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Structural analysis of reinforced concrete chimneys subjected to uncontrolled fire

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ABSTRACT

We studied the behavior and residual structural capacity of reinforced concrete chimneys subjected to an uncontrolled fire. We used a combination of a heat transfer finite element model – to obtain the temporal distributions of temperature during the fire event – and the structural model of concrete chimney design provided by the American Concrete Institute (ACI 307–08). This approach allows estimating the reduction in the vertical (axial) strength and moment strength of the chimney both during a fire and post-fire, and gives a direct estimate of the reduction in the safety factors of the concrete chimney. Using this method, we examined the impact of various design parameters on the residual structural capacity of a concrete chimney subjected to an internal fire. An iterative finite element method was also presented as an alternative to the ACI 307 calculations. Moreover, finite element calculations were used to study the role of thermal stresses on the axial strength of the chimney during fire. Our study provides insight into possible failure mechanisms of concrete chimneys damaged due to fire and could suggest possible approaches for minimizing the risk of chimney failure due to an uncontrolled fire.

1. Introduction

Concrete chimneys are used in power plants for venting hot flue gases or smoke to the outside atmosphere. In recent years, the height of power plant concrete chimneys has increased to enhance the draw of air for combustion and to disperse pollutants over a greater area to reduce pollutant concentrations. While the number of reported chimney collapses due to an internal fire is very small, the consequences of chimney damage could be costly in terms of economic and human loss. The popularity of fiberglass reinforced plastic (FRP) liners – which are combustible materials – has made the risk of a fire in tall chimneys even more relevant in recent years. The FRP liners are used in reinforced concrete chimneys to protect the chimney shell from the effect of hot flue gases. Some of the possible sources of ignition in chimneys with FRP liners can be hot work inside the chimney during FRP installation or maintenance, ignition of stored flammable materials at the base of the chimney, ignition inside the flue gas desulfurization system or other equipment upstream of the chimney.

A critical effect of an uncontrolled fire in a chimney is the reduction in concrete strength [1–6], which leads to a decrease in the chimney load carrying capacity and service life. At an elevated temperature, the concrete experiences a variety of chemical and physical changes. For example, large volume changes resulting from non-uniform thermal expansion of aggregates and shrinkage of the cement paste, results in cracking and spalling. Spalling which is usually explosive and critical for structural integrity, is induced by mechanical and thermal stresses and pore pressure [7]. Spalling generally occurs at high temperatures, even though it is also observed at temperatures as low as 200 °C [8,9]. For spalling to occur, there needs to be a minimum moisture content as well as a temperature gradient of approximately 5–8 K/mm [6]. Temperature gradients induced by heating or uncontrolled fire depend not only on the heating source temperature but also on the heating rate.

In Fig. 1, we have re-plotted the Eurocode 2 [10] data (curve 1) for a concrete with siliceous aggregates which is commonly used in tall chimneys. These data suggest that the concrete compressive strength at 600 °C reduces ∼50% from its strength at room temperature. This reduction in strength is qualitatively similar to the behavior of structural steel, where high temperature could lead to significant weakening and in many cases catastrophic failure of the structure [11–13]. However, steel strength almost fully recovers as the steel cools down after the fire, so there is little concern about the behavior of steel structures post-fire. Concrete strength further decreases as it cools down from a high temperature, as the incompatibility between the thermal deformations of the concrete constituents leads to propagations of existing microcracks and formation of new ones [4]. The amount of reduction in the strength of the concrete is a complex function of the cooling method and rate. Sakr and Hakim [4] measured the role of cooling methods on the residual compressive strength

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