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Rational design of hollow core planks for fire resistance

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ABSTRACT

The utilization of precast hollow core plank systems in multi-storey buildings is prevalent these days. This is due to small onsite labour cost and high quality control. Precast hollow core planks are most extensively known for providing economical, efficient floor and roof systems. When properly matched for alignment, the voids in a hollow core planks may perhaps be utilized for electrical or mechanical runs. Among different precast plank systems, prestressed hollow core planks are the most well accepted system because of their lightweight nature and the economical use of concrete. Yet the structural behaviour of such systems under fire exposure is not clear-cut to be predicted because of the complex geometry, composite construction and an extensive range of possible support conditions. The aim of this paper is to discuss the characteristics of hollow core planks and the advantages of this system. Additionally, evaluation on the requirements and recommendations to the fire design of concrete planks from different standards will also be presented. These requirements will form the framework of future research focuses on providing a new method for the fire design of structures with hollowcore concrete plank systems.

Keywords : Precast planks, flooring system, slab system, fire design, hollow core slab, fire resistance

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INTRODUCTION

The precast concrete plank systems are becoming established and well accepted in many countries throughout the world due to low onsite labour cost and high quality control. Over the past four decades, hollow core plank system has become the material of choice for housing and low-rise commercial premises, largely replacing timber. Among diverse precast plank system, prestressed hollow core concrete planks are among the popular because of their light weight and the economical use of concrete (Figure 1).

Figure 1. Precast concrete plank systems

Hollow core concrete plank systems are precast and pre-tensioned concrete planks. Dimensions of every unit is 1.2m wide, the depths of available unit are 150, 200, 300 or 400 mm, and the span length can be up to 20 m for 400 mm deep units. The units span one-way, and the current practice in all countries requires a layer of cast in-situ topping concrete which increases the shear strength and connects the hollow core concrete units together laterally. The topping concrete can offer the completed floor some two-way spanning ability. There are two different processes that can be employed to create the voids within the hollow core units: extrusion or slip form. In this process, zero slump concrete is pierced by an extrusion machine which creates the voids [1]. Due to the nature of this process, it is not possible to include reinforcement in the hollow core concrete units. The prestressing strands are placed in the casting bed and stressed before the concrete is cast. With pre-tensioned concrete, anchorages for the prestressing steel are not used and the prestressing force in the strands is transmitted to the concrete only by bond stresses [2].

It should be pointed out that it is broadly acknowledged that the behaviour of hollow core planks under fire condition is more complex than that of solid planks. The cavities at the centre of the slabs cause discontinuity of the thermal transfer, and the thermal gradient needs to be addressed correctly to precisely model the temperature induced mechanical strains in the webs [3]. The support conditions also have major influence on the structural behaviour of floors [4], this is particularly so in hollow core plank system [2, 5], and the effect of the support conditions should be considered in design. The existence of prestressing stress has been verified to noticeably influence the envisaged overall structural performance [6] as the hollow core units have no reinforcing and the resistance to tensile stresses comes from the prestressing tendons. Hence, the fire design of the hollow core plank system needs to be proficient to accommodate different support conditions in diverse building types, and the designers should also distinguish the fact that prestressed structural members exhibit different behaviour to usual members.

Figure 2. Cavities at the centre of the planks cause discontinuity of the thermal transfer during fire condition

For that reason, it is very significant to distinguish the fire resistance of the floor planks in multi-storey building design. If the given fire resistance of the floor planks is less than the worst predictable fire severity, the outcome can be disastrous once the fire happens. Whilst the trend in the world of fire engineering is changing towards performance-based design, the present method to establish the fire resistance of hollow core concrete system is still using tabulated data from the concrete standards, which in many countries are based upon equivalent plank thickness and not actual experimental results. It is quick and simple for designers to use tabulated data for the fire design of hollow core concrete planks. Because tabulated data is not performance based, by using it the designers decide to pay no attention to the structural behaviour of hollow core plank systems under fire.

Thus, this paper will focus on the characteristics of the hollow core planks and the advantages. Furthermore, this particular paper will also compare the requirements and recommendations to the fire design of hollow core planks from different countries and code of practice.

1. ADVANTAGES OF HOLLOW CORE PLANKS

Hollow core planks are highly engineered structural products manufactured under factory controlled conditions. The advantages of this system are summarized in Table 1

Table 1. Advantages of hollow core planks

Advantages	Descriptions
Short construction time	Production and transport of hollow core planks is quick and simple. Additionally, because of decreased weight and suitable dimensions planks can be assembled directly from delivery vehicle, whereby reducing the effort and the time of assembly. Prefabrication is lowering the costs of expensive and complicated sheaths, and assembled slabs are used as a platform for works. Well established team of assemblers in one day can assemble up to 500m^2 of these slabs
Lighter in weight	The hollow core planks are lighter than custom prestressed slabs from 37 to 54%. Therefore, the cost of construction is lower, and pillars and beams are having less load. In addition, there are smaller dimensions for bearing constructions and for foundations
Large spans	Hollow core planks can bridge the spans of 16 m without any support, and accordingly it lowers the number of supports. These planks will transfer the load in one direction
Flexibility in design	Hollow core planks can be produced in different dimensions and carved under different angles in shape of rhombus, which gives the capability to the designers to form curved layout solutions.
Adaptive for any type of construction	Hollow core planks are not only used in prestressed concrete structures but in masonry and steel structures, despite of whether it is prefabrication or traditional construction
Saving in materials	Use of hollow core planks saves up to 50% of concrete and 50% of framework, all compared to traditional planks. It means that in structures of 1000m^2, 35 tons of concrete and 7.5 tons of framework is saved
Simple fabrication	Using the same amount of materials, labour and energy, you can produce 1m^2 of traditional slabs and 2.5m^2 of hollow core planks. Production of hollow core planks is entirely automated
Fast production	In 24 hours around 500 m^2 of hollow core planks could be fabricated
Loading	Hollow core planks can hold up to 2000 kg/m^2, typical for production plants and warehouses
Excellent quality	The production of hollow core planks are vastly equipped with machinery and performed in firmly controlled conditions
Hollow utilization	Production is highly equipped with machinery and performed in strictly controlled conditions
Fire resistance	Hollow core slabs are immune on fire with two levels of fire resistance REI 90 and REI 120 minutes
Sound insulation	Hollow core planks matching even the most precise standards, and are suitable for all types of buildings particularly for housing facilities.
Various saving	Since they are smooth, these planks do not need formation of descending ceilings

2. FIRE DESIGN REQUIREMENTS AND RECCOMENDATIONS OF HOLLOW CORE PLANKS

In terms of the structural stability and safeguard against fire spread, the structural members exposed to fire shall allow sufficient time for people to evacuate securely and also allow fire service personnel to undertake rescue and fire fighting operations. This is achieved by providing structural members with a fire resistance rating in accordance with ISO834 [7]. Within the claimed duration of fire resistance under the ISO834 standard fire shown in Figure 3, the load capacity of the floor should be maintained, flames or hot gases should not penetrate the planks, and the floor should prevent an average temperature rise of 140°C or a local maximum of 180°C on the unexposed face. These three requirements, in such order, are also known as the stability, integrity and insulation criteria for the structural members.

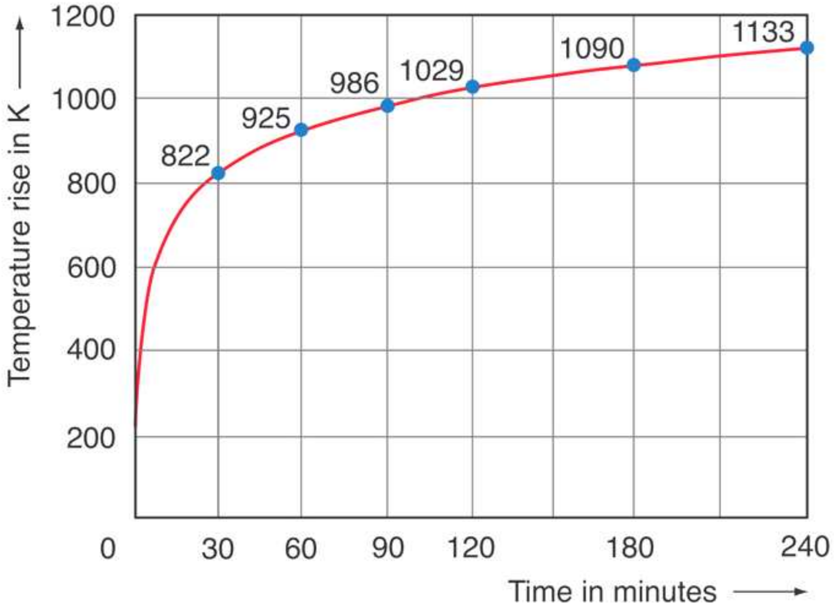

Figure 3. ISO 834 standard temperature-time curve [7]

In Europe, the performance requirement of the structures in fire is defined in Eurocode 1 which includes an adequate level of load bearing ability, as well as integrity and insulation of the structural members to allow the evacuation of the occupants and the rescue operation by the fire-fighters.

3.1 Eurocode requirements and recommendations
Eurocode 2 [8] for the design of concrete structures re-states the idea of retaining stability, integrity and insulation of the structural members as stated in Eurocode 1, but with much more detail. Other than using engineering design, Eurocode 2 also provides information on concrete planks to fulfil there criterions which are stability, integrity and insulation. Stability is the standard specifies a minimum concrete cover to the tendons to achieve a particular fire resistance rating. This is also affected by the rotational restraints at the supports. Hence the fire resistance of continuous planks are considered separately, and the two-way supported planks are considered separately from one-way supported planks and have different fire resistance based on the aspect ratio. Integrity is the standard states that a plank has a fire resistance rating for integrity if it meets the requirements for both insulation and stability for that rating. Finally insulation is the criterion which depends on the effective thickness of the planks and the type of aggregate of the concrete. The effective thickness of hollow core planks is the net cross-sectional area divided by the width of the cross section. In addition, Eurocode 2 also provides three alternative design methods for calculating the fire resistance:

i. Simplified calculation methods
Eurocode 2 suggests two simplified calculation methods for assessing the ultimate load-bearing capacity of heated concrete members: 500°C isotherm method and zone method. The first method disregards the part of the cross section with concrete heated above 500°C and full strength is used for the remaining cross-section. In the second method the cross section of the element is divided into zones, each with a different amount of strength.

ii. Advanced calculation methods
Advanced calculation methods are based upon the fundamental physical behaviour aiming to provide a reliable approximation of the expected structural behaviour under fire. Both thermal and mechanical analysis should consider the temperature dependent properties of the materials. The result should be verified against relevant test results.

iii. Tabulated data
This tabulated data gives standard fire resistance based on minimum plank thickness and cover to the reinforcement.

3.2 ASTM E119 requirements and recommendations
ASTM E119 [9] specifies laboratory procedures and criteria for determining fire resistance ratings of different proprietary floor systems. Fire testing of concrete members or assemblies according to ASTM E119 is often decided on the following two criteria [10]:

i. Heat transmission
This criterion limits the temperature rise of the unexposed surface. To meet this criterion, the walls, floors or roofs are required to have a sufficient thickness.
ii. Load carrying ability

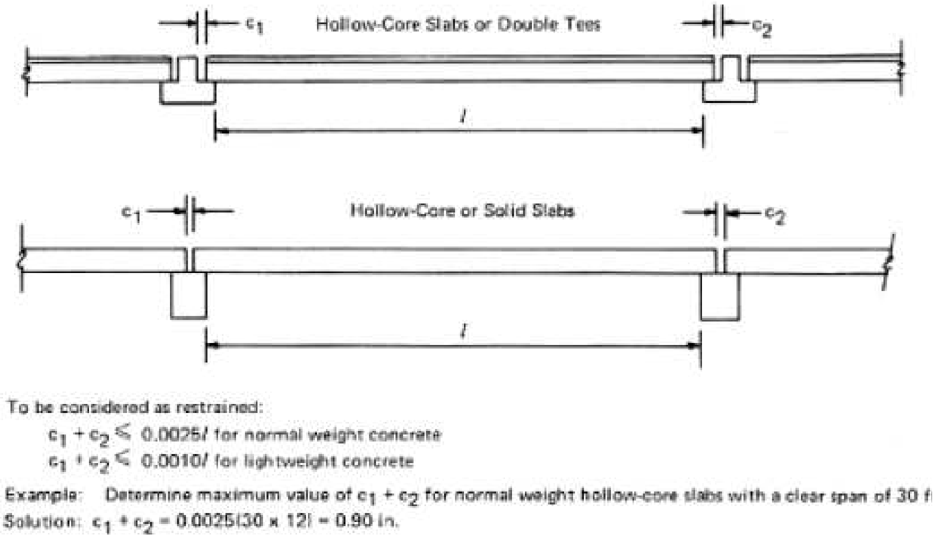

Figure 4. Definition of restraint by ASTM E119 for precast systems [9]

This criterion limit the thermally reduced yield strength of steel reinforcement be at least 50% of the yield strength at ambient temperature. This is achieved by providing sufficient thickness of concrete cover. ASTME119 also recognises the difference in the fire resistance of concrete floor planks caused by the restraint conditions at the supports. For a precast plank system to be qualified as restrained, ASTM119 states the requirement that the space between the ends of precast units and the vertical faces of the supports, or between the ends of solid or hollow-core plank units does not exceed 0.25 percent of the length for normal weight concrete members or 0.1 percent of the length for structural lightweight concrete members. This definition is schematically illustrated in Figure 4.

3.3 Prestressed Concrete Institute (PSI) requirements and recommendations

According to the 1989 design manual from PCI Fire Committee, it shows some calculation methods to evaluate the fire resistance of structures with precast and prestressed concrete but not specifically for hollow core planks [11]. The standard fire follows ASTM E119, in which the time-temperature curve is shown along with the ISO834 standard fire in Figure 5.

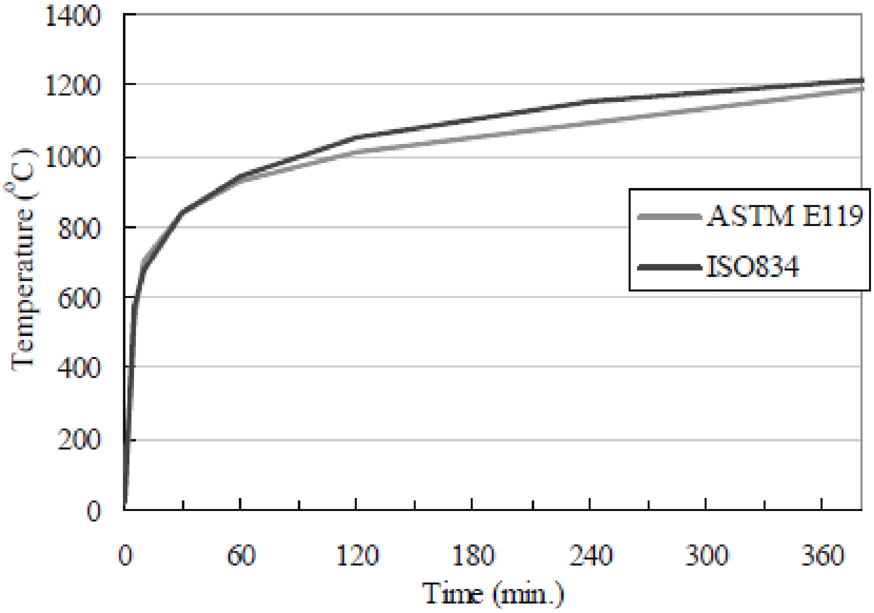

Figure 5. Standard fire temperature curves

The manual considers different restraint conditions on the planks. In simply supported planks the ends of the plank are free to rotate and move. The recommended calculation method focuses on the flexural failure mode; this is reflecting the fact that in all the fire tests none of the simply supported prestressed planks designed according to ACI 318 has failed in shear. This flexure calculation method considers the loss of moment capacity during fire, resulting from the reduction of tensile strength in the prestressed strands and not by the loss of compressive strength in concrete. This is because the compression zone, which is near the top of the plank, remains at low temperatures during fires. The steel or concrete temperature with different cover thickness or depth after different time of exposure is obtained from experimental results and given as graphs in the manual.

The continuous plank is taken as having an intermediate support in the simply supported plank, therefore both ends of the plank can still rotate and displace freely, but the bending moment diagram is different due to the presence of the intermediate support. The schematic drawing of a continuous plank, as well as the bending moment diagrams before and after the exposure of fire are shown in Figure 6. In the continuous plank the topping is used to provide continuity across the support, but it has been observed that the reinforcing bars in the topping around the support, which are the negative moment reinforcement, yield early during the fire tests and cause the redistribution of bending moments [12]. The behaviour of continuous beams and planks in fire was tested on a series of 300mm by 350mm deep beams. At the support there are six no.6 (20mm diameter) reinforcement bars at the top and two at the bottom, at the midspan there are two bars at the top and four bars at the bottom.

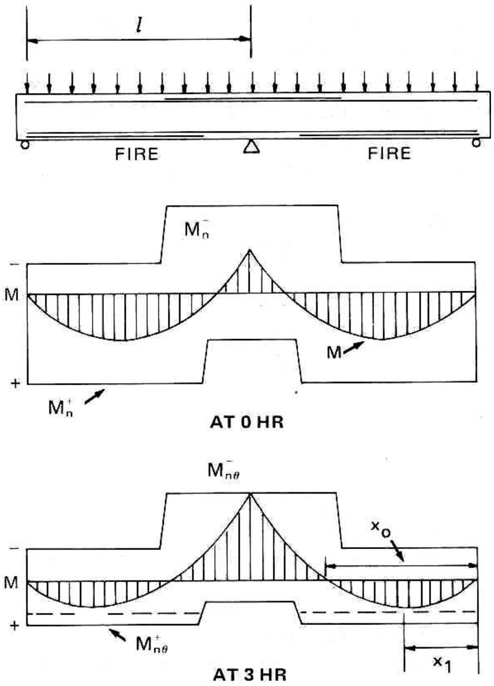

Figure 6. Schematic drawing of a continuous plank; the bending moment diagram at cold condition and after 3 hours of the ASTM E119 standard fire [9]

During the fire test the bottom of the beams was hotter than the top; therefore it expanded more and created thermal bowing. The thermal bowing caused the ends of the beam to lift from their supports and consequently increased the reaction at the interior supports causing a redistribution of moments. In summary, thermal bowing increases the negative moment along the length of the beam.

When the negative moment reinforcement yields, the negative bending moment capacity is reached, hence the amount of moment redistribution depends upon the amount of negative moment reinforcement. It is important to limit the negative moment reinforcement so that compression failure in the negative moment region does not occur. Furthermore, the length of the negative moment reinforcement must be long enough to accommodate the complete redistributed moment and change in the inflection points. Therefore it is recommended that at least 20% of the maximum negative moment reinforcement is extended throughout the span.

This design method indicates that the positive bending moment capacity can be designed as for simply supported plank, and the negative bending moment capacity should be designed as the total bending moment minus the positive bending moment. The total moment is the maximum bending moment the beam or plank would encounter if it is simply supported, for uniformly distributed load that means $wL^2/8$, where w is the uniformly distributed load and L is the length of the span; the positive bending moment can be obtained from the figures in the appendix of PCI Design for Fire Resistance of Precast Prestressed Concrete [11] or tables in Chapter 5 of PCI Design Handbook [13].

3. ENGINEERING DESIGN METHOD

All the standards mentioned above allow for using an engineering design method to calculate the required dimensions for structural members to meet the desired fire resistance. There are several computer programs available to analyse the behaviour of concrete structures under fire conditions, in both micro and macro scale. Due to the advancing of computational power, finite element programs such as Vulcan [14] and SAFIR [15] are used not only for research or forensic analysis purposes but also for design by industry. Nevertheless, in terms of fire design of hollow core concrete planks, to the author's knowledge there is no ideal computer model for such purpose so far, hence one of the aims of this research is to create such a model.

4. PROPRIETARY FIRE RATING OF HOLLOW CORE UNITS

Proprietary fire rating is the fire resistance rating of proprietary products made by specific manufacturers. These ratings are obtained by either testing or by calculation depending on the manufacturers, and the engineer should consult the manufacturer to confirm the accuracy of the fire rating. In the US, Underwriters Laboratories has conducted more than 30 standard fire tests on hollow core floor assemblies and published the results for more than 50 designs of hollow core planks which qualify for ratings of 1 to 4 hours. For hollow core units not found in the

Underwriters Laboratories ratings, the fire resistance rating can be obtained by conducting standard fire tests in accordance with ASTM E119 [9] as mentioned before or by using the effective thickness method described in the PCI Manual [11]. Engineers should give different levels of caution to the prescribed fire ratings depending on the methods used.

CONCLUSION

This paper has discussed some significant characteristics of the hollow core planks and recommendations and requirements to the fire design of from different countries and code of practice. It is vital to distinguish the fire resistance of the floor planks in multi-storey building design. If the given fire resistance of the floor planks is less than the worst expected fire sternness, the result can be devastating once the fire occurs. It is expected that the obligations and requirements discussed in this paper will shape the framework of potential and future research focuses on providing a new means for the fire design of structures with hollow core concrete plank systems.

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