THREE-DIMENSIONAL HEAT TRANSFER EFFECTS IN BUILDING COMPONENTS

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Three-Dimensional Heat Transfer Effects in Building Components

Summary

The thermal performance of building envelope components, such as windows, doors and walls, are regularly being evaluated with computer simulation methods such as VISION and FRAME, particularly for building code requirements. The former performs a one-dimensional analysis on centre-of-glass, the latter two-dimensional analysis of frame and wall sections.

This report investigates three-dimensional effects at corners and where significant thermal bridging is suspected to occur, in order to assess limitations and potentially improve conventional two-dimensional modelling. Ten cases are studied with three modelling techniques.

For most cases good agreement is obtained between two- and three-dimensional modelling and with physical tests. However conductive components that span materials, such as steel bolts in curtain walls, can have a substantial impact on heat transfer. For these cases, area of influence is the best two-dimensional modelling method.

Effets en trois dimensions des transferts de chaleur dans les éléments de construction

Résumé

Le rendement thermique des divers éléments de l'enveloppe d'un bâtiment, comme les fenêtres, les portes et les murs, fait l'objet d'évaluations régulières à l'aide de méthodes de simulation informatique, par exemple VISION et FRAME, en ayant particulièrement en vue le respect des exigences propres au Code du bâtiment. Le logiciel VISION permet d'effectuer une analyse à une dimension de la zone située au centre d'une vitre quelconque, alors que le FRAME, lui, permet une analyse à deux dimensions de certaines parties des cadres et des murs.

Le présent rapport explique l'investigation menée au sujet des effets à trois dimensions que l'on peut constater dans les recoins et les endroits susceptibles de subir d'importants ponts thermiques. Cette investigation vise à évaluer les limites et à améliorer, si possible, la modélisation habituelle à deux dimensions. On a donc recours à trois techniques de modélisation pour étudier dix cas.

Dans la majorité des cas, il y a harmonisation entre les tests à deux et à trois dimensions, et les tests mécaniques. Toutefois, les corps conducteurs qui séparent les matériaux, tels que les boulons d'acier dans les murs rideaux, peuvent considérablement influer sur les transferts de chaleur. Lorsque cela se produit, il vaut mieux se tourner vers la méthode de modélisation à deux dimensions.

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1.0 INTRODUCTION

Computer simulation is being widely used to evaluate the thermal performance of building components including windows, walls, and doors. The CSA A440.2 and A453 standards require that the U-value of windows and doors be determined with the FRAME and VISION computer programs. These programs are also referenced in the 1995 National Energy Code as a suitable means for evaluating the performance of opaque building assemblies.

The VISION program performs a one-dimensional analysis of the glazing system and FRAME performs a two-dimensional analysis of the edge-glass and opaque regions of windows, walls and doors. The total U-value is determined by area-weighting the VISION and FRAME results with either a spreadsheet or the FRAMEplus program. Thus, the total or three-dimensional heat flow is approximated as a series of one- and two-dimensional cases.

For most building components this is a reasonable assumption. There are, however, some cases where 3-D effects may be significant and must be accounted for in order to obtain an accurate value for the total product U-value. Examples of 3-D effects include corners in windows and walls, screws in steel-framed walls, bolts in curtain wall systems, and cross-strapping in framed wall systems.

One solution would be to require that all 3-D effects be analysed with a 3-D heat transfer program. This presents two problems. First, 3-D programs are much more difficult and time consuming to use than 2-D programs. In some cases it may be cheaper to test the building component rather than having to perform a 3-D analysis. Second, some 3-D effects may be small and can be ignored, thereby saving time and money.

This report presents the results of a study into the 3-D effects in building components. The purpose of the study is two-fold:

- to assess the magnitude of common 3-D effects and thereby determining whether they can be ignored,
- to develop techniques that can be used with 2-D computer programs to approximate the 3-D effect.

It is hoped that this work can improve the accuracy of 2-D computer simulation without increasing the level of effort or cost. Furthermore, this work will provide guidance on how the CSA standards can be expanded to include building systems that were specifically excluded because of these problems, for example curtain walls.

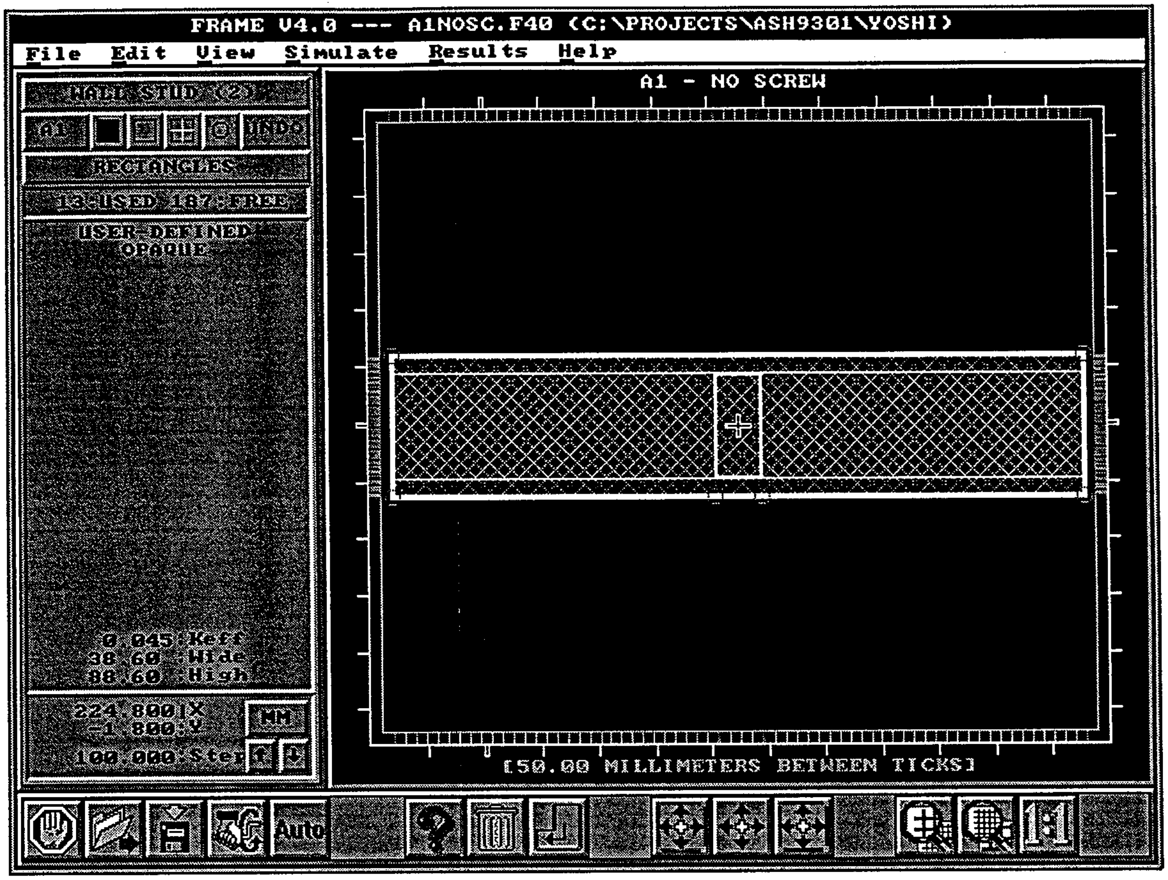
2.0 METHODOLOGY

The objective of this study is to assess the magnitude of 3-D effects and to develop techniques for 2-D programs to approximate the 3-D effects. The impact of three-dimensional effects is studied using a 3-D program, HEAT3 [Blomberg, 1995]. HEAT3 is a finite-difference computer program developed by the Lund Institute of Technology in Sweden. To run HEAT3, the user creates a simple ASCII text file which defines the characteristics of the 3-D model. The first part of the file defines the segments which determine the dimensions of the structure. Next, rectangular boxes are defined by the segments and conductivity values are assigned to those boxes. The final part of the datafile contains, temperatures and surface resistances at the boundaries. The models are simulated by feeding data files and parameters to HEAT3 which is a command line executable program. HEAT3 outputs the total heat loss (Q in Watts) and the heat loss coefficient (U-value in W/m2K). To ensure that the program was being used correctly, HEAT3 results were compared with guarded hot box tests for two steel frame wall assemblies.

The FRAME program was selected as the 2-D program because it is widely used and referenced in the CSA window and door standards [Enermodal, 1995]. FRAME4 has a CAD interface (Figure 2.1) which allows visual input of building components. A cross-section of the structure is drawn and parameters including material conductivity and boundary condition are defined. Because the program is two-dimensional, material dimensions and properties are assumed constant in the direction not shown (i.e., into the page or screen). The results are given in heat loss and heat loss coefficient per unit length.

Three techniques are examined that would allow FRAME to model 3-D effects. The results from these three techniques are compared with the results from HEAT3 to determine which technique is the most accurate. Three sets of building systems covering 10 cases were studied:

- 6 steel-stud wall systems with variations in stud depth and exterior insulated sheathing with the 3-D effect of steel screws,
- 2 curtain wall systems with the 3-D effect of bolts spanning the thermal break, and
- 2 steel-stud wall systems with the 3-D effect of steel cross-strapping.



0.045 Keff
38.60 Wide
88.60 High
224.800 X
-1.800 Y
100.000 Step

Figure 2.1 Sample Screen of FRAME4

Three modelling techniques are examined: parallel path, effective conductivity and area of influence. These techniques are described below.

The Parallel Path Method

One of the most common ways of analysing the performance of non-homogeneous assemblies is the parallel path approach. The U-value through each different path is calculated and area-weighted. How this approach is applied to wall systems is documented in Chapter 22 of the ASHRAE Handbook of Fundamentals and the National Energy Code.

In this case 2-D simulation is being used to get an accurate assessment of heat transfer in two directions and the parallel path approach is used to account for the third dimension. Thus, the FRAME program would be run twice: with and without the 3-D effect (e.g., a screw). The linear U-values output by FRAME would be weighted by the length of the thermal bridge and the length of the remainder of the assembly. The parallel path equation is defined as follows:

$$U_{parallel\ path} = (UL_{screw} \times H_{screw} + UL_{no\ screw} \times (H_{assembly} - H_{screw})) / H_{assembly}$$

where

UL_{screw}	is the linear heat loss coefficient in W/mK of the case with the screw
$UL_{o\ screw}$	is the linear heat loss coefficient in W/mK of the case without the screw
H_{screw}	is the height of the screw in metres
$H_{assembly}$	is the height of the entire assembly in metres

Heat transfer theory says that the parallel path method should underestimate the actual 3-D effect because the method restricts the heat to flow in parallel paths. Thus, the effect is limited to only the depth of the thermal bridge.

The Effective Conductivity Method

The effective conductivity method, or sometimes referred to as the isothermal planes method, is the companion method to the parallel path method. In this technique the resistance of each layer in the building assembly is added together to get the total R-value of the assembly. If a layer is made up of more than material, the conductances are area weighted to get an average conductance. This method is very easy to apply in the FRAME program. An effective conductivity is used for the materials that are not constant in the third dimension. The calculation of the effective conductivity is as follows:

$$K_{effective} = (K_{screw} \times H_{screw} + K_{insulation} \times (H_{assembly} - H_{screw})) / H_{assembly}$$

where

K_{screw}	is the conductivity of the screw in W/m·°C
$K_{insulation}$	is the conductivity of the insulation in W/m·°C
H_{screw}	is the height of the screw
$H_{assembly}$	is the height of the entire assembly.

Heat transfer theory says that this method should overestimate the 3-D effect because the heat is permitted to travel laterally through the whole layer. This method has the advantage that only one 2-D model needs to be generated to account for the 3-D effect.

The Area of Influence Method

A third method, referred to as "the area of influence" is a compromise between the parallel path method and the effective conductivity method. The area of influence method estimates the depth that the 3-D effect acts over, somewhere between the parallel path assumption of only the depth of the thermal bridge and the effective conductivity assumption of the full depth. This method is documented in the simulation workbook entitled 'Procedures for Modelling the Energy Performance of Building Components: Walls and Doors' [Enermodal, 1996]. The area of influence is determined by viewing a heat flow plot of the assembly and noting the maximum distance that the heat flow lines that pass through the 3-D effect spread out in the other materials. Figure 2.2 shows an example. The U-values with and without the effect are then weighted according to this distance. Mathematically, the equation is as follows:

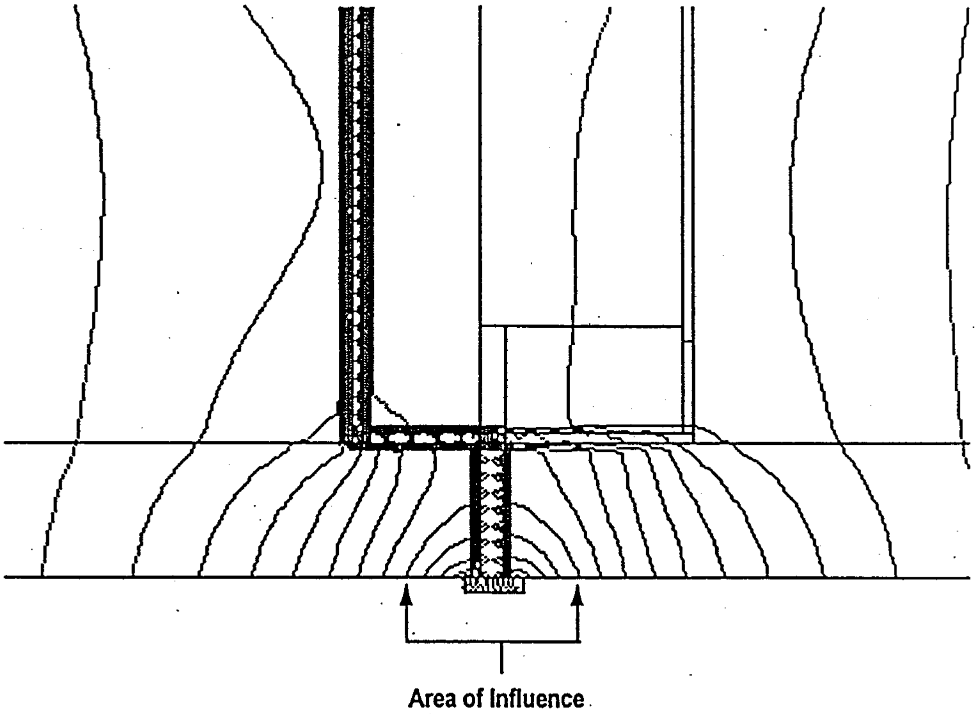
$$U_{total} = (UL_1 \times H_{influence} + UL_2 \times (H_{assembly} - H_{influence})) / H_{assembly}$$

where

UL_1	is the linear heat loss coefficient with the 3-D effect
UL_2	is the linear heat loss coefficient without the 3-D effect
$H_{influence}$	is the distance the 3-D effect operates over (as determined from simulation, for circular effects (e.g., screws) the distance should be multiplied by 3.14/4

Theoretically, the area of influence should be determined by performing a 2-D simulation showing the third dimension (i.e., into the page or screen). This means that 3 FRAME simulations would be required to assess the magnitude of the 3-D effect. If however, the 3-D effect is a point effect (e.g., screws and bolts) in a relative homogenous material, then the depth of the 3-D effect can be assumed to be the same as the width of the 3-D effect. This would mean that only two FRAME runs are required: with and without the 3-D effect – the same as with the parallel path method. For linear 3-D effects, such as cross-strapping, the requirement for 3 FRAME simulations probably makes this method too time consuming.

Figure 2.2: Definition of Area of Influence



3.0 VALIDATION OF PROGRAMS

3.1 Comparison of HEAT3 and FRAME4 for 2-D Cases

It is important to demonstrate that the HEAT3 and FRAME4 programs yield the same results for 2-D cases before proceeding with the simulation of complex 3-D assemblies. If the two programs give the same results for the 2-D case but diverge for the 3-D case, then the difference must be due to inaccuracies in using a 2-D program to model a 3-D case.

A series of six steel-stud wall cross-sections with no screws were modelled for this comparison. The wall sections are based on six wall systems that were extensively modelled and tested in the recently completed ASHRAE Research Project 785-TRP [Enermodal, 1996b]. The A series walls are constructed with 41mm x 91mm steel studs with varying amounts of insulated sheathing while the B series walls are constructed with 41mm x 151mm steel studs with varying amounts of insulated sheathing. A complete description of the wall systems is given in Table 3.1

In HEAT3, an entire 600 mm x 600 mm wall section with steel stud is modelled, whereas in FRAME4 a horizontal cross-section of the same wall is analysed and the result multiplied by the 600 mm depth. In other words, the HEAT3 model is the extruded case of the cross-section modelled in FRAME4. In both cases, the simulation programs have identical dimensions, material properties and boundary conditions for each model.

Table 3.1 Detail of A and B Series Walls, Layer by Layer

Wall	A1	A2	A3	B1	B2	B3
Interior Gypsum Board (W/m·K)	0.190			0.190		
Thickness (mm)	16.3			16.3		
Insulation (W/m·K)	0.0446			0.0446		
Thickness (mm)	91.0			151.0		
Steel Stud (W/m·K)	68.5			68.5		
Dimensions	41mm x 91mm			41mm x 151mm		
Exterior Gypsum Board (W/m·K)	0.190			0.190		
Thickness (mm)	16.3			16.3		
Expanded Polystyrene (W/m·K)	---	0.0356	0.0388	---	0.0356	0.0388
Thickness (mm)	---	23.9	36.8	---	23.9	36.8

Notes :

1. All walls have an inside temperature and heat transfer coefficient of 20° and 8.3 $W/m^2 \cdot K$, respectively.
2. All walls have an outside temperature and heat transfer coefficient of -18° and 30.0 $W/m^2 \cdot K$, respectively.
3. Steel studs have a thickness of 1.2mm.

Table 3.2 presents the results from the HEAT3 and FRAME4 modelling for the six wall assemblies. There is very good agreement between the programs for these 2-D cases. The FRAME4 results are within +/-1.20% of the HEAT3 simulation results. This small difference is believed to be due to differences in solution techniques, finite-difference meshing and convergence criteria.

Table 3.2 : Heat Flow Results of Steel Stud Walls with No Screws

Wall	HEAT3	FRAME4	Difference	% Difference
A1	9.309 W	9.343 W	-0.034 W	-0.37%
A2	6.242 W	6.185 W	0.057 W	0.93%
A3	5.492 W	5.447 W	0.045 W	0.84%
B1	7.254 W	7.271 W	-0.017 W	-0.23%
B2	5.090 W	5.030 W	0.060 W	1.20%
B3	4.584 W	4.534 W	0.050 W	1.11%

3.2 Comparison to Physical Tests

To test the accuracy and the implementation of the HEAT3 and FRAME4 programs, their results were compared to the physical test results for two 2.4 m X 2.4 m wall specimens: the complete assembly of the A1 and A2 wall systems. In HEAT3, it is time-consuming to simulate an entire wall, thus the wall is broken down into sections. One is a corner section of the wall which is 0.3 m x 1.2 m and the other is a 0.6 m X 1.2 m middle section. Hence, the wall system consists of four corner sections and six 'T' sections which compose the 2.4 m x 2.4 m wall. The results from the two models are area weighted to yield a total value for the system.

In FRAME4, two models are necessary: a cross-section through the steel stud (similar to the models used in Section 3.1) and a cross-section at edge of the wall (i.e., head and sill plates). The FRAMEplus program area weights the two results to arrive at total wall heat flow.

The results are presented in Table 3.3. Results of the entire wall sections as modelled by FRAME4 and FRAMEplus agree within one percent of the results simulated by HEAT3. The effect of screws was not included in the simulations. The good agreement between the two programs shows that the area-weighting procedure in FRAMEplus is a reasonable approximation to the 3-D effects in the corners. The HEAT3 results were within 3 % of the physical test result -- within the level of uncertainty of the test.

Table 3.3 : Heat Flow Results of Entire Wall without Screws

Wall	HEAT3	FRAME4	Percent Difference
A1	106.74 W	107.79 W	0.99%
A2	65.69 W	66.15 W	0.30%

4.0 RESULTS OF 3-D STUDY

4.1 Effect of Steel Screws in Steel Studs

Steel screws are typically used to attach drywall on the inside and insulated sheathing on the outside to steel studs. The steel screws are a thermal bridge increasing heat transfer through the steel stud. To examine this effect, the six steel-stud wall assemblies described in Section 3.1 were modelled with the two programs. Two cases were modelled for each wall system: with and without the screws. The steel studs are on 600 mm centres and the screws are located every 300 mm along the studs. As in the previous section, a 600 mm x 600 mm wall section is modelled.

For HEAT3, 3-D models for both the wall with screws and without screws are produced. The increase in heat transfer due to the screws is determined by subtracting the heat flow of the case without screws from the heat flow of the case with screws. For FRAME4, 2-D models were prepared to compute the 3-D effect using the procedures presented in Section 2.

The results of the analysis are presented in Table 4.1. The HEAT3 results suggest that there is little difference of between the cases with the screw and without the screw in the steel stud wall. The screws increase wall heat transfer by between 0.2 and 0.6 %. As predicted, the parallel path and effective conductivity methods provide the lower and upper bounds of the actual answer as simulated by HEAT3. The spread between the two methods is quite large. The parallel path method under estimates the screw effect by a factor of three; whereas the effective conductivity method gives values an order of magnitude too high (between 3.6 and 7.7 %). The area of influence method gives a result which is much closer to the HEAT3 result. As a percentage difference, the effect of the screw as predicted by the area of influence method is still significantly different from the HEAT3 result. In terms of total wall heat transfer, however, the difference between the 3-D and 2-D results is small.

Table 4.1 : Increase in Wall Section Heat Flow Due to Screws (in Watts)

WALL	HEAT3			FRAME4		
	Total - With Screw	Total - No Screw	Difference Due to Screw	Parallel Path	Area of Influence	Effective Conductivity
A1	9.359	9.343	0.016	0.006	0.039	0.335
A2	6.209	6.185	0.024	0.008	0.038	0.408
A3	5.479	5.447	0.032	0.010	0.048	0.421
B1	7.284	7.271	0.013	0.005	0.022	0.280
B2	5.051	5.030	0.021	0.007	0.033	0.390
B3	4.562	4.534	0.028	0.008	0.037	0.372

4.2 Steel Stud Wall with Steel Cross-Strapping

In this case the wall construction consists of vertical 41mm x 91mm steel studs and horizontal 25 mm x 25 mm steel stud which make contact with each other every 600 mm. The assembly contains 116.4mm of insulation and 16.3mm of gypsum board on the interior and exterior surfaces. Two cases were examined for this type of construction: no exterior sheathing (case A) and a 23.9mm layer of EPS on the exterior (case B).

Both the A and B cases were modelled in HEAT3 to obtain the heat loss for the true 3-D effect of the steel cross-strapping. Next, the assemblies were modelled in FRAME4. It is difficult to apply the area of influence and parallel path methods to this assembly because of the complex shape of the cross-strapping studs. Thus, only the effective conductivity method was used. The layer with the smaller stud or the horizontal component is modelled separately to yield an effective conductivity value for that layer. The procedure used is similar to that used to determine effective conductivities for edge spacers and is documented in the simulation workbooks described earlier. The conductivity value for that layer is used for the model of the cross-strapping/insulation layer.

The results of the analysis is given in Table 4.2. The two sets of simulations give total wall heat flows that are within 1.25%. As expected the results from FRAME4 using the effective conductivity are higher than the HEAT3 results.

Table 4.2 : Heat Flow Results for Steel Cross-Strapping

Wall	HEAT3	FRAME4	Percent Difference
A1	7.041 W	7.120 W	1.12%
A2	4.967 W	5.029 W	1.25%

4.3 Curtain Wall with Bolts

In curtain wall construction, the glazing support system is site-assembled. Bolts connect the exterior framing system (glazing caps) to the interior framing system. In many cases these bolts bridge the thermal break reducing its effectiveness. The bolts can be mild steel or stainless steel. Two curtain wall systems (with a thermal break and without a thermal break) were modelled with HEAT3 and FRAME4 using all three techniques for accounting for the 3-D effects. A cross-section of the model (with thermal break) in FRAME4 is shown below in Figure 4.1. The bolts are made of steel (conductivity of 68 W/mK) and are spaced 300 mm on centre.

Figure 4.1 : Curtain Wall Cross-section Modelled in FRAME4

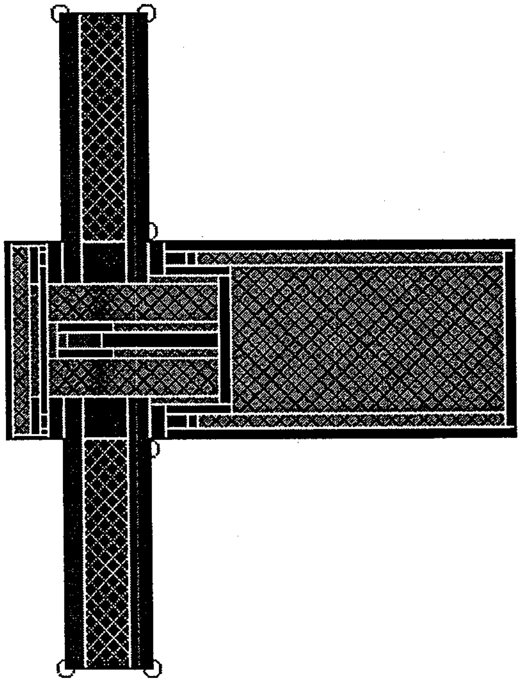


Table 4.3 presents the results of the analysis. According to the HEAT3 program, the addition of bolts has no effect on the heat transfer through the assembly. All of the 3-D techniques used with FRAME4 show no effect. The situation is quite different for the thermally broken case. The addition of the bolts increases the heat transfer through this section of the curtain wall by 8%. The section analysed included 63.5 mm of glazing on each side of the curtain wall framing. If the curtain wall framing members were 1200 mm on centre, the impact of the bolts would be reduced to 3.8% of the total system U-value. The effect would be twice as great (7.4%) if the bolts were placed every 150 mm and would be smaller if stainless steel bolts were used.

Table 4.3 also shows the results for the three FRAME4 techniques. Once again, the parallel path and effective conductivity methods provide lower and upper limits of the 3-D effect. The actual value (HEAT3 result) is approximately mid-way between these two cases. The area of influence method is reasonably close to the HEAT3 result.

Table 4.3 : Heat Flow Results for Curtain Wall Assembly

WALL	HEAT3			FRAME4		
	Total - With Bolts	Total - No Bolts	Difference Due to Bolts	Parallel Path	Area of Influence	Effective Conductivity
TB	13.47	12.48	0.99	0.06	0.70	2.50
No TB	17.92	17.92	0.00	0.00	0.00	0.00

5.0 CONCLUSIONS

For the two complete wall systems studied (which have minor 3-D effects) both the FRAME4 and HEAT3 programs give results very close to physical testing. The FRAME4 and HEAT3 programs also give similar results for 2-D modelling situations.

Steel screws in steel frame walls have a minor impact on overall heat transfer (less than 1%) and their effect can be ignored in most cases. The effect of steel cross-strapping and steel bolts in curtain walls is more significant. Bolts that span the thermal bridge in curtain walls can increase total heat transfer by up to 7.4% (when located every 150 mm).

The parallel path and effective conductivity methods when applied to 2-D models provide the lower and upper bounds of the 3-D case. The area of influence provides results closest to the 3-D although it is the most time consuming to perform.

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