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Fundamental principles of structural behaviour under thermal effects

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Abstract

This paper presents theoretical descriptions of the key phenomena that govern the behaviour of composite framed structures in fire. These descriptions have been developed in parallel with large scale computational work undertaken as a part of a research project (The DETR-PIT Project, Behaviour of steel framed structures under fire conditions) to model the full-scale fire tests on a composite steel framed structure at Cardington (UK). Behaviour of composite structures in fire has long been understood to be dominated by the effects of strength loss caused by thermal degradation, and that large deflections and runaway resulting from the action of imposed loading on a 'weakened' structure. Thus 'strength' and 'loads' are quite generally believed to be the key factors determining structural response (fundamentally no different from ambient behaviour). The new understanding produced from the aforementioned project is that, composite framed structures of the type tested at Cardington possess enormous reserves of strength through adopting large displacement configurations. Furthermore, it is the thermally induced forces and displacements, and not material degradation that govern the structural response in fire. Degradation (such as steel yielding and buckling) can even be helpful in developing the large displacement load carrying modes safely. This, of course, is only true until just before failure when material degradation and loads begin to dominate the behaviour once again. However, because no clear failures of composite structures such as the Cardington frame have been seen, it is not clear how far these structures are from failure in a given fire. This paper attempts to lay down some of the most important and fundamental principles that govern the behaviour of composite frame structures in fire in a simple and comprehensible manner. This is based upon the analysis of the response of single

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structural elements under a combination of thermal actions and end restraints representing the surrounding structure.

Keywords: Composite structures; Thermal expansion; Thermal bowing; Restraint to thermal actions; Non-linear geometrical responses

1. Introduction

This paper is based upon work undertaken as a part of a large multi-organisation project of modelling the behaviour of steel framed structures in fire [1] (namely the full-scale tests at Cardington [2]). In executing this project and identifying the key governing phenomena it was found necessary to make use of the fundamental principles repeatedly in order to understand the complex interactions of the different structural mechanisms taking place. This led to the development of a number of important principles that were found to govern the overall behaviour of the structure. These principles are very useful in interpreting the results from much larger and sophisticated computational models and in helping to develop a coherent picture of the behaviour. Most of these ideas have already been presented at the INTERFLAM [3] and SiF [4] conferences.

This work was undertaken because the assessment of the adequacy of composite steel frame structures in fire continues to be based upon the performance of isolated elements in standard furnace tests. This is despite the widespread acceptance amongst structural engineers that such an approach is over-conservative and even more importantly *unscientific*. This view has gained considerable strength in the aftermath of the Broadgate fire [5] and has been reinforced by the Cardington tests. Current codes such as BS 5950 Part 8 and EC3 (draft) allow designers to take advantage of the most recent developments in the field by treating fire-related loading as another limit state. The advances in understanding structural behaviour in fire achieved in the last few years have been considerable with a large number of groups across Europe undertaking extensive research projects and concentrating on a number of different aspects of structural behaviour in fire [6–9]. These advances combined with the findings of the DETR-PIT project [1] make it possible for engineers to treat the design for fire in an integrated manner with the design of a structure for all other types of loading. This can be done by using the numerical modelling tools that have been instrumental in developing this understanding. However, the use of such tools, which are indispensable for research, is not practical in the design office. Exploitation of the new knowledge can only become feasible in practice if the understanding generated is further developed into simpler analytical expressions, enabling consulting engineers and designers to undertake performance-based design of steel frame structures without having to resort to large scale computation. The principles presented here constitute a step towards generating the analytical tools necessary for such use.

All analytical expressions developed in this paper have been developed ab initio from fundamental structural mechanics. The most fundamental relationship that