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Defining the thermal boundary condition for protective structures in fire

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ABSTRACT

Protective structures are designed explicitly to fulfil a function that in many cases is an extreme event; therefore, an explicit design has to properly and precisely account for the nature of the solicitation imposed by the extreme event. Extreme events such as explosions or earthquakes are reduced to design criteria on the basis of either empirical or historical data. To determine the design criteria, the physical data has to be translated into physical variables (amplitudes, pressures, frequencies, etc.) that are then imposed to the protective structure. While there is debate on the precision and comprehensive nature of this translation, years of research have provided strong physical arguments in supporting these methods. Performance is then quantified on the basis of the structure's capability to perform its required function. Classified solicitations may then be used to translate performance into prescribed requirements that provide an implicitly high confidence that the structure performs its function. When addressing fire, performance has been traditionally determined by imposing standardized requirements that necessarily attempt to bear a strong relationship with the reality of potential events – the fire performance of a protective structure is thus defined as a fire resistance period. This paper addresses the concept of fire resistance and its relevance to the design of protective structures. The mathematical description of the thermal boundary conditions for a fire is of extreme complexity, therefore simplified approaches, that include the Fire Resistance concept, are currently used. By using classical heat transfer and structural engineering arguments, the work described herein demonstrates that an adequate level of complexity and precision for the thermal boundary conditions and input parameter is fundamental to correctly describe the response of a structure during a fire event. Simple criteria are presented to qualify the relevance of current approaches and to highlight important issues to be considered.

1. Introduction

The capability of a protective structure to perform its function is defined by a design process that should contemplate the different solicitations that a structure may have. In many cases, this requires understanding the effects of single or potentially multiple solicitations. Moreover, critical infrastructure is generally design to withstand combined hazards, therefore, protective structures are also generally designed to perform their function when affected by combined hazards. While protective structures can be designed to withstand the effects of fire, it is often necessary to introduce fire as part of a multiplicity of hazards. This is the case when designing mines protective seals against explosions, where fires tend to follow explosions, or when designing structures that protect the core of nuclear reactors that could be subject to terrorist attacks or earthquakes followed by fires. When considering the potential of combined hazards, the design of structural protection to fire assumes that the capability of the structure to withstand fire remains intact. This assumption has the potential of not being realistic (or even un-conservative), nevertheless, because of the nature of the fire safety design process, the assumption is often unavoidable. When designing for fire, performance is not explicitly calculated but is calculated on the basis of a presumption that "fire resistance" represents a worst case fire scenario condition that if imposed onto a single element of the structure, will result in a solicitation not exceeded by any realistic potential fire.

Fire is an extremely complex combination of physical phenomena that currently cannot be fully described by means of mathematical models. Thus, some level of simplification is always necessary. In particular, in the case of structural analysis the necessary simplifications are very significant because the structure also needs to be described. When focusing on structural performance, coupling between gas and solid phase is commonly avoided and the fire is treated as a thermal boundary condition. The choice of what is the appropriate complexity necessary for the thermal boundary condition and to what section of the structural system

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should it be applied remains a matter of current debate. This paper will review some basic concepts to clarify the implications of specific simplifications and establish simple criteria that allow to establish when more or less complexity is needed.

In current practice, the fire solicitation and its manifestation on the behavior of the structure is typically solely defined in the temperature domain and does not require any explicit quantification of heat transfer (energy conservation) or mechanical structural performance. During design, elements of the structure might be subject to the standard "fire resistance" testing procedures – for assuring the compliance of single elements considered in isolation. Single element performance under fire as part of a whole structural system behavior is rarely addressed. Once the requirements for "fire resistance" are met, then it is assumed that all serviceability requirements for the structure will be met independent of any other solicitation or the integral nature of the structural system. This approach implies strong simplifications that assume that global structural behavior can be bounded by single element performance assessment and that heat transfer from the fire to the structure can be adequately characterized by gas phase temperatures and standardization of the thermal environment (i.e. a standard fire resistance test using a furnace).

This paper examines the two stages that must be considered as part of any design process for a structureto withstand the effects of fire. Specifically considered are:

- the assessment of thermal performance i.e. the fire and how thermal energy released during fire is transferred into the structure;
- the structure. i.e. how the structure responds as a function of the thermal boundary conditions.

The paper evaluates, in very simple terms, the conditions under which certain simplification are valid or invalid – and thereby allows clarification of the limitations of current performance assessment procedures. Given the complexity of the fire-structure interactions there will be many criteria that can be used and a comprehensive treatment is beyond the scope of this paper. Instead, as a very relevant example, the focus of this particular paper is on the role of the thermal gradients in structural behavior inferring when it is necessary to precisely establish these gradients. This approach, in principle, applies to any structure, but in particular to protective structures, given their critical function.

2. Assessing thermal performance

2.1. Fire dynamics

At the core of a fire there is a flame or a reaction front that is effectively the result of a combustion process, and thus is governed by the mechanisms and variables controlling combustion [1]. The interaction between fire and its surrounding environment determines the behavior of the flame and nature of the combustion processes. An extensive introduction to the topic is provided by Drysdale [2].

As indicated by Drysdale [2], the dynamics of a fire involve a compendium of different sub-processes that start with the initiation of a fire and end with its extinction. The onset of the combustion process, i.e. ignition, in a fire is a complex process that implies not only the initiation of an exothermic reaction but also a degradation process that provides the fuel effectively feeding the fire. During a fire, it is common to have different materials involved in the combustion process, and given the nature of the fire growth many could be involved simultaneously but others sequentially. The sequence of ignitions of items in an enclosure will affect the nature of the combustion processes. Thus, ignition mechanisms set the dynamics of the fire and also are affected by the fire itself, creating a feedback loop [3].

Once a material is ignited, the flame propagates over the condensed fuels by transferring sufficient heat to the fuel until a subsequent ignition occurs. This process is commonly referred to as flame spread and is described in detail by Fernandez-Pello [4]. Flame spread defines the surface area of flammable material that is delivering gaseous fuel into the combustion process. The quantity of fuel produced per unit area is known as the mass burning rate. The mass burning rate multiplied by the surface area determines the total amount of fuel produced. If the total amount of fuel produced is multiplied by the effective heat of combustion (energy produced by combustion per unit mass of fuel burnt), it yields the heat release rate. Generally, the heat release rate is considered the single most important variable to describe fire intensity [5]. Given the nature of the surrounding environment, the oxygen supply might not be enough to consume all the fuel, thus in many cases combustion is incomplete (i.e. under-ventilated) and therefore the heat of combustion is not a material property but a function of the interactions between the environment and the fire. In these cases, it is usually deemed appropriate to calculate the heat release rate as the energy produced per unit mass of oxygen consumed multiplied by the available oxygen supply.

If the fire is within a compartment, smoke will accumulate in the upper regions of the compartment. Hot smoke will radiate and/or convect heat towards all surfaces in the compartment. If the surfaces are flammable, remote ignition of different materials might occur. If remote ignition occurs in the lower (i.e. cold) layer then the fire tends to suddenly fill the entire compartment. This transition is generally known as flashover. Before flashover, the lower layer tends to have enough oxygen to burn the pyrolyzing fuel and the heat release rate is determined by the quantity of fuel generated. This period is termed pre-flashover, fire growth or fuel limited fire. After flashover, fuel production tends to exceed the capability of air to enter the compartment, the compartment becomes oxygen starved and the heat release rate is determined by the supply of oxygen through the various ventilation inlets/outlets of the compartment (e.g. doors, windows, etc.). This period is termed as post-flashover, fully developed fire or oxygen limited fire. The process of fire growth and the definition of the different variables affecting it is provided by Drysdale [2].

For small compartments (approximately $4\,\text{m} \times 4\,\text{m} \times 4\,\text{m}$) a characteristic time to flashover is of the order of 4–6 min while the post-flashover period can reach tens of minutes depending on the compartment size and fuel available [6]. Structures tend to have high thermal inertia, thus the temperature increase, at the surface (or in-depth) of solid elements, to levels where the loss of mechanical properties is significant, takes also in the order of tens of minutes. Thus for purposes of structural assessment, the effects of fires tend to be only considered at the post-flashover stage [7]. The temperature inside the compartment as well as the burning rate can be established simply as a function of the available ventilation, this process can follow different levels of complexity; Drysdale [2] reviews all these. It is important to note, that while the compartment temperature can be established by means of a simple energy balance, the heat being transferred to each structural element does not necessarily correlate with this temperature [6]. These relationships and time scales are of particular importance for protective structures, given that fires can cover a very wide range of characteristics when originating in environments that are different from the conventional compartment. Any analysis involving unusual compartments will have to revisit the evolution of the fire in a very detailed manner because many of the assumptions embedded in current design practices will no longer be valid.

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