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Modelling the bond between concrete and reinforcing steel in a fire

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ABSTRACT

A non-linear procedure is presented for modelling the bond characteristic between concrete and reinforcing steel for reinforced concrete structures in a fire. The accuracy and reliability of the model are demonstrated by the analysis of one pull-out test and one beam test at ambient temperature and four full-scale beams tested under two fire conditions. The model is clearly capable of predicting the response of reinforced concrete members and structures in a fire with acceptable accuracy. The bond-link element has been found to have good computational stability and efficiency for 3D analysis of reinforced concrete structures in fires. It is shown that the bond condition between the concrete and reinforcing steel bar has an important influence on the fire resistance of reinforced concrete structures, especially when the temperature of the reinforcing steel bar is high (more than 500 °C). Hence, the current assumption of a perfect bond condition for analysis of reinforced concrete structures under fire conditions is unconservative.

1. Introduction

The behaviour of structures exposed to fire is usually described in terms of the concept of fire resistance, which is the period of time under exposure to a standard fire time–temperature curve at which some prescribed form of limiting behaviour occurs. In performance-based design this limiting behaviour may be defined either as real structural collapse or as a failure of integrity which would allow fire-spread to occur, but is more usually defined in terms of a deflection limit. The most recent design codes, EN 1992-1-2 [1] and EN 1994-1-2 [2] have taken a step towards full performance-based design by allowing designers to treat fire as one of the basic design limit states, taking account of:

- Non-uniform heating due to partial protection, which may be inherent in the framing system or specially applied,
- The level of loading at the fire limit state, using partial safety factors lower than those used for ultimate limit states, because of the relative improbability of such accidental combinations,
- Realistic stress–strain characteristics of structural materials at elevated temperatures.

The main limitation of these codified approaches is that they are based on the behaviour under test of isolated simply supported members, usually heated according to the standard ISO834 [3] time–temperature curve. In real buildings structural elements form part of a continuous assembly, and building fires often remain localised, with the fire-affected region of the structure being subject to significant restraint from cooler areas surrounding it. The real behaviour of these structural elements can therefore be very different from that indicated by standard furnace tests. An additional encouragement towards this end is the increasing volume of evidence from full-scale fire tests in building structures [4] that members which form part of a connected frame do not behave similarly to their performance in isolation in furnace tests. The interaction between the key effects (differential heating of cross-sections, material degradation as temperatures rise, and the capacity for load-sharing and restraint to thermal expansion provided by a cool surrounding structure) makes the real behaviour extremely complex. If such interactions are to be used by designers in specifying fire protection strategies as part of an integrated limit state structural design process rather than as an adjunct to it, then this cannot practically be based on large-scale testing because of the extremely high implicit costs. It is therefore becoming increasingly important that software models be developed to enable the behaviour of such structures to be predicted with sufficient accuracy under fire conditions.

In recent years a number of numerical models has been developed to represent the behaviour of reinforced concrete structures in fire [5–10], but none of these has taken the influence of the bond characteristic between concrete and reinforcing steel into account. In a number of previous research projects for modelling the bond characteristics between concrete and reinforcing steel at ambient temperature [11–21], two common types of models have been used. The first one is to use the so called bond-link element which connects the concrete element and the reinforcing steel element at the nodes [11–13]. Normally, the link element has no physical dimensions, for example, the

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two connected nodes from two different types of elements have the same coordinates at the beginning of the analysis. The second approach is to use a 'bond-zone connect' element [14–19]. In this approach, the characteristics of the contact surface between the concrete and reinforcing steel is represented by a material law which considers the properties of the bond zone. In this model it is assumed that the contact element provides a continuous connection between the concrete and reinforcing steel. Hence, a more fine mesh is needed within the bond zone area in order to achieve reasonable accuracy. In comparison, for modelling the global structural behaviour of reinforced concrete structures the bond-link element provides a reasonable compromise between accuracy and computational efficiency.

In recent years, a robust 3-noded beam–column element has been developed at the University of Sheffield for 3D modelling of steel, composite and reinforced concrete frames under fire conditions [22,23]. In this model both material and geometric non-linearities are considered. The cross-section of the beam–column element is divided into a matrix of segments, and each segment may have different material, temperature and mechanical properties. The complications of structural behaviour in fire conditions, such as thermal expansion, degradation of stress–strain curves, failure of concrete segments by cracking and crushing, and yielding of reinforcement segments, are included. In this beam–column element, it is possible to offset the nodes by predetermined distances, the elements can easily be combined with shell or plate elements to model reinforced concrete or composite structures in a fire. Of course, a problem with these developments is that they ignore the influence of the bond between the concrete and reinforcing steel on the structural behaviour of the reinforced concrete structures. Hence, the main objective of this paper is to develop a bond-link element to model the interaction between plain concrete and reinforcing steel. The element developed permits the modelling of full, partial and even zero interaction between the concrete and reinforcing steel within the reinforced concrete structures. Also, the bond-link element can be used to model the interaction between the concrete and reinforcing steel for reinforced concrete slabs in a fire.

2. Non-linear procedure

As shown in Fig. 1(a) a reinforced concrete beam is modelled as an assembly of finite plain concrete, reinforcing steel bar and bond-link elements. It is assumed that the nodes of these different types of element are defined in a common reference axis. For modelling of reinforced concrete frame structures the reference axis is normally assumed to coincide with the central axis of the cross-section of the beam and column members (see Fig. 1 (a)). Its location is fixed throughout the analysis. Hence, in Fig. 1(a) the plain concrete beam element is represented as a 3-noded beam–column element with zero offset, and the reinforcing steel bar element is modelled as a 3-noded beam–column element with the offsets of Δy and Δz, respectively. A bond-link element makes the connection between a plain concrete element node and a reinforcing steel bar element node. That means one 3-noded steel bar element needs only three bond-link elements in order to make the connection with the plain concrete element. Therefore, the model proposed here is very computationally effective.

2.1. Plain concrete beam–column and reinforcing steel bar elements

As shown in the Fig. 2, the cross-sections of the plain concrete beam and steel bar elements are divided into a matrix of segments in order to consider the variation of temperature and material properties within the cross-sections. In this model a "void segment" is introduced to represent the volume occupied by the reinforcing steel bar within the cross-section of plain concrete elements (see Fig. 2(b)). It is assumed that the "void segment" has zero mechanical strength and stiffness. The detailed formulations of the 3-noded beam–column element and the constitutive modelling of concrete and steel at elevated temperatures have been presented previously [22,23]. For the constitutive modelling of the materials, the compressive and tensile strengths of concrete, yield strength of reinforcing steel, Young's moduli of concrete and steel are all reduced at elevated temperatures following the models specified in Eurocode 2 [1].

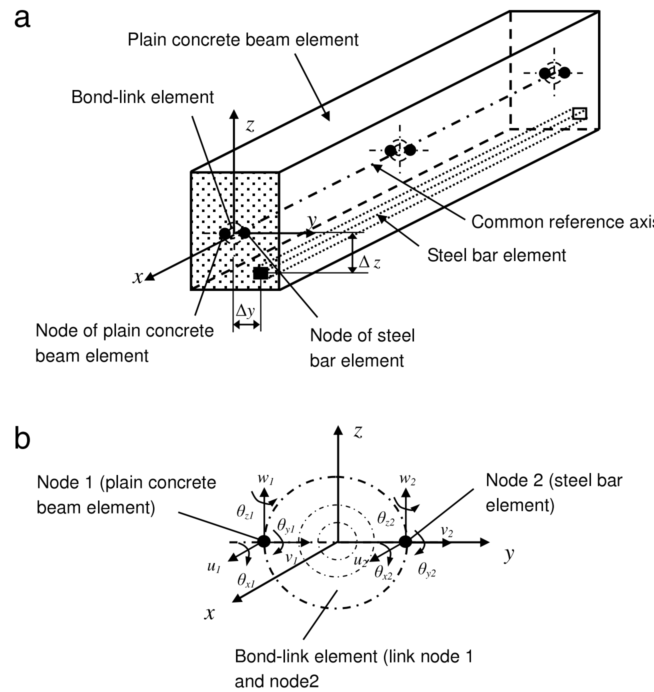

Fig. 1. Reinforced concrete beam: plain concrete, reinforcing steel bar and bond-link elements.

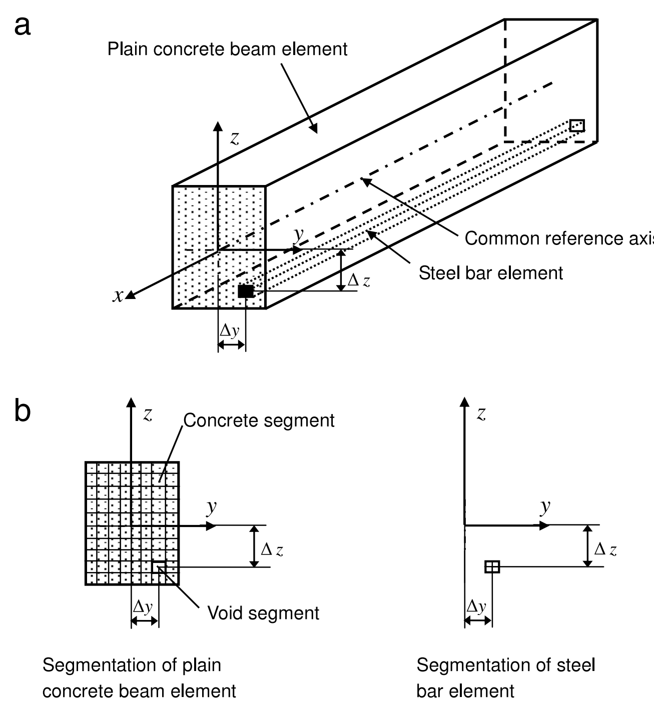

Fig. 2. Segmentation of plain concrete beam and reinforcing steel bar elements.