Sheet steel - mineral wool fire protection in steel columns

Sheet Steel – Mineral Wool Fire Protection of Steel Columns

Protection contre le feu au moyen de tôle d'acier et de laine minérale

Brandschutztechnische Verkleidung aus Mineralwolle mit Stahlblechummantelung

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SUMMARY

The paper summarizes the results of fire tests of steel columns protected by various number of mineral wool layers separated by aluminium foils and covered by sheet steel box. The influence of different fixing methods and the cracks appearing in the corners of the columns of the efficiency of the protection system were studied. The efficiency of different protection systems is compared by the aid of virtual thermal resistances. The aim of the study was to develop a box type fire protection system which could be fabricated industrially to ensure better quality and lower costs.

RÉSUMÉ

Cet article rend compte des résultats obtenus lors d'essais de protection contre le feu effectués sur des colonnes en acier protégées par un certain nombre de couches de laine minérale séparées par des feuilles d'aluminium et revêtues d'une gaine en tôle d'acier. L'effet sur l'efficacité du système de protection de diverses méthodes de fixation et de fissures qui apparaissent dans les coins des colonnes est également étudié. La comparaison de l'efficacité des divers systèmes de protection s'est faite à l'aide de résistances thermiques virtuelles. Le but de cette étude était de mettre au point un système de protection contre le feu du type «à gaine» qui puisse être fabriqué de façon industrielle en vue d'en améliorer la qualité et d'en réduire le coût.

ZUSAMMENFASSUNG

Berichtet wird über Brandversuche an Stahlstützen, die mit mehreren jeweils durch Aluminiumfolien getrennte Mineralwollschichten und einem Mantel aus Stahlblech verkleidet waren. Untersucht wurde der Einfluss verschiedener Befestigungsarten sowie die Auswirkung von Rissen, die während der Brandprüfung in den Eckbereichen entstehen. Die Wirksamkeit der verschiedenen Systeme wurde verglichen mit Werten, die nach der Methode der virtuellen thermischen Widerstände errechnet worden sind. Ziel der Untersuchungen war es, eine Ummantelung zu entwickeln, die in hoher Qualität wirtschaftlich hergestellt werden kann.

1. INTRODUCTION

The aim of the production development project considered was to find out such a mineral wool fire protection system for steel columns, which would meet the requirements corresponding to different fire resistance times. The primary demand imposed for the structure was to be industrially fabricated to ensure better quality of the product and lower costs of workmanship.

Galvanized steel sheet casing systems containing different combinations of mineral wool of various densities, air gaps and aluminium foils dividing the mineral wool into multiple layers were selected and investigated experimentally. The effect of the fixing method of insulation layers (mechanical or gluing) as well as the painting of steel columns and steel boxes with paints lowering the emissivity were also examined. The protection systems assembled using mineral wool sheets imbricated in the corners were compared with those made by wrapping the mineral wool layers and aluminium foils around the steel column.

This kind of casing protection system consisting of mineral wool insulation fixed already in the factories into two halves of steel sheet boxes and locked together at the building site was chosen by the reason of before mentioned advantages. In addition the compact protection system is also easy to be transported and mounted at the building site. Covering steel sheets protect the light-weight insulation layers from damages during storing, transportation, building and usage.

The experimental work was carried out in the Fire Technology Laboratory of the Technical Research Centre of Finland and was sponsored by the steel company Rautaruukki Oy and mineral wool manufacturer Oy Partek Ab.

2. EXPERIMENTAL WORK

2.1 Test specimens

The steel columns used were steel tubes Fe 44 D with dimensions of 200×200 mm^2 and wall thickness 10 mm. The length of columns varied from 2300 mm to 3200 mm. One of the most slender load-bearing column types ($F/V \approx 100\ m^{-1}$) was selected for tests in order to find out the most critical case. Altogether 28 columns were tested. The cross sections of the columns with insulation layers are presented in Fig. 1.

The insulation consisted of two kinds of mineral wool layers, the light one with density of 40 kg/m^3 and the heavier with density of 140 kg/m^3. The different mineral wool layers were separated by aluminium foils with thickness of 0.04 mm to reduce the heat convection and radiation through insulation layers, which has significant influence in heat transfer for example in case of lightweight insulations. The aluminium foils were either glued onto the mineral wool sheets or they were wrapped around the column between different insulation layers. The outermost mineral wool layer was fixed to the steel sheet either mechanically by steel nails welded on the steel sheet casing or by silicate glue (1.2 kg/m^2).

The covering steel box was made of hot zinced steel sheets with thickness of 1.0 mm. The two halves of the box were locked to each other in the corners and additionally screwed.

Steel tube and the inner surface of the steel sheet box were painted with silicon-aluminium paint to reduce the emissivity and increase the surface thermal resistance.

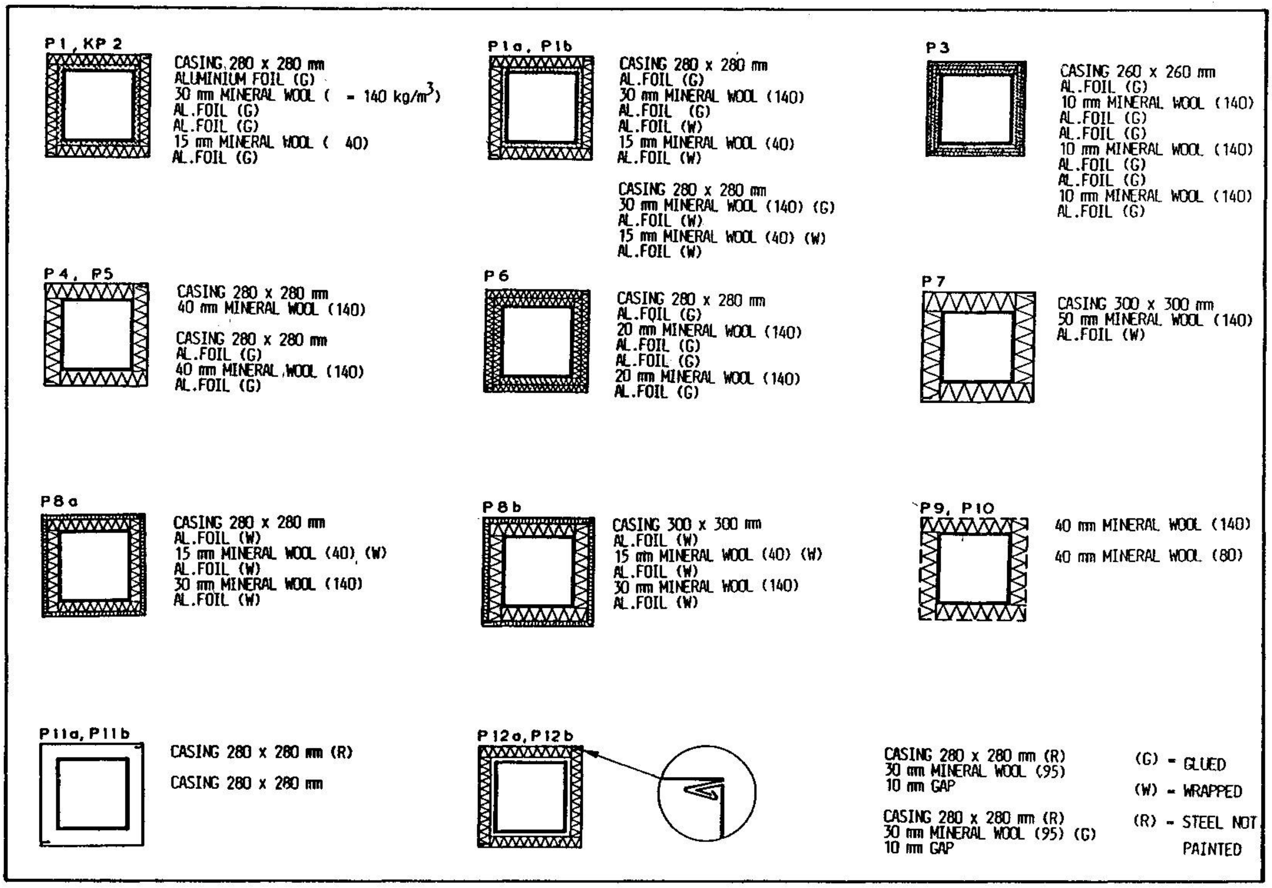

Fig. 1. Cross sections of the columns

2.2 Test arrangements

The tests were performed according to the international testing standard ISO 834. The columns were mounted vertically inside the furnace and tested unloaded (Fig. 2a) Four of the tests were carried out so that the column passed through the ceiling and the bottom of the furnace (Fig. 2b) in order to find out the cooling effect of the penetration.

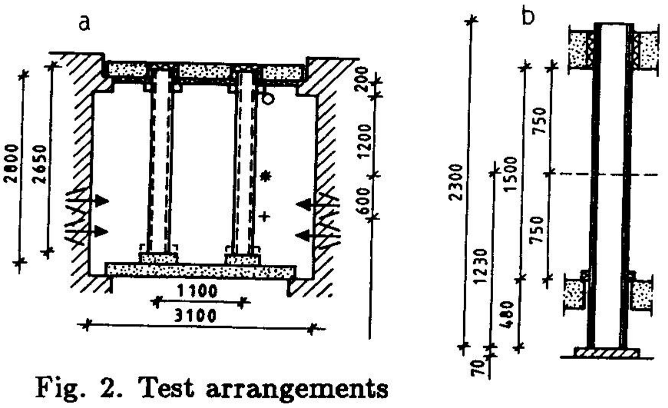

Fig. 2. Test arrangements

During the tests the temperatures of the steel tube, the aluminium foils and the steel sheet casing were measured at the midheight of the column.

3. THE VIRTUAL HEAT RESISTANCE

3.1 Heat conduction model

The problem can be approximated mathematically as a one-dimensional heat conduction problem in the region $0 \leq x \leq L$ with unit area, in which L is the total thickness of insulation layers. The initial temperature T_0 is the temperature of the environment and the

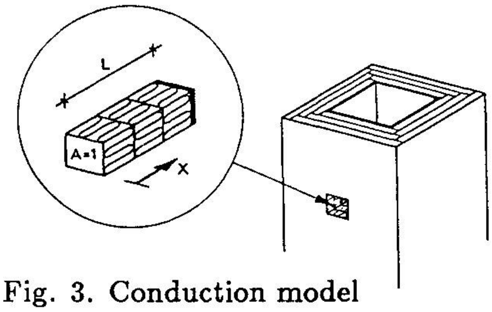

Fig. 3. Conduction model

temperature in the furnace $T_1(t)$ follows the standard time-temperature fire curve (ISO 834). Due to the symmetry of the structure the heat flow is assumed to be one-dimensional. The heat is tranfered to the surface of the casing by convection and radiation and flows through the insulation layers to the steel column which is assumed to be in perfect thermal contact with the insulation.

The mathematical formulation of the problem is

$$\frac{\partial}{\partial x}\left(k^{(i)}\frac{\partial T}{\partial x}\right) = \rho^{(i)}c^{(i)}\frac{\partial T}{\partial t}, \quad 0 \leq x \leq L, \quad t \geq 0 \tag{1}$$

with the initial condition

$$T(x,0) = T_0 \tag{2}$$

and the boundary conditions

$$k^{(i)}\frac{\partial T}{\partial x} = h(T_1(t) - T) \quad at\ x = 0 \tag{3}$$

$$k^{(i)}\frac{\partial T}{\partial x} + \rho^{(s)}c^{(s)}\delta^{(s)}\frac{\partial T}{\partial t} = 0 \quad at\ x = L \tag{4}$$

In Eqs. k, ρ and c are material properties conductivity, density and specific heat, respectively, h is the heat transfer coefficient at the outer surface of the structure and δ is the wall thickness of the steel column. The superscripts i and s correspond to the insulation material and steel, respectively.

The test results showed that the difference between the temperature of the casing and the temperature of the furnace was very small after some first minutes of the test, so the boundary condition (3) could be replaced by the condition of equality of the temperatures of the casing and the furnace.

3.2 Calculation of virtual heat resistance

In the structure considered the heat flow is directed towards the steel column through various insulation layers. These layers and the outer surface of the structure (emissivity etc.) constitute a resistance for the heat flow. This resistance describes very well the efficiency of the insulation system. The resistance can be determined for separate insulation layers or for the total system. It is defined at $x = x_j$ for the insulation layer with thickness δ by the equation

$$R_j = \frac{\delta^{(i)}}{k^{(i)}} = \frac{\delta^{(i)}\frac{\partial T}{\partial x}}{\dot{q}(x_j,t)} \tag{5}$$

in which $\dot{q}(x_j,t)$ is the heat flow through the surface considered.

The heat resistance of the insulation layer between coordinates (x_j, x_{j-1}) is calculated at the time $t = t_m$ using the scheme

$$R_j = \frac{(T_j^m - T_{j-1}^m)\cdot\Delta t}{\sum_{k=j+1}^{N}\frac{1}{2}\rho_k^{(i)}c_k^{(i)}\delta_k^{(i)}\left(T_k^m - T_k^{m-1} + T_{k-1}^m - T_{k-1}^{m-1}\right) + \rho^{(s)}c^{(s)}\delta^{(s)}\left(T_s^m - T_s^{m-1}\right)} \tag{6}$$

in which the superscript m of the temperature T corresponds to the time t_m and subscripts j and s to the coordinate x_j and to steel, respectively. The total number of insulation layers is N.

4. TEST RESULTS

The influence of different insulation systems on the thermal behaviour of the columns can be seen in Figs. 4-12 which present either the steel temperatures or the heat resistance of various fire protection systems.

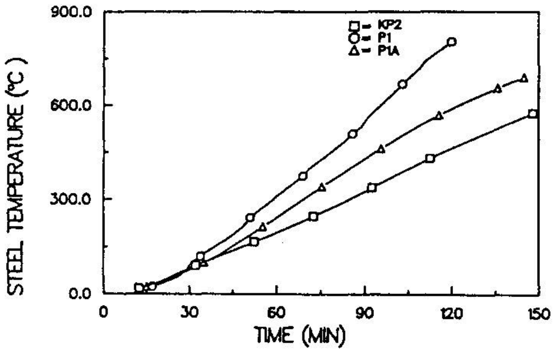

Fig. 4. Steel temperature vs. time

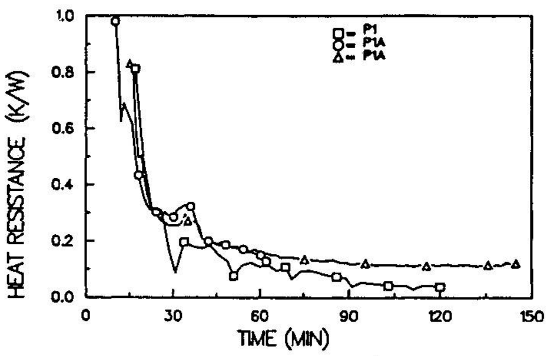

Fig. 5. Heat resistance vs. time

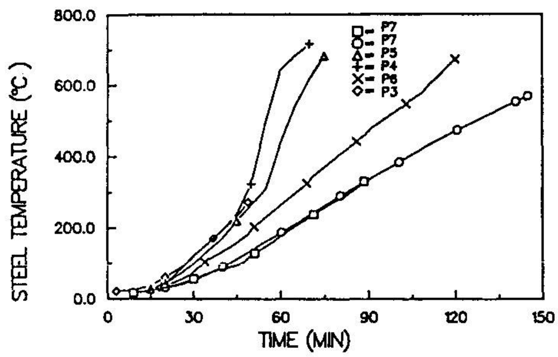

Fig. 6. Steel temperature vs. time

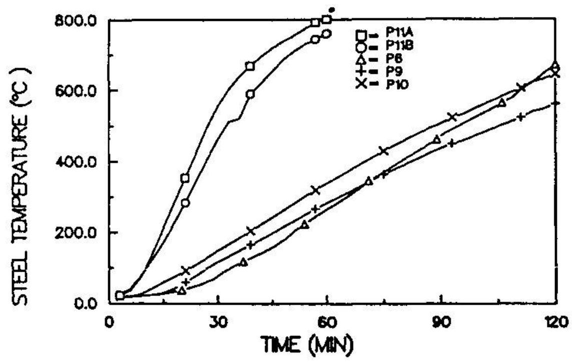

Fig. 7. Steel temperature vs. time

Fig. 4 shows the effect of the assemblage of the column. The column KP2 passed through the ceiling and the bottom of the furnace in the test and the column P1 with similar insulation was mounted totally inside the furnace. The difference in the steel temperature is significant.

Fig. 5 describes the difference between the imbricating (P1) and wrapping (P1A) of the innermost insulation layer by the aid of the virtual heat resistance of the total protection system. The same effect is to be seen in Fig. 4 showing the respective steel temperatures.

The influence of the thickness of the imbricated mineral wool protection and the aluminium foils dividing the mineral wool into several layers can be seen in Fig. 6. The steel temperatures of the columns P3 and P6 where mineral wool was divided into layers show the beneficial influence of the aluminium foils reducing the heat transfer by convection and radiation. The influence of steel sheet box comes apparent in Fig. 7. The steel temperature show that the column protected only with the casing (P11A, P11B) can reach the fire resistance time of 30 min. The casing retards the steel temperature rise, which can also be seen when comparing the steel temperatures of wool insulated columns with casing (P6) and without (P9, P10).

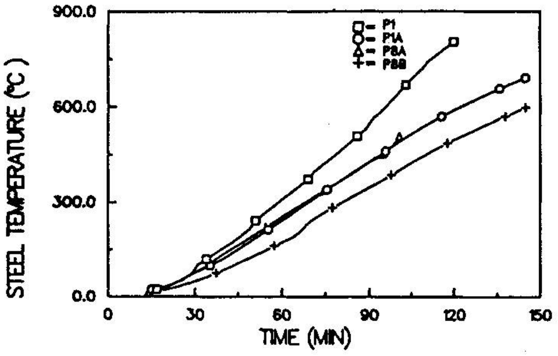

Fig. 8. Steel temperature vs. time

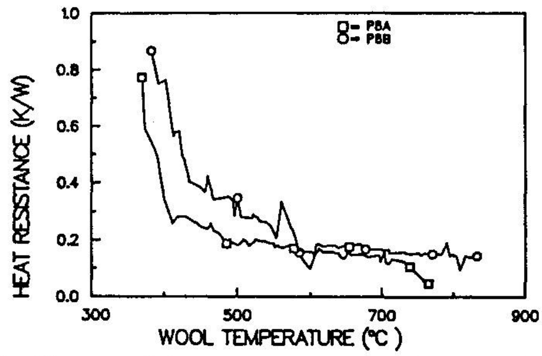

Fig. 9. Heat resistance vs. average temperature

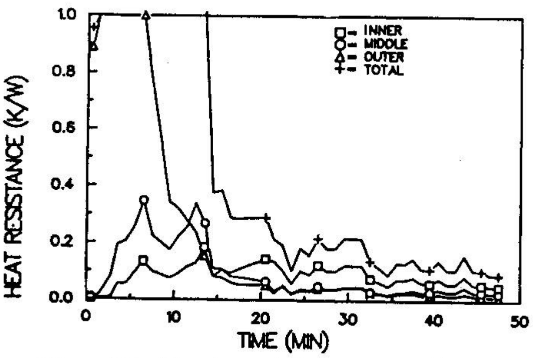

Fig. 10. Heat resistance vs. time

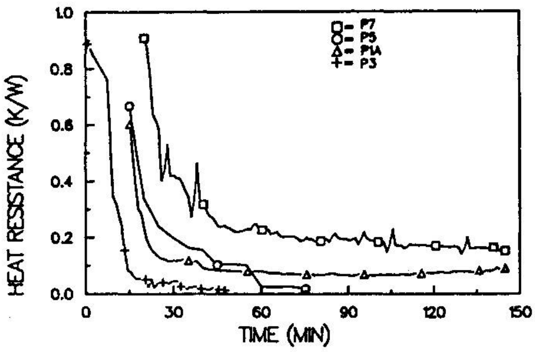

Fig. 11. Heat resistance vs. time

In the columns P1A and P8A the light and heavy mineral wool layers were located in the reverse order. This had no influence on the steel temperature as can be seen in Fig. 8 When the same insulation layers were packed looser in the bigger casing the steel temperature rise was considerably lower (P8A, P8B). The virtual heat resistance curves which were calculated from the experimental data show the same effect in Fig. 9.

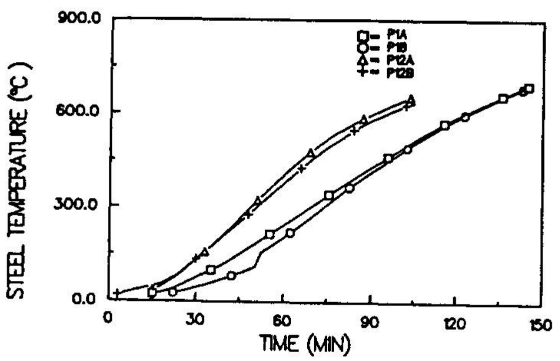

Fig. 12. Steel temperature vs. time

Fig. 10 depicts the function of the insulation system (P3) by the aid of heat resistance curves. At first the outermost layer is activated and after certain time the inner ones begin to act.

The heat resistances of the outermost mineral wool layers having different thicknesses are presented in Fig. 11. Fig. 12 shows that the type of fixing the outermost mineral wool (mechanical $\Longleftrightarrow$ gluing) has only a minimal influence on the development of steel temperatures.

5. CONCLUSIONS

Test results show that best results concerning fire resistance can be obtained when using a system composed of a wrapped layer of light mineral wool combined with a heavier one. Wrapping prevents the formation of critical cracks in the corners of the insulation casing and retards so the heat tranfer by convection. Sequential arrangement as well as number of different layers and aluminium interlayers and the painting of the steel tube respectively the interior of the steel sheet box are of minor importance. The type of fixing the mineral wool to the casing has nearly no influence. Although the steel sheet casing reduces convection and heat transfer a little,it practically does not extend the fire resistance time.