EZ-Barrier – An easy-to-use spreadsheet model to estimate time of failure of timber framed walls in real fire

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ABSTRACT

Several complex models for timber framed walls in fire have been written in recent years and the phenomena affecting the behavior of timber walls have been researched by a number of people. There is still the need to develop models which fire engineers can generally use. To achieve wide usage, the logic and the limitations of a models must be transparent. The model must be user-friendly and provide information the engineer needs. EZ-Barrier has been developed using the simplifications and dominant phenomena apparent from the previous research. It uses spreadsheets with which engineers are familiar and feel confident in understanding the numerical processes. EZ-Barrier produces predictions of temperatures and times of failure to generally within 10% of experimental values from standard fires. Validation of the model has revealed that thermal properties currently used in modeling timber walls in hydrocarbon fires are not reliable and further research is required.

INTRODUCTION

Up until about ten years ago most building fire safety practice was prescriptive and based on experience. During the 1990's, however, performance based codes have been gradually introduced in Australia, New Zealand, UK, Sweden and other countries. These performance-based codes specify objectives for fire engineers to achieve and thereby assure building fire safety. Since performance-based codes do not make reference to materials, there will be much increased scope for the use of timber in building construction.

Because wood burns, many people mistakenly assume that timber structures have poor behavior in fire. However, timber structures can be designed to perform well in fires, either by using heavy timber members that have significant residual fire resistance after charring, or by protecting light timber members with fire resisting material, such as gypsum board.

Lightweight wall systems are now widely used in multi-story construction; with the changes in codes it is now possible to use these systems for both load bearing and non-load bearing applications in a wide range of buildings. Some load-bearing fire-rated timber framed wall and floor systems have been developed that enable the entire structure to be built from timber framed systems (Collins et.al. 1993).

OBJECTIVES

In the past, the lack of a method of extrapolating test results for structures in fire to cover the multitude of load and height/span configurations encountered in practice meant that all designs would require individual testing. This coupled with the relatively high cost of testing to determine the fire resistance of an element of construction was a barrier to their increased application (Collins et.al. 1993).

A number of theoretical models have been created (Takeda et.al, 1998, Thomas et.al. 1996, König et.al. 1997, Gammon 1987, Clancy 1999, Young 2000), but the industry is still lacking simple, easy-to-use aids to assist engineers involved in fire safety design.

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The aim of this project was to develop a practical method and software which can be used by fire engineers in the design of timber framed walls to achieve a guaranteed level of resistance against realistic fires. EZ-Barrier was aimed to be an easy-to-use spreadsheet model which calculates the heat transfer through timber framed walls and thereafter estimates the time of failure of that particular wall, hence giving the engineer a valuable and handy tool to use. The objectives for the model were that its logic be simple and transparent, that it be reasonably accessible and that the accuracy of its predictions of the time of failure be within ±10%. It was also attempted to achieve visual displays of the key results during computation, such as graphs of temperature distribution.

METHODOLOGY

The theoretical approach for the model was adopted because it is necessary for real fires. The simplifications, which achieved comparable accuracy with existing models, were made according to advances in the understanding of the behavior of walls in fire. The spreadsheets which perform the calculations were chosen because engineers feel comfortable with these. Visual Basic for Excel was the programming language chosen for the main processes of the model to create customized functions and processes. The main processes in EZ-Barrier are summarized in the flowchart in Figure 1.

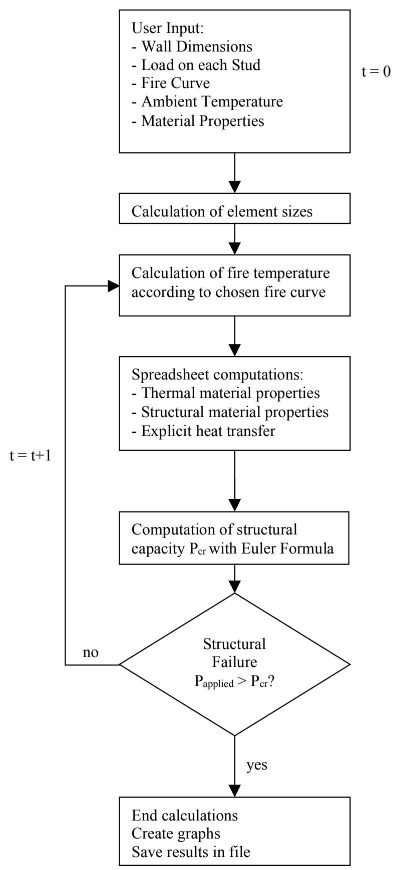

Figure 1 - Flow Chart for EZ-Barrier

HEAT TRANSFER MODEL

Overview

The model analyses the heat transfer through a representative portion of a wall shown in Figure 2. The simplified heat paths are shown in Figure 3. In the model, heat is transferred from the fire to the boundary nodes of the sheeting by one-dimensional radiation and convection. Inside the sheeting, heat is transferred by conduction, also one-dimensionally. Convective and radiative heat is transferred between the cavity surfaces via a single node which represents the entire cavity. The paths between the surfaces and the nodes are all one dimensional. Two dimensional thermal conduction is modeled in the timber stud. One dimensional thermal conduction is modeled in the sheeting on the ambient side. At the boundary of the ambient side, heat is transferred by convection and radiation to air which is assumed to remain at ambient temperature

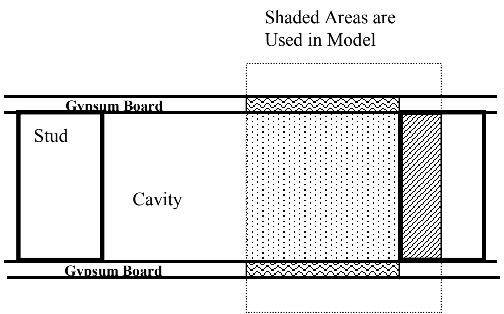

Figure 2 - Modeled Areas in Cross-Section

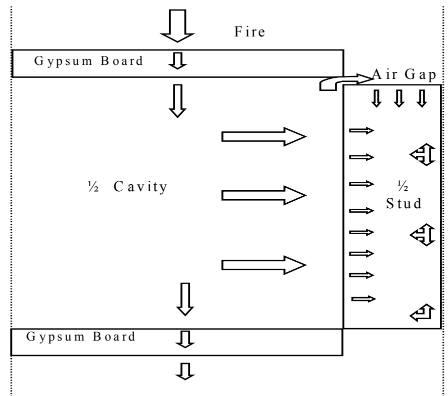

Figure 3 - Heat Flow in Modeled Areas

<u>Heat Transfer Equations Adopted</u>

Three modes of heat transfer were with the following equations:

$$q = -kA\frac{dt}{dx}$$ (1) for conduction, with k being the thermal conductivity

$$q = hA(T_{solid\ body} - T_{fluid})$$ (2) for convection, with h being the convection heat transfer coefficient and

$$q = A_1\varepsilon_1\sigma\left(T_1^4 - T_2^4\right)$$ (3) for radiation, where ε_1 is the emittance of the gray surface and σ is the Stefan-Boltzmann constant.

The variable A is the area through which heat is transferred, q is the rate of heat flow ($W.m^{-2}$) and T represents the temperature (°C or K).

<u>Numerical Solution Procedures for Heat Transfer Analysis</u>

The temperature distribution with time was found by incorporating equations (1)-(3) in an energy balance method of explicit finite difference analysis which has been well established (Patankar 1980, Croft et al 1977). Specific details, simplifications and novelties of the analysis, that was developed in EZ-Barrier, are listed below:

- All heat transfer through the cavity modeled with one node:
  One simplification is the modeling of the entire wall cavity as a single node. The cavity is assumed to have a uniform temperature distribution. Similar modeling has been undertaken previously (Mehaffey et al 1994) but it appears that there were concerns that it this simplification was a crude approximation. Modeling by Clancy (1999), which considered varying transmissivities of smoke in cavities, showed that approximation was much more accurate than was first thought. Whether the cavity contained completely opaque smoke or was clear, had little effect on temperature distribution in the studs.
- No heat transfer across the interface between timber studs and sheeting on the ambient facing side:
  An insulation boundary was assumed in the heat transfer analysis It appears that this assumption has not been tested before. It is justifiable because the temperature gradients are low on the ambient side of the timber studs.
- Maintenance of numerical stability and solution speed during large radiative heat flows.
  Modeling radiative heat flows at high temperatures, particularly above 600°C, can involve problems with over-prediction of temperatures and subsequent numerical instabilities. One solution is to use very small time steps. This

solution, however, leads to large computation times. Since the radiative heat paths used in the model were one-dimensional, it was possible to rationally limit the temperature rises in each time step. The temperature computed at a node receiving radiation, was limited to an upper bound value taken from an emitting node. This simplification is justifiable for several reasons. Well established explicit analysis procedures permit the temperatures to be analysed one node at a time. If the solution of the temperature of the receiving node was carried out with sub-divided time steps until the full time step had expired, the temperature difference between the emitting and receiving nodes would reduce and the temperature of the receiving node would not exceed the temperature of the emitting node. The method of limiting the temperature rise is more approximate than using sub-divided time steps but it enabled the acheivement of the modeling objectives of faster solution speeds and acceptable accuracy compared with experimental results.

- Development of a shrinkage gap between timber and sheeting on the fire side:
  Previous research (Clancy 1999) has shown that during the fire exposure of a timber framed wall, a shrinkage gap opens at the interface of the sheeting and the timber stud on the fire side when the temperature at the interface approaches 250°C. Radiated heat from this gap to the cavity prevents the temperatures rising in the gap to the large values predicted at interface by earlier models. Earlier predictions were as much as 150°C higher than measured values. In experiments it has been observed that the gap temperature was similar to the cavity temperature. The were no significant differences in predicted temperatures when the gap was assumed to be present at initial conditions compared with case of the gap opening at 250°C. EZ-Barrier incorporates the assumptions that greatly simplify modeling - the presence of a gap from the beginning of fire exposure, and the gap having the same temperature as the cavity.

The finite difference grid used in the analysis is shown in Figure 4. The grid is limited to the parts of the walls that wre directly modeled. At the intersection of the gridlines are nodes. Each node is in the center of an element with the dimensions Δx_n and Δy_n. Node spacings are varied to improve computational efficiency. In areas with normally higher temperature gradients the node spacings are smaller than in areas where low temperature gradients are expected.

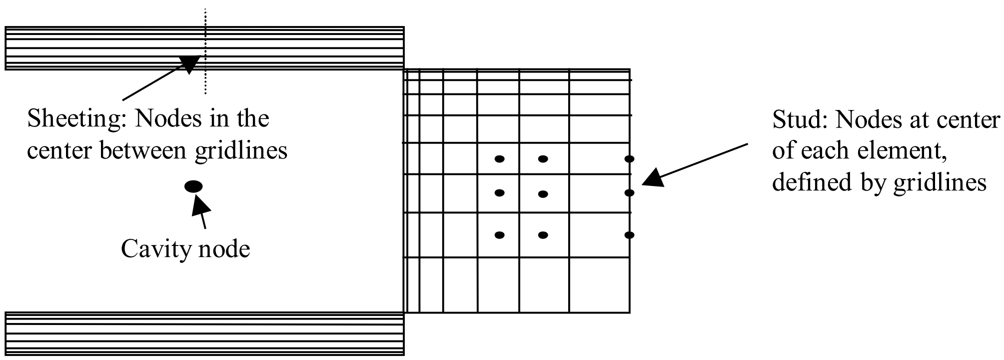

Figure 4 - Grid Adopted in Modeled Wall Section

STRUCTURAL MODEL

The structural response model is based on Euler equation for column buckling.

$$P_{cr} = \frac{\pi^2 EI}{k_e L} \tag{4}$$

where P_{cr} is the critical load (N), EI is the flexural stiffness of the stud (N.m^{-2}), L is the wall height (m) and k_e is the effective length factor which depends on the restraints at the end of the member. The equation is applied to the studs and ignores any structural contribution of the sheeting. These assumptions have been validated by Young (2000) who recommended that the effective length factor k_e should be taken 0.5 to achieve predictions closest to experimental results, rather than the conservative values of 0.7-0.9 which are commonly used in engineering design.

Flexural Stiffness is calculated as follows:

$$EI = \sum_{i=1}^{n} \left[E_i \frac{B_i D_i^{\,3}}{12} + E_i B_i D_i (x_i - \overline{x})^2 \right] \tag{5}$$

where,

$$\overline{x} = \frac{\sum_{i=1}^{n} E_i A_i x_i}{\sum_{i=1}^{n} E_i A_i} \tag{6}$$

and where E_i is the modulus of elasticity ($N.m^{-2}$) of element i, A_i is the area of element I (m^2), n is the number of elements in the timber stud, B_i is the width of element I (m), D_i is the height of element I (m), and x_i is the vertical distance (m) between the center of gravity of element i and the chosen level of reference.

NUMERICAL SOLUTION PROCEDURES FOR STRUCTURAL RESPONSE ANALYSIS

The structural analysis is performed with the heat transfer analysis in the same set of spreadsheets in MS Excel. Visual Basic is also used to customize functions and achieve efficient analysis. Each "element" as defined by the gridlines in Figure 2, is represented as a cell in Excel. On different spreadsheets the properties for the cells are laid out. From these cells on the spreadsheets, the different property values for each element are computed immediately after the heat transfer analysis at each time step. Simple conditional statements within the cells and in the main structure of the software (Visual Basic) allow for different options and accurate results.

VERIFICATION OF THE MODEL PREDICTIONS

A number of comparisons were undertaken to validate the model. The material properties that were adopted were the same as those given in Clancy (1996, 1999).

Validation against Boral Fire Test Boral FSV 0223 on 21.10.1992 (Pohl et.al, 1999):
The specimen was an ordinary hollow wall with stud size of 90mm x 35mm, 16mm fire resistant gypsum board on both sides and 9kN load on each stud. The fire regimen was Australian Standard Fire, AS15304. In the test, structural failure occurred at **52 minutes**. EZ-Barrier predicted the time of structural collapse at **50 minutes**. This value compares well with the actual time of failure. However, the test did not have well controlled boundary conditions – particularly the end studs charred only on one side – and therefore the wall was kept standing longer.

Validation against Warrington Pilot Scale Standard Fire Test F91767 on 02.08.1999 (Pohl et.al, 1999):
The test was a pilot scale test involving wall panels about 1x1m in elevation. The specimen was an ordinary hollow wall with stud size 90mm x 45mm and 13mm gypsum board on both sides. The fire regimen was Australian Standard Fire. From temperature values measured at the ambient side of the wall, insulation failure[3] was determined to occur at **74 minutes**. EZ-Barrier predicted the time of insulation failure resulting from the temperature predictions at the relevant positions at **69 minutes**. This result is very good considering that the temperature gradient at the relevant locations at that time is very flat and therefore small deviations in temperature can cause large errors in time estimates.

Good comparisons between measured and predicted temperatures are apparent in Figure 5.

[3] In the Australian Standard AS1530.4-1990 insulation failure is deemed to have occurred when either the average temperature of the relevant thermocouples attached to the unexposed face of the test specimen rises by more than 140K above the initial temperature or the temperature of any of the relevant thermocouples attached to the unexposed face of the test specimen rises by more than 180K above the initial temperature.

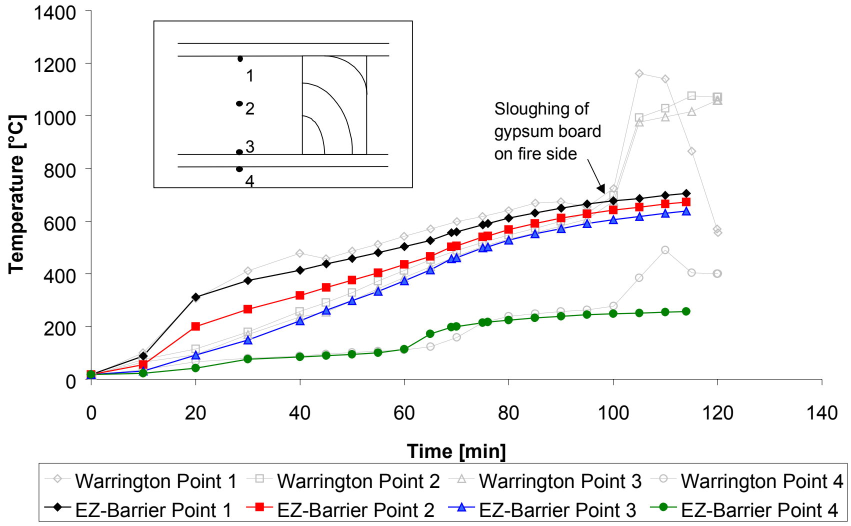

Figure 5 - Temperature comparisons between Warrington F91767 and EZ-Barrier

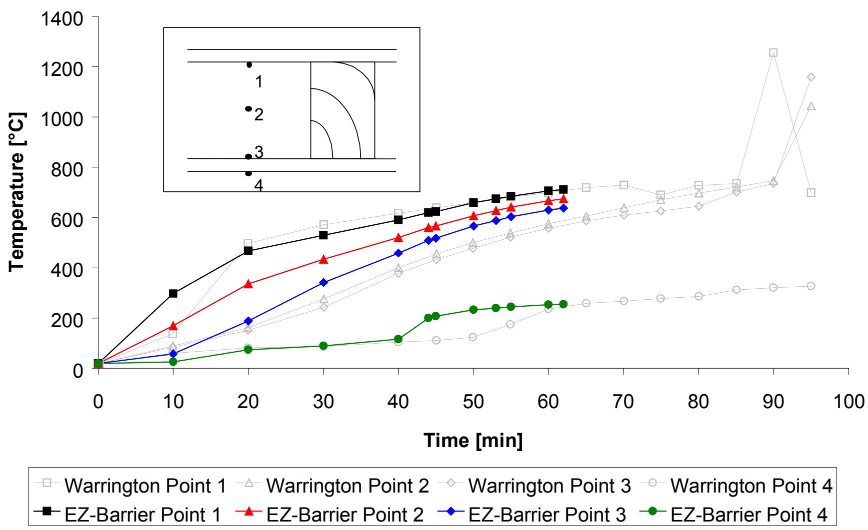

Figure 6 - Temperature comparisons between Warrington F91768 and EZ-Barrier

Validation against Warrington Pilot Scale Hydrocarbon Fire Test F91768 on 28.07.1999 (Pohl et.al, 1999):

The test was a pilot scale test involving wall panels about 1x1m in elevation. The specimen was an ordinary hollow wall with stud size 90mm x 45mm and 13mm gypsum board on both sides. The fire regimen was a Hydrocarbon Fire. From temperature values measured at the ambient side of the wall failure was determined to occur at **57 minutes**. EZ-Barrier predicted the time of insulation failure at **44 minutes**. This is a conservative, reliable result. The temperature values predicted by EZ-Barrier deviate slightly from those measured in the test. One reason for this are uncertainties in emissivity values for gypsum board. Further research in this area is recommended. Temperature values were compared at some points through the cross-section (Figure 6).

Validation against Fire Barrier (Pohl et.al, 1999):

EZ-Barrier was validated against results from Clancy and Young's (Clancy, 1999, Young, 2000) complex model, Fire Barrier. Predictions of the two models have been compared for an ordinary hollow cavity wall with stud size 90mm x

45mm, 16mm gypsum board on both sides and 8kN load on each stud. The fire regimen was Australian Standard Fire. Fire Barrier predicted the time of structural failure at **59 minutes**, while EZ-Barrier's prediction was for **62 minutes**. Temperature values were compared at some points throughout the cross-section of the wall, as shown in Figure 7.

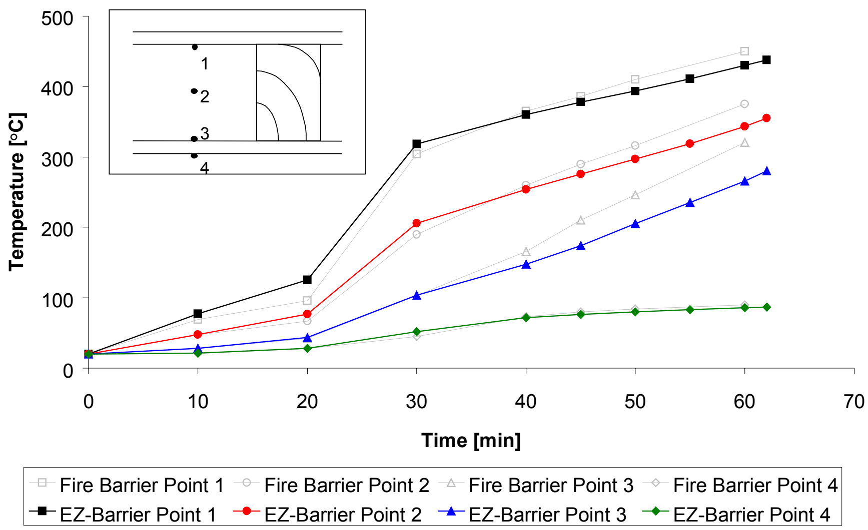

Figure 7 - Temperature comparisons between Fire Barrier and EZ-Barrier

CONCLUSIONS

The aim of this project was to provide the designer with an easy-to-use and dependable model for estimating time of failure in timber framed walls in fire. The modeling is sufficiently simple for thermal and structural analyses to be carried out with a spreadsheet in a short period of time. Use of spreadsheets facilitates design in a format with which engineers are familiar. Logic, material properties, results and calculations are all accessible and transparent to the user. The spreadsheet format of the model facilitates graphical display of most of the input and output, and hence satisfies the objective of user friendliness. Use of Visual Basic macros also makes the coding in cells secure against inadvertent corruption. The model objectives were achieved by adopting simplified boundary conditions and dominant phenomena which have been found in recent research.

Comparisons of model predictions temperatures with experimental results have demonstrated that the predictions of EZ- are accurate to within 10%. for ordinary hollow walls in standard fire (AS1530.4).

The temperature predictions for ordinary hollow walls in hydrocarbon fire are less accurate. Thermal properties adopted in models in recent years appear not to be valid for real fires in general and further research is required. The properties appear to be not only dependent on temperature but also on rate of heating; that is the degree of thermal shock.

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