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Experimental investigation of moment redistribution in ultra-high performance fibre reinforced concrete beams

P. Visintin *, M.S. Mohamad Ali, T. Xie, A.B. Sturm

School of Civil, Environmental and Mining Engineering, The University of Adelaide, South Australia 5005, Australia

HIGHLIGHTS

- An experimental study of moment redistribution in UHPC 2 span continuous beams.
- Shows members fail through rupture of reinforcement.
- Approaches in national codes of practice are not always conservative.

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ABSTRACT

In the design of statically indeterminate structures the concept of moment redistribution is used to reduce the absolute magnitudes of moments in critical regions, to fully utilise the capacity of non-critical cross sections, and to simplify detailing by enabling a reduction in reinforcement ratios. Due to the complex mechanisms which control the formation and rotation of plastic hinges, moment redistribution capacities are commonly empirically based, and hence not necessarily applicable outside of the bounds of the testing regime from which they were derived. This paper presents the results of an experimental study of the moment redistribution capacity of four two-span continuous beams constructed from ultra-high performance fibre reinforced concrete (UHPFRC) and with various reinforcement ratios, such that the suitability of extending of exiting empirical design approaches to UHPFRC can be investigated. The results of the experimental investigation show that for beams where the hinge formed at the support, the observed moment redistribution was greater than the code predictions. However for the beam where the hinge formed under the load points, observed moment redistribution was significantly less than codes predictions. Hence, the results of this study show current design guidelines do not always provide a conservative prediction of moment redistribution in UHPFRC beams.

1. Introduction

The recent expansion in research directed towards high performance materials has seen the development of a number of reliable mix designs for ultra-high performance fibre reinforced concretes (UHPFRC), including a number of commercially available products [4,3,23]. These materials which are characterised by a very high compressive strength, a non-negligible tensile strength, high material ductility and enhanced durability have the potential to revolutionise the design of structures allowing for longer spans, reduced member sizes and increased design lives. To date numerous studies have focused on developing mix designs and characterising material performance, and in a more limited way structural tests have been performed on simple beam elements [8,27,28,19]. This research has culminated in the development of initial design guidelines for the use of UHPFRC [10,1]. While these guidelines present methodologies for the design of simple structural members the behaviour of indeterminate UHPC members has not yet been considered.

In statically indeterminate beams, a redistribution of internal forces arises due to the inelastic nature of reinforced concrete. The phenomenon of moment redistribution occurs at all limit states due to a difference in the relative stiffness of individual cross sections [17], but is typically utilised by designers at the ultimate limit. Moment redistribution allows the designer to reduce both the maximum hogging and sagging elastic moments, thereby reducing the overall moment demanded across a span, enabling a reduction in reinforcement requirements. Additionally, the ability to shift moments away from less efficient cross sections towards other more efficient cross sections may allow for savings in reinforcement costs and the easing reinforcement congestion [16].

* Corresponding author.
E-mail address: phillip.visintin@adelaide.edu.au (P. Visintin).

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These factors may be particularly important for UHPFRC which has higher material costs than conventional concrete and has the potential to perform poorly in regions of congested reinforcement if fibres cannot be uniformly distributed around reinforcement.

At the ultimate limit, moment redistribution occurs due to the formation and gradual rotation of plastic hinge regions, and has also been shown to be highly dependent on the stiffness or flexural rigidity of the non-hinge regions [14,17,25]. Hence the mechanics of moment redistribution is incredibly complex as it is defined by the localised mechanism which control crack widening and tension stiffening as well as the formation and sliding of concrete softening wedges [25]. Due to the complexity of the problem an empirical approach is often adopted to quantify hinge rotation and moment redistribution, and a review of approaches by Panagiotakos and Fardis [15] has shown that these typically perform poorly outside of the bounds of the test results from which they were derived.

To date the majority of experimental investigations into moment redistribution have been performed on members constructed from normal strength concrete, with few studies considering the influence of high-strength concrete (HSC). In these studies [6,17,7] it has been suggested that the brittle nature of HSC may influence hinge rotation and that the increased bond between the reinforcement and concrete may lead to a higher tension stiffening effect in cracked regions and therefore a significant deviation away from the behaviour expected from conventional concrete members. To allow for the change in behaviour which occurs with increased concrete strengths, national codes of practice often set different limits for moment redistribution in HPC [9], it is however unknown if these expressions can be further extended to UHPFRC beams.

Previous studies into the material performance of UHPFRC have shown that the addition of fibres to concrete improves the bond between reinforcement and concrete and restrains sliding along concrete to concrete interfaces, thereby improving shear-friction material properties and compressive ductility [23,26]. It can therefore be expected that the addition of fibres to concrete will change the magnitude of hinge rotation and therefore moment redistribution in statically indeterminate beams. Although the addition of fibres can be expected to influence moment redistribution, little experimental work has been undertaken to date, with that available limited to members without reinforcement [12,13].

In this paper the moment redistribution behaviour of two span continuous beams manufactured from UHPFRC is investigated on beams with a range of reinforcing ratios. Existing methods for predicting moment redistribution prescribed by various national codes of practice are then applied to determine if they can be extended for application to UHPFRC.

2. Experimental program

The experimental program has been devised to provide both an experimental investigation of the moment redistribution behaviour of UHPFRC beams and also to provide a range of material properties such that the results may be of use in the future validation of novel analytical procedures. As such in addition to four continuous beam tests, material tests were undertaken to quantify the compressive and tensile stress-strain and stress-crack width behaviour of the UHPFRC and the stress-strain characteristics of the reinforcement.

3. Mix design

All beams were cast using a mix design developed at the University of Adelaide as part of a project to develop ultra-high performance fibre reinforced concretes which require only conventional concrete manufacturing materials and equipment, and which do not require special curing regimes [23]. It may also be worth noting that these mixes have also been used for extensive material and member level testing reported elsewhere [23,19].

The full mix design is given in Table 1, in which the sulphate resisting cement had a fineness modulus of 365 m^2/kg, a 28 day compressive strength as determined in accordance with AS 2350.11 [21] of 60 MPa and a 28 day mortar shrinkage strain determined in accordance with AS 2350.13 [22] of 650 microstrain. The silica fume was undensified with a bulk density of 625 kg/m^3. The steel fibres were cold drawn hooked end wire fibres with a total length of 35 mm, an aspect ratio of 64 and a minimum yield strength of 1100 MPa. The superplasticiser was a third generation high range water reducer with an added retarder.

The concrete was manufactured by first mixing the cement, silica fume and sand for 1 min in a 750 L pan mixer until well blended. The water and superplasticiser were then added and the concrete mixed until visibly flowable; this took approximately 35 min. After the concrete started to flow, the fibres were added and mixed for a further 5 min. All specimens were cast in 4 batches on different days with each batch consisting of one beam as well as cylinders to determine the compressive and tensile strengths of the concrete. All dog-bone specimens were cast along with beam 3. Note that to achieve a uniform distribution of fibres, sufficient mixing time was applied to ensure that the fibres were evenly mixed with the matrix. When placing the concrete, to avoid settlement of fibres, all beams were cast horizontally by pouring the concrete into the form in layers which were individually compacted.

3.1. Beam test specimens

To investigate the moment redistribution capacity of UHPFRC, four two-span continuous beams were tested. Note that a rectangular section was chosen in order to simplify analysis and because it is the most common beam cross section tested. It may however be useful to investigate T-sections in the future. As shown in Fig. 1 these beams had a total length of 5500 mm and were tested with point loads located at the mid-point of each span of length 2500 mm. To investigate the influence cross sectional ductility on the moment redistribution capacity each beam had a different tensile reinforcement ratio ranging from 1.48% to 1.94% in the sagging region and 1.28% to 1.94% in the hogging region. The reinforcement arrangement was chosen for the first three beams to investigate the relationship between reinforcement ratio and moment redistribution, and in the final beam to investigate the behaviour when moment redistribution occurs from the sagging to the hogging region. To prevent shear failure, 6 mm diameter stirrups were placed at 100 mm centres. Full details of the reinforcement are given in Table 1.

3.2. Instrumentation and testing

To capture the deformation of the hinge region a series of five linear variable displacement transducers (LVDTs) were placed at

Table 1
UHPFRC mix design.

Material	kg/m^3
Sulphate resisting cement	937.50
Washed river sand	937.50
Silica fume	250.00
Steel fibres	165.00
Water	160.00
High range water reducing agent	52.50