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Review

Review of concrete flat plate-column assemblies under fire conditions

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ABSTRACT

The flat plate-column connection is a critical region in concrete structures because of the possible punching shear failure due to brittleness, which is aggravated in the presence of fire. Many studies have been carried out on flat plate-column connections in ambient conditions. However, only a handful of experimental works have examined this region's behaviour under high temperature conditions. This paper aims to present, discuss, and compare the available experimental tests on the mechanical behaviour of flat plate-column connections under high temperatures. The effects of decay on concrete material properties, as well as test configurations, support types, load conditions, and other parameters, are discussed. Moreover, this paper presents the available thermo-mechanical models that evaluate the behaviour of this region in fire conditions.

1. Introduction

Fire accidents continue to occur despite developments in the construction industry to avoid such cases. Therefore, studies that clarify structural and structural member performance under fire conditions are still required. According to the International Association of Fire and Rescue Services [1], 40% of fire accidents around the world during 2013 were defined as structural fires. Moreover, in the USA, 494,000 structural fires were reported during 2014–2015. In England, 154,700 fire incidents were recorded, 28,200 of which were accidental dwelling fires. Therefore, the fire phenomenon should be understood and the performance of buildings under both ambient and fire conditions should be well assessed. This assessment can be conducted experimentally or with analytical and computational tools.

An active and easier way to assess a structure's behaviour is by investigating the critical elements and the connections between them, i.e., the candidate failure regions. One critical region in concrete structures is the flat plate-column joint. Flat plates are widely used worldwide because of their constructional and economical advantages. However, this type of connection has a significant risk of punching shear failure due to brittleness around the columns. Although a vast number of experiments have been listed in the databank [2] on slab-column connection behaviour during the last few decades, punching shear behaviour is complex and difficult to understand; thus, it requires more study.

Because the flat plate-column connection is a critical region in concrete structures, special provisions in concrete design codes were issued to avoid its punching shear failure. In the case of accidental fires, material strength decay can lead to the punching shear failure of this critical region, followed by the probable collapse of the structure. Therefore, the behaviour of flat slab-column connections under high temperatures should be studied intensely.

A handful of experimental and numerical studies on the slab-column connection are available. Most of these experiments were designed for different cases; e.g., different fire scenarios, test setups, and applied loads. This paper aims to present a state-of-the-art literature review on proposed thermo-mechanical behaviour models of concentric flat plate-column connections under high temperatures. Summarized reviews of recent information about punching shear strength and the effect of fires on structures, materials, and concrete's mechanical properties are also included in this article.

2. Flat plate under fire conditions

The criterion for determining a structure member's endurance for a specific period of fire exposure is that it must neither collapse nor reach a specific temperature on the side away from the fire. Shear failure due to fire is generally uncommon for ordinary structures; however, for flat plates, the case is different [3].

In general, any study on flat plate's behaviour under fire conditions should cover three main themes: fire scenarios, thermal analysis, and structural behaviour. For fire scenarios, most investigations are based on one of two standard temperature-time curves, either ISO 834 (the

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International Standard Organization's fire resistance tests) [4] or ASTM E119 (the American Society for Testing and Materials' Standard Test Methods for Fire Tests of Building Construction and Materials) [5], while only a few real fire tests were found in the literature. In this paper, the term ‘real fire’ refers to full-scale fire tests using burned materials.

Bamonte et al. [6] and Annerel et al. [7] studied the effects of a real fire model on an underground car park structure constructed using the slab system with slab-column connections. The results of the two studies showed that heating the non-uniform spans resulted in increased shear force in the slab-column joint. Subsequently, it led to an increase in the column axial force by 50% more than in ambient conditions; this is attributed to the varying thermal curvature. Moreover, a comparison between a real fire and the ISO 834 standard fire showed that the real fire caused a less severe thermal field, which means less deterioration in the material properties. However, the indirect effects, e.g., a redistribution of internal forces, were more severe in the real fire.

2.1. Thermal analysis of reinforced concrete slabs

In this section, the behaviour and effect of fire on concrete slabs is reviewed through a discussion on heat transfer and the degradation of the materials' thermal and mechanical properties.

2.1.1. Heat transfer in slabs

In a fire, the heat transfers along all three dimensions of the slab. However, because of the semi-infinite configuration of the slabs (the long two-plane dimensions of the slab compared to its thickness), the heat transfer can be analysed as a transient (unsteady) one-dimensional problem. This analysis would be easy if the slab was exposed to a standard temperature-time curve with a uniform temperature distribution on one side.

In most experimental cases, the initial conditions are assumed to be constant and uniform (initial temperature, thermo-physical properties, and no internal heat generation). However, the temperature distribution across the slab thickness is nonlinear; hence, the thermal strains are also nonlinear, while the total deformation (thermal elongation and thermal curvature) is linear [7]. This nonlinearity varies significantly between the concrete and steel in reinforced concrete. The concrete elements show obvious nonlinear behaviour with the temperature, while the steel elements seem to have linear behaviour. This is because of the significant thermal-conductivity difference between steel and concrete. The effect of the reinforcing steel bars on the temperature distribution is rather negligible.

The general three-dimensional heat-conduction equation can be reduced to one-dimensional heat conduction, as in Eq. (1),

$$\frac{\partial T(x,t)}{\partial t} = \alpha \times \frac{\partial^2 T(x,\ t)}{\partial x^2}, \tag{1}$$

subjected to $T(x,\ 0) = T_0$,where $\alpha = k_c/\rho c_p$ is the concrete thermal diffusivity, ρ is the density, c_p is the specific heat, and k_c is the thermal conductivity.

The solution to the heat-transfer equation should satisfy the initial and boundary conditions. The boundary conditions usually include the convection and radiation thermal loads on the exposed surfaces. The solution to the heat-transfer differential equation can be achieved using various analytical and numerical approaches. Among these methods are

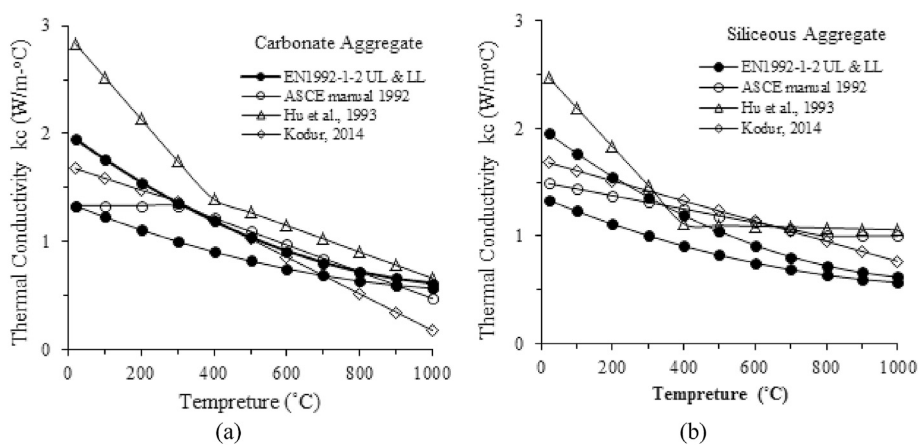

Fig. 1. Variation of concrete's thermal conductivity with temperature for (a) carbonate aggregate concrete and (b) siliceous aggregate concrete.

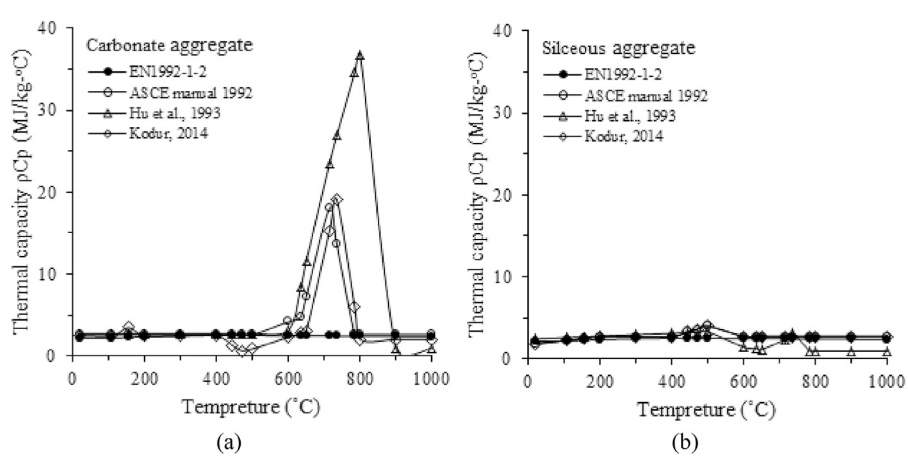

Fig. 2. Variation of the thermal capacity of normal-weight concrete with temperature for (a) carbonate aggregate concrete and (b) siliceous aggregate concrete.