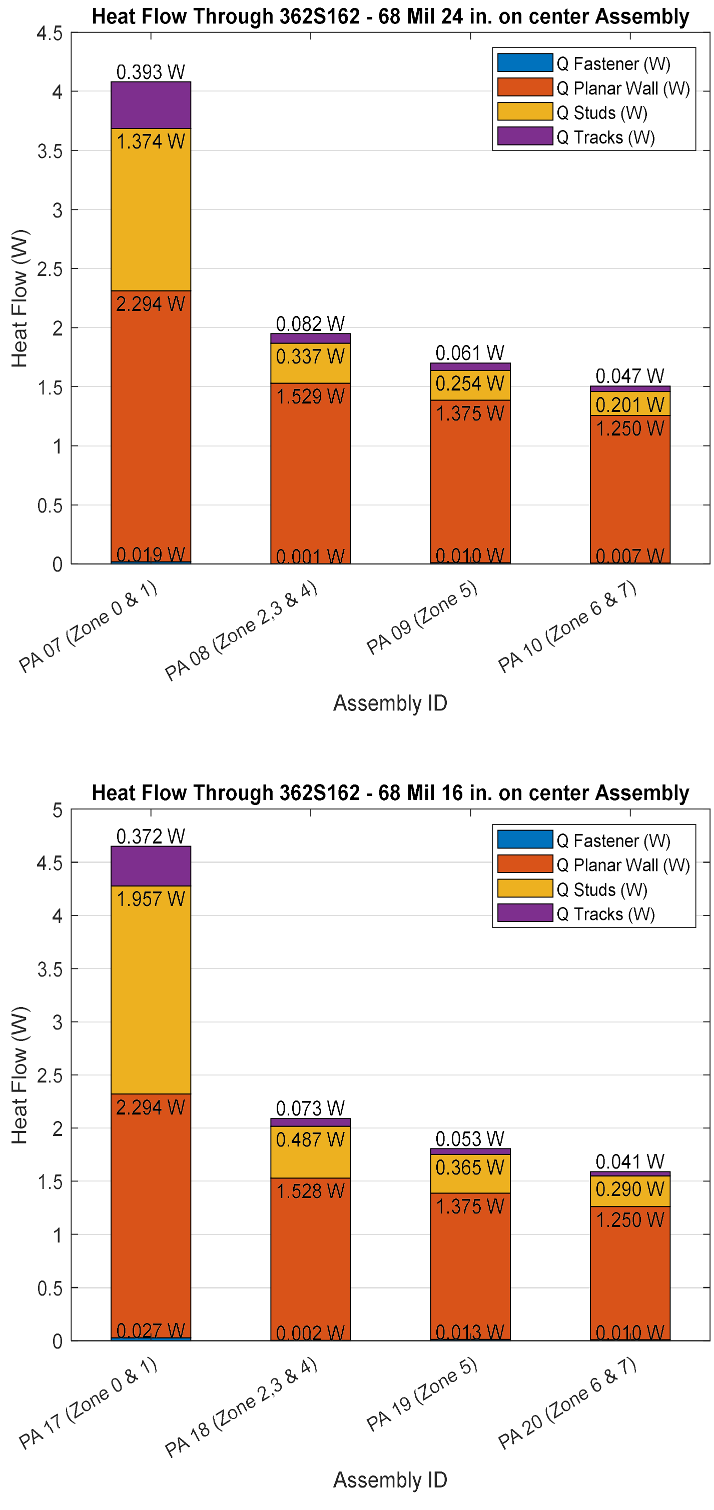
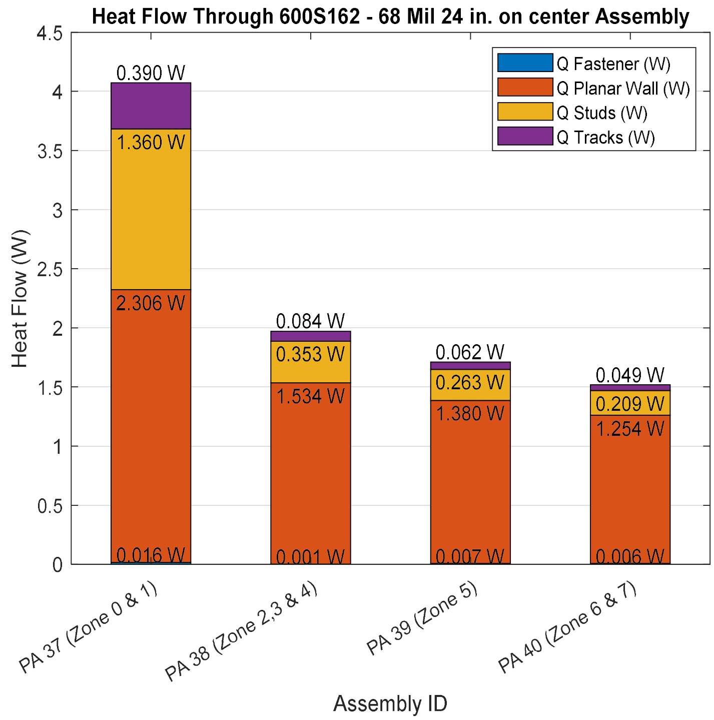


Figure 20: Comparison of heat flow through 362s162 - 68 mil 24 in. on center and 362s162 - 68 mil 16 in. on center assemblies



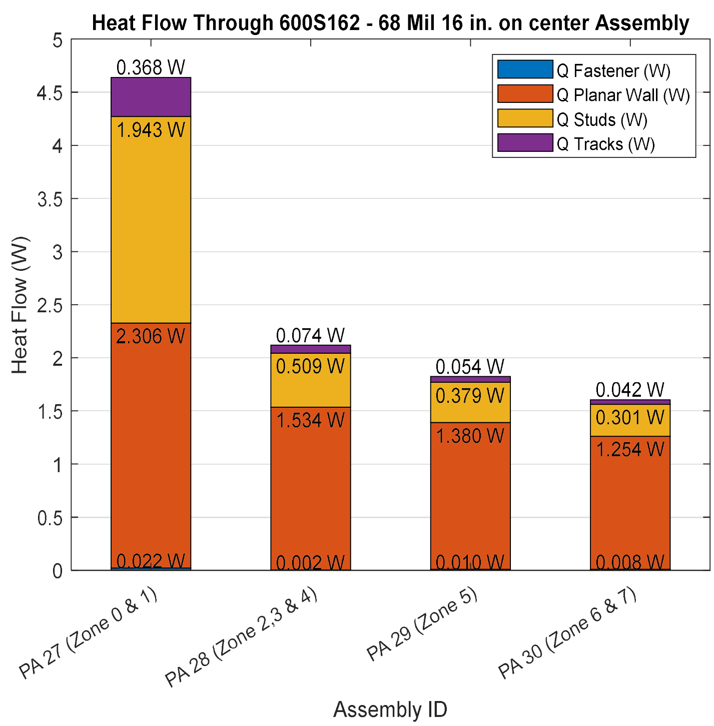


Figure 21: Comparison of heat flow through 600s162 - 68 mil 24 in. on center and 600s162 - 68 mil 16 in. on center assemblies

5.4 Effect of increasing external insulation

To study the dependence of thermal transmission coefficients and overall heat flow with external insulation, 80 wall assemblies were analyzed for the seven climate zones (CZ) that are included in the parametric evaluation.

It was observed that modifying the external insulation had a drastic effect on the overall heat flow (Q_{CW})and thermal transmittance coefficients. As external insulation was increased, both the overall heat flow and thermal transmittance coefficients decreased. This decrease was most significant when R-7.5 continuous insulation was added to CZ 0 and 1 assemblies to make them compliant with CZ 2, 3, and 4. The overall change in heat flow was -55% and the linear transmittance coefficients of studs and tracks decreased by -75% and -80% respectively.

Similarly, when an additional layer of R2.5 XPS was added to CZ 2,3, and 4 assemblies to make them compliant with CZ 4, Q_{CW} decreased by 14% and ψ_{Studs} and ψ_{Tracks} decreased by -25% and -26% respectively. Furthermore, when the continuous insulation R-value was increased by another R2.5 (R12.5 total continuous insulation) for the assembly to be compliant with CZ 6 and 7, Q_{CW} decreased by 11%. The corresponding change in ψ_{Studs} and ψ_{Tracks} was found to be -20% and -22% respectively.

The reduction in heat flow showed diminishing returns and these trends were observed in all the comparison assemblies and Table 29 through Table 32 in Appendix C. summarizes the same. Figure 22 below represent the breakdown of heat flow through different components of the wall assembly for 600S162 stud - 54 and 97 mil wall assemblies as external insulation is increased.

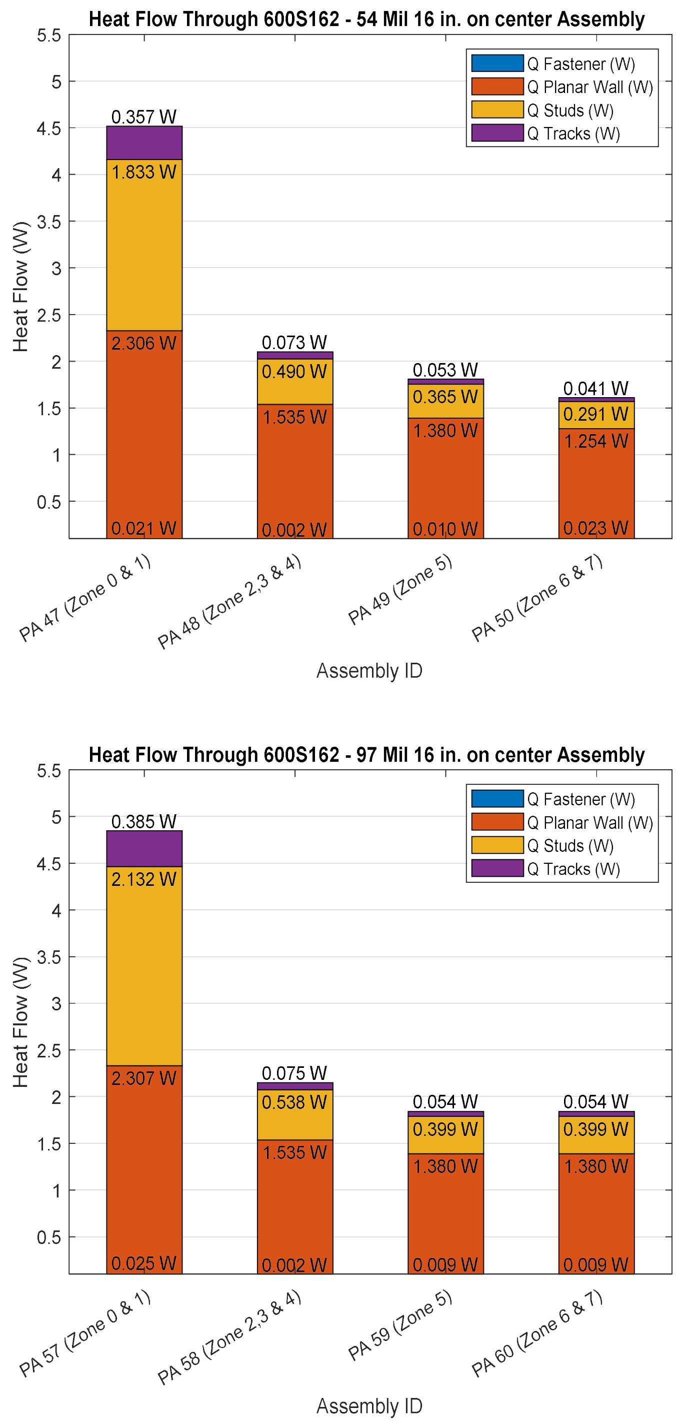


Figure 22: Heat flow through 600s162 - 54 mil 16 in. on center and 600s162 - 97 mil 16 in. on center assemblies

5.5 Effect of increasing fastener diameter and penetration

To study the dependence of thermal transmission coefficients and overall heat flow with fastener diameter and penetration, 20 wall assemblies were analyzed. The fastener pattern was kept the same for all the assemblies and fasteners were spaced 6 inches on center from one another along the height of the stud.

It was observed that increasing fastener penetration and diameter had a negligible impact on the overall heat flow and linear transmittance coefficients of the studs and tracks. This can also be observed in Figures 14 through 22 on the previous pages where the heat flow through the fasteners (depicted in blue at the bottom of the stacked bars) is negligible enough that it does not register on the graphs. The point transmittance coefficient for fasteners increased drastically and was maximum for Climate Zone (CZ) 1 assemblies and minimum for Climate Zone 6 and 7 where external insulation was maximum. However, this drastic increase in fastener transmittance had a negligible effect on the overall performance of the wall assemblies.

Figures 23 provides a summary of the effect of increasing fastener diameter and penetration for the different climate zones analyzed as part of the parametric evaluation. Detailed results for heat flow in individual climate zones due to variation in fasteners can be found in Table 29 through Table 32 in Appendix C.

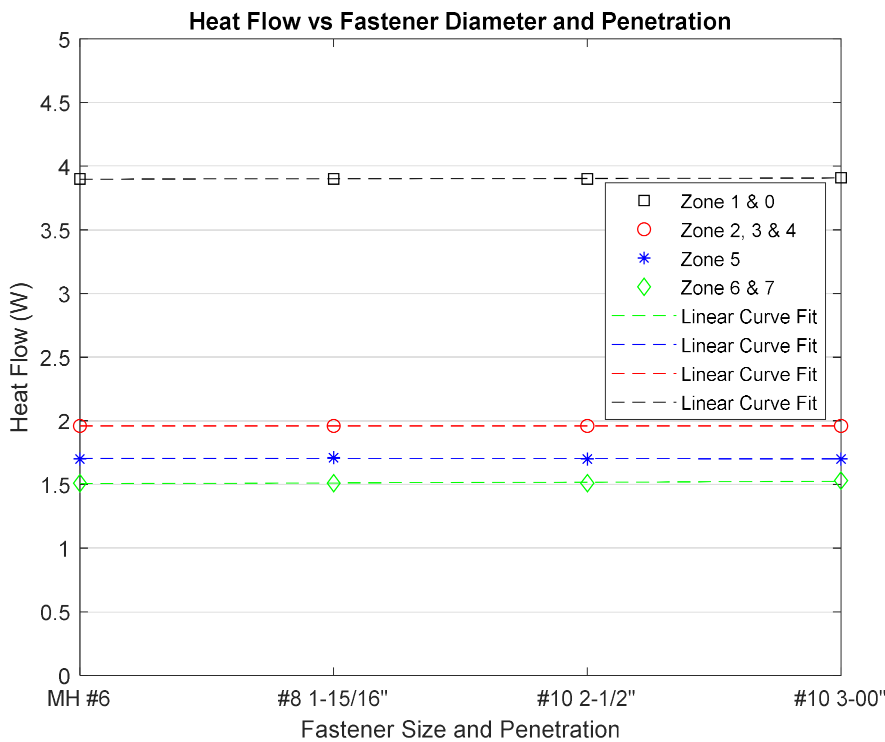


Figure 23: Heat flow vs fastener diameter and penetration for different ASHRAE Climate Zones

The slope of the curve fit lines was found to be nearly zero. The zero-slope indicated that even though the curve fit lines represent the trend perfectly, a change in fastener diameter or length has no impact on heat flow.

CHAPTER 6

CONCLUSIONS AND RECOMMENDED FUTURE WORKS

6.1 Conclusions

Based on the parametric evaluation, the following conclusions can be made about the impact of selected parameters on the overall U-value and thermal transmittance coefficients –

- There exists a direct relationship between overall heat flow through the assemblies and the thickness of CFS members being used. By taking advantage of this relationship, benchmarked heat flow values can be potentially modified to include other member thicknesses. This provides designers with the option to expand upon existing verified methods and test results.

- Increasing stud and track depth has a nominal effect on overall heat flow through the assembly (-1 to 2%). The same changes the linear transmittance coefficient of studs by -4% to +5% and the linear transmittance coefficient of tracks by -4% to +3%.

- Decreasing stud spacing from 24 inches on center to 16 inches on center has a significant impact on overall heat flow, and the change is approximately +6 to +14%. The increase in linear thermal transmittance coefficient of the studs is +2 to +3% and the decrease in thermal transmittance coefficient of the tracks is -4 to -15%.

- External insulation thickness has a significant impact on overall heat flow and the thermal transmittance coefficients of studs and tracks. When the external insulation is increased from no insulation to R-7.5, the overall heat flow through the assembly is reduced by approximately 50 to 55% and the reduction in thermal transmittance coefficients of the studs and tracks was found to be 72 to 75%, and 77 to 82% respectively. However, diminishing reduction in overall heat flow is observed when additional insulation is added. The reduction in overall heat flow was found to be approximately 14% for R-7.5 to R-10 and approximately 11% for R-10 to R-12.5. This corresponded with a reduction of 25% and 21% in the linear thermal transmittance coefficient studs and 27% and 23% in the linear transmittance coefficient of tracks.
- Increasing fastener diameter and penetration had a negligible impact on the overall heat flow and the linear thermal transmittance coefficients of studs and tracks. However, the point thermal transmittance coefficient of fasteners increased by approximately 108% for Climate Zone (CZ) 1 assemblies and 5% for assemblies located in CZ - 6 and CZ - 7. The net effect was a maximum increase of 1% in the overall heat flow for assemblies located in CZ - 1.

6.2 Recommended future works

Based on the results of this research, the authors believe that the following work will serve to be most beneficial to future research that promotes sustainable, energy efficient, and improved building design recommendations and guidelines for engineers and architects alike –

- Additional parametric evaluations to calculate transmission coefficients for more stud depths, flange widths, framing factors, framing techniques (ex – ledger vs platform), etc. The work performed here has shown that the transmission coefficients calculated can predict heat flows through walls with high accuracy and there exists trend which can be exploited to come up with tables that can ease thermal calculation by reducing the need for additional finite element models. Additionally, this proposed work can potentially be used to develop simplified equations such as the ones proposed by Santos et al. which are more suited to the North American CFS industry. These in combination with the transmission coefficient tables can serve as a great tool for estimating the thermal performance of CFS walls for the purpose of compliance.

- Further, evaluation of mitigation strategies on the thermal as well as the structural performance of the wall assemblies can provide excellent insight into the advantages and disadvantages of using various mitigation strategies. Experimental testing of the impact of mitigation strategies on the structural performance can provide relevant information to develop high fidelity finite element models which can be used to study the performance of these strategies and come up with solutions that are most suited for the different scenarios being studied. Such a study can also be used to come up with possible design recommendations for including thermal break strategies in the detailing of CFS construction.

APPENDIX A

MATERIAL PROPERTIES USED FOR PROJECT ASSEMBLIES

Tables 13 below provides a summary of material properties used for the project models.

Table 13: Summary of material properties used for the project assemblies

Material Properties for Project Assemblies

Material	Thickness (in)	Conductivity K-Value (BTU-in/hr·ft^2 ^{o}F)	Component R-Value (hr·ft^2 ^{o}F/BTU)	Thickness (m)	Conductivity K-Value (W/m·K)	Component R-Value (m^2 K/W)
Exterior Finishes						
Stucco	0.7500	9.3750	0.0800	0.0191	1.3521	0.0141
Exterior Insulation						
R-7.5	1.5000	0.2000	7.5000	0.0381	0.0288	1.3208
R-10.0	2.0000	0.2000	10.000	0.0508	0.0288	1.7611
R-12.5	2.5000	0.2000	12.500	0.0635	0.0288	2.2014
Outer Sheathing						
Gypsum	0.6250	1.1100	0.5631	0.0159	0.1601	0.0992
Steel Stud						
362S162-43 Mil	0.0428	495.00	--	0.0011	71.393	--
362S162-68 Mil	0.0677	495.00	--	0.0017	71.393	--
600S162-33 Mil	0.0329	495.00	--	0.0008	71.393	--
600S162-43 Mil	0.0428	495.00	--	0.0011	71.393	--
600S162-54 Mil	0.0538	495.00	--	0.0014	71.393	--
600S162-68 Mil	0.0677	495.00	--	0.0017	71.393	--
600S162-97 Mil	0.0966	495.00	--	0.0025	71.393	--

			Steel Track			
362T162-43 Mil	0.0428	495.00	--	0.0011	71.393	--
362T162-68 Mil	0.0677	495.00	--	0.0017	71.393	--
600T162-33 Mil	0.0329	495.00	--	0.0008	71.393	--
600T162-43 Mil	0.0428	495.00	--	0.0011	71.393	--
600T162-54 Mil	0.0538	495.00	--	0.0014	71.393	--
600T162-68 Mil	0.0677	495.00	--	0.0017	71.393	--
600T162-97 Mil	0.0966	495.00	--	0.0025	71.393	--

Material Properties for Project Assemblies (Continued)

Material	Thickness (in)	Conductivity K-Value (BTU-in/hr·ft^2 ^{o}F)	Component R-Value (hr·ft^2 ^{o}F/BTU)	Thickness (m)	Conductivity K-Value (W/m·K)	Component R-Value (m^2 K/W)
			Steel Channel			
150U150-33 Mil	0.0329	495.00	--	0.0008	71.393	--
150U150-43 Mil	0.0428	495.00	--	0.0011	71.393	--
150U150-54 Mil	0.0538	495.00	--	0.0014	71.393	--
150U150-68 Mil	0.0677	495.00	--	0.0017	71.393	--
150U150-97 Mil	0.0966	495.00	--	0.0025	71.393	--
			Cavity Insulation			
Air Cavity	3.6250	4.0278	0.9000	0.0921	0.5809	0.1585
R-13	3.6250	0.2788	13.000	0.0921	0.0402	2.2894
Air Cavity	6.0000	6.6667	0.9000	0.1524	0.9615	0.1585
R-13	6.0000	0.4615	13.000	0.1524	0.0666	2.2894
			Interior Sheathing			
Gypsum	0.6250	1.1100	0.5631	0.0159	0.1601	0.0992

APPENDIX B

MODELLING MATRIX FOR PROJECT ASSEMBLIES

This appendix summarizes the 80 unique wall assemblies that were analyzed for this research project. For viewing convenience, the matrix has been broken down into Table 14 through Table 29. The title of the tables represents the cold-formed steel thickness, stud depth, and stud spacing used in these assemblies.

APPENDIX B.1 – Summary of 362S162 - 43 Mil assemblies (24" on center)

Table 14: Summary of 362S162 - 43 mil assemblies (24" on center)

362S162 - 43 Mil @ 24" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
1	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
2	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
3	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
4	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
5	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
1	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	3.625	Gypsum	0.625
2	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625
3	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625
4	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625
5	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625

APPENDIX B.2 – Summary of 362S162 - 68 Mil assemblies (24" on center)

Table 15: Summary of 362S162 - 68 mil assemblies (24" on center)

362S162 - 68 Mil @ 24" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
6	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
7	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
8	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
9	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
10	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
6	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	Air Cavity	3.625	Gypsum	0.625
7	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625
8	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625
9	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625
10	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625

APPENDIX B.3 – Summary of 362S162 - 43 Mil assemblies (16” on center)

Table 16: Summary of 362S162 - 43 Mil assemblies (16” on center)

362S162 - 43 Mil @ 16" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
11	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
12	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
13	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
14	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
15	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
11	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	3.625	Gypsum	0.625
12	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625
13	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625
14	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625
15	362S162 - 43 Mil	362T125 - 43 Mil	150U150 - 43 Mil	R-13	3.625	Gypsum	0.625

APPENDIX B.4 – Summary of 362S162 - 68 Mil assemblies (16” on center)

Table 17: Summary of 362S162 - 68 Mil assemblies (16” on center)

362S162 - 68 Mil @ 16" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
16	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
17	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
18	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
19	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
20	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
16	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	Air Cavity	3.625	Gypsum	0.625
17	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625
18	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625
19	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625
20	362S162 - 68 Mil	362T125 - 68 Mil	150U150 - 68 Mil	R-13	3.625	Gypsum	0.625

APPENDIX B.5 – Summary of 600S162 - 43 Mil assemblies (16" on center)

Table 18: Summary of 600S162 - 43 Mil assemblies (16" on center)

600S162 - 43 Mil @ 16" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
21	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
22	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
23	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
24	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
25	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
21	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	6.000	Gypsum	0.625
22	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
23	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
24	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
25	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.6 – Summary of 600S162 - 68 mil assemblies (16” on center)

Table 19: Summary of 600S162 - 68 Mil assemblies (16” on center)

600S162 - 68 Mil @ 16" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
26	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
27	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
28	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
29	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
30	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
26	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	Air Cavity	6.000	Gypsum	0.625
27	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
28	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
29	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
30	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.7 – Summary of 600S162 - 43 Mil assemblies (24" on center)

Table 20: Summary of 600S162 - 43 Mil assemblies (24" on center)

600S162 - 43 Mil @ 24" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
31	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
32	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
33	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
34	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
35	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
31	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	6.000	Gypsum	0.625
32	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
33	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
34	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
35	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.8 – Summary of 600S162 - 68 Mil assemblies (24” on center)

Table 21: Summary of 600S162 - 68 Mil assemblies (24” on center)

600S162 - 68 Mil @ 24" on center

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
36	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
37	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
38	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
39	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
40	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
36	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	Air Cavity	6.000	Gypsum	0.625
37	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
38	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
39	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
40	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.9 – Summary of 600S162 - 33 Mil assemblies (16” on center) with #6 fasteners

Table 22: Summary of 600S162 - 33 Mil assemblies (16” on center) - #6 fastener

600S162 - 33 Mil @ 16" on center - #6 Fastener

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
41	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
42	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
43	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
44	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
45	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
41	600S162 - 33 Mil	600T125 - 33 Mil	150U150 - 33 Mil	Air Cavity	3.625	Gypsum	0.625
42	600S162 - 33 Mil	600T125 - 33 Mil	150U150 - 33 Mil	R-13	3.625	Gypsum	0.625
43	600S162 - 33 Mil	600T125 - 33 Mil	150U150 - 33 Mil	R-13	3.625	Gypsum	0.625
44	600S162 - 33 Mil	600T125 - 33 Mil	150U150 - 33 Mil	R-13	3.625	Gypsum	0.625
45	600S162 - 33 Mil	600T125 - 33 Mil	150U150 - 33 Mil	R-13	3.625	Gypsum	0.625

APPENDIX B.10 – Summary of 600S162 - 54 Mil assemblies (16” on center) with #6 fasteners

Table 23: Summary of 600S162 - 54 Mil assemblies (16” on center) - #6 fastener

600S162 - 54 Mil @ 16" on center - #6 Fastener

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
46	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
47	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
48	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
49	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
50	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
46	600S162 - 54 Mil	600T125 - 54 Mil	150U150 - 54 Mil	Air Cavity	6.000	Gypsum	0.625
47	600S162 - 54 Mil	600T125 - 54 Mil	150U150 - 54 Mil	R-13	6.000	Gypsum	0.625
48	600S162 - 54 Mil	600T125 - 54 Mil	150U150 - 54 Mil	R-13	6.000	Gypsum	0.625
49	600S162 - 54 Mil	600T125 - 54 Mil	150U150 - 54 Mil	R-13	6.000	Gypsum	0.625
50	600S162 - 54 Mil	600T125 - 54 Mil	150U150 - 54 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.11 – Summary of 600S162 - 43 Mil assemblies (24” on center) with #8 1-15/16 inches fasteners

Table 24: Summary of 600S162 - 43 Mil assemblies (24” on center) - #8 1-15/16" fastener

600S162 - 43 Mil @ 24" on center - #8 1-15/16"

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
51	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
52	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
53	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
54	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
55	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
51	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	6.000	Gypsum	0.625
52	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
53	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
54	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
55	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.12 – Summary of 600S162 - 97 Mil assemblies (16” on center) with #6 fasteners

Table 25: Summary of 600S162 - 97 Mil assemblies (16” on center) - #6 fastener

600S162 - 97 Mil @ 16" on center - #6 Fastener

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
56	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
57	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
58	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
59	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
60	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
56	600S162 - 97 Mil	600T125 - 97 Mil	150U150 - 97 Mil	Air Cavity	6.000	Gypsum	0.625
57	600S162 - 97 Mil	600T125 - 97 Mil	150U150 - 97 Mil	R-13	6.000	Gypsum	0.625
58	600S162 - 97 Mil	600T125 - 97 Mil	150U150 - 97 Mil	R-13	6.000	Gypsum	0.625
59	600S162 - 97 Mil	600T125 - 97 Mil	150U150 - 97 Mil	R-13	6.000	Gypsum	0.625
60	600S162 - 97 Mil	600T125 - 97 Mil	150U150 - 97 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.13 – Summary of 600S162 - 43 Mil assemblies (24” on center) with #10 2-1/2 inch fasteners

Table 26: Summary of 600S162 - 43 Mil assemblies (24” on center) - #10 2-1/2” fastener

600S162 - 43 Mil @ 24" on center - #10 2-1/2"

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
61	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
62	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
63	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
64	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
65	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
61	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	6.000	Gypsum	0.625
62	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
63	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
64	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
65	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.14 – Summary of 600S162 - 43 Mil assemblies (16" on center) with #10 3-00 inch fasteners

Table 27: Summary of 600S162 - 43 Mil assemblies (16" on center) - #10 3-00" fastener

600S162 - 43 Mil @ 16" on center - #10 3-00"

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
66	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
67	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
68	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
69	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
70	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
66	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	6.000	Gypsum	0.625
67	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
68	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
69	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
70	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.15 – Summary of 600S162 - 43 Mil assemblies (24" on center) with #10 3-00 inch fasteners

Table 28: Summary of 600S162 - 43 Mil Assemblies (24" on center) - #10 3-00" fastener

600S162 - 43 Mil @ 24" on center - #10 3-00"

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
71	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
72	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
73	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
74	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
75	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
71	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	Air Cavity	6.000	Gypsum	0.625
72	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
73	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
74	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625
75	600S162 - 43 Mil	600T125 - 43 Mil	150U150 - 43 Mil	R-13	6.000	Gypsum	0.625

APPENDIX B.16 – Summary of 600S162 - 68 Mil assemblies (24" on center) with #10 3-00 inch fasteners

Table 29: Summary of 600S162 - 68 Mil assemblies (24" on center) - #10 3-00" fastener

600S162 - 68 Mil @ 24" on center - #10 3-00"

Assembly No.	Exterior Finish	Exterior Finish Thickness (in)	Exterior Insulation	XPS Thickness (in)	Interior Fastener Pattern	Outer Sheathing	Outer Sheathing Thickness (in)
76	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
77	Stucco	0.750	--	--	6" o.c	Gypsum	0.625
78	Stucco	0.750	R-7.5	1.500	6" o.c	Gypsum	0.625
79	Stucco	0.750	R-10.0	2.000	6" o.c	Gypsum	0.625
80	Stucco	0.750	R-12.5	2.500	6" o.c	Gypsum	0.625
Assembly No.	**Steel Stud**	**Steel track**	**Steel Bridging**	**Cavity Insulation**	**Cavity Insulation Thickness (in)**	**Interior Sheathing**	**Interior Sheathing Thickness (in)**
76	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	Air Cavity	6.000	Gypsum	0.625
77	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
78	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
79	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625
80	600S162 - 68 Mil	600T125 - 68 Mil	150U150 - 68 Mil	R-13	6.000	Gypsum	0.625

APPENDIX C

SUMMARY OF RESULTS

This appendix summarizes the results of the parametric evaluation. Table 30 through Table 32 provide detailed breakdown of heat flow values and thermal transmittance calculations for all of the analyzed wall assemblies.

APPENDIX C.1 – Summary of PA-01 to PA-30

Table 30: Summary of results of the parametric evaluation (PA-01 to PA-30)

Assembly No	Heat Flow	U - Value	R - Value	Ψ_{stud}	Ψ_{track}	$\chi_{Fastener}$	Predicted U - Value	Percentage Difference
	(W)	$W/m^2 \cdot K$	$m^2 \cdot K/W$	$W/m \cdot K$	$W/m \cdot K$	W/K	$W/m^2 \cdot K$	%
362S162 - 43 Mil @ 24" on center								
1	12.070	1.9962	0.5009	0.0276	0.0222	0.0002	1.9964	-0.01%
2	3.9493	0.6532	1.5310	0.1019	0.0751	0.0002	0.6489	0.65%
3	1.9455	0.3218	3.1076	0.0260	0.0163	0.0002	0.3211	0.20%
4	1.6893	0.2792	3.5812	0.0196	0.0120	0.0001	0.2785	0.25%
5	1.5002	0.2480	4.0323	0.0156	0.0095	0.0001	0.2473	0.29%
362S162 - 68 Mil @ 24" on center								
6	12.149	2.0093	0.4977	0.0326	0.0246	0.0002	2.0101	-0.04%
7	4.1107	0.6799	1.4709	0.1127	0.0793	0.0002	0.6749	0.73%
8	1.9690	0.3258	3.0693	0.0277	0.0165	0.0000	0.3223	1.07%
9	1.7060	0.2821	3.5446	0.0208	0.0123	0.0001	0.2809	0.42%
10	1.5131	0.2502	3.9966	0.0165	0.0096	0.0001	0.2491	0.44%
362S162 - 43 Mil @ 16" on center								
11	12.205	2.0185	0.4954	0.0276	0.0194	0.0001	2.0157	0.14%
12	4.4784	0.7400	1.3513	0.1037	0.0722	0.0002	0.7357	0.59%
13	2.0847	0.3449	2.8993	0.0268	0.0144	0.0000	0.3394	1.59%
14	1.7940	0.2967	3.3707	0.0202	0.0106	0.0001	0.2953	0.47%
15	1.5834	0.2618	3.8191	0.0160	0.0082	0.0001	0.2605	0.51%
362S162 - 68 Mil @ 16" on center								
16	12.318	2.0372	0.4909	0.0332	0.0234	0.0002	2.0377	-0.02%
17	4.6948	0.7764	1.2880	0.1147	0.0751	0.0002	0.7691	0.94%
18	2.1183	0.3505	2.8532	0.0285	0.0146	0.0000	0.3455	1.43%
19	1.8179	0.3006	3.3266	0.0214	0.0107	0.0001	0.2988	0.61%
20	1.6018	0.2649	3.7752	0.0170	0.0083	0.0001	0.2632	0.64%
600S162 - 43 Mil @ 16" on center								
21	12.129	2.0060	0.4985	0.0247	0.0198	0.0001	2.0053	0.03%
22	4.4021	0.7280	1.3737	0.0992	0.0691	0.0002	0.7211	0.95%
23	2.1031	0.3479	2.8741	0.0273	0.0145	0.0000	0.3430	1.43%
24	1.8059	0.2986	3.3487	0.0204	0.0107	0.0001	0.2963	0.79%
25	1.5936	0.2635	3.7947	0.0163	0.0082	0.0001	0.2614	0.81%
600S162 - 68 Mil @ 16" on center								
26	12.281	2.0311	0.4923	0.0318	0.0234	0.0002	2.0291	0.10%
27	4.6924	0.7760	1.2887	0.1139	0.0742	0.0002	0.7673	1.12%
28	2.1519	0.3560	2.8088	0.0298	0.0148	0.0000	0.3503	1.61%
29	1.8403	0.3043	3.2859	0.0222	0.0108	0.0001	0.3014	0.97%
30	1.6201	0.2679	3.7326	0.0176	0.0084	0.0001	0.2653	0.98%

APPENDIX C.2 – Summary of PA-31 to PA-60

Table 31: Summary of results of the parametric evaluation (PA-31 to PA-60)

Assembly No	Heat Flow	U - Value	R - Value	Ψ_{stud}	Ψ_{track}	$\chi_{Fastener}$	Predicted U - Value	Percentage Difference
	(W)	$W/m^2 \cdot K$	$m^2 \cdot K/W$	$W/m \cdot K$	$W/m \cdot K$	W/K	$W/m^2 \cdot K$	%
600S162 - 43 Mil @ 24" on center								
31	12.001	1.9848	0.5038	0.0242	0.0204	0.0001	1.9840	0.04%
32	3.8951	0.6442	1.5523	0.0974	0.0726	0.0002	0.6393	0.75%
33	1.9607	0.3244	3.0826	0.0265	0.0164	0.0000	0.3209	1.09%
34	1.6999	0.2811	3.5574	0.0199	0.0122	0.0001	0.2795	0.56%
35	1.5095	0.2496	4.0061	0.0159	0.0095	0.0001	0.2482	0.58%
600S162 - 68 Mil @ 24" on center								
36	12.115	2.0037	0.4991	0.0425	0.0246	0.0002	2.0252	-1.07%
37	4.1081	0.6794	1.4718	0.1115	0.0787	0.0002	0.6734	0.89%
38	1.9960	0.3303	3.0279	0.0289	0.0170	0.0000	0.3262	1.23%
39	1.7249	0.2852	3.5058	0.0216	0.0126	0.0001	0.2833	0.70%
40	1.5288	0.2528	3.9555	0.0172	0.0098	0.0001	0.2510	0.70%
600S162 - 33 Mil @ 16" on center - #6 MH Fastener								
41	12.034	1.9903	0.5024	0.0203	0.0167	0.0001	1.9899	0.02%
42	4.1852	0.6922	1.4447	0.0885	0.0653	0.0002	0.6880	0.60%
43	2.0624	0.3411	2.9317	0.0252	0.0141	0.0000	0.3368	1.27%
44	1.7770	0.2939	3.4026	0.0189	0.0104	0.0001	0.2919	0.68%
45	1.5934	0.2599	3.8483	0.0163	0.0082	0.0001	0.2613	-0.57%
600S162 - 54 Mil @ 16" on center - #6 MH Fastener								
46	12.210	2.0194	0.4952	0.0285	0.0216	0.0001	2.0179	0.07%
47	4.5648	0.7550	1.3246	0.1074	0.0720	0.0002	0.7471	1.04%
48	2.1309	0.3524	2.8375	0.0287	0.0147	0.0000	0.3472	1.48%
49	1.8255	0.3019	3.3122	0.0214	0.0108	0.0001	0.2992	0.90%
50	1.6088	0.2661	3.7584	0.0170	0.0083	0.0002	0.2662	-0.04%
600S162 - 43 Mil @ 24" on center - #8 1-15/16" L								
51	12.007	1.9858	0.5036	0.0237	0.0206	0.0002	1.9841	0.08%
52	3.8972	0.6445	1.5517	0.0971	0.0726	0.0002	0.6392	0.82%
53	1.9609	0.3243	3.0833	0.0263	0.0165	0.0000	0.3206	1.15%
54	1.7038	0.2817	3.5505	0.0201	0.0123	0.0001	0.2807	0.35%
55	1.5125	0.2500	3.9992	0.0160	0.0096	0.0001	0.2490	0.40%
600S162 - 97 Mil @ 16" on center - #6 Fastener								
56	12.424	2.0548	0.4867	0.0387	0.0264	0.0002	2.0516	0.15%
57	4.9086	0.8118	1.2318	0.1249	0.0777	0.0002	0.8019	1.22%
58	2.1858	0.3615	2.7662	0.0315	0.0150	0.0000	0.3555	1.67%
59	1.8640	0.3083	3.2438	0.0234	0.0110	0.0001	0.3047	1.15%
60	1.6383	0.2710	3.6907	0.0185	0.0084	0.0001	0.2678	1.15%

APPENDIX C.3 – Summary of PA-61 to PA-80

Table 32: Summary of results of the parametric evaluation (PA-61 to PA-80)

Assembly No	Heat Flow	U - Value	R - Value	Ψ_{stud}	Ψ_{track}	$\chi_{Fastener}$	Predicted U - Value	Percentage Difference
	(W)	$W/m^2 \cdot K$	$m^2 \cdot K/W$	$W/m \cdot K$	$W/m \cdot K$	W/K	$W/m^2 \cdot K$	%
600S162 - 43 Mil @ 24" on center - #10 2-1/2"								
61	12.016	1.9873	0.5032	0.0236	0.0204	0.0003	1.9853	0.10%
62	3.8972	0.6463	1.5472	0.0962	0.0708	0.0002	0.6358	1.62%
63	1.9619	0.3247	3.0802	0.0261	0.0164	0.0000	0.3203	1.35%
64	1.7104	0.2830	3.5334	0.0202	0.0124	0.0000	0.2794	1.29%
65	1.5116	0.2497	4.0045	0.0159	0.0095	0.0001	0.2486	0.44%
600S162 - 43 Mil @ 16" on center - #10 3.00"								
66	12.156	2.0104	0.4974	0.0238	0.0198	0.0004	2.0073	0.16%
67	4.4216	0.7313	1.3675	0.0981	0.0692	0.0000	0.7150	2.22%
68	2.1053	0.3482	2.8720	0.0266	0.0095	0.0000	0.3373	3.14%
69	1.8272	0.3022	3.3091	0.0210	0.0107	0.0001	0.2984	1.25%
70	1.6100	0.2663	3.7556	0.0167	0.0083	0.0002	0.2654	0.31%
600S162 - 43 Mil @ 24" on center - #10 3.00"								
71	12.020	1.9879	0.5030	0.0234	0.0206	0.0004	1.9856	0.12%
72	3.9091	0.6463	1.5472	0.0963	0.0727	0.0003	0.6396	1.05%
73	1.9624	0.3247	3.0802	0.0258	0.0164	0.0000	0.3198	1.50%
74	1.7107	0.2830	3.5334	0.0199	0.0124	0.0000	0.2789	1.44%
75	1.5294	0.2529	3.9542	0.0168	0.0098	0.0001	0.2505	0.96%
600S162 - 68 Mil @ 16" on center - #10 3.00"								
76	12.305	2.0351	0.4914	0.0238	0.0198	0.0004	2.0073	1.37%
77	4.4196	0.7309	1.3681	0.0980	0.0688	0.0003	0.7203	1.45%
78	2.1538	0.3562	2.8073	0.0294	0.0243	0.0004	0.3654	-2.58%
79	1.8422	0.3047	3.2822	0.0218	0.0108	0.0001	0.3006	1.32%
80	1.6216	0.2682	3.7287	0.0173	0.0106	0.0003	0.2718	-1.36%

APPENDIX D

FASTENER MODELLING

This section of the appendix discusses the methodology and reasoning behind modelling the fasteners as they were for the purpose of this project. For all the assemblies, the fasteners were modelled as square cuboids with the same cross-sectional area as the shank of the fastener being modelled. The length of these square prisms was kept the same as the original fastener length (including the fastener head). This was done due to the geometric limitation in Heat3 which does not allow modelling of non-prismatic members. Figure 24 below shows typical fasteners as modelled in Heat3.

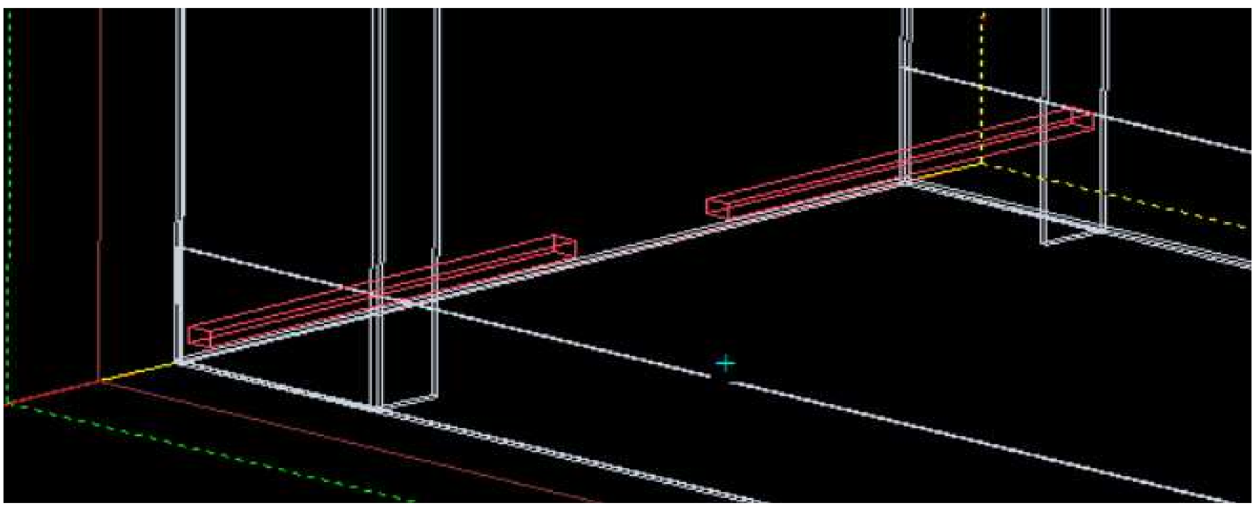


Figure 24: Typical fasteners as modelled in heat3 for project assemblies

Additionally, no fastener heads and threads were modelled. This was done because the increased area of the fastener head was determined to have a negligible difference on the overall heat flow of the assembly. Table 33 below represents the geometric and material properties for the assembly used to verify this assumption.

Table 33: Summary of geometric and material properties used for the assembly used to verify fastener modelling assumptions

Element	Description	Thickness (in)	Conductivity K-Value (BTU-in/hr ft^2 ^oF)	Component R-Value (hr ft^2 ^oF/BTU)
Exterior Finish	Stucco	0.75	9.375	0.08
Exterior Insulation	--	--	--	--
Interior Fastener Pattern (#10, 3-00")	6" o.c	0.19	346	--
Exterior Fastener Pattern	--	--	--	--
Outer Sheathing	Gypsum	0.625	1.12	0.56
Steel Stud (16.0 in. o.c.)	600S162 - 68 Mil	0.0677	495	--
Steel track	600T125 - 68 Mil	0.0677	495	--
Steel Channel	150U150 - 68 Mil	0.0677	495	--
Cavity Insulation	R-13 (6")	6.000	0.46	13.00
Interior Sheathing	Gypsum	0.625	1.10	0.57

This assembly was determined to be the most critical case for studying the impact of fastener heads for the following reasons –

- no external insulation is present and R-13 cavity insulation is present which corresponds with CZ-0 and CZ-1
- diameter and length of the fastener represent the maximum case of the parametric evaluation cases (#10, 3-00")

Due to this, the impact of fastener heads on the overall heat flow is the maximum possible. It was observed that with the fastener heads the net heat flow through the assembly increased by only 0.58% from 4.420 W to 4.445W. Based on the findings of this analysis, fastener heads were neglected in project models.

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