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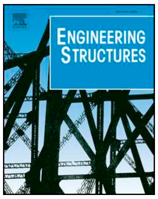

Flexural performance of steel fibre reinforced concrete beams designed for moment redistribution

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A B S T R A C T

This paper presents an experimental study to investigate the flexural and moment redistribution performance of six full-scale two-span continuous reinforced concrete beams with and without steel fibres. The beams were reinforced with conventional bar reinforcement with longitudinal steel reinforcement ratios of between 0.0069 and 0.0138; four of the six beams also contained either 30 kg/m^3 or 60 kg/m^3 of steel fibres. The specimens were tested under monotonically increasing displacement-controlled loading. The primary variables within different test specimens were the arrangement of longitudinal steel bar and the dosage of steel fibres. The beams were designed for 30% of positive and negative moment redistribution with respect to the linear-elastic condition, the maximum allowed by different codes and standards. Test results showed that the inclusion of steel fibres increases the load carrying capacity of the reinforced concrete beams. Furthermore, the addition of steel fibres increased the number of cracks and decreased the crack spacing. For the steel reinforcement ratios tested, the RC-SFRC beams were found to have good ductility. It was shown that the RC-SFRC beams achieved full moment redistribution demand to form the collapse mechanism, and maintained their load carrying capacity for large plastic-hinge rotations. The guidelines of AS 5100.5-2017 were found to give a good prediction of the load carrying capacity of the tested RC-SFRC beams.

1. Introduction

The fastest and most widely adopted approach for analysis and accordingly design of reinforced concrete (RC) members is based on linear elastic assumption for materials. In linear elastic analysis, it is assumed that both the concrete and the tensile reinforcement behave elastically until the reinforcement yields, and the bending moment and shear force are calculated by assuming a constant flexural stiffness for the member. However, the flexural stiffness of an RC member varies with respect to level of cracking and thus, in reality, the member behaves non-linearly after the formation of cracks. Moreover, all the sections of a member do not crack and yield at the same time, and the member does not fail as soon as the moment of a particular section exceeds its design moment capacity. If the section has sufficient rotation capacity, a plastic hinge is formed, and the hinge region starts rotating at almost a constant moment. Further application of load will lead to transfer of bending moments from that section to other sections. This process is called moment redistribution. The load can be increased until multiple plastic hinges are formed to develop a failure mechanism.

The incorporation of moment redistribution into linear elastic analysis has some benefits. The amount of longitudinal reinforcement in congested areas such as beam-column joint regions can be reduced by shifting bending moments away from beam-column connection zone toward mid-span that in turn leads to an improved concrete quality and better bonding in those congested areas. The incorporation of moment redistribution into design also contributes to cost saving by utilising the full capacity of the member, redistributing moments at different load combinations and resulting in a narrower bending moment envelope [1]. Moreover, use of linear elastic analysis in conjunction with moment redistribution is simple and reasonably accurate for practical applications, compared to plastic and nonlinear analyses that require complex calculations.

The available amount of moment redistribution depends mainly on the ductility or the rotation capacity of critical sections. However, a limited amount of moment redistribution without explicitly verifying the rotation capacity of the sections is allowed by most of the design codes [2–6]. According to the existing design codes [2–6], the maximum negative or positive moment calculated by linear elastic analysis can be reduced provided that the moments in the other sections are increased to maintain static equilibrium. The permissible amount of moment redistribution depends on strain in the tensile reinforcement, steel ductility and concrete strength, and, provide the longitudinal

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tensile reinforcement does not fracture, can be calculated as a function of the ratio of the neutral axis depth to the effective depth of the cross-sections.

The inclusion of steel fibres into concrete mix started over half a century ago with the concept of bridging micro and macro cracks that occur in concrete matrix due to various states of stress [7]. It is now well-established that steel fibre reinforced concrete (SFRC) has superior post cracking tensile strength and superior resistance to crack propagation, than that of plain concrete [8]. The crack bridging property of SFRC can transform the behaviour from one of quasi-brittle to ductile [9]. Many studies have been conducted to investigate the flexural performance of conventionally reinforced concrete beams containing steel fibres (RC-SFRC beams), and steel fibres have been found to improve the deformational and cracking behaviour of RC beams [8,10–12]. The inclusion of steel fibres increases both the service and post-peak stiffness of the beams resulting in substantial reduction of deflection, strain in reinforcing steel, rotation and curvature at all stages of loading [8,10,11]. The addition of steel fibres inhibits the propagation of cracks and decreases the width, length and spacing of the cracks at service loading condition [12–14]. Apart from improvements at service loading condition, the inclusion of steel fibres can improve the yield and ultimate bending moment capacity of the RC beams [15]. Furthermore, SRFC exhibits significant inelastic deformation [10] and ductility at failure [9,16], and have higher flexural toughness than plain concrete [17,18]. The effects of steel fibres on performance and behaviour of RC members varies with the reinforcing proportion. The effects of steel fibres have been found to be more pronounced in lightly RC beams than more heavily reinforced sections [14,18], as fibres have a proportionally higher contribution to the overall behaviour.

Although SFRC has been researched for over 50 years, guidelines available for the design of SFRC remain limited. The first international standard to introduce fibres in a comprehensive way was the New Zealand Standard NZS 3101:Part 1-2006 [19]. Since this time a number of other international standards have evolved that deal with fibre reinforced concrete in some way, including ACI 318-14 [2], *fib* Model Code 2010 [4], DAfStb Guideline [20] and AS 5100.5-2017 [21]. AS 5100.5-2017 [21] is the first standard in Australia to include design procedures for SFRC. While rules have been introduced for flexure and shear design of SFRC, strict limitations are placed on application where large plastic rotations are expected. The reason is the lack of testing undertaken to clearly show that SFRC moment hinges and connections can maintain their capacity during large rotations and moment redistributions. There are few studies found in the literature on the moment redistribution performance of SFRC members. Liu et al. [22] studied the moment redistribution of prestressed concrete beams made of high strength concrete and SFRC. Abas et al. [23] studied the moment redistribution of composite slabs with deep trapezoidal steel decking and SFRC. Iskhakov et al. [24] studied the moment redistribution of two-layer beams made of steel fibre reinforced high strength concrete in the compression zone and normal strength concrete in the tensile zone. The authors used the ratio of the bending moments at intermediate support to the bending moments at mid-span to evaluate the moment redistribution and found that RC-SFRC specimens exhibited excellent capacity for moment redistribution. However, none of these studies quantified the amount of moment redistribution for different fibre dosages.

Research on the flexural performance of RC-SFRC continuous beams, especially on the rotation capacity and moment redistribution of RC-SFRC continuous beams, is limited. Moreover, SFRC members exhibit higher stiffness at a cracked state than for members without fibres [25,26], which might modify the amount of moment redistribution. Therefore, there is a need to investigate the flexural performance and moment redistribution of RC-SFRC continuous beams; this is the focus of this study. Accordingly, four full-scale two-span continuous RC-SFRC beams and two control RC beams were cast and tested under monotonically increasing displacement-controlled load up to failure. The amount of moment redistribution and the improvement in the bending moment capacity and ductility of the RC-SFRC beams is evaluated with respect to the control RC beam. The laboratory test results are further analysed to determine if RC-SFRC moment hinges can maintain their capacity during large plastic rotations and if internal forces can be redistributed to under-utilised regions of the member.

Table 1
Specimen details.

Series	Specimen	Fibre dosage (kg/m^3)	Negative reinforcement at intermediate support (mm^2)	Positive reinforcement at mid-span (mm^2)
A	B00(+30) B30(+30) B60(+30)	0 30 (0.4%) 60 (0.8%)	1240 (1.38%)	620 (0.69%)
B	B00(−30) B30(−30) B60(−30)	0 30 (0.4%) 60 (0.8%)	620 (0.69%)	930 (1.03%)

2. Experimental investigation

2.1. Description of test specimens

To provide insight into flexural and moment redistribution behaviour of RC-SFRC continuous beams, an experimental study was undertaken on two series, with three specimens in each series, of six full scale continuous two-span beams, which simulate statically indeterminate flexural members that allow for moment redistribution. The details of the test specimens are shown in Table 1; the longitudinal reinforcement ratios varied between 0.69% and 1.38%. The geometry, loading, boundary conditions and arrangement of longitudinal and transverse reinforcements for the tested specimens are shown in Fig. 1. The primary variables within different test specimens were the arrangement of longitudinal reinforcing steel bar and the dosage of steel fibres. The nominal dosages of steel fibres were 0, 30 and 60 kg/m^3. The beams were designed for a 30% redistribution of moment with respect to the linearly-elastic condition, the maximum moment redistribution allowed by AS 3600-2009 [3], *fib* Model Code 2010 [4] and Eurocode 2 [6]. Accordingly, the designation BW(± 30) for specimens is used with respect to 'B' the member type (Beam) and 'W' the dosage of steel fibres (in kg/m^3) and (± 30) denotes the expected percentage of the redistributed moment from mid-span to intermediate support, and vice versa. More specifically, the BW(+30) specimens (Series A) were designed for 30% more moment with respect to elastic theory in their negative moment region (intermediate support) to simulate negative moment redistribution, whereas the BW(−30) specimens (Series B) were designed for 30% less moment in their negative moment region to simulate positive moment redistribution. The design bending moments were adjusted to ensure that the total static moment equilibrium is satisfied.

2.2. Preparation of test specimens and material properties

In all specimens, D500N (D-deformed, N-normal ductility) grade steel bars with nominal yield strength of 500 MPa were used for longitudinal reinforcement, and R250N (R-round, N-normal ductility) grade steel bars with nominal yield strength of 250 MPa were used for stirrups. The average measured yield strength of N20 (20 mm diameter), N28 (28 mm diameter) and R10 (10 mm diameter) bars were 520, 540 and 325 MPa, respectively. The average measured elastic modulus of N20, N28 and R10 bars were 196, 197 and 210 GPa, respectively. The uniaxial stress-strain curves for the reinforcing bars used in this study are shown in Fig. 2.

The steel fibres used in this study were 0.9 mm in diameter, 60 mm