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Original Article

Effect of Insulation Properties on the Fire Resistance Rating of Steel Beams

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Abstract *- Steel's strength and lightness make it a prime material for modern construction. Nevertheless, and importantly, their load-bearing structure poses unique challenges when exposed to elevated temperatures, demanding comprehensive attention to effective temperature control. Passive fire protection systems are regularly deployed, though their efficacy largely pivots on material dimensions, thermal insulation capacity, and moisture saturation. This study sought to determine these parameters and their effects on the fire resistance ratings assigned to steel beams. A simply supported steel beam was evaluated under standard fire exposure conditions. The ECCS best-fit method was used to estimate the duration for the critical steel temperature to be reached, and the insulation thickness was between 0 mm (unprotected) and 40 mm (protected). Individual and cumulative effects were studied under two thermal conductivity conditions (0.1 and 0.2 W/mK) and moisture levels (0% and 15%). Fire resistance rating correlated with insulation thickness as predicted. Increasing insulation thickness above 20 to 25 mm resulted in diminishing returns. The performance was notably superior under lower thermal conductivity conditions, and the 0.1 W/mK provided 70% additional fire resistance as opposed to 0.2 W/mK for equivalent insulation thickness. Moisture content of 15% improved predicted fire resistance due to some of the latent heat effects during evaporation, although this benefit was temporary and dependent on the prevailing conditions. There is a more effective way of addressing this issue. Rather than simply increasing the insulation thickness, using insulation materials with lower thermal conductivity is a better approach, and moisture content should be addressed in the design. The findings provide guidance on fire protection systems of steel structures, which is a considerable improvement on the design.*

Keywords *- Steel beam, Fire resistance rating, Standard fire, Parametric fire, Passive fire protection.*

1. Introduction

1.1. Background

In modern construction, steel frame structures are popular due to their lightweight, high strength, and good performance in earthquakes. These qualities make steel versatile for many structural uses. Nevertheless, steel loses a considerable amount of its strength and stiffness when exposed to fire, especially over 600 °C, for prolonged periods. Structural failure becomes more likely with the increased risk of serious danger to safety and property in the event of a fire [1-3]. For this reason, the improvement of fire resistance on steel structures has become a focus in the field of structural engineering.

The Cardington facility has conducted groundbreaking experiments that outline fire engineering principles and understand the behaviour of steel structures during and after a fire [4-7]. These studies indicate that a complete steel frame system is safer during a fire compared to individual structural members. This is primarily due to the activation of structural mechanisms that occur during large-scale deformations, such as membrane action within the floor slabs and other intricate system interdependencies at elevated temperatures [8-10]. Several other studies have researched the thermal equilibrium, behaviour, and the general stability of a steel frame building under fire and have understood the performance of such structures during a fire [11-13].

1.2. Literature Review

Designing and analysing structures during a fire situation is no small feat. Many assumptions, like stable loading, material linearity, and constant boundary conditions, are fundamentally invalid at higher temperatures. Fires lead to uneven thermal action because of radiation and convection at higher temperatures, producing sharp gradients within structures. These gradients, causing uneven thermal expansion, internal stresses, and breaks in equilibrium, lead to dynamic redistributions of stresses in the structure [14-16]. Additionally, the weakening of steel's mechanical attributes during a fire (especially the yield strength, elastic modulus, and stress-strain behaviour) alters the loading conditions [17-19]. This, added to the limits of thermal expansion and structural flexibility, will absolutely lead to the creation of significant internal forces and huge structural deflections. These deflections are not an indicator of collapse. Predicting these behaviours requires models that integrate material degradation and geometric change. This material covers the gaps in current methods that attempt to describe the coupled fire exposure thermomechanics of structural components.

Improving the fire resistance of structural steel elements has become a hot topic of enquiry. The slowed heat transfer method of fireproofing and enhancing fire resistance ratings of steel uses passive protection, such as fire shields. Systems fire shields SFRMs, board systems, and intumescent coatings are all insulation materials that have been researched. Each has different thermal and mechanical properties [20-24]. Alongside practical experimentation, numerical modelling has become a crucial aspect of fire engineering. The standard fire curves (ISO 834) [25] and parametric fire scenarios [26] provide combined heat transport and structural reaction of steel beams using Finite Element Analysis (FEA) techniques. These models provide the framework for parametric studies that enable the assessment of the impact of insulation systems without huge test constructions[27-29]. However, the reliability of these models is dependent on the reliable material properties at elevated temperatures, realistic boundary conditions, and the thorough assessment of the thermal and mechanical nonlinearity.

1.3. Research Gap and Objective

Given that previous studies highlight the importance of insulation thickness and thermal conductivity as variables on fire resistance of steel beams, most studies have focused on one insulation type, compared different types of insulation, or have analysed these variables in isolation, without considering applied loads, geometry of the beams, or fire exposure conditions. This hinders one's ability to assess these variables' independence, and in conjunction with fire resistance. Also, there appears to be an absence of integration of the insulation thermal attributes and fire resistance rating, and a lack of studies that systematically assess the thermal performance of insulation versus fire rating and the structural behaviour of the steel members. The performance of insulation materials in fire conditions, especially with varying moisture content, is also significant in practice and has largely been neglected in fire resistance studies. These gaps create uncertainty and highlight the need for gaps to be filled.

Novel contribution of this work is performing insulation thickness, insulation thermal conductivity, and insulation moisture content systematically and comparatively with the same analytical framework using the ECCS best-fit method under ISO 834 standard fire conditions. Previous studies examined these parameters largely in isolation. This work demonstrated the influence of these parameters on the fire resistance rating of steel beams under identical structural and loading conditions. By addressing this, this work offers practical and design-driven perspectives aimed at the effective and safe fire protection system design in steel structures.

2. Methodology

As shown in Figure 1, this study uses a simply supported steel beam as the reference structural member. A Universal Beam (UB) 356 × 171 × 45 with a nominal yield strength of 345 MPa was chosen. This size of beam represents medium-span floor beams, as they are often used in the construction of multistorey buildings. An applied loading of a live load of 2.0 kN/m² aligned with occupancy loads and a uniformly distributed dead load of 1.0 kN/m² was used, which represented the self-weight of floor finishes and nonstructural elements. Considering the use of a simply supported configuration, it is possible to assess the thermal–structural response to fire exposure without the effects of moment continuity from adjacent spans, isolating the influence of the insulation properties on fire resistance performance.

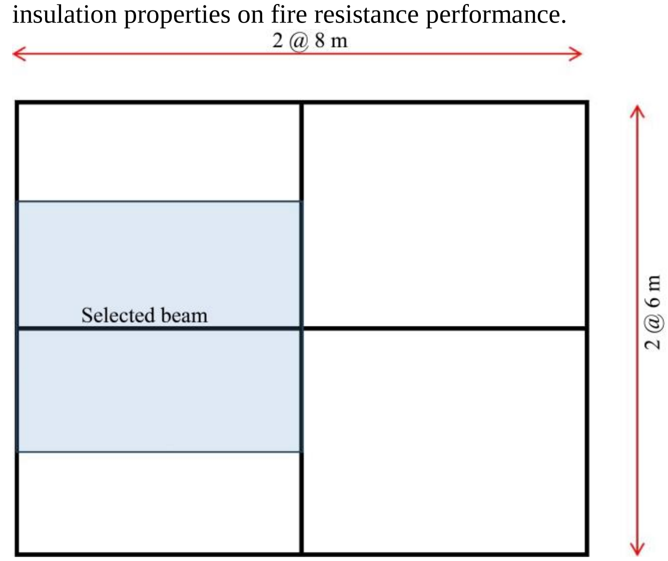

Fig. 1 Building configuration

This research aimed to evaluate insulation thicknesses ranging from none (0 mm) to fully protected (40 mm). It was considered that thermal protection was uniform over the encased beam, insulating all cross-sectional surfaces. At a density of 800 kg/m³, the insulation had a thermal conductivity (k_i) of 0.1 W/mK for both 0% (dry) and 15% (wet) moisture contents. Other conditions, with k_i = 0.2 W/mK, were used to evaluate insulation's fire performance variability, as compared to other scenarios, with a more dominant effect on fire performance.

The beam was subjected to the following application of the ISO 834 standard fire curve [25], which plots the gas temperature (T_g) against time.

$$T_g = 345\, log_{10}(8t + 1) + T_0 \tag{1}$$

Where T_0 is the ambient temperature, and t is the time in minutes.

The European Commission for Constructional Steelwork (ECCS) [30] fire resistance rating of the steel beams, constructive elements, was derived using the best-fit method. It determines an approximate value of the duration a steel object can be exposed to fire to reach a predetermined limiting temperature. The following predictive equation was used:

$$t = 40(T_{lim} - 140)\left[\frac{d_i/k_i}{F/V}\right]^{0.77} \quad (2)$$

Where t is the predicted time to reach T_{lim}, d_i is the insulation thickness, k_i is the thermal conductivity of the insulation, and F/V is the section factor, defined as the ratio of the heated perimeter to the cross-sectional area of the steel member.

T_{lim} is the temperature of the steel at which a member will fail without any load sharing or backing, and the member will no longer provide structural support and it will fail. This was computed as follows.

$$T_{lim} = 905 - 460 r_{load} \quad (3)$$

Where r_{load} is the load ratio defined by,

$$r_{load} = \frac{M_{fire}}{M_n} \quad (4)$$

Where M_{fire} is the bending moment in the beam under fire conditions, and M_n is the bending strength at ambient temperature.

This technique offers a practical and efficient way to estimate the fire resistance rating for various insulation scenarios. It takes into account how insulation thickness and section factor affect the heating rate of the steel.

3. Results and Discussion

For two thermal conductivity values, $k = 0.1$ and $k = 0.2$ W/mK, Figure 2 shows how the fire resistance rating varies with insulation thickness over the thickness range of 0 (unprotected) to 40 mm. The fire resistance rating increased nearly linearly with the insulation thickness in both situations, suggesting that the additional thickness successfully postponed the heat transfer to the steel beam. However, owing to the lower rate of heat conduction, the slope of the curve was significantly steeper for insulation with lower conductivity.

The beam with $k = 0.1$ W/mK insulation had a significantly higher fire resistance than that with $k = 0.2$ W/mK insulation at any given thickness. For instance, at a thickness of 20 mm, the estimated fire resistance for $k = 0.1$ W/mK is approximately 100 min, whereas for $k = 0.2$ W/mK, it is only approximately 70 min. In line with the inverse relationship between the heating time and $k_i^{0.77}$, this translates to a performance improvement of approximately 60%.

When insulation layers have more thickness, the material's thermal conductivity becomes more significant, as the difference in thickness becomes larger. From a practical standpoint, choosing thicker insulation with lower thermal conductivity would help achieve the desired fire resistance rating without overly oversized insulation, which streamlines material consumption, installation, and structural requirements. On the other hand, materials with higher thermal conductivity will require thicker layers to achieve the same results, which could complicate construction and inflate costs.

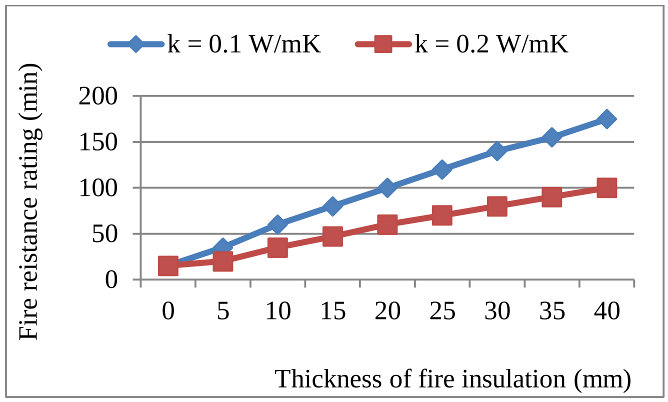

Fig. 2 Effect of insulation thermal conductivity on fire resistance rating of the steel beam

Figure 3 shows how the insulation thickness affects the fire resistance rating for two different moisture content levels: 0% (dry condition) and 15% (moist condition). The fire resistance rating for both conditions increased steadily as the thickness of the insulation increased, suggesting that thicker layers provided the steel beam with more time before reaching its limiting temperature. However, across all thicknesses, the predicted fire resistance was consistently higher when the insulation was wet than when it was dry.

It can be interpreted that moisture contributes additional thermal buffering, which can be primarily attributed to the latent heat of vaporization it absorbs during the heating cycle. Heat penetration to the steel surface becomes delayed when the insulation warms, as the moisture in the insulation absorbs and undergoes a phase change. That phase change can absorb a significant amount of heat without raising the temperature, causing a "heat sink" effect. For the case with 15% moisture content, insulation at 40 mm thickness saw over 220 minutes, compared to the 170 minutes that dry insulation at the same thickness saw, a difference of about 30% in performance. Furthermore, the difference in fire resistance with increased moisture content and dry conditions became more prominent with increased thickness.

Keep in mind that moisture can enhance fire resistance at first; however, this benefit does not last long. After moisture evaporates, the insulation's thermal properties will depend on its dry state. Also, in practice, environmental conditions will influence the moisture content, and extreme moisture content presents other problems like excess weight, deterioration of the material, and loss of adhesion. Therefore, in order to be conservative, the dry-state performance should be the basis of design specifications, even if slight moisture will provide limited benefits in fire resistance for a short period.

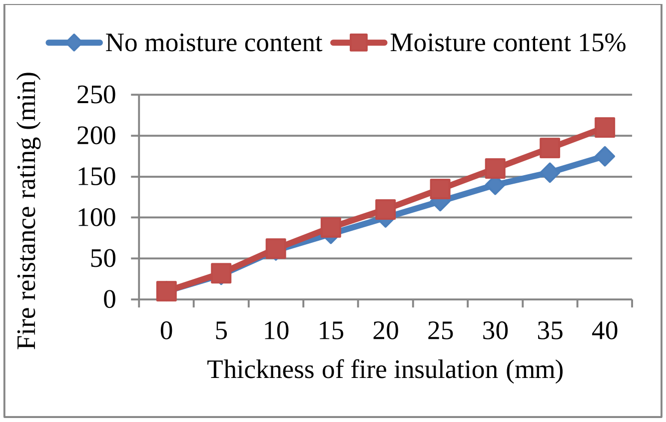

Fig. 3 Effect of insulation moisture content on fire resistance rating of the steel beam

This study's results reinforce how critical environmental factors and characteristics of insulation materials are in attaining the required fire resistance ratings of steel beams. The findings suggest that the use of low-thermal-conductivity materials results in fire resistance increases that are more consistent, predictable, and frequent than simply increasing the thickness of insulation. Although improving performance in the short term, the moisture content of the insulation should not be accounted for in design calculations due to its unpredictability and eventual dissipation during exposure to fire. One of the best fire protection techniques that satisfy fire rating requirements should, in the end, provide a reasonable compromise between insulation thickness, thermal conductivity, and moisture content durability. Increased thickness, which may lead to construction and weight issues, can be taken to offset performance deficits when low-thermal-conductive materials are not available or excessively priced.

This research is also beneficial when compared to the state-of-the-art techniques described in the literature, including large-scale fire tests and finite element simulations. Costly and often limited in scope, the realistic results provided by experimental testing fall short of advanced numerical modelling, which, although requiring extensive calibration and performing coupled thermal-structural simulations, is computationally intensive. Taking the ECCS best-fit method, this study analysed the systematic framework in parameters that focuses on the independent and combined effects of thickness, conductivity, and moisture. This approach captures the fundamental patterns documented in prior studies and builds on this by measuring the diminishing returns of thickness that are a little over 20-25 mm, the ~70% gain that is possible with low conductivity insulation, and the moisture's transient and, in practice, relevant effect. These insights promote design in a computationally efficient way, integrating experimental, numerical, and analytical methods, and an advanced state understanding of the fire protection of steel beams.

4. Conclusion

This study employed the ECCS best-fit method to examine how fire insulation attributes affect fire resistance ratings of steel beams. Factors like insulation thickness, thermal conductivity, and moisture content influence fire rating. A simply supported steel beam of UB 356 × 171 × 45 with unprotected insulation up to 40 mm thickness was studied under standard fire conditions. To measure their respective and combined effects on the time to reach the critical steel temperature, the analysis considered variations in moisture content (0% and 15%) and thermal conductivity (0.1 and 0.2 W/mK). The findings showed that in every case, the fire resistance rating increased as the insulation thickness increased, although the rate of improvement slowed after approximately 20 to 25 mm. Fire performance is greatly improved by lower thermal conductivity; for the same thickness, k = 0.1 W/mK offers up to 70% longer fire resistance than k = 0.2 W/mK. Because of the latent heat effects during evaporation, a 15% moisture content was found to increase the predicted fire resistance in comparison to the dry condition; however, this benefit was temporary and contingent on environmental factors. The results validate that, from a design standpoint, it is more effective to prioritise low-conductivity insulation materials rather than simply thickening them, especially for members with high section factors. Because of its unpredictability and eventual loss of moisture during extended fire exposure, moderate moisture content should not be relied upon in design calculations, even though it can temporarily improve the performance. Estimating fire resistance and analysing parametric changes to insulation properties and variations in the ECCS best-fit method provide valuable insight into initial design and optimization of fire protection systems.

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Ethical Approval

This study did not involve human participants, animal subjects, or confidential data, requiring ethical approval. All analyses were conducted with respect to academic integrity. The authors affirm that the data presented are original and have not been manipulated or fabricated.

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Author Contribution

RS prepared the manuscript, MS reviewed the manuscript, and RH reviewed the manuscript.

Data availability

Data analysis https://zenodo.org/records/16792192

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