AN EVALUATION OF THE BS EN 1996-1-2 SIMPLIFIED MODEL FOR PREDICTING FIRE RESISTANCE OF LOADBEARING CLAY MASONRY WALLING

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ABSTRACT

The paper describes the BS EN1996-1-2 simplified model for predicting the time to failure of load bearing masonry walls subject to fire. The performance of the simplified model is assessed in relation to actual fire tests on loadbearing clay brickwork walls.

It was found that the model probably underestimates the fire resistance of 100mm thick brickwork walls. In addition, the limited data provided in the model relating to temperature gradients and thermally induced deflections in clay brickwork may not be appropriate for all types of bricks and mortar. Fire resistance predicted by the model was dependent upon the values of the coefficient of linear thermal expansion of brickwork and the strength reduction factor for clay brickwork in fire. The current lack of these latter data prevents the performance of the model from being fully evaluated. Use of the simplified model for all types of loadbearing clay brickwork walling may be problematic.

KEY WORDS: Masonry, fire resistance, modeling

NOTATION

θ_1	temperature up to which the normal (20°C) strength of masonry may be used
θ_2	temperature above which the material has no residual strength
$A_{\theta 1}$	area of masonry up to temperature θ_1
$A_{\theta 2}$	area of masonry between temperature θ_1 and θ_2
N_{Ed}	design value of the vertical load at normal temperature, i.e. 20°C
N_{Rd}	design value of the vertical resistance at normal temperature, i.e. 20°C
$N_{Rd,fi}$	design value of the vertical resistance in fire
$f_{d\theta 1}$	design compressive strength of masonry up to θ_1
$f_{d\theta 2}$	design strength of masonry in compression between θ_1 and θ_2, taken as $cf_{d\theta 1}$

c constant obtained from stress strain tests at elevated temperature

Φ capacity reduction factor for the mid-height of the wall taking into account the additional eccentricity, $e_{\Delta\theta}$

$e_{\Delta\theta}$ eccentricity due to variation of temperature in masonry cross-section

f_k characteristic compressive strength of masonry

k_θ reduction factor for strength or deformation property

$\gamma_{M,fi}$ partial safety factor for the relevant material property

t_{Fr} thickness of the cross-section whose temperature does not exceed θ_2

α coefficient of linear thermal expansion of clay masonry

The subscript fi refers to the fire situation.

INTRODUCTION

Within the UK, the fire resistance of construction materials and building products has traditionally been determined by standard fire tests. In the case of masonry, this involves subjecting a 3m x 3m wall to a ‘standard fire’, or heating curve, and noting its response. The results from such tests form the basis of the prescriptive (tabular) data in BS5628 Pt 3 (BSI 1992), which specify the minimum thicknesses of masonry walls for different periods of fire resistance i.e. 30, 60, 90 or 120 minutes, according to their type and function i.e. loadbearing, non-loadbearing, separating and the criteria being considered i.e. R (stability), E (integrity), and I (thermal insulation).

This prescriptive approach to fire resistance has been continued in BS EN1996-1-2 (BSI 2005b). This is one of the suite of new masonry Eurocodes which will, in due course, replace individual EEC member states’ national codes of practice for the structural fire design of masonry structures. In BS EN1996-1-2, these tabular data are contained within each country’s National Annex and are based on the results of fire tests carried out in each of the member states.

A major criticism of standard fire tests to determine fire resistance is that they take no account of the interactions that normally occur between adjacent structural elements within a building during a fire, e.g. axial and rotational restraint of walls by floors, which may enhance the structural performance of the individual elements. In addition, in a standard fire test the structural member is subjected to its full ambient temperature design load, which is considered unrealistic. Fires in buildings are also likely to be of a different severity or duration to that in a standard fire test, with its single pre-defined heating curve. As such, standard fire tests do not give a true indication of how individual structural elements, let alone whole buildings, will behave in actual fires. In spite of these drawbacks, Bailey considers that ‘the standard fire test has, to date, been adequate for ensuring a minimum level of fire safety in buildings’ (Bailey 2004). An additional drawback with standard fire testing is cost; in the UK this is currently in excess of £5000 for a 3m x 3m brickwork wall, excluding the cost of building the wall itself.

To overcome these deficiencies, a ‘performance-based’ approach to the fire resistance of construction products and forms of construction has been developed over the past twenty or so years. Essentially, this involves carrying out a thermal, as well as structural, analysis of the individual member, frame, or whole building for the fire situation. This more fundamental

approach to assessing behaviour in fire should enable the fire resistance of loadbearing masonry walls, for instance, to be predicted without the need for actual fire tests. This, in turn, should lead to savings in both development costs and the time taken to introduce new masonry products and walling configurations to the market generally.

For concrete and steel structures, 'performance-based' fire engineering models (design tools) are already capable of simulating structural conditions that are very difficult to study, even in a full-scale fire test (Bailey 2004). In the case of masonry very little work has, however, been carried out and few models currently exist. This paper critically reviews that provided in Annex C of BS EN1996-1-2. This is a simplified model for assessing the structural behaviour of individual loadbearing masonry walls and columns i.e. a 'member analysis' design tool.

STRUCTURAL FIRE-PERFORMANCE MODELS

Figure 1 shows the general procedure involved in the performance-based approach to structural fire resistance. Stage 1 determines the characteristics of the fire i.e. its severity and duration. Stage 2 is concerned with estimating the variation of temperature in the member or structure, whilst Stage 3 predicts the structural response of the member, frame or whole building.

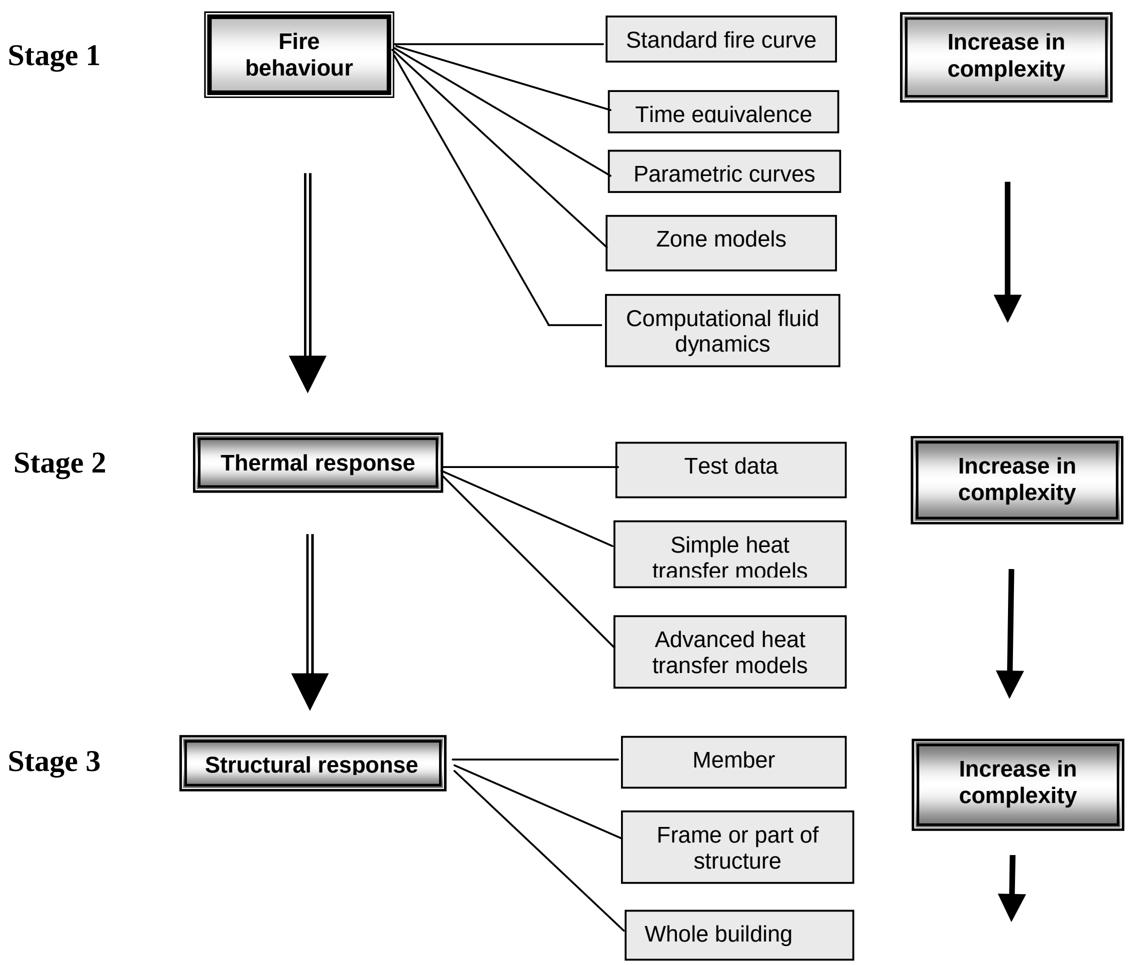

Figure 1. Performance-Based Approach to Structural Fire Safety (Bailey 2004)

BS EN1996-1-2 ANNEX C SIMPLIFIED CALCULATION MODEL

Description of Simplified Model

The model adopts the same approach as that in BS EN1996-1-1 (BSI 2005a) for the design of masonry walls subjected to mainly vertical loading at normal temperature i.e. 20°C. This involves use of a capacity reduction factor, Φ, to allow for the effects of slenderness and eccentricity of loading. In the fire situation, however, the model assumes that design vertical resistance is influenced by two further factors, namely

1) a change in the effective thickness of the walling, t_{ef}, due to a temperature-induced reduction in the compressive strength of the masonry

2) an eccentricity, $e_{\Delta\theta}$, caused by thermal bowing towards the heat source. This is in addition to any eccentricities due to loads and/or initial construction imperfections, as described in BS EN1996-1-1.

The model takes account of 1) and 2) by using a modified version of the equation for the design vertical resistance of the wall at the mid-height of the wall i.e. equation 6.2 in BS EN1996-1-1. As with BS EN1996-1-1, the simplified model assumes that, in fire, the wall behaves as a vertical strip i.e. plane strain conditions.

Limitations of Simplified Model

In relation to stage 1 of Figure 1, the model is only valid for masonry walls and columns exposed to a standard fire. At stage 2, the model recommends that the temperature distribution across a masonry section should be obtained either from tests or a database of test results. Where these are unavailable, data provided with the model may be used. It should be noted, however, that these data are derived principally from tests carried out on masonry products found in France and Germany involving highly perforated clay block units (private communication with the UK Brick Development Association Ltd). As such, they may not be appropriate for the types of brick used in other EU member countries e.g. 102.5mm wide solid or frogged units. At stage 3, member analysis only is possible using this method i.e. individual loadbearing walls or columns.

Importantly, the model has, to date, only been validated against a limited number of unit and mortar combinations. For clay brickwork, its use is consequently limited to walls built with

Group 1S or Group 1 units, characteristic unit strength (f_b); 20N/mm^2 $< f_b <$ 40N/mm^2, gross density; 1000 - 2000kg/m^3, brickwork to be laid in general purpose mortar

BS EN1996-1-2 does, nevertheless, permit the underlying principles of the simplified model to be used with other unit/mortar combinations, provided there is validation.

Design Resistance at the Fire Limit State

At the limit state for the fire situation, the design value of the vertical load applied to the wall (or column), N_{Ed}, is required to be less than, or equal to, the design value of the vertical

resistance, $N_{Rd,fi}$, i.e.

$$N_{Ed} \leq N_{Rd,fi} \quad (1)$$

where

$$N_{Rd,fi} = \Phi(f_{d\theta_1} A_{\theta 1} + f_{d\theta_2} A_{\theta 2}) \quad (2)$$

Use of the model involves the following procedure:

i) Determine temperature distribution across masonry for the specified period of fire resistance
ii) Calculate reduction in effective cross-sectional area of masonry at this time
iii) Calculate the additional load eccentricity due to thermal bowing, $e_{\Delta\theta}$, in middle 1/5th height of wall at this time.

These are then used to determine $N_{Rd,fi}$. The clay brickwork data provided with the Annex C simplified model relating to i) and ii) above are described in more detail below.

Annex C Temperature Distribution Data

As already noted, the data provided in Annex C may be used when no specific test results are available. An example of these is given in Figure 2, which shows the assumed distribution of temperature through 100mm of clay brickwork after different periods of exposure to fire.

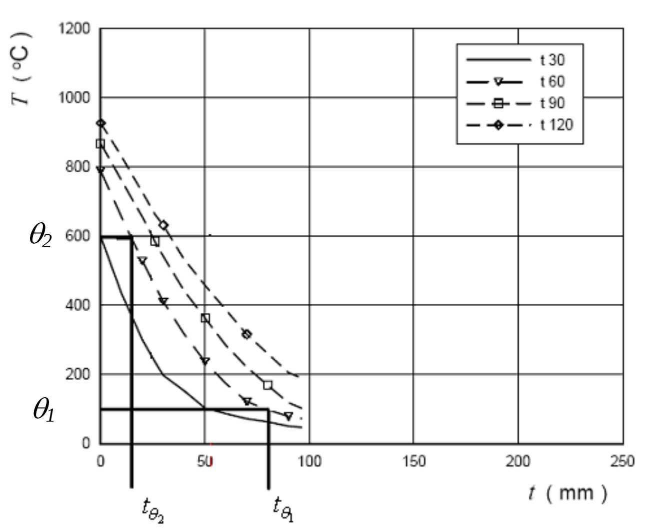

Figure 2. Annex C Temperature Distribution Data. (These represent the temperature distribution through approximately 100 mm of clay masonry after 30 (t30), 60 (t60), 90 (t90) and 120 (t120) minutes exposure to a standard fire.)

Reduction in Cross-Sectional Area of Masonry

Above a certain temperature, θ_2, the model considers that masonry will no longer have any compressive strength (Figure 3). The area of masonry below θ_2, but above a second

temperature θ_1, i.e. A_{θ_2} in Figure 3, is deemed to have a reduced compressive strength. The area of masonry at a temperature less than θ_1 is referred to as A_{θ_1}; this is deemed to have full compressive strength. Values for θ_1 and θ_2 are tabulated in Annex C. In the case of clay brickwork, the recommended values of θ_1 and θ_2 are 100ºC and 600ºC, respectively. The combined area $(A_{\theta_1} + A_{\theta_2})$ is referred to as the residual cross-section, t_{F_r}

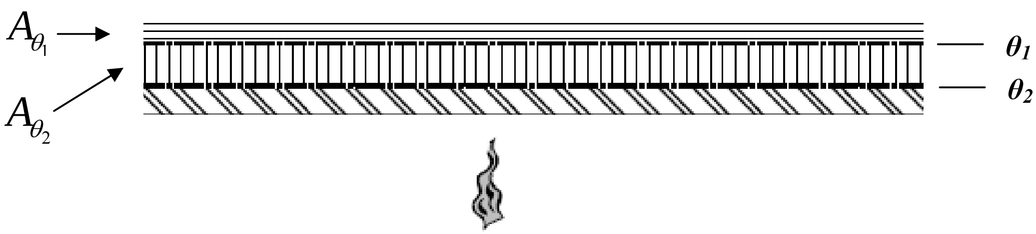

Figure 3. Cross-Section of Masonry Wall after Exposure to Fire on One Side

Load Eccentricity due to Thermal Bowing

For wall elements heated from one side, response is characterised by bowing towards the heat source (Cooke 1988). The line of action of the vertical load will then be eccentric to the centroid of the wall section. The additional eccentricity in the mid 1/5th height of the wall, $e_{\Delta\theta}$, may be obtained from test results. In their absence, the model states that $e_{\Delta\theta}$ may be calculated using

$$e_{\Delta\theta} = \frac{1}{8} h_{ef}^2 \frac{\alpha(\theta_2 - 20)}{t_{Fr}} \leq h_{ef}/20 \qquad (3)$$

It should, however, be noted that equation 3 is derived from simple bending theory. As such, it does not take account of any changes in the mechanical or thermal properties of the masonry in the fire situation.

Design Compressive Strength of Masonry in Fire

In the fire limit state, the design compressive strength of masonry, $f_{d,fi}$, is defined as

$$f_{d,fi} = \frac{k_\theta f_k}{\gamma_{m,fi}} \qquad (4)$$

The partial safety factor $\gamma_{m,fi}$ is a nationally defined parameter, although the value recommended in BS EN1996-1-2 is 1. This reflects the global reductions in safety factors generally for the fire situation, as outlined in BS EN1991-1-2 (BSI 2002).

For $A_{\theta 1}$ this gives

$$f_{d\theta_1} = \frac{k_\theta f_k}{\gamma_{m,fi}} = f_k \qquad (5)$$

using k_θ=1, $\gamma_{m,fi}$=1 (k_θ= 1, as masonry below θ_1 is deemed to have full compressive strength)

Similarly, for A_{θ_2}

$$f_{d\theta_2} = cf_{d\theta_1} \; (= cf_k) \qquad (6)$$

where the coefficient, c, is a factor to allow for the reduction in strength of the masonry with temperature. Again, this is a nationally defined parameter which should be derived from tests carried out on masonry at elevated temperatures. It should be noted, however, that values of c for clay masonry products are not yet widely available.

PERFORMANCE OF THE SIMPLIFIED METHODOLOGY

A major factor influencing the fire resistance of loadbearing clay masonry walling is slenderness ratio (de Vekey 2004, Lawrence et al 1998). To evaluate the performance of the simplified model in this respect, the fire resistance of 100mm thick clay brickwork walls of different slenderness ratios are predicted using the data provided in Annex C. These are then compared with the results of actual fire tests on 90mm to 110mm thick walls. The effect on design fire resistance of changes in the coefficient of linear thermal expansion of brickwork, α, and the strength reduction coefficient, c, is also examined.

Design Load Level, N_{Ed}

BS EN 1996-1-2 states that, as a simplification, the design load level in the fire situation, N_{Ed}, may be expressed as 65% of the design load level at normal temperature, calculated using EN1996-1-1. In the limit, this is equivalent to $0.65N_{rd}$, where N_{rd} is the design vertical resistance of the wall at ambient temperature i.e. 20°C. For a 100mm thick brickwork wall with a unit strength of $40N/mm^2$ and a general purpose mortar, the variation in design load level in the fire situation, N_{Ed}, with slenderness ratio is shown in Figure 4.

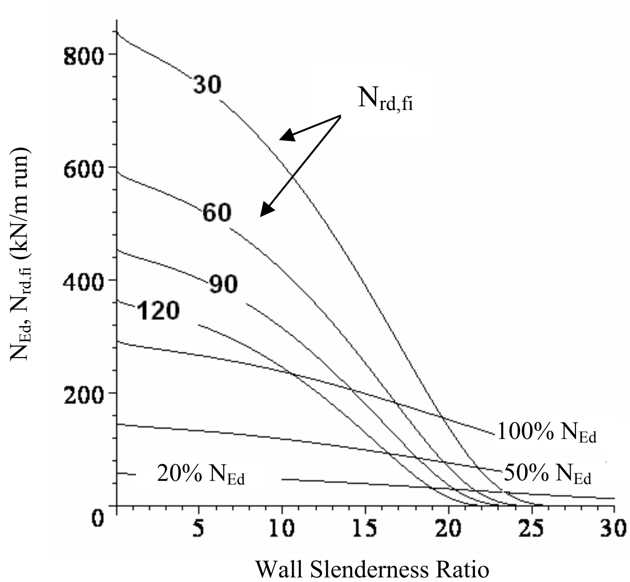

Figure 4. N_{Ed} and $N_{rd,fi}$ as Functions of Wall Slenderness Ratio

Design Vertical Resistance, $N_{rd,fi}$

Using the data provided with the model, the design vertical resistance of the above 100mm wall in the fire situation, $N_{rd,fi}$, may similarly be expressed as a function of wall slenderness ratio (taken as 0.75 x effective height) for different periods of fire resistance (Figure 4). These are based on a value of 6 x 10^{-6}/ºC for the coefficient of linear thermal expansion of clay brickwork, α, as recommended in BS EN1999-1-2 and a value of 0.5 for the strength reduction coefficient, c. This latter value is an approximation and is derived from previous work on the hot properties of clay bricks and mortar (Edgell 1982).

In Figure 4 the intersection of the curves for $N_{rd,fi}$ with those for N_{Ed} define the maximum allowable slenderness ratios for the four different periods of fire resistance considered. The maximum slenderness ratios for reduced values of N_{Ed} are also shown in Figure 4. These allow the designer to assess the effects on fire resistance of reductions in design load. To achieve 120 minutes fire resistance under the full design load (100%N_{Ed}) it can be seen that the model limits the slenderness ratio of the wall to a maximum of 11. Similarly, to achieve 30 minutes fire resistance, the slenderness ratio is limited to approximately 20 with walls with slenderness ratios in excess of 20 deemed to have no fire resistance. In relation to actual fire tests on 90mm to 110mm thick loadbearing clay brickwork walls (Figure 5), the model predictions appear to be very conservative when based on these values of α and c.

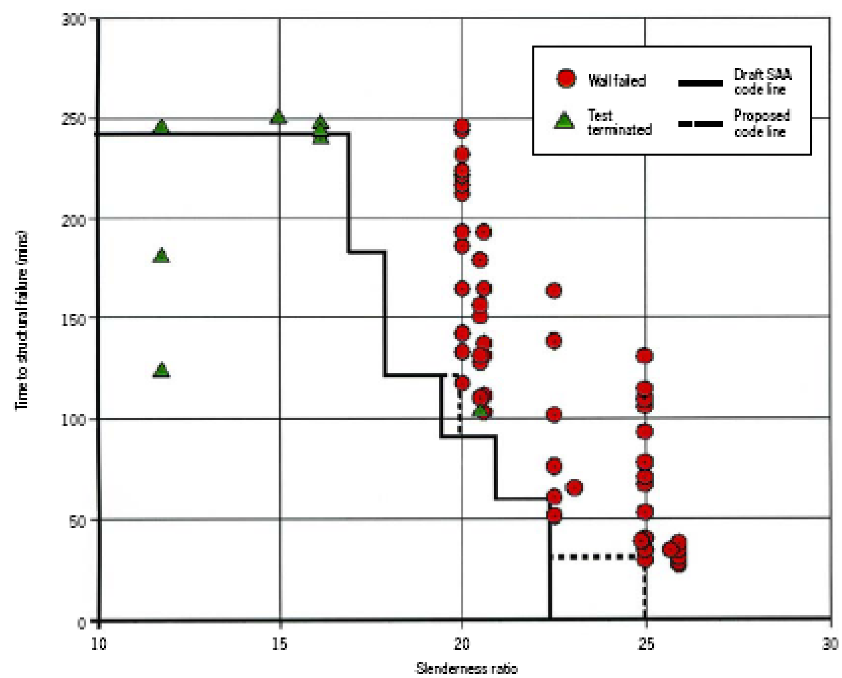

Figure 5. Australian Data for Stability Failure of Clay Masonry Versus Slenderness Ratio, with a Proposed Code Line (de Vekey 2004)

The effect of changes in α and c on, for example, the 30 minute design vertical resistance of the 100mm thick wall described above, according to the model, is shown in Figure 6 for different slenderness ratios (SR's).

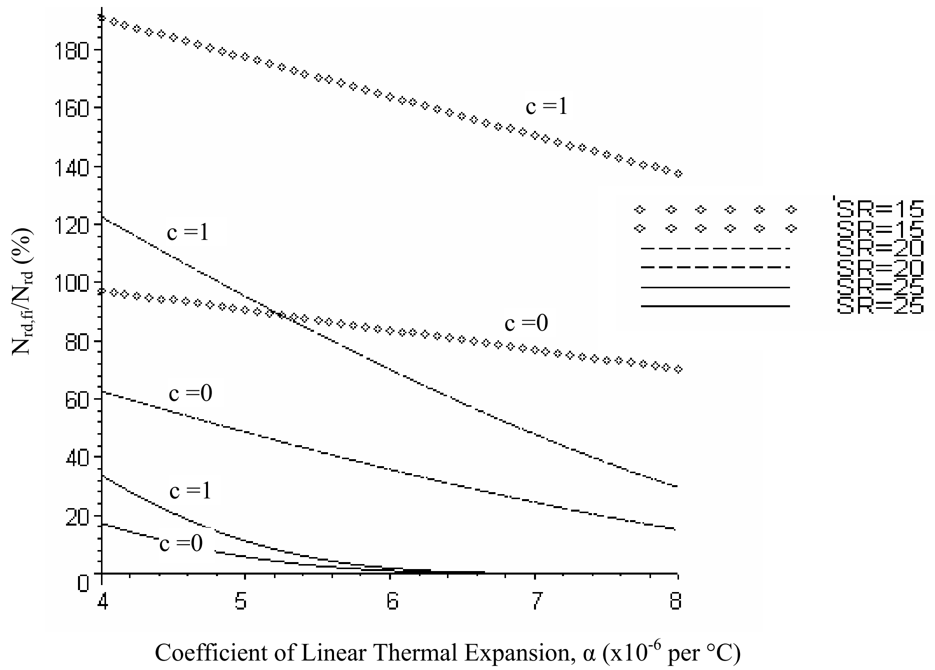

Figure 6. Effect on 30 Minute Design Fire Resistance of Changes in c and α

It can be seen that the design vertical resistance is highly dependent upon the values of α and c. In practice, whilst information relating to the coefficient of thermal expansion of brickwork, α, may be available from brick manufacturers, values for c are currently very limited due to the lack of research in this area. The lack of these latter data therefore prevents the performance of the simplified model from being fully evaluated at the present time, and further work is required to obtain values of c for a range of brick types and mortar combinations. This will then enable the performance of the Annex C model to be better assessed overall. Until such data become available, use of the simplified Annex C model to predict the fire resistance of loadbearing clay brickwork masonry walls is likely to be problematic.

ACKNOWLEDGMENTS

This research was sponsored by the UK Brick Development Association Ltd and the UK Engineering and Physical Sciences Research Council (EPSRC).

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