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DESIGN CHARTS FOR ESTIMATING OVERALL THERMAL RESISTANCE OF TYPICAL CONCRETE MASONRY CAVITY WALLS

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ABSTRACT

To reduce the energy consumption in masonry buildings and comply with newer, more stringent energy codes, one possibility is to increase the thermal resistance of masonry wall systems. However, this approach comes with several challenges. One of them is the inability of a quick estimate of the effective thermal resistance of masonry walls with sufficient precision due to the complexity of masonry construction. Currently, the options to deal with non-typical details are; using simplified assumptions that often lead to inaccurate results (e.g. area weighted method), or conducting expensive and time-consuming numerical modelling (e.g. linear transmittance method). This study focuses on concrete masonry cavity walls. The main objective of this paper is to provide -using numerical modelling- the overall R-values of common concrete masonry cavity wall assemblies in form of simple design charts. The numerical modelling results were validated with experimental results provided in the literature. The design charts combine the mechanical (the masonry compressive strength, (f_m')), thermal (overall R-value) and physical (density of blocks) properties of different cavity wall assemblies. These charts aim to guide the designers to reliably estimate and choose the appropriate structural and thermal properties of common concrete masonry walls. Many parameters are addressed by using numerical modellings such as the type and density of the concrete blocks, the insulation R-value, as well as, the ties and shelf angle's shape and material. The numerical models and design charts are also used to evaluate and compare the impact of different parameters on the overall thermal resistance of masonry walls.

KEYWORDS: *experiments, masonry cavity walls, numerical modelling, R-value charts, R-value estimation, thermal Resistance*

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INTRODUCTION

The thermal properties of the materials and thermal bridging are two of the main aspects that need further consideration when improving the thermal design. Thermal bridging in building envelopes occurs mostly in places where structural and insulating materials have different thermal conductivities. This phenomenon appears through the ties, hangers, shelf angles, and insulation fasteners, which penetrate the insulation layer of the building envelope. Significant thermal bridging also occurs at the structural floor or slabs and partition penetrations through the insulation plane [1, 2]. Due to the high demand for energy-efficient buildings in Canada, designers face a tradeoff between the structural and the thermal behaviour of the masonry walls when determining the material properties of the wall components. For instance; high concrete block density increases the block's compressive strength, however, reduces the thermal resistance of the blocks. Also, the choice of the ties and shelf angels' material and shape has a significant effect on the overall thermal and structural behaviour of masonry walls.

Many studies were performed to find optimum material properties and elements design to satisfy both, the structural and thermal requirements of masonry walls [1, 3]. The shape, size, material, and configuration of ties and shelf angles have been revolutionized to improve structural and thermal performance. Several tie shapes with different materials have been introduced to the market to minimize thermal bridging while meeting structural requirements [4]. Slotted ties can be fastened to the face shell of structural backing instead of being inserted in between blocks as traditional ties are typically used. Holes within the tie body are introduced to reduce the cross-sectional area, thus minimizing thermal conductance. Intermittent structural support, which offset shelf angles from backing systems were introduced to the market to reduce thermal bridging (e.g. knife plates and hollow structural section tubes) [5].

To comply with the continuously evolving energy and building code requirements, the masonry construction industries are looking for an effective approach for thermal resistance calculation. Therefore, there is a need to review and thereby improve the masonry walls' thermal resistance. Also, energy modelling requires an accurate estimation method for the wall's R-values. To serve the above-mentioned purposes this study investigated and compared a few of the common wall assemblies used in construction in Canada with different ties and shelf angles (shape and material properties), the density of the concrete blocks and insulation R-value. The overall R-values of the assemblies are estimated by using a three-dimensional simulation finite element analysis program (ANSYS). The numerical modelling results were validated with experimental results provided in the literature [6-8]. Then the results are presented in form of design charts that combine the mechanical, thermal and physical properties of different cavity wall assemblies. The charts will be used for comparison purposes. Also, these charts will be able to guide the designers to the required structural and thermal behaviour of common concrete masonry walls easily.

LITERATURE

One way to reduce energy consumption in the operation of masonry buildings is by increasing the thermal resistance of masonry wall systems. Modern concrete blocks and masonry veneers can be significant constituents in the transition to sustainable buildings. Masonry can be aesthetically pleasing, energy-efficient and durable [9, 10]. The inability to quickly and precisely estimate the effective thermal resistance of masonry components due to the complexity of masonry construction is a challenge. To have an accurate estimation of the overall thermal resistance of masonry concrete walls, many parameters should be considered [11]. There have been a few methods at estimating the R-value of a complete wall including all its components (e.g. air gaps, ties and shelf angles). Some of these methods are insufficient due to their limitations to specific cases and conditions (e.g. weighted area method [12, 13]). The rest of the methods depend mainly on computer simulations (e.g. linear and point transmittance [12, 13]). These methods are required to be modified and investigated further to provide a reliable estimation method of the effective R-values for different masonry walls which can represent any detail required without limitations on the conditions, configurations, or material properties.

With the rapid change and the higher standards of building envelope thermal requirements; masonry construction needs viable design improvements to meet the stringent building energy requirements [14, 15] This study aims to provide design charts that combine the concrete blocks' density, the masonry compressive strength, (f_m') and thermal resistance (overall walls' R-value) of different cavity wall assemblies. Providing easy charts to the designer to compute the R-values will help in having a reliable estimation of energy needs for the buildings and a guideline for improving the thermal envelope or calculating the heating and cooling equipment requirements.

FINITE ELEMENT SIMULATION

The finite element (FE) modelling is considered a reliable analysis method for the thermal behaviour of elements, as it shows advantages on both economical and practical sides [16]. Real tests obtained to monitor the thermal behaviour of elements are expensive as well as there is a technical difficulty in case it is required to investigate big sized elements as concrete walls and cavity walls, which usually required to be investigated in full size and real scale, and this will be difficult experimentally. Also, this type of experimental investigation "big sized elements" requires immense execution and preparation time. Finite element programs were introduced to the market to simulate the thermal behaviour of different elements.

Model Description

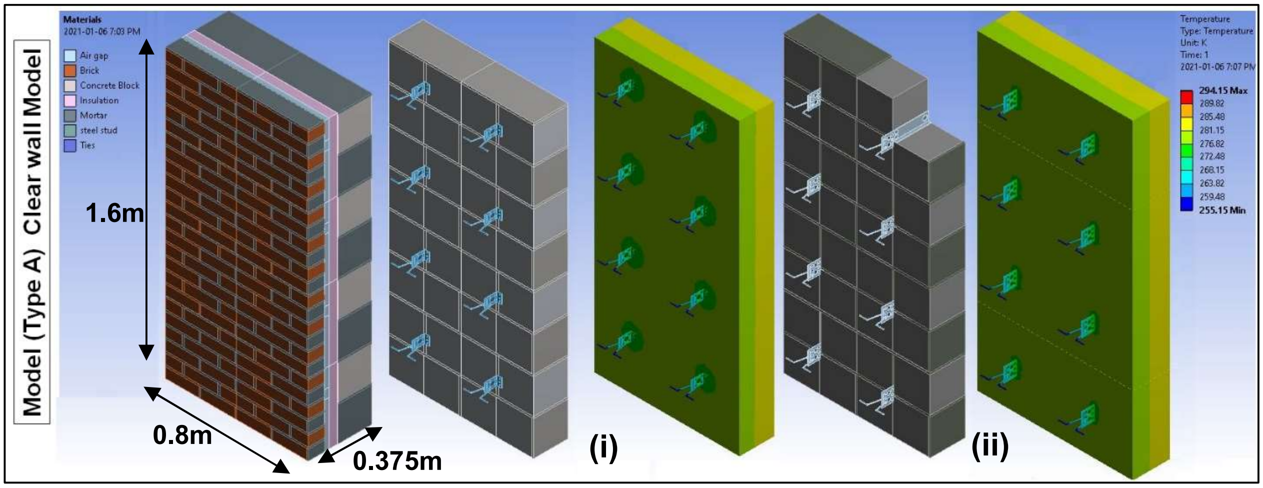
In this study, ANSYS Workbench was used to perform steady-state finite element thermal analysis simulations of typical brick veneer cavity wall assemblies. Simulations were addressed to calculate the overall R-value for different wall configurations as shown in Figure 1. There are some modelling assumptions considered in this study; the model was analyzed at a steady-state and air leakage was not considered. The models were evaluated at -18C° is the exterior temperature and 21 C° is the interior. All the material properties were considered from the ASHRAE Handbook

[17]. The air gap between the wall back up and the brick veneer thermal properties were obtained from the literature [8]. The element used to simulate the wall components in the ANSYS modelling is SOLID70 based on its properties which complies well with the assemblies required to be investigated. SOLID70 has a three-dimensional thermal conduction capability. The element has eight nodes with a single degree of freedom, temperature, at each node. The element can be applied to a three-dimensional, steady-state or transient thermal analysis. Meshing was done by using ANSYS's advanced sizing feature. A mesh was automatically generated that is relatively fine for each part in the model without setting a global size criterion. This is a significant feature as some wall components as the ties are relatively thin and need more elements and refined mesh, while the blocks, the brick veneer and the insulation boards used do not need the same size elements to accurately resolve heat flow through them. Finally, adiabatic boundaries were applied to the edge surfaces of the assemblies.

Parameters and Cases Studied

There are two schemes for the assemblies considered in this study as shown in Figure 1; Clear cavity wall (Type A), Intermediate floor intersection with directly attached large shelf angle and intermediate floor intersection with a bracket shelf angle (Type B).

Type A assemblies were addressed using four types of ties; solid block ties and slotted ties, fastened on the block's surface solid and slotted ties. While Type B assemblies were addressed using solid block ties only. Besides, two-shelf angles were considered; directly attached large shelf angle and bracket shelf angle as shown in Figure 2.



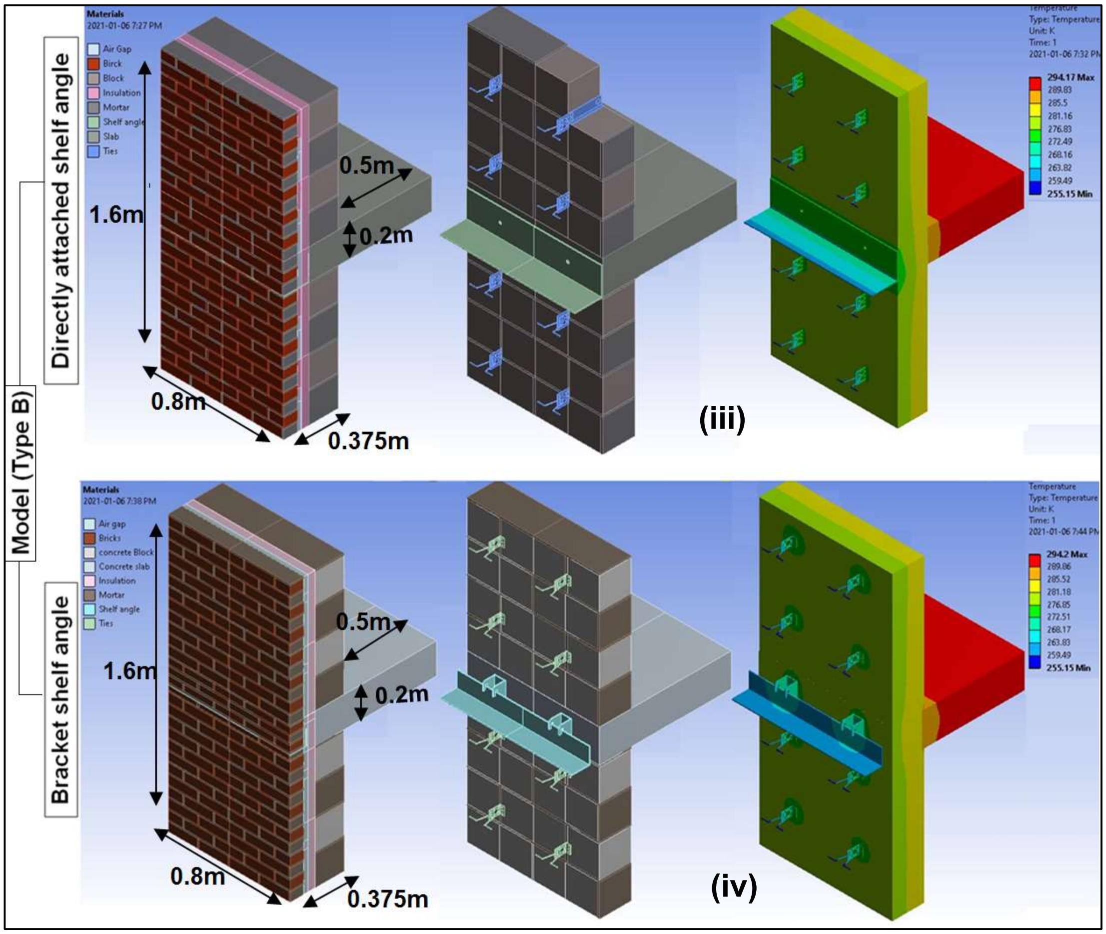


Figure 1: Type and dimensions of 3D finite element models studied and thermal distribution of concrete backup wall including ties and shelf angle; (i) Clear wall with fastened on the block's surface ties (ii) Clear wall with block ties (iii) Directly attached shelf angle with block tie (iv) Bracket shelf angle with block ties

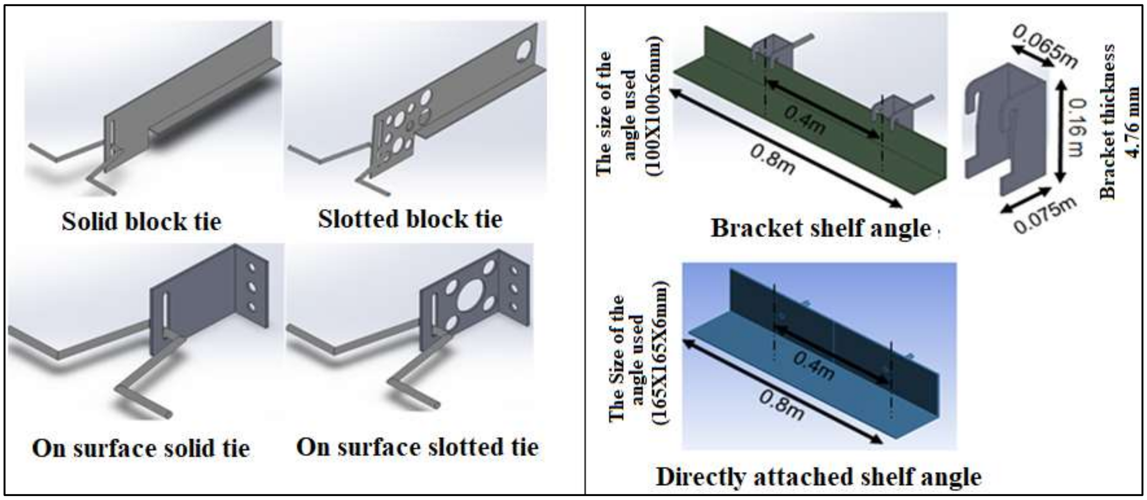


Figure 2: Types of ties and shelf angles studied

Table 1 presents the material properties which are fixed for all the studied schemes. The values were selected from the ASHRAE Handbook and literature [8, 17]. A total of 360 models were studied for scheme Type A and 120 models for schemes Type B to discuss different parameters and compare their effect on the thermal resistance on different wall assemblies. Table 2 presents the variables considered for each studied scheme.

Table 1: Common material thickness and properties used in the studied scheme

Component	Thickness (mm)	Conductivity (W/m K)
Standard concrete Block Size Block 390X190X190 mm (Size block no.20)	190	Varies
Cement Mortar	10	1.2
Masonry ties (400mm on center)	14 gauge	Varies
Insulation	50	Varies
Shelf angle	Varies	Varies
Concrete slab	200	1.8
Brick veneer	90	0.81
Air Gap	25	0.3571

Table 2: The variables considered in each studied scheme

Scheme	Variables considered
General variables considered for each assembly	tie type\ ties' material \ insulation R-value\ concrete block density\ concrete blocks' type\ shelf angle material\ shelf angle type
R-values in BTU/(ft^2·°F·hr) and in (m^2K/W) for insulation	R-15 (2.64)\R-20 (3.52)\ R-25(4.40)
Block Density (kg/m^3) (conductivity (k) W/m K)	Hollowed:2100(k=1.17)\1800(k=0.87)\1550(k=0.66)\1380 (k=0.6)/1150(k=0.35) Fullygrouted:2100(k=1.9)\1800(k=1.13)\1550(k=0.78)\1380(k=0.6)/1150(k=0.36)
Type of wall	Hollow block wall\ Fully grouted wall
Tie type	Block solid tie \Fastened on surface solid \Block slotted tie\ Fastened on surface slotted (Shown in Figure 2)
Ties materials (conductivity (k) W/m K)	Galvanized steel (k=50)\ Stainless steel (k=17)\ GFRP (k=0.2)
Shelf angle type	Directly attached shelf angle\ Bracket shelf angle (Shown in Figure 2)
Shelf angle materials (k=W/m K)	Galvanized steel(k=50) \ Stainless steel (k=17)

In addition to the thermal properties, these charts also consider the mechanical and physical properties of different wall assemblies. The charts combine between the overall R-value of the assembly, the blocks' density [17] and the masonry compressive strength (f_m'). The masonry compressive strength was determined by using the unit strength approach, where f_m' is evaluated based on the masonry block compressive strength and the mortar type. The f_m' values were obtained from the Canadian masonry standards (CSA S304) [18] which follow the unit strength approach in computing the masonry compressive strength. The density of the blocks was assumed to be 2100,1800,1550,1380 and 1150 kg/m^3 respectively and the compressive strength of units (f_b) was considered for each block type to be 35, 30, 20, 15, 10 MPa respectively and the mortar used is S-type. And then the specified compressive strength normal to the bed joint f_m' is 13.5, 10, 7.5 and 5 MPa for the grouted hollow units and 17.5, 13, 10, 6.5 MPa for the un-grouted hollow units (clauses 5.1.3.3, 5.1.3.5.2 and D 6.1 Tables 4 in the CSA S304 [18, 19]). The presence of the thermal properties and the structural properties in the same chart will help the designers to choose the appropriate material properties to provide the required structural and thermal masonry walls behaviour easily.

RESULTS AND DISCUSSION

Clear Wall Brick Veneer Assemblies (Type A)

The clear wall assembly's dimensions are shown in Figure 1. Steady-state finite element simulation models were performed to obtain the overall thermal resistance of different assemblies with variables presented in Table 2. The overall R-value, density and masonry compressive strength f_m' for both grouted and un-grouted clear wall assemblies with galvanized steel solid block tie is shown in Figure 3. The cases presented in Figure 3 were found to have the lowest thermal resistance values if compared to the other studied cases as stainless steel and GFRP ties. The solid block tie case was considered to be the reference case for Type A analysis. By comparing all assemblies' R-values results with the reference case, factors were obtained to represent the R-value of each case with respect to the reference case as shown in Table 3. The relationship between each studied case and the reference clear wall case (solid galvanized steel block tie case) is shown in Table 3.

Table 3: R-values for different clear wall schemes compared to the galvanized steel solid block tie (reference case)

Schemes / Tie material	To obtain the overall clear wall R-values of the below cases; Multiply R-values obtained from Figure 3 by the following factors			
	Block tie solid	**Block tie slotted**	**On surface tie Solid**	**On surface tie slotted**
Galvanized steel	1 (reference)	1.058	1.130	1.204
Stainless steel	1.158	1.210	1.235	1.313
GFRP*	1.40	1.40	1.44	1.44

* Alternative materials, such as fibre-reinforced polymers (FRP), even though they are much less conductive, have issues common to new technologies. In many cases, a code-based acceptance procedure is not available for these new materials, alternative tests must be demonstrated, and special approvals are required, which can cause reluctance when considering such materials.

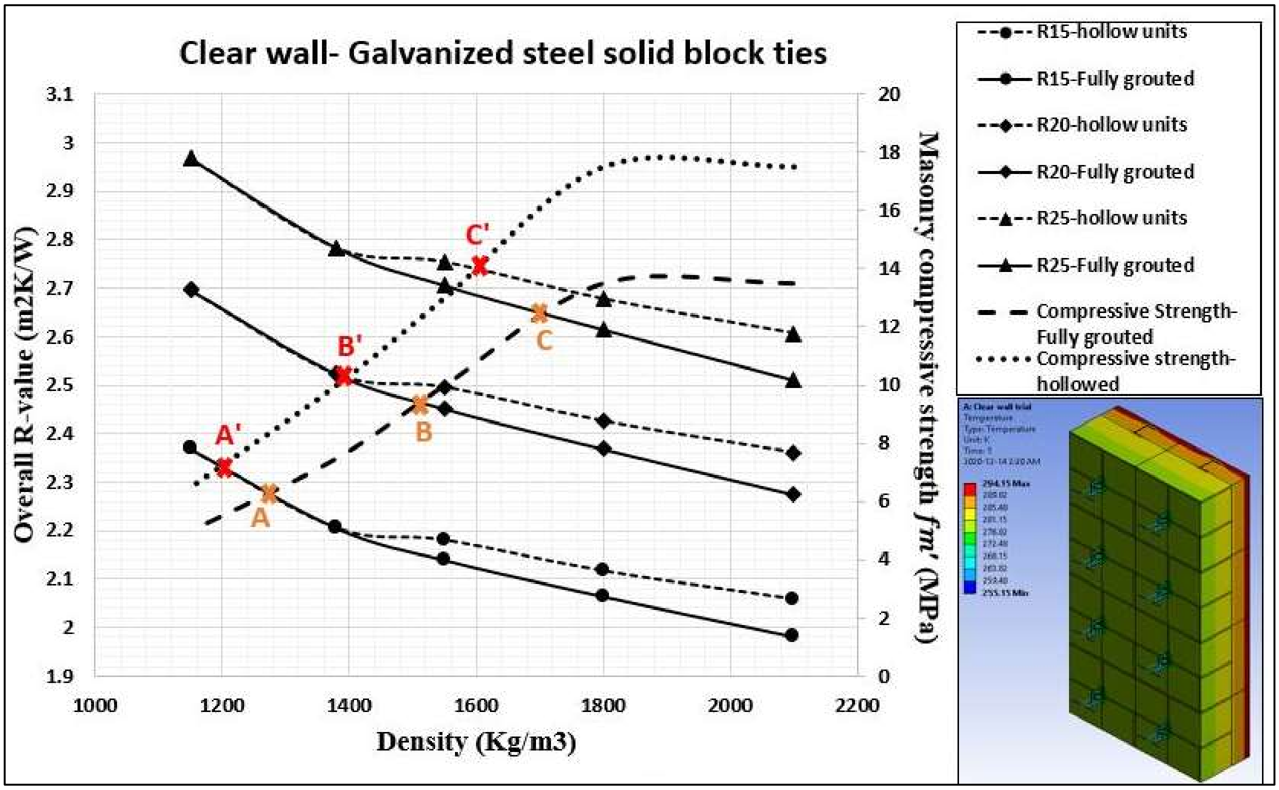


Figure 3: Overall R-value, density and f_m' for both grouted and un-grouted clear wall assemblies with different insulation and using galvanized steel solid block tie

Results show that there is no significant change in the thermal resistance of the hollowed and fully grouted blocks in case of blocks density lower than 1400 kg/m^3. Points A, B, and C are the intersection density values with respect to the insulation R-value used (R-15, R-20 and R-25) for the fully grouted clear walls with solid galvanized steel block tie type. While points A', B' and C' are the intersection density values for the hollowed clear walls with solid galvanized steel block tie type with respect to the insulation R-value used (R-15, R-20 and R-25). Any density value before these points has a priority for the thermal resistance over the masonry compressive strength. While any density value after these points has a priority for masonry compressive strength over the thermal resistance. The points in which there is no trading of any property over another property are the intersection points. By considering the intersection points in the design the concrete material properties are fully used structurally and thermally. It is possible to obtain these points for the other studied clear wall cases with different tie types and materials by constructing a graph for each case similar to Figure 3 using the factors presented in Table 3. Also, results show that; in the case of GFRP, the presence of slots and using different ties types didn't show any significant effect on the overall R-values due to their low conductivity.

Shelf Angle Assemblies (Type B)

Finite element models were performed to obtain the overall thermal resistance of intermediate floor intersection of different assemblies with the following parameters; insulation R-value; the blocks type and shelf angle type and material. Figure 4 shows the overall R-value, density and masonry compressive strength for both grouted and un-grouted directly attached galvanized steel shelf angle assemblies with galvanized steel solid block tie. The cases presented in Figure 4 were found to have the lowest thermal resistance values if compared to the other studied cases. Table 4 shows the relation between R-values for intermediate floor intersection assemblies with different shelf angle material and type (Note: all wall assemblies studied have solid galvanized block ties but different shelf angles).

Table 4: R-values for intermediate floor intersection assemblies with different shelf angle types and materials compared to the galvanized steel directly attached shelf angle (all assemblies have solid galvanized steel block ties)

Schemes / Material	To obtain the overall R-values of the below cases; Multiply R-values obtained from Figure 4 by the following factors	
	Directly attached large shelf angle	**Bracket shelf angle**
Galvanized steel	1 (reference)	1.06
Stainless steel	1.24	1.30

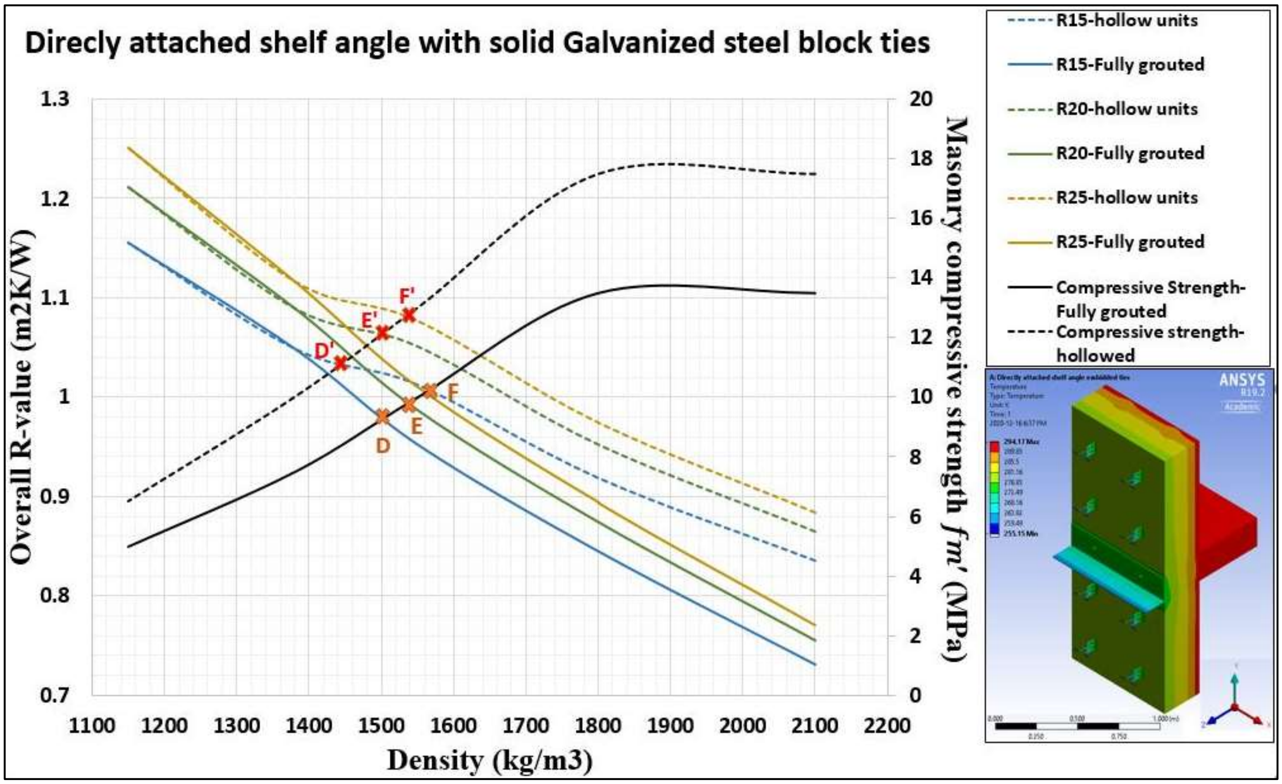


Figure 4: Overall R-value, block's density and f_m' for both grouted and un-grouted intermediate floor intersection with different insulation and galvanized steel solid block tie

Points D, E and F are the intersection density values for the fully grouted assemblies. While points D', E' and F' are the intersection values for the hollowed assemblies with respect to the insulation R-value used (R-15, R-20 and R-25). It is possible to obtain the intersection design points for the other shelf angle cases by constructing a graph for each case similar to Figure 4 using the factors presented in Table 4. Also, the overall R-values of different intermediate floor intersection assemblies and different tie types could be predicted by using both factors together presented in Tables 3 and 4.

CONCLUSION

The conclusion of this study is summarized as follows; for clear cavity walls, the lowest thermal resistance values were for the galvanized steel solid block ties (reference case). The reference case was compared to other cases using galvanized steel but different ties; slotted block tie, solid fastened on surface tie and slotted. Higher thermal resistance values were shown for these cases; 5.8%, 13% and 20% respectively. Stainless steel was also compared to the galvanized steel solid block ties case. Significant improvement in the overall R-values was observed. The R-value exceeds the reference case by 15.8%, 21%, 23% and 31% for block solid ties, block slotted ties, fastened on surface solid and slotted ties respectively. Glass fibre reinforced polymers (GFRP) material was also investigated in clear wall assemblies and showed a remarkable increase in the overall R-value when compared to the reference case. The R-values increased by 40% in the case of block ties and 44% in the case of fastened on surface ties. The presence of slots didn't show any significant effect on the overall R-values in the case of GFRP ties due to their low conductivity. Two types of shelf angles were studied (directly attached large angle and bracket) and two shelf angles' materials were considered; galvanized steel and stainless steel. Results showed that the galvanized steel for the directly attached shelf angle with solid galvanized steel block ties has the lowest overall R-value. The stainless steel directly attached large shelf angle has higher overall R-values by 24%, the bracket galvanizes and stainless steel shelf angles have higher overall R-values by 6% and 30% respectively. Results showed that the shelf angle and ties materials and shape have a significant effect on the overall walls' R-value and can improve the overall thermal resistance by up to 44% in some cases. This study provides a design aid to combine and predict the mechanical, physical and thermal properties of common masonry wall assemblies.

FUTURE RECOMMENDATIONS

Many parameters are affecting the overall masonry wall's R-value and not considered in this study (e.g. air gap ventilation effect, the materials ageing effect, loading effect and the temperature dependency effect on the material properties). Relations between different parameters and the R-value are required to be addressed further. Accurate and quick approaches are required to estimate the overall walls' R-values without experimental investigations or computer simulations.

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