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Design optimization of insulated cavity rammed earth walls for houses in Australia

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ABSTRACT

This paper presents an optimization study of the design parameters for houses using rammed earth walls, including window sizes, window shading, the amount of thermal mass and the amount of insulation in the external walls. The optimization is based on two objectives: (1) energy use reduction and (2) life-cycle cost minimization.

It was found that, in general, the thicker the walls/insulation was applied, the less the energy load, but the higher the life-cycle cost. In hot arid climates, small windows and large window shadings lead to a lower energy load while the minimum life-cycle cost was achieved with the smallest window and window shading. In warm temperate climates, the optimum size of north facing window was 30% and 40% of the wall area to achieve the minimum energy load and life-cycle cost while the sizes of the windows on the other walls as well as the window shading needed to be as small as possible. In cool temperate climates, small south facing windows and large windows in the other walls would result in the lowest energy load; however, to achieve the minimum life-cycle cost, all the windows and window shadings should be as small as possible.

1. Introduction

Buildings in Australia, including residential premises, are important contributors to greenhouse gas emissions and climate change [1,2] where the residential sector (in 2006–07) consumes 8% of the total energy use [3] and more than 40% of this consumption is used for space heating and cooling [4]. Therefore, the development of residences containing low embodied energy and which require little energy for space heating and cooling is of prime interest to architects and builders.

Rammed earth (RE) wall houses are perceived to be sustainable as they carry extremely low embodied energy, in particular when locally available material is used [5–7]. In addition, with their large thermal mass, RE wall houses are assumed to perform in a thermally desirable manner because the mass can effectively delay the heat transmission through the external walls, particularly in summer when peak indoor temperatures are delayed by a long thermal time lag. In a relatively mild climate without extended periods of heat or cold, energy conservation can be achieved and temperature smoothed out [8–10]. Moreover, a study conducted by Allinson and Hall [11] indicated that RE walls can potentially save the energy for indoor humidification.

Such perceptions of RE walls mean that their construction has attracted increasing interest recently as architects develop greater interest in sustainability principles. However, considered more realistically, the smoothing of the temperature in mild climates is offset by the fact that when summer and winter are more extreme (hot and cold for long periods), the low thermal resistance (*R*-value) of RE could result in poor thermal performance. Once the interior space is warm during several hot days, it is difficult to cool unless night-time ventilation is applied. In cold days the earthen material does not effectively prevent heat draining from the inside to the outside of the house, which means that a large amount of energy may be required for space heating. Because of this behaviour, it is currently difficult for house designs using only RE walls to satisfy the Deemed-to-Satisfy provisions of the Building Code of Australia within the Australian National Construction Code (NCC) [12], which require a minimum *R*-value for external walls of 2.8 m^2 K/W for Class 1 buildings (detached residential) for all climatic zones in Australia except the Alpine zone, where the minimum requirement is 3.8 m^2 K/W. According to previous studies [13–16], a typical 300 mm thick RE wall has an *R*-value of only 0.27–0.70 m^2 K/W. The NCC has an alternative requirement for external walls with

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a surface density greater than 220 kg/m^2, which states that an equivalent wall insulation with an R-value of 0.5 to 1.0 m^2 K/W (depending on other design parameters) shall be added. A typical 300 mm thick RE wall has a surface density much greater than 220 kg/m^2 (usually between 540 and 660 kg/m^2 [16]). Thus insulation with an R-value of 0.5 to 1.0 m^2 K/W is required for solid RE walls in all climate zones except for the Alpine zone.

2. Insulated cavity RE walls

For RE, rigid insulation (extruded polystyrene or polyisocyanurate) can be inserted in the middle of the wall to preserve the aesthetics of the wall surfaces [17]. Extruded polystyrene (XPS) with a thickness of 1 m has an R-value of 28.6–40.0 m^2 K/W [18]. If the average value of 34.3 m^2 K/W is applied, a solid RE wall would need to be insulated by XPS with a thickness of 15 to 30 mm, in order to satisfy the minimum R-value requirement of the NCC.

Although adding 15 mm to 30 mm thick XPS insulation enables RE wall houses to meet the minimum R-value requirement of the BCA, it does not guarantee satisfactory thermal performance without taking into account the other design parameters including window size, window shading, insulation thickness and the amount of thermal mass [19]. The effects of insulation as well as these other design parameters on thermal performance are discussed in the following sections of this paper.

3. Star rating requirement and methods for reducing energy load

There is another option for Class 1 buildings (residential) to satisfying the requirement of BCA [20]: the Energy Efficiency requirement, also known as the star rating method. There are 10 star ratings (1 to 10) in the Nationwide House Energy Rating Scheme (NatHERS), where more stars correspond to less energy loads. Note, in the BCA, the star rating is based on predicted space heating and cooling loads only, hence the star rating bands vary according to climatic regions. Other energy demands such as domestic hot water (DHW) are not included. According to the NatHERS, Australia is divided into 69 climate regions of similar climate; each is represented by a city with typical local climate condition. For example, in Adelaide (climate region 16: warm temperate climate), the 6-star rating corresponds to a maximum energy load of 96 MJ/m^2 per annum, while in Ballarat (climate region 66: cool temperate climate) the 6-star rating corresponds to an energy load of 197 MJ/m^2 per annum. By comparing the predicted energy loads for heating and cooling in order to maintain indoor thermal comfort to the reference value for each star rating load, a building design can be assigned a star rating. Starting from 2010, new residential buildings have been required to meet a 6-star rating as a minimum. In other words, the total predicted energy load for heating and cooling of the building must be equal to or less than the maximum allowed for each climate region for a 6-star rating.

Passive design strategies such as direct solar gain for passive heating and natural ventilation for passive cooling are effective to reduce the heating and cooling loads, respectively [21,22]. The direct gain strategy requires a large amount of thermal mass to absorb and store solar heat that comes through the windows during the day and to release this stored energy slowly during the night [22]. Natural ventilation (for example opening windows when the outdoor temperatures are lower than indoors) helps to cool a house and reduces the cooling load [21]. In order to effectively implement these passive strategies, the windows must be sized accordingly as a large amount of heat flow between the inside and outside of a building as well as the natural ventilation in a building is transferred through windows. Window shading should also be taken

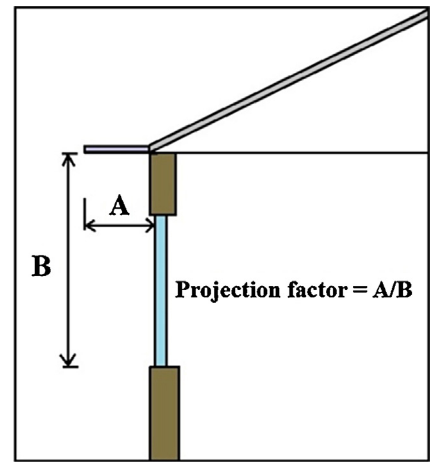

Fig. 1. Calculation of projection factor. This figure illustrates how the projection factor is calculated. Projection factor is the ratio of the depth of window eave to the distance between the window sill and the bottom of window eave.

into account as it controls the amount of solar gain through the windows. In summary, many researchers have confirmed that substantial energy saving on space heating and cooling can be obtained through optimized window design [23,24] and proper use of thermal mass and insulation [25–27].

4. Investigations

The study aims to investigate the relationships between each parameter and the energy loads as well as total life-cycle cost, thus providing information for designers and house owners to make strategic design decisions. For example, small window areas in some climates can result in low energy loads; however, the occupants may prefer large windows for better natural light or frame view. With the information provided by this study, occupants can make more informed decisions by balancing the advantages and costs of increasing window size. It should be noted that the recommendations provided from this study are for residential buildings. For other building types (such as office buildings), the basic model as well as the assumptions of the simulation should be modified accordingly. In order to achieve this aim, the following objectives need to be fulfilled:

(a) Quantify the effects of four design parameters on the heating and cooling loads of hypothetical RE houses. They are: (1) the size of each window in relation to the walls (window to wall area ratio, WWR); (2) the window shading (expressed as the projection factor, which is the ratio between the width of window shading and the distance between the bottom of the window shading and the window sill, as shown in Fig. 1); (3) the amount of thermal mass (RE wall thickness); and (4) the amount of external wall insulation (insulation thickness); and
(b) Evaluate the effect of each parameter on the total life-cycle costs which comprise the initial cost for construction (including air conditioner/heater) and the running cost (for space heating and cooling).

The options for each parameter were:

- *Window to wall ratio:* Five options of the WWR were evaluated—10%, 20%, 30%, 40% and 50%. The minimum value 10% was selected considering that the house needs some natural light and ventilation. The maximum value 50% is restricted by the wall length as the window area was determined by the window width