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Three-Dimensional Heat Transfer Analysis of Metal Fasteners in Roofing Assemblies

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Abstract: Heat transfer analysis was performed on typical roofing assemblies using HEAT3, a three-dimensional heat transfer analysis software. The difference in heat transferred through the roofing assemblies considered is compared between two cases—without any steel fasteners and with steel fasteners. In the latter case, the metal roofing fasteners were arranged as per Factor Mutual Global (FMG) approvals, in the field, perimeter, and corner zones of the roof. The temperature conditions used for the analysis represented summer and winter conditions for three separate Climate Zones (CZ) namely Climate Zone 2 or CZ2 represented by Orlando, FL; CZ3 represented by Atlanta, GA; and CZ6 zone represented by St. Paul, MN. In all the climatic conditions, higher energy transfer was observed with increase in the number of metal fasteners attributed to high thermal conductivity of metals as compared to the insulation and other materials used in the roofing assembly. This difference in heat loss was also quantified in the form of percentage change in the overall or effective insulation of the roofing assembly for better understanding of the practical aspects. Besides, a comparison of 2D heat transfer analysis (using THERM software) and 3D analysis using HEAT3 is also discussed proving the relevance of 3D over 2D heat transfer analysis.

Keywords: roofing assemblies; steel fasteners; heat transfer; energy impact

1. Background

Understanding the heat transfer through roof assemblies is crucial as these envelope systems receive the maximum amount of direct solar radiation. According to the data from U.S. Energy Information Administration (EIA), the energy consumed by the building sector is 47.6% of total energy produced in U.S. and 74.9% of net electricity produced in U.S. is used only to operate the buildings. Out of this vast amount of energy used for several purposes to operate the building, space heating and cooling are among the top three usages along with lighting. This implies that a substantial amount of energy is transmitted or more precisely lost through this unintentional energy exchange through the roofing, between the interior and the exterior of the building. However, unintentional, this energy loss is not entirely uncontrollable. Several researches have attempted to improve the roofing performance by reducing this energy loss through advancements in roofing materials including insulation, different layers, and their arrangements. To reduce energy loss through building envelope systems, building energy standards such as the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2013) [1] offers prescriptive approaches. In the case of roofing assemblies, although such Standards

provide the necessary minimum insulation requirements, but they do not take into consideration, the heat loss that happens through metal fasteners. Such modes of heat loss involving fasteners and plates fall under the category of thermal bridges. There are no implicit guiding requirements in these Standards that relates to roofing fasteners. In other words, the heat loss through the roofing metal fasteners is generally ignored while prescribing the insulation requirements for a roofing system. This paper establishes the importance of heat transfer through thermal bridging and the requirement of analysis based on the assembly type and the number of metal fasteners used.

The heat is transferred from inside to the outside of the building during winter conditions and from outside to inside in summer conditions. This direction of heat transfer is justified by the zeroth Law of Thermodynamics that every system tries to reach the equilibrium, which means the heat flows from the hotter areas to cooler areas and as evident in Figure 1, the thermal bridges due to metal fasteners and plates facilitates this heat exchange.

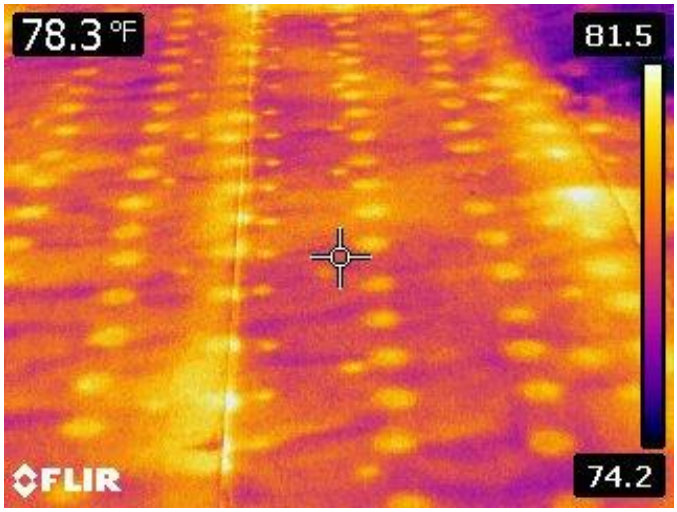


Figure 1. Infrared image of roofing, under cold conditions showing higher temperatures and thus greater heat loss at the location of metal fasteners.

Other researchers have attempted on quantifying the heat loss through these thermal bridges. One of the early researches done on the topic was Burch et al., (1986) [2], who used a finite difference model to analyze the overall thermal resistance in metal and wood-deck roofing systems with insulation thickness ranging from 1″ to 6″. The paper however provided the starting platform and a basic idea so as how the heat loss is affected by the thermal bridges but due to technological limitations at the time, different roofing assemblies and climatic conditions were not analyzed. Another prominent research was conducted by Olson et al., (2015) [3] who used the HEAT3 software (three-dimensional heat transfer analysis tool) to analyze the change in effective R-Value of insulation due to the metal fasteners among others. This research was accurate in terms of factors included, and the technology and method adopted, but it was limited to only a single roofing assembly under specific climatic conditions. In a recent research work analyzed by Gulati et al., (2016) [4], several re-roofing and re-cover assemblies were analyzed to study the effects of thermal bridges for different climatic zones. However, the accuracy of this work was limited as it used THERM software (2015), a two-dimensional heat transfer analysis software. This study can be considered an extension to the work of Gulati et al., (2016) [4] and Suddappalli et al., (2016) [5] using three-dimensional heat transfer analysis for improved results. This study analyzes the heat transfer through the metal fasteners under several roofing assemblies and three separate climatic zones to quantify their effect on the entire roof assembly's effective Resistance. In addition, the results obtained are quantified in a manner to formulate a general pattern so as to how the number, length, and arrangement of these fasteners affects the heat loss. This data can be used to optimize the heat loss through roofing and more importantly design the roofing assemblies that

are consistent with the prescribed R-Value of the insulation. The software used for the simulations is HEAT3 by Blocon (2016) [6]. HEAT3 analyzes the heat transfer in three dimensions with the use of Finite Element Analysis (FEA) method.

2. Description of the Metal Deck Roofing Systems

The roof is an integral part of the building envelope and is the building's first line of defense to the outside climatic conditions. A typical low-slope roof assembly from structural deck above, consists of the mainly the following components.

- Metal deck at the base.
- Thermal barrier, as required.
- Insulation layer, made up of materials such as polyisocyanurate, expanded polystyrene, extruded polystyrene or lightweight insulating concrete.
- Cover board such as gypsum roof board.
- Modified Bitumen roof membrane or single ply.
- Metal plates and fasteners running through the entire section of the assembly or a hybrid system where a roof assembly is partially fastened mechanically and partially with cold applied adhesive system.

Another important roofing concept is the division of the total roof surface area in three segments i.e., field, perimeter, and the corner, see Figure 2. This is done because the wind uplift pressures vary in these three areas (source FMG approvals) [7]. Typically, in low slope roofs, corner areas experience higher uplift pressures than perimeter and field areas. Corner area gets the highest density of metal fasteners due to high wind pressure and thus constitutes the maximum amount of heat transfer per unit area due to thermal bridging. Second segment is the Perimeter, the area on the sidelines between the corner zones. The fastener density here is lesser than the corner but higher than the Field area and so is the heat loss. The major amount of surface area is covered under the Field zone which lies in the center of the roof and has the minimum heat loss and fastener density per unit area among the all 3 zones. Table 1 shows the roofing assemblies used in this work; they are referred to as 1A, 1B, 3A, and 3B. These reference match the ones that were used in Gulati et al., (2016) [4] and Suddappalli et al., (2016) [5].

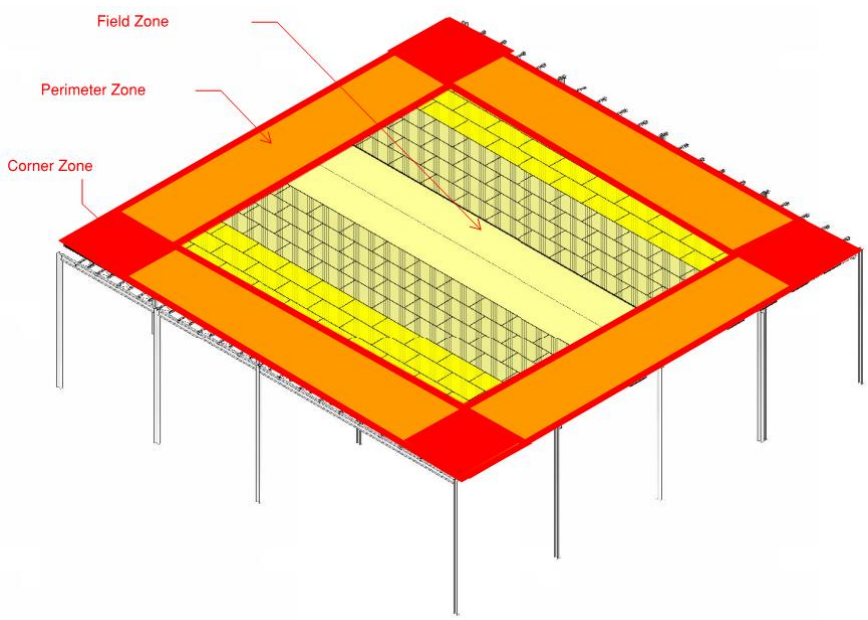
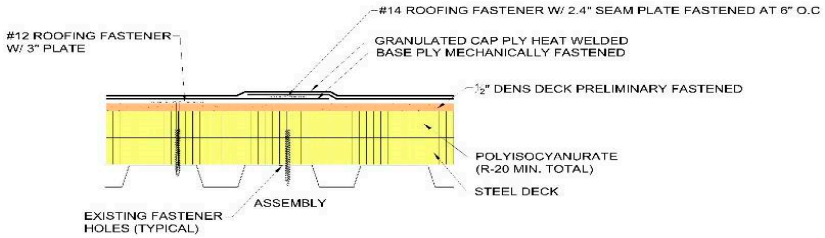
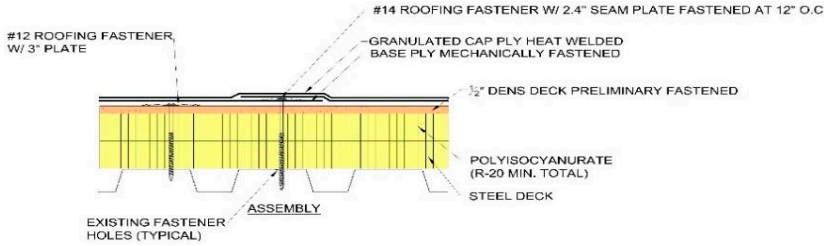
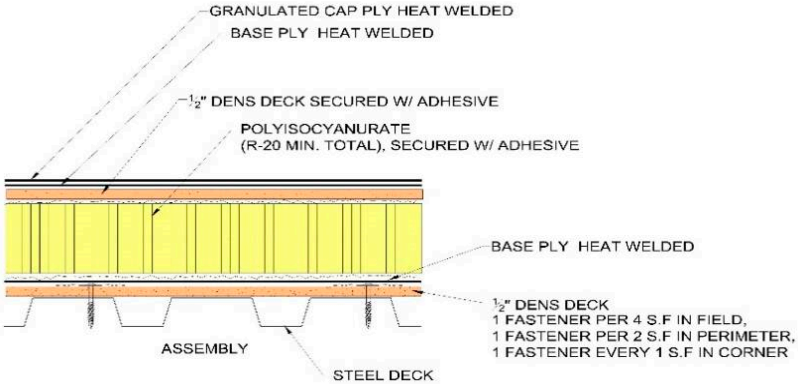
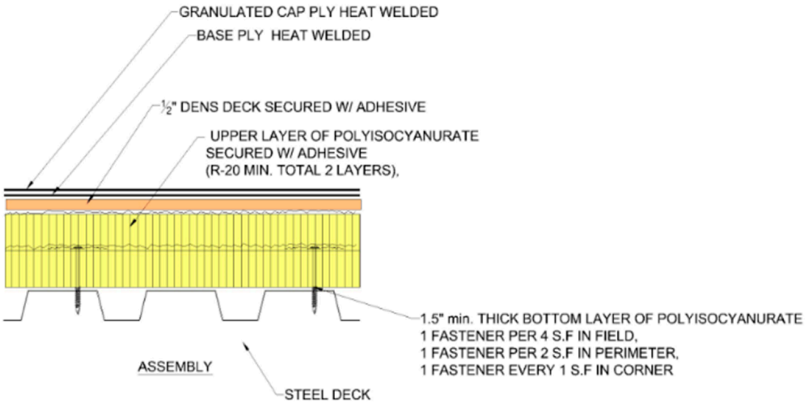


Figure 2. Axonometric view of roofing system that shows the three zones—field, perimeter, and corner.

Table 1. Description of roofing assemblies analyzed in this study. (Refer Appendix B).

1A		Base ply mechanically fastened at laps 6″ O.C.; perimeter mechanically fastened at laps 6″ O.C. with one additional row of fastening in the center; Corner mechanically fastened at laps 6″ O.C. with two additional rows of fastening. Insulation and Cover board preliminary fastened. Base Ply is mechanically fastened and top ply is adhered.
1B		Base ply mechanically fastened at laps 12″ O.C.; perimeter mechanically fastened at laps 12″ O.C. with one additional row of fastening in the center; Corner mechanically fastened at laps 12″ O.C. with two additional rows of fastening. Insulation and Cover board preliminary fastened. Base Ply is mechanically fastened and top ply is adhered.
3A		Field 1 fastener every 4 ft^2; Perimeter 1 fastener every 2 ft^2 and Corner 1 fastener every 1 ft^2.
3B		Field 1 fastener every 4 ft^2; Perimeter 1 fastener every 2 ft^2 and Corner 1 fastener every 1 ft^2.

3. Heat Transfer Properties and Assumptions

3.1. Heat Transfer Properties of Roofing Materials Used

Table 2 lists the thermal properties of the materials used. These properties are taken from the National Roofing Contractors Association (NRCA) Manual 2014, Appendix 3—Typical Thermal Properties of Building Materials [8].

Table 2. Material Properties.

Material	Thermal Conductivity		Thickness	
	Btu·in/h·ft^2·F	W/m-K	Inches	m
Polymer Modified Bitumen	1.125	0.1621	3/8	0.00952
Single Ply	1.125	0.1621	3/8	0.00952
Gypsum Roof Board	0.895	0.129	1/2	0.0127
Polyisocyanurate Insulation	0.179	0.0258	2 × 1.8	2 × 0.04572
Metal Deck Steel	311.1	44.8	0.03	0.00076
Steel Fasteners—Galvanized Steel (0.14% C)	430.42	61.98	Depends on the assembly	
Adhesive	0.263	0.038	0.03	0.00076

3.2. Assumptions

The roof is considered to be low slope with uniform R-20 insulation as per ASHRAE 90.1-2013 standard. It is to be noted that this study uses a R-20 insulation as the baseline for consistency purposes which is useful for comparison across various other climatic zones. The authors are aware of the change in roof insulation across climatic zones post ASHRAE 90.1-2007. However, using varied roof insulation values will not provide a clear understanding of the impact of roofing assemblies across these climatic zones. The roof area used for this study purpose is 10,000 sq. ft. with 6400 sq. ft. for field, 3200 sq. ft. for perimeter, and 400 sq. ft. for corner areas. Thermal conductivity values for the materials involved were obtained from NRCA Manual 2014 as shown in Table 2. For the analysis in HEAT3 software, the cross-section of fasteners was modeled as square with same surface area as the circular cross-section fasteners due to software limitations. The metal deck is modeled as a thin plate in HEAT3.The contact resistance between the layers of insulation is ignored because being an extremely thin layer, its effects on the overall heat analysis were negligible. In addition, the thermal resistances of the air film above and below the assembly are taken from the NRCA Manual 2014 with separate values for summer and winter as shown in Table 3 below.

Table 3. Thermal Resistance of Air Films in contact with the inside and the outside surfaces of the assembly.

	Summer Design Conditions		Winter Design Conditions	
	h·ft^2·F/Btu	m^2·K/W	h·ft^2·F/Btu	m^2·K/W
Inside	0.92	0.1621	0.61	0.1075
Outside	0.25	0.0441	0.17	0.0299

Simulations are done under steady-state conditions taking the design temperature as constant. Inside zone temperature is taken constant at 72 °F (295.4 K) for both summer and winter conditions and as for the outside zone, the entire analysis is performed for the following three climatic conditions, as mentioned in Table 4 below.

Table 4. Design conditions used in analysis.

Climate Zone	Summer Design Temperature			Winter Design Temperature		
	°F	°C	°K	°F	°C	°K
CZ3 (Atlanta, GA)	93	33.89	307	18	−7.78	265.4
CZ2 (Orlando, FL)	94	34.4	307.6	37	2.78	275.9
CZ6 (St. Paul, MN)	91	32.78	305.9	−16	−26.67	246.5

4. Results and Observations

The entire assembly is modeled in zones as the Field, Perimeter and the Corner zone separately with fastener density specified in the standards for the specific areas. Figure 3 below shows the isometric view of one of the models to get a clear understanding of the assembly analyzed. The results are presented in three sections emphasizing on comparing the effect of metal fasteners in a single assembly, the comparison of different roofing assemblies with standard fastener arrangements and graphical analysis of the impacts of thermal bridging on the basis of heat transfer.

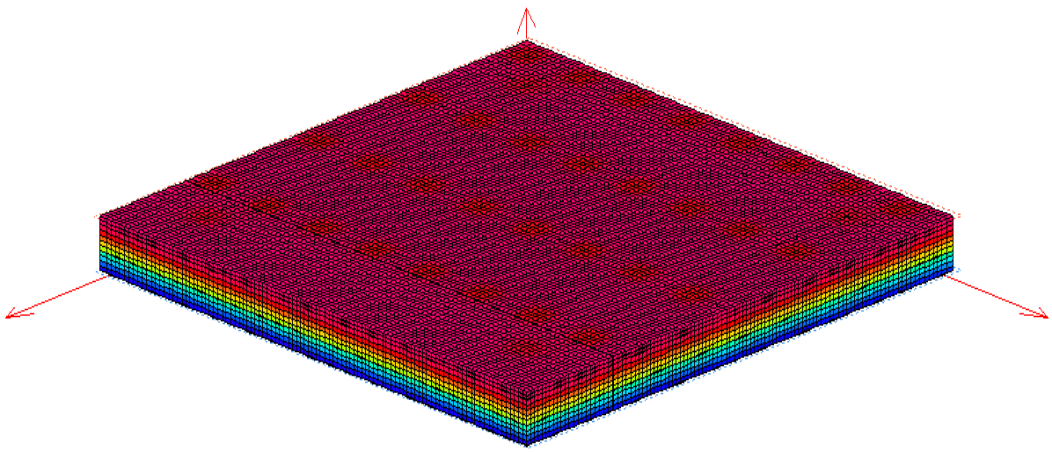


Figure 3. Isometric view of the corner zone of 1A assembly with 36 fasteners modeled in HEAT3, arranged according to standards.

4.1. Analysis of the Effect of Fastener Density on Heat Transfer through the Roofing Assemblies

In this section, the effect of thermal bridging on a particular assembly is analyzed. In other words, the heat transfer through the roofing assembly is quantified and tabulated as per different zones under different climatic conditions. These different zones are basically the measure of fastener density with the field zone having minimum and the corner zone having the maximum number of fastener per unit area. Heat transfer per unit area is tabulated in Table 5 below along with the metal deck temperatures for all 3 zones of Assembly 1B, taken as example, under different climatic conditions. The "total" heat loss per unit area calculated in each case is based on the averaged value of heat transfer over a 10,000 sq. ft. roof with 6400 sq. ft. as field zone, 3200 sq. ft. as perimeter zone and 400 sq. ft. at the corner zone.

In order to understand the results, Assembly 1B is emphasized (12″ O.C.) and the heat transfer data is tabulated. It is clearly evident from Table 5, that as the fastener density increases, the heat loss also increases which can be attributed to the much higher thermal conductivity of metal fasteners as compared to the insulation and other roofing materials. The heat flowing through the assembly tends to take the route with the least resistance and thus the major portion of heat flows through the metal fasteners instead of going through the insulation layers. As a result of this process, the majority of heat transfer occurs through the metal fasteners. This hypothesis can be clearly understood with Figure 4.

Table 5. Heat transfer per unit area and the metal deck temperatures for the three Climatic Zones in case of Assembly 1B.

Climate Zones		No Fastener	Field	Perimeter	Corner	Total (Including Field, Perimeter and Corner Zones)
Atlanta Summer 307 K (93 °F)	Heat Transfer per unit Area W/m^2 (Btu/h·ft^2)	2.8 (0.9)	4.4 (1.4)	4.7 (1.5)	5.4 (1.7)	4.6 (1.4)
	Metal Deck Temperature °K (°F)	295.8 (72.8)	299.2 (78.8)	299.2 (78.8)	299.4 (79.2)	
Atlanta Winter 265.4 K (18 °F)	Heat Transfer per unit Area W/m^2 (Btu/h·ft^2)	7.57 (2.4)	11.4 (3.6)	12.9 (4.1)	14.2 (4.5)	12 (3.8)
	Metal Deck Temperature °K (°F)	294.5 (70.5)	286.1 (55.4)	286.2 (55.5)	286.2 (55.5)	
Orlando Summer 307.6 K (94 °F)	Heat Transfer per unit Area W/m^2 (Btu/h·ft^2)	3.2 (1.0)	4.4 (1.4)	5.0 (1.6)	5.7 (1.8)	4.7 (1.5)
	Metal Deck Temperature °K (°F)	295.8 (72.8)	299.2 (78.9)	299.2 (78.9)	299.3 (79.1)	
Orlando Winter 275.9 K (37 °F)	Heat Transfer per unit Area W/m^2 (Btu/h·ft^2)	5.0 (1.6)	7.6 (2.4)	8.2 (2.6)	9.2 (2.9)	7.9 (2.5)
	Metal Deck Temperature °K (°F)	294.8 (71.0)	289.4 (61.2)	289.4 (61.2)	289.4 (61.2)	
St. Paul Summer 305.9 K (91 °F)	Heat Transfer per unit Area W/m^2 (Btu/h·ft^2)	2.5 (0.8)	3.8 (1.2)	4.4 (1.4)	4.7 (1.5)	4.3 (1.3)
	Metal Deck Temperature °K (°F)	295.8 (72.7)	298.8 (78.1)	298.8 (78.1)	298.8 (78.2)	
St. Paul Winter 246.5 K (−16 °F)	Heat Transfer per unit Area W/m^2 (Btu/h·ft^2)	12.3 (3.9)	18.6 (5.9)	20.8 (6.6)	23 (7.3)	19.6 (6.2)
	Metal Deck Temperature °K (°F)	294.0 (69.5)	280.4 (45.0)	280.6 (45.5)	280.4 (45.0)	

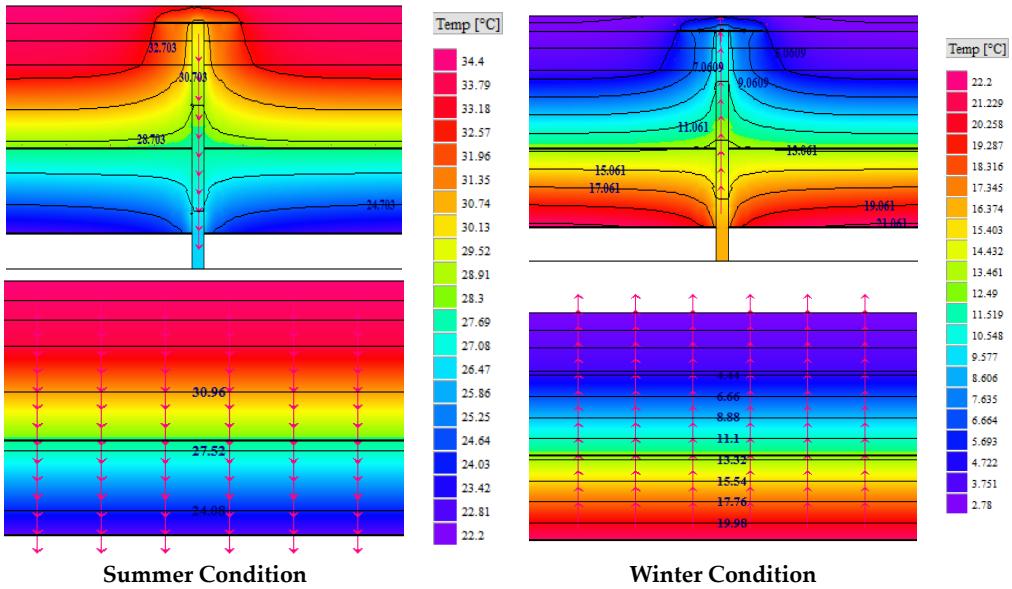


Figure 4. Comparison between the cases of "with fasteners" (first row) and "without fasteners" (second row) using isotherms and the Heat Flow direction, in case of 1A Orlando Summer and Winter Conditions.

As can be seen from Figure 4, in case of summer, the heat flows from outside towards inside through the route of metal fasteners. In addition, the temperature around the fastener is seen to be higher than the rest of the assembly. On the other hand, in case of "no fasteners", the heat flow and the temperature distribution is uniform throughout the assembly. This figure clearly indicates the mechanism of heat flow through an assembly with metal fasteners acting as the major career of heat flow and also provides an evident justification that why there is a sudden increase in heat loss going from cases of "No Fasteners" to the Field zone with fasteners. For in-depth understanding, isotherms for each case analyzed are provided in Appendix A.

In addition, the percentage change in *R*-Value is calculated through the difference between the case of "No Fasteners" and the "Total" including all three zones with their areas according to the ASHRAE standards. The following formula is used to calculate the effective *R*-Value of the entire assembly.

$$\boldsymbol{R - \text{Value}} = \frac{\Delta T}{q}$$

where ΔT is the temperature difference between inside and outside of the assembly; q is the heat transferred per unit area.

The percentage *R*-Value change is calculated taking the effective *R*-Value using the given formula in case of "No Fasteners" as baseline.

$$\%\ \text{Change in } R_{effective} = \frac{R_{effective}\ (\text{with fasteners}) - R_{effective}\ (\text{without fasteners})}{R_{effective}\ (\text{without fasteners})}$$

Using this formula, the percentage change in effective *R*-Value for Assembly 1B is about 35% in total (including field, perimeter and corner zones). A change of this magnitude in overall effective resistance can be understood practically on the basis of the fact that in case of the 1B assembly considered, the length of the fastener runs almost through the entire section of the assembly thus providing a considerably low resistance pathway for the heat to travel and avoiding the high thermal resistance path through the insulation.

When noted separately in the field zone of 1B, where the fastener density is 1 fastener per ft^2, the change in $R_{effective}$ was found to be 32%. These results coincide with the previous work of Olson et al.

(Table 2) [3] where the percentage change in $R_{effective}$ came out to be around 28% when 1 fastener per ft^2 was considered. The 4% difference in the results can be attributed to the different fastener sizes used in the Olsen et al., (2015) study. This work used the # 14 (0.245″ thread diameter) fasteners as opposed to # 12 fasteners (0.22″ thread diameter) used in case of Olson et al., (2015) which directly infers an increase in cross-sectional area of fasteners by about 24%.

A cut out section from the corner zone assembly is shown in Figure 5 to provide a graphical representation of how the temperature varies through various layers.

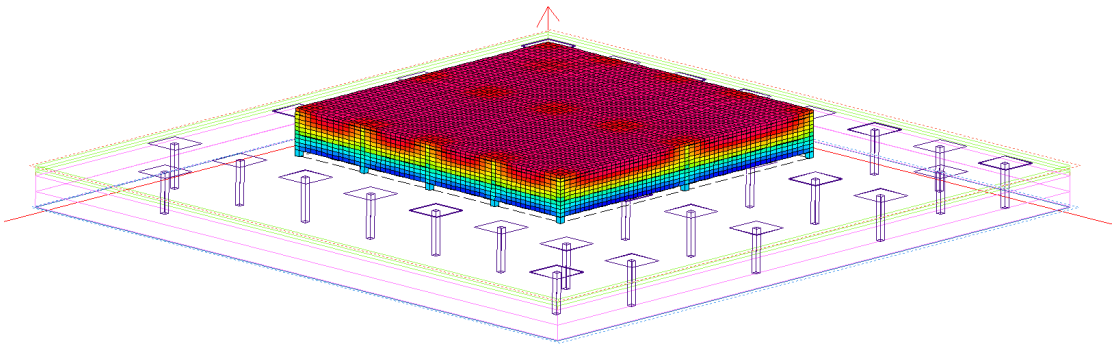


Figure 5. A section of 1A assembly shown with temperature variations in 3D.

4.2. Comparative Analysis of Different Roofing Assemblies with Fasteners

In this section, different roofing assemblies and the extent of change in $R_{effective}$ (h·ft^2·°F/Btu) due to fasteners in each case are discussed. The only case considered here for explanation is for CZ2 (Orlando Summer) and all the data in Table 6 is based on total area of 10,000 sq. ft. containing the field, perimeter, and corner zones.

Table 6. Comparison of $R_{effective}$ Values showing the difference between Prescribed Design Conditions Case (baseline) and final assembly with taking into consideration, the effect of fasteners for all the climatic conditions analyzed.

	$R_{effective}$ (Ft^2·°F·h/Btu)	Atlanta (CZ3)		Orlando (CZ2)		St. Paul (CZ6)	
		Summer	Winter	Summer	Winter	Summer	Winter
1A	Prescribed Design Value	22.6	22.3	22.7	22.3	22.6	22.3
	Actual Value	11.8	11.2	11.8	11.2	11.8	11.2
1B	Prescribed Design Value	22.6	22.3	22.7	22.3	22.6	22.3
	Actual Value	14.7	14.2	14.7	14.2	14.7	14.2
3A	Prescribed Design Value	23.6	23.3	23.7	23.3	23.6	23.3
	Actual Value	23.6	23.3	23.7	23.3	23.6	23.3
3B	Prescribed Design Value	22.6	22.2	22.7	22.3	22.6	22.2
	Actual Value	22.1	21.6	22.1	21.6	21.9	21.6

The "Prescribed design value" case mentioned in Table 6 denotes the $R_{effective}$ value of the entire assembly where R-20 insulation is used and no effect of fasteners is considered, as is prescribed by the Standards. On the other hand, the "Actual Value" is calculated with taking into account the effect of thermal bridging due to metal fasteners arranged accordingly in the Field, Perimeter and Corner zones of a 10,000 ft^2 roof.

The data in Table 6 shows a much higher change in $R_{effective}$ in case of assemblies 1A and 1B as compared to 3A and 3B assemblies. In addition to the fact that assemblies 3A and 3B has comparatively less fastener density than 1A and 1B, this difference can be understood by the composition of the two assemblies, as in case of 1A and 1B the fasteners run through the entire thickness of the roof

and connects two very different boundary conditions with their high thermal conductivity and thus transfers more heat. On the other hand, in case of Assembly 3A and 3B the fasteners cover only a small fraction of the thickness of the assembly with not so different boundary conditions on their two ends. For this reason, very low amount of heat transfers through them and the majority of the heat loss has to go through the insulation with extremely less thermal conductivity. The difference between the cases of Assembly 1A and 1B can be understood on the basis of the density of fasteners as in case of 1A the fasteners are 6″ O.C. as compared to 12″ O.C. and it is already established under section 1 that heat loss and thus the percentage change in $R_{effective}$ is directly proportional to the fastener density.

Also if a single assembly is considered under different climatic conditions, there is a slight difference among the percentage $R_{effective}$ change values for summer and winter conditions but the change is not prominent and can be explained on the basis of the fact that there is higher temperature difference in case of winter conditions. This variation is shown in the Table 7 below.

Table 7. Percentage $R_{effective}$ changes for all 4 Assemblies under different design conditions.

Percentage Change in $R_{effective}$	Atlanta (CZ3)		Orlando (CZ2)		St Paul (CZ6)	
	Summer	Winter	Summer	Winter	Summer	Winter
1A	48.0%	49.6%	48.0%	49.6%	48.0%	49.6%
1B	35.1%	36.4%	35.1%	36.4%	35.1%	36.5%
3A	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%
3B	2.4%	2.8%	2.5%	2.8%	2.5%	2.8%

The percentage $R_{effective}$ change is seen to slightly higher in case of winter condition due to higher temperature difference between inside and outside design conditions and the metal plate present on the inside of the assembly i.e., high conductivity metal in exposure to the warmer region.

4.3. Energy Loss Analysis

Now in order to get a better understanding of the practical impacts of this thermal bridging, the energy loss is quantified in case of each assembly under all three design conditions. As discussed earlier, the total area here is 10,000 ft^2 with standard Field, Perimeter, and Corner zones in case of "Actual Value". Where else the case of "Prescribed Design Value" depicts the energy loss where no effect of thermal bridging is considered as in case of Standards. The data presented in Table 8 consists of heat transfer per unit area averaged over a total area of 10,000 sq. ft.

Table 8. Heat transfer per unit area (BTU/h·ft^2) in each assembly under three separate design conditions.

Heat Transfer Per Unit Area W/m^2 (BTU/h·ft^2)		Atlanta (CZ3)		Orlando (CZ2)		St Paul (CZ6)	
		1	2	3	4	5	6
		Summer	Winter	Summer	Winter	Summer	Winter
1A	Actual Value	5.7 (1.8)	−15.1 (−4.8)	6.0 (1.9)	−9.8 (−3.1)	5.0 (1.6)	−24.9 (−7.8)
	Prescribed Design Value	2.8 (0.9)	−7.6 (−2.4)	3.2 (1.0)	−5.0 (−1.6)	2.5 (0.8)	−12.3 (−3.9)
1B	Actual Value	4.4 (1.4)	−12.0 (−3.8)	4.7 (1.5)	−7.9 (−2.5)	4.1 (1.3)	−19.6 (−6.2)
	Prescribed Design Value	2.8 (0.9)	−7.6 (−2.4)	3.2 (1.0)	−5.0 (−1.6)	2.5 (0.8)	−12.3 (−3.9)
3A	Actual Value	2.8 (0.9)	−7.3 (−2.3)	2.8 (0.9)	−4.7 (−1.5)	2.5 (0.8)	−12.0 (−3.8)
	Prescribed Design Value	2.8 (0.9)	−7.3 (−2.3)	2.8 (0.9)	−4.7 (−1.5)	2.5 (0.8)	−12.0 (−3.8)
3B	Actual Value	2.8 (0.9)	7.9 (−2.5)	3.2 (1.0)	−5.0 (−1.6)	2.8 (0.9)	−12.9 (−4.1)
	Prescribed Design Value	2.8 (0.9)	7.6 (−2.4)	3.2 (1.0)	−5.0 (−1.6)	2.5 (0.8)	12.3 (−3.9)

The data in Table 8 is plotted separately for each assembly, depicting the difference between the heat loss values inducted due to the presence of metal fastener. The six weather conditions depicted in Table 8 are represented as different bar charts numbered from 1 through 6.

Figures 6–9 shows the comparative study of heat transfer through the roofing assemblies under different design conditions. It also provides a graphical representation of the extra heat wastage in the practical/actual case compared with the ideal design case without considering any effect of metal fasteners. It is clearly visible that a large amount of heat losses incurred due to the phenomenon of Thermal Bridging due to metal fasteners and plates. Another notable synopsis is that the heat losses in case of Assemblies 3A and 3B are not only much lower than 1A and 1B but also the relative change in heat loss due to Thermal Bridging is minimal.

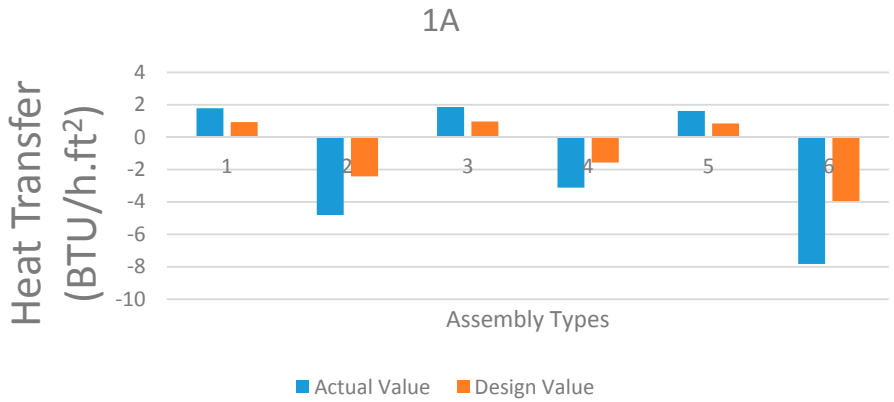


Figure 6. Heat losses in Assembly 1A (with series 1–6 representing the weather conditions as given in Table 8).

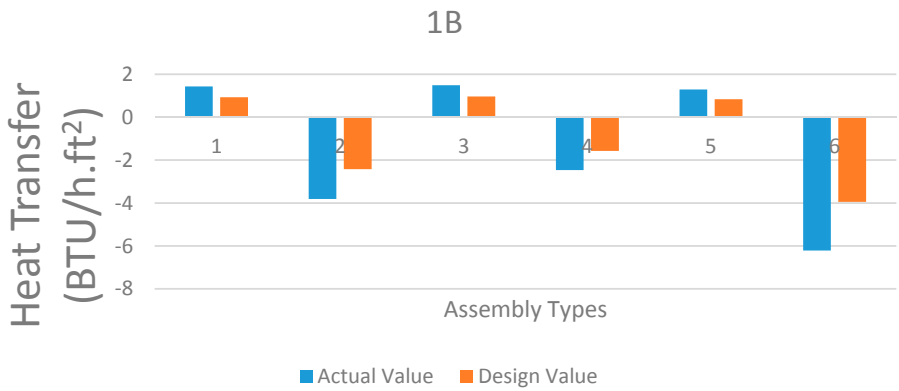


Figure 7. Heat losses in Assembly 1B (with series 1–6 representing the weather conditions as given in Table 8).

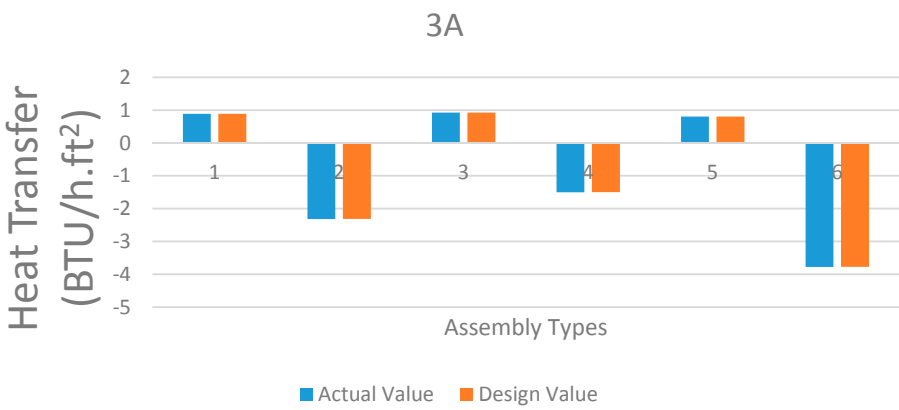


Figure 8. Heat losses in Assembly 3A (with series 1–6 representing the weather conditions as given in Table 8).

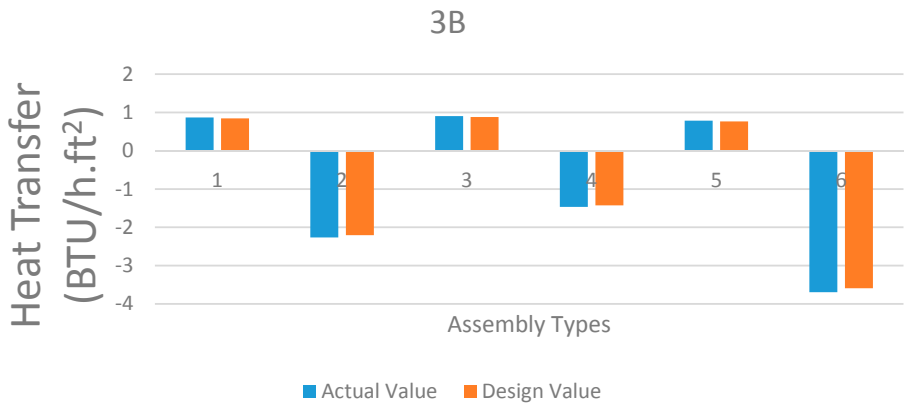


Figure 9. Heat losses in Assembly 3B (with series 1–6 representing the weather conditions as given in Table 8).

4.4. Comparison of 2D (THERM) and 3D (HEAT3) Analysis

However, the results when compared with those of Gulati et al., (2016) [4] and Suddappalli et al., (2016) [5], turned out to be substantially different. The net heat transfer in case of 3D analysis turned out to be comparatively less and the metal deck temperatures were moderate as compared to the 2D THERM analysis. The following Table 9 summarizes the comparison of metal deck temperatures in case of CZ2 (Orlando, FL) zone.

Table 9. Difference in metal deck temperatures between HEAT3 (3D) and THERM (2D) Analysis in case of Orlando (CZ2).

Area	Assembly Type	Orlando (CZ2)			
		Summer (34.4 °C/94 °F)		Winter (2.78 °C/37 °F)	
		Heat3 °C (°F)	Therm °C (°F)	Heat3 °C (°F)	Therm °C (°F)
Field 6400 sq. ft.	1A	299.2 (78.8)	302.0 (83.9)	289.8 (61.9)	283.3 (52.0)
	1B	299.2 (78.9)	302.0 (84.0)	289.4 (61.2)	283.3 (52.0)
	3A	295.9 (72.9)	296.8 (74.5)	294.7 (70.8)	293.6 (68.9)

The reason for this difference can be accredited to the limitations of two-dimensional analysis. In case of Gulati et al., (2016) and Suddappalli et al., (2016), the net energy loss is calculated using Convective Heat Transfer Equations based on the metal deck and fastener tip temperatures where else in this analysis the heat loss is obtained by direct simulations through the software. In order to understand the difference, another single fastener assembly was modeled in HEAT3 with minimizing the depth (dimension in y-direction) to a minimum possible value i.e., less than the depth of the fastener and thus eliminating one dimension for heat dissipation through the fastener. This was done to make the three-dimensional model as similar as possible to the two-dimensional model. The results of this simulation in three-dimensional came out to be almost similar and tending towards the two-dimensional analysis as the metal deck temperatures came to coincide. The results of this analysis proved the reason for difference in results to be the transition from two to three Dimensions. To understand the practical difference in the two cases, in case of two-dimensional, there is one less direction for dissipation of heat and thus more heat travels through the assembly via fasteners. In addition, in case of two-dimensional, there is no surface area for fasteners to dissipate heat in any direction other than upwards and downwards through the Assembly which results in much more heat flux flowing through the fastener. As opposed to this mechanism, the fasteners in case of three-dimensional model have surface area in each direction and thus heat flows in all three directions. This heat flow system is coincident with the actual heat flow mechanism through the Assembly.

5. Conclusions

This paper analyzed the impact of roofing fasteners on the commonly used roofing assemblies under three climate zones (both summer and winter conditions). In total, four roofing assemblies were analyzed and their heat losses have been quantified for CZ2 (Orlando, FL), CZ3 (Atlanta, GA) and CZ6 (St. Paul, MN) design conditions. For consistency purposes, R-20 insulation is used as per ASHRAE 90.1-2013 requirements in all the Roofing Assemblies and fastener pattern is standard to the industry practice. Besides, discussing the thermal Impacts of metal fasteners, this paper also presents a quantified analysis comparing the performance of the roofing assemblies discussed in the form of heat loss and percentage change in $R_{effective}$ due to fasteners under different design conditions. In order to make the work more meaningful for practical implementations, the percentage change in $R_{effective}$ is calculated for each assembly due to consideration of metal fasteners. A few major observations from this work are summarized below.

- The effect of Metal Fasteners is not negligible as considered by general standards. In fact, they are seen to cause as much as 48% change in the effective *R*-Value of the assembly, in case of 1A with very high density of metal fasteners. However, in other assemblies, as the fastener density decreases, the change in *R*-Value also decreases. Therefore, it is safe to say that the heat loss due to thermal bridging or the depreciation in roof performance is directly proportional to the fastener density, provided they are of same length.
- Of all the Assemblies analyzed, 3A and 3B proved to be most efficient with minimum amount of heat lost. In addition, the effect of metal fasteners is also seen to be almost negligible in these cases which may be attributed to the fact that the length of fasteners here is small and they do not pass through the entire thickness of the assembly as opposed to the cases of Assembly 1A and 1B.
- The winter performance of the same assembly depreciates under winter design conditions. The reason for this effect can be understood in two parts. Firstly, the temperature difference between inside and outside conditions is more in winters which results in higher rate of heat flow; Secondly, since the assemblies have a metal deck as the most interior layer, it acts as a highly conductive surface for the heat to enter the assembly, when inside conditions are hotter than the outside. This provides a head start for the heat travelling from inside to outside in such conditions.

The data and analysis provided in this paper will help the engineers to comprehend the effect of metal fasteners and decide the correct *R*-Value of roofing to be used in order to provide the desired performance. In addition, since this work also explained the reasoning behind the analyzed roofing performance, it can be used as reference to devise better roofing assemblies or optimize the use of other techniques other than mechanical fastening. Further research can be done including the relative humidity and moisture penetration in the analysis. Different structures such as parapets and piping can also be incorporated. Due to several other factors involved (as discussed above), this research however may not be taken as the sole basis of roof assembly design. Another phase of this research is the analysis of roofing in transient condition rather than steady state which could provide the real time data with temperature variations throughout the year, rather than just the design conditions.

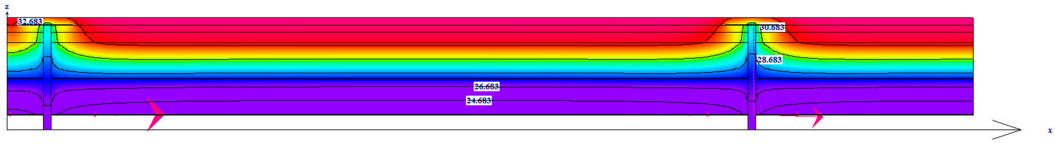
Author Contributions: Manan Singh, Rupesh Gulati and Ravi S. Srinivasan contributed to the technical aspects of the paper, including Data collection, Analysis and Observations. Mahabir Bhandari reviewed the work.

Conflicts of Interest: The authors declare no conflict of interest.

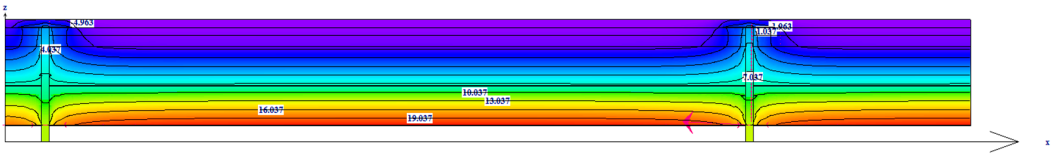
Appendix A

Isotherms in case of all the Assemblies analyzed for every Weather Condition.

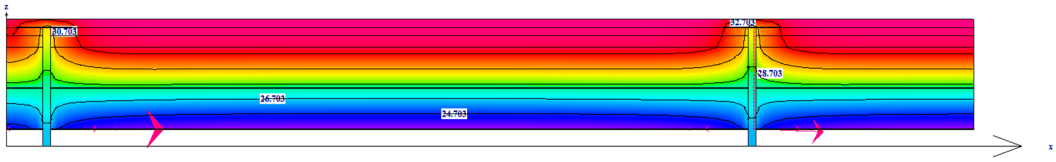
1A



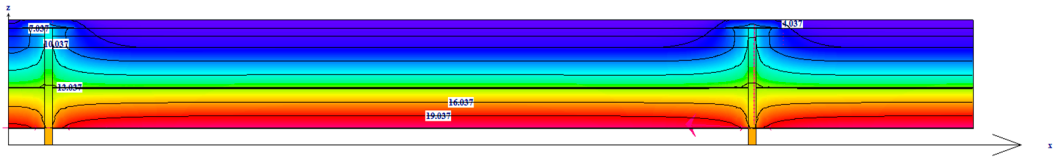
Atlanta Summer



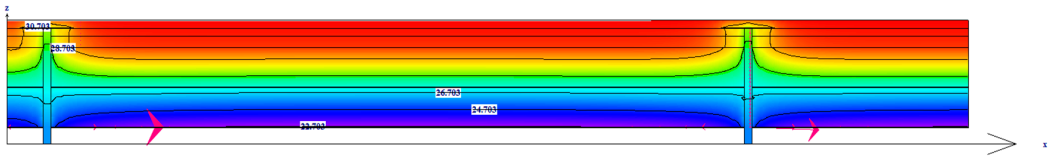
Atlanta Winter



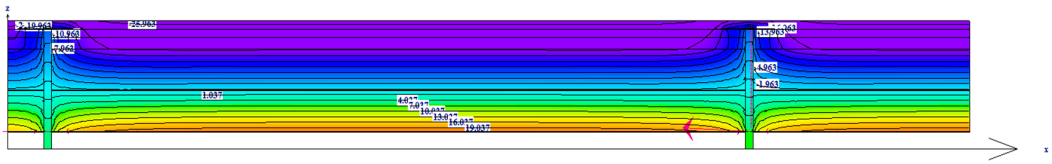
Orlando Summer



Orlando Winter

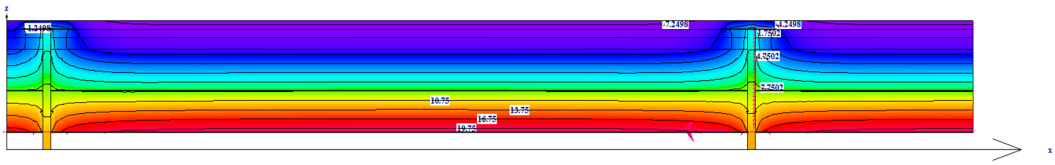


St. Paul Summer

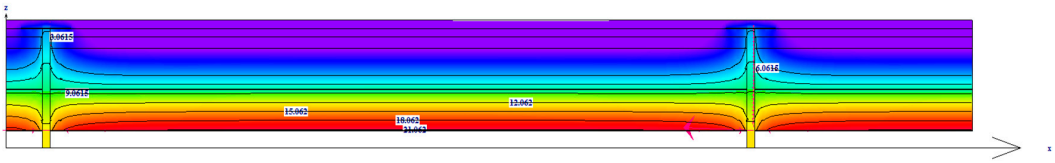


St Paul Winter

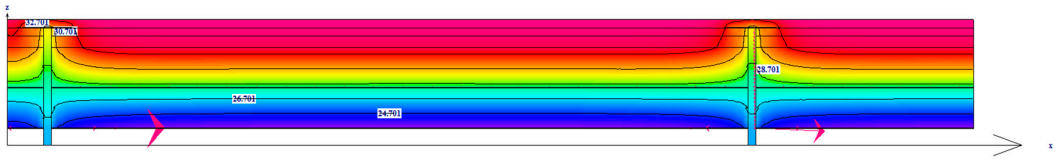
1B



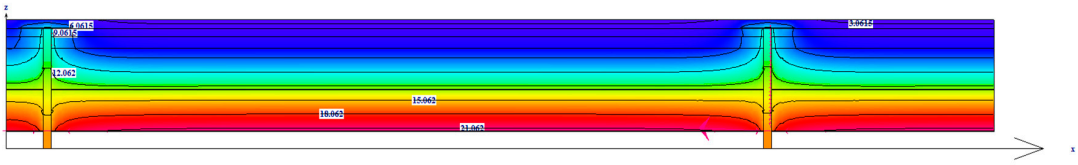
Atlanta Summer



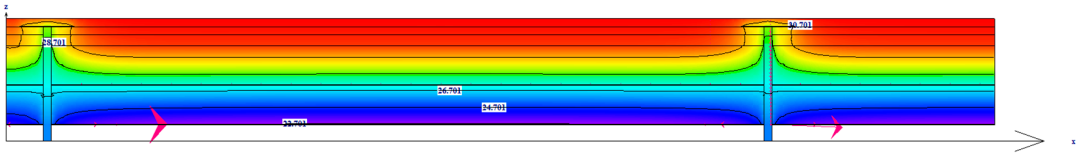
Atlanta Winter



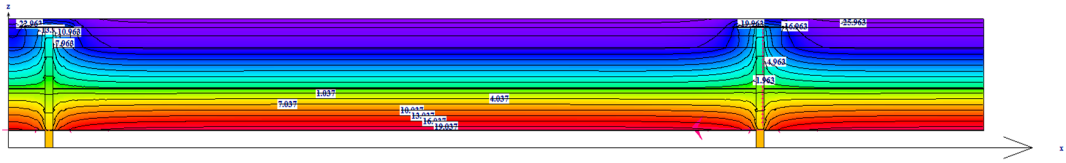
Orlando Summer



Orlando Winter

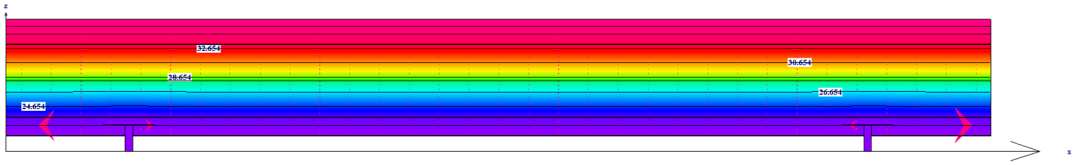


St. Paul Summer

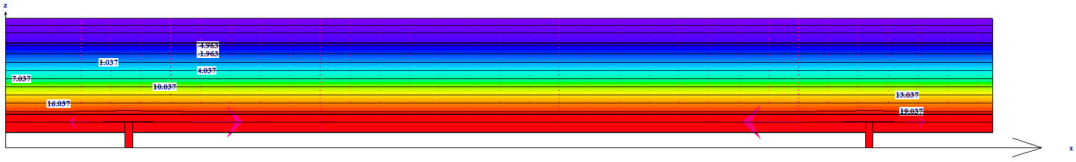


St. Paul Winter

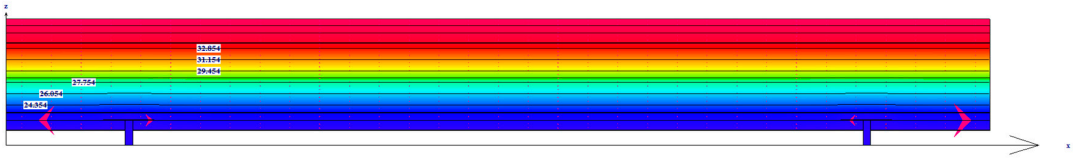
3A



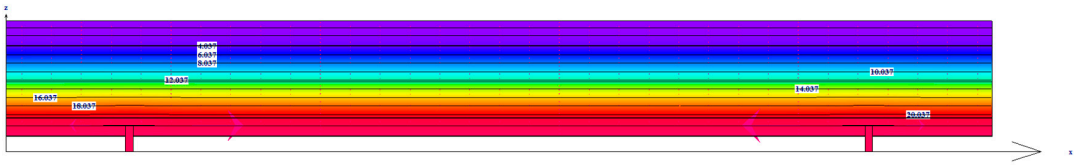
Atlanta Summer



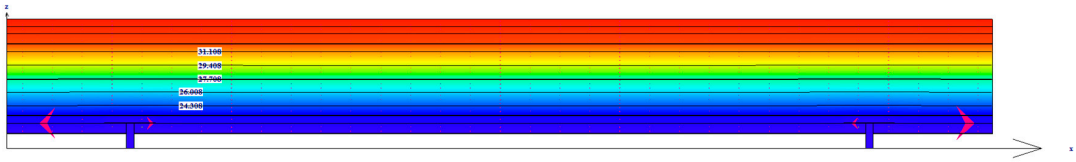
Atlanta Winter



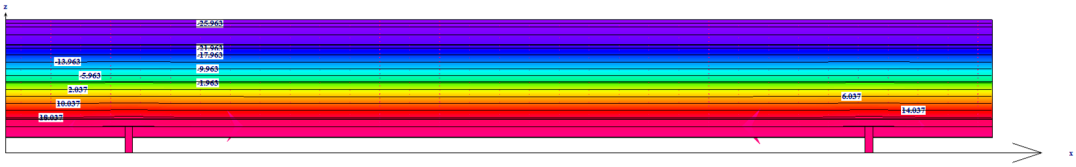
Orlando Summer



Orlando Winter

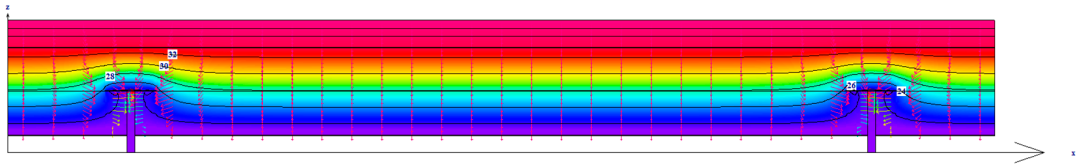


St. Paul Summer

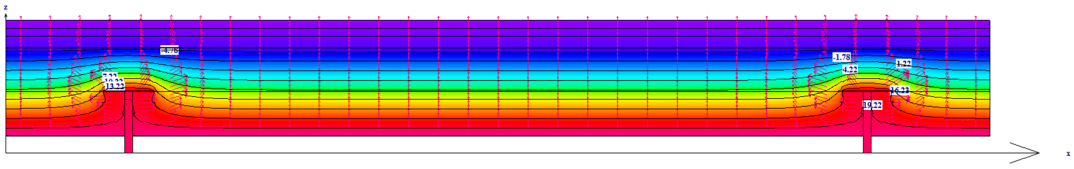


St. Paul Winter

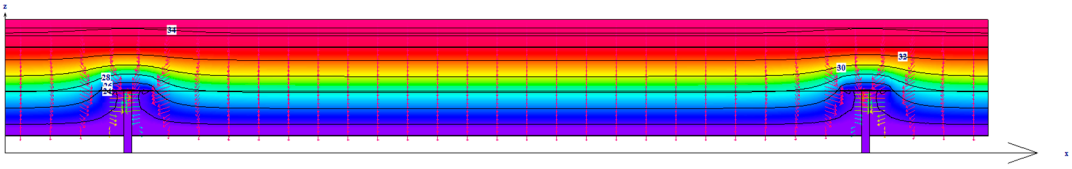
3B



Atlanta Summer



Atlanta Winter



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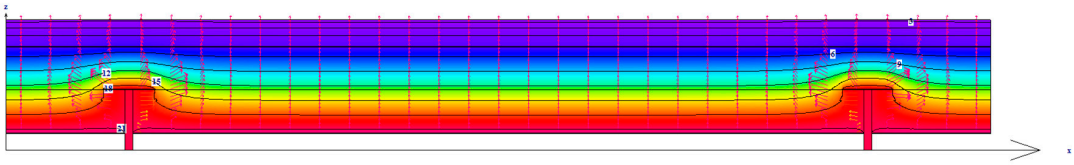

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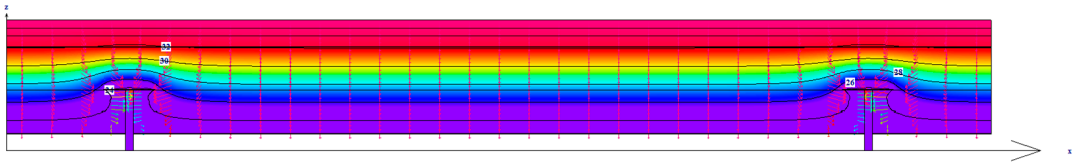

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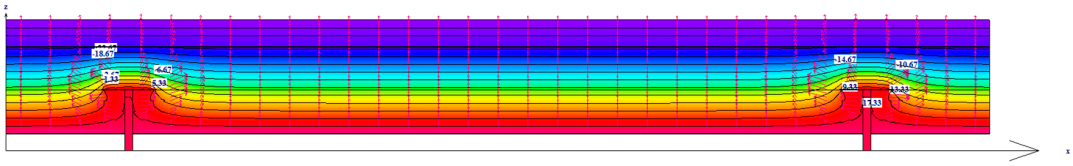

St. Paul Winter

Appendix B. Roof Assembly Description from Structural Deck above

Recover/Reroofing					**Reroofing**		
Roof Assembly		**Type 1A**	**Type 1B**	**Type 1C**	**Type 3A**	**Type 3B**	**Type 3C**
Reference		FM Data Sheet 1–29, 2.2.7.2, Manufacturer fastening pattern	FM Data Sheet 1–29, 2.2.7.2, Manufacturer fastening pattern	FM Data Sheet 1–29, 2.2.7.2, Manufacturer fastening pattern	FM Data Sheet 1–29, 2.2.1.5, Adhesive ribbon spacing per manufacturer	FM Data Sheet 1–29, 2.2.1.5, Adhesive ribbon spacing per manufacturer	FM Data Sheet 1–29, 2.2.1.5, Adhesive ribbon spacing per manufacturer
Thermal Barrier/Cover board	**Material**	None	None	None	Gypsum	None	None
	Attachment	None	None	None	Mechanical	None	None
Vapor/Air Barrier	**Material**	None	None	None	Modified Bitumen base ply	None	None
	Attachment	None	None	None	Torched	None	None
Insulation	**Material**	R20 Polyiso (single layer)	R20 Polyiso (single layer)	R20 Polyiso (single layer)	R20 Polyiso (single layer)	R20 total: R10 Polyiso (single layer) mechanically fastened, followed by R-10 Polyisocyaurate adhered	R20 total: R10 Polyiso (single layer) mechanically fastened, followed by R-10 Polyisocyaurate adhered
	Attachment	Mechanical	Mechanical	Mechanical	Adhered	First layer Polyisocyanurate Mechanically fastened, second layer Polyisocyanurate adhered	First layer Polyisocyanurate Mechanically fastened, second layer Polyisocyanurate adhered
Cover board	**Material**	Gypsum Roof Board	Gypsum Roof Board	Gypsum Roof Board	Gypsum Roof Board	Gypsum Roof Board	Gypsum Roof Board
	Attachment	Mechanical	Mechanical	Mechanical	Adhered	Adhered	Adhered
Roof Membrane	**Material**	Modified Bitumen (1)	Modified Bitumen (2)	Modified Bitumen (2)	Modified Bitumen	Modified Bitumen	Modified Bitumen, Cap ply meeting cool roof requirements for emissivity, reflectivity and solar roof index
	Attachment	Mechanical	Mechanical	Mechanical	Adhered	Adhered	Adhered

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