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Investigating geometrical size effect on the flexural strength of the ultra high performance fibre reinforced concrete using the cohesive crack model

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HIGHLIGHTS

- Cohesive crack model successfully predicted load–deflection curves in UHPFRC.
- Peak load more sensitive to tensile strength than fracture energy.
- Specimen size observed to have a small effect on flexural strength.

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ABSTRACT

Geometrical size effect on the flexural strength of the ultra high performance fibre reinforced concrete was investigated by experimental test data and numerical simulation. Comparison of the simulation results to existing experimental test results indicates that the Cohesive Crack Model (CCM) with a bilinear traction–separation curve can provide predictions of both the load–deflection curves and peak load of 100 and 150 mm deep UHPFRC test specimens to =/−6% with a little size effect observed on the flexural strength. However, for the 50 mm deep beams a difference of =/−25% was observed between model predictions of the peak load and experiment test data possibly due to a surface layer size effect.

1. Introduction

Concrete-based materials have many important applications within building and civil engineering construction. However their brittleness makes crack formation and growth critical to their mechanical behaviour and has in many cases limited the way in which they can be used.

Ultra high performance fibre reinforced concrete (UHPFRC) is a relatively new construction material with significantly higher compressive and tensile strength in addition to having much more ductility compared to normal reinforced concrete. The development of UHPFRC can be viewed within a historical context of continuing efforts to improve crack resistance of concrete based materials [19]. Due to its enhanced fracture properties, UHPFRC has many potential applications both in the construction of new and rehabilitation of old structures.

However, a better understanding of its mechanical behaviour and its crack propagation properties is still required from both experimental study and numerical modelling (Habel [11] and Lappa [15]). As the cost of testing UHPFRC is considerably more compared to normal concrete numerical modelling and simulation has the potential to significantly reduce the number of experiment tests required for UHPFRC.

Elices and Planas [10] proposed a framework for classifying concrete models based on the damage mechanisms occurring within and outside the fracture zone and the adopted crack localisation criteria. Though damage within the fracture zone will always result in energy dissipation from the surrounding material, the linear elastic assumption within the material bulk is adopted in many commonly used concrete models where the effect on the overall result is observed to be small. Models incorporating this assumption have been used successfully with both discrete crack [13]

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and crack band [5] localisation approaches to model the load–deflection curves and failure loads for UHPFRC. For example the smeared concrete model in ABAQUS used by Le [16] to model UHPFRC load–deflection curves uses the crack band localisation approach. The model also assumes that damage involves only stiffness degradation so that unloading occurs to the origin. The Concrete Damage Plasticity (CDP) model in ABAQUS used by Mahmud et al. [17] on the other hand to model UHPFRC specimens adopts general damage within both the material bulk and fracture zone involving both stress loss and stiffness degradation. Though CDP adopts a crack band (smeared crack) localisation approach, it can be classified as a 'damage model' in that its constitutive formulation uses the internal variables which are more sophisticated in representing real life materials.

However, analytical studies by Habel [11] and Lappa [15] and numerical work by Le [16] on modelling UHPFRC cite the difficulty in determining the appropriate reference length as being a significant limitation in applying the smeared crack approach to UHPFRC with a suggestion that the use of Cohesive Crack Models (CCM) may be more appropriate for eliminating this difficulty. Su et al. [23] has also suggested that the discrete crack approaches in general and the cohesive crack models in particular could be more appropriate in cases where macro-cracks with strong discontinuity need to be modelled and which lend themselves to the use of cohesive interface elements in finite element methods.

Compared to other factors that could influence its mechanical behaviour such as fibre type, content and distribution, studies to fully establish the size effects of UHPFRC specimens are limited [17], most likely due to the high cost involved in testing the wide range of sizes required.

Size effect refers to the variation of the specimen strength with specimen size and generally in concrete nominal strength is observed to decrease with increase in specimen depth. However, of the limited studies of size effect reported for UHPFRC, there are significant inconsistencies some finding a significant size effect [16] and others little (Spasojevic et al. [22], Wille and Parra-Montesinos [25]).

A recent study on size effects by Mahmud et al. [17] concluded that there is little size effect on the beam nominal strength of UHPFRC specimens due to the material's high ductility. However the specimens used were geometrically similar only in their notch/depth ratio but not in their overall span/depth ratio.

Some of the main sources of size effects in concrete-based material relate to the boundary layer effect and fracture mechanics [6]. However, for concrete-based materials the size effect caused by fracture mechanics is thought to be the most significant [6]. The fracture mechanics size effect is caused by the fact that larger structures release more strain energy per unit crack extension compared to smaller ones. Hence crack propagation and failure in larger structures would be expected to occur at lower nominal stresses. Brittle materials exhibit a stronger size effect because they have no mechanism to restrict crack growth with resulting strain energy released being used to further propagate cracks. Ductile materials on the other hand have different ways of inhibiting crack propagation and hence have higher fracture energy.

Concrete size effect response lies between that of purely ductile materials which exhibit no size effect and that of pure brittle materials that have a strong and constant size effect [6].

This study benefits from access to test data from previous experiments carried out on geometrically similar UHPFRC specimens. As the crack path is known in advance, the cohesive crack model will be used with interface elements to simulate progressive crack propagation and failure mechanism of UHPFRC test specimens, and predict their load capacities. The modelling results will be compared to existing experimental test results with a view to investigating the influence of specimen size.

2. CCM formulation

The Cohesive Crack Model (CCM) assumes that the stress–strain behaviour for concrete is isotropic linear elastic before cracking starts [13] after which the fracture (cohesive) zone is replaced by a single crack that can still transfer the remaining cohesive stress. Cracks are initiated at a given point using criteria such as the maximum principal stress at that point reaching the tensile strength. The orientation of the crack at that point is perpendicular to the principal stress direction. The crack evolution is such that the cohesive stress (σ) is a function of the crack opening (w). For concrete, this function decreases with crack opening width (w) and is therefore called the softening curve. The function defining the curve can be written as:

$$\sigma = f(w) \tag{1}$$

The area below the σ–w curve is equal to the fracture energy G_f such that.

$$G_f = \int \sigma dw \tag{2}$$

If the general shape of the σ–w curve for concrete based material is known, a good estimate of the curve for a specific mix can be made from a determination of fracture energy and tensile strength [12]. However, one of the limitations of the cohesive crack model is the difficulty in obtaining the parameters required as material inputs. While the difficulties of performing stable direct tensile test for concrete are well documented [18], fracture energy values obtained by the commonly used three point test on notched specimens have been observed to be size dependent [1].

Unlike normal concrete where a bilinear softening curve is generally accepted as providing good results, there is still a lack of agreement as to which curve is best for UHPFRC. The ideal way to obtain the complete softening curve is via a stable direct tensile test which in practice has been found to be extremely difficult. Inverse analysis from bending tests like Three Point Bending (TPB) has been adopted by several studies but differences still exist with suggestions including bilinear [27], trilinear [14] and exponential [9] softening relations.

While CCM is very well suited to analysing failure by single or discrete cracks perpendicular to applied tensile loading, many materials have multiple cracks which are randomly distributed and oriented. The use of CCM is justified in this study where specimens are used in which the location of the predominant crack is known in advance to be in the notched section.

2.1. Constitutive response of cohesive elements

Cohesive elements can simulate several types of behaviours at interfaces where the interface load carrying capability is lost [8]. The cohesive elements in ABAQUS FE software have been adopted in this study as they are based on the cohesive crack model by Hillerborg et al. [13].

The cohesive elements used in this study are formulated using a stress-crack width curve that is typically characterized by peak strength (σ) and fracture energy (G_f) (Fig. 1) [21].

These cohesive elements are based on an initial linearly elastic response followed by damage as described below.

2.1.1. Pre-damage response

Linear elasticity defines behaviour before initiation of damage with nominal stress and strain quantities used by ABAQUS for the traction separation law. Hence a unit thickness is specified for the element so that the nominal strain corresponds to the separation value. The elastic modulus for traction separation law is