Proc. 1st International Conference on Structural Engineering Research (iCSER 2017)
20-22 Nov 2017, Sydney, Australia
ISBN: 978-0-6480147-6-8

Test-aided Calibrations for Design of Steel Fibre Reinforced Recycled Aggregate Concrete Beams

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Abstract

This research proposes to combine recycled aggregate concrete (RAC) with steel fibres (SF), to provide an environment-friendly, sustainable, and structurally sound alternative to natural aggregate concrete (NAC). When steel fibre reinforced recycled aggregate concrete (SFRRAC) is used in construction, the existing design equations and associated safety factors need to be revised; the existing design provisions are applicable only to NAC and cannot be applied to SFRRAC directly. In this research, safety factors of design equations for beams provided in the current Australian, American, and European design codes are calibrated based on the first-order reliability method (FORM) when used for the structural design of SFRRAC beams. This is carried out based on a proposed prediction model for the flexural capacity of SFRRAC, which considers the contribution of SF unlike the conventional prediction model for RC beams. The uncertainty of the prediction model is estimated based on nine experimental results of secondary SFRRAC beams tested for flexural failure under three-point bending. These beams are fabricated with varying contents of recycled aggregate and steel fibre ratios. Furthermore, the reliability index ratios of the different SFRRAC mixes considered are estimated.

Keywords: Reliability analysis, Concrete structures, Recycled aggregates, Steel fibres, Safety factor calibration.

1. INTRODUCTION

Using recycled aggregate (RA) in concrete decreases the environmental impact of concrete production and provides an effective alternative for meeting the demands of the construction industry. However, recycled aggregate concrete (RAC) has inferior mechanical properties compared to natural aggregate concrete (NAC) (Kang et al 2017). Although replacement of NA with RA by up to 25% does not significantly change the mechanical properties of concrete, higher replacement proportions affect its performance (Etxeberria et al 2007). On the other hand, steel fibre (SF) increases the performance of concrete under different load actions. The degree of improvement in mechanical properties by adding SF is greater in RAC than in NAC (Erdem et al 2011). To exploit the advantages of both RA and SF, they are combined to produce a new material, namely steel fibre reinforced recycled aggregate concrete (SFRRAC). Previous studies have focussed on the use of RAC and SFRC individually and not on their combination, SFRRAC at the member level.

The flexural test of SFRRAC beams recently conducted by Mirza et al (2017), in which nine SFRRAC beams were tested with different combinations of RA and SF contents, is a preliminary part of this research. This study was carried out to apply their experimental observations to real structural design. This study aims to evaluate the relation between the safety factor and the target reliability level for SFRRAC beams, based on a newly developed material strength prediction model. The reliability analysis method is extensively based on the calibration method discussed in Eurocode (2002) and ISO 2394 (1998). The reliability index ratios of all the beams tested by Mirza et al. were evaluated.

2. TEST RESULTS

The following were the moment capacities of the beams tested by Mirza et al. (2017).

Table 1. Moment capacities

Beam no. (RA%-SF%)	**1** (0-0)	**2** (30-0)	**3** (100-0)	**4** (0-0.3)	**5** (30-0.3)	**6** (100-0.3)	**7** (0-0.6)	**8** (30-0.6)	**9** (100-0.6)
Mom. Capacity (kN-m)	375	385	378	413	420	406	476	413	420

3. MODEL FOR PREDICTING THE CAPACITY OF SFRRAC BEAMS

In this section, a prediction model is proposed for theoretically calculating the flexural resistance of SFRRAC beams by considering the effect of SF and it is used for the reliability analysis in the next section. Fig. 1a shows the stress strain diagram of a NAC beam having a rectangular cross section (Bandyopadhyay 2008) without SF. According to the Linear Bending Theory of reinforced concrete beams, the concrete part below the neutral axis in a rectangular cross section (the unshaded region in Fig. 1a) is disregarded in strength and moment capacity calculations (Bandyopadhyay 2008). In Fig. 1a, the compressive force in concrete (C_c) and the compressive force in the compression reinforcement (C_s) are balanced by the tensile force in the tension reinforcement (T_s).

In SFRRAC, the added SF improves the tensile behaviour of SFRRAC as shown by the horizontally striped region below the neutral axis in Fig. 1b. Although the tensile strength of RAC is negligible, SF increases its load and moment carrying capacities improving the tensile strength of SFRRAC. An additional tensile force representing the tensile strength of SFRRAC (T_{SFRRAC}) acts as shown in Fig. 1b. In this study, an equation that represents this tensile strength of SFRRAC under flexure is proposed. The equation form proposed by Song and Hwang (2008) is adopted. A regression analysis on the tensile strength data of SFRRAC obtained by Vaishali and Rao (2012) and Bhikshma and Manipal (2012) was used to obtain the following equation.

$$f_{ct,sp} = 0.54\sqrt{f_c'} + 3.0451\, V_f - 1.5177\, V_f^2 \qquad (1)$$

where $f_{ct,sp}$ is the split tensile strength of concrete, f_c' is the compressive strength of concrete, and V_f is the volume of SF in concrete. The axial tensile strength of a concrete matrix (f_{ct}) in a beam is related to its experimentally measured split tensile strength ($f_{ct,sp}$) as follows (AS 3600, 2009):

$$f_{ct} = 0.9 \times f_{ct,sp} \qquad (2)$$

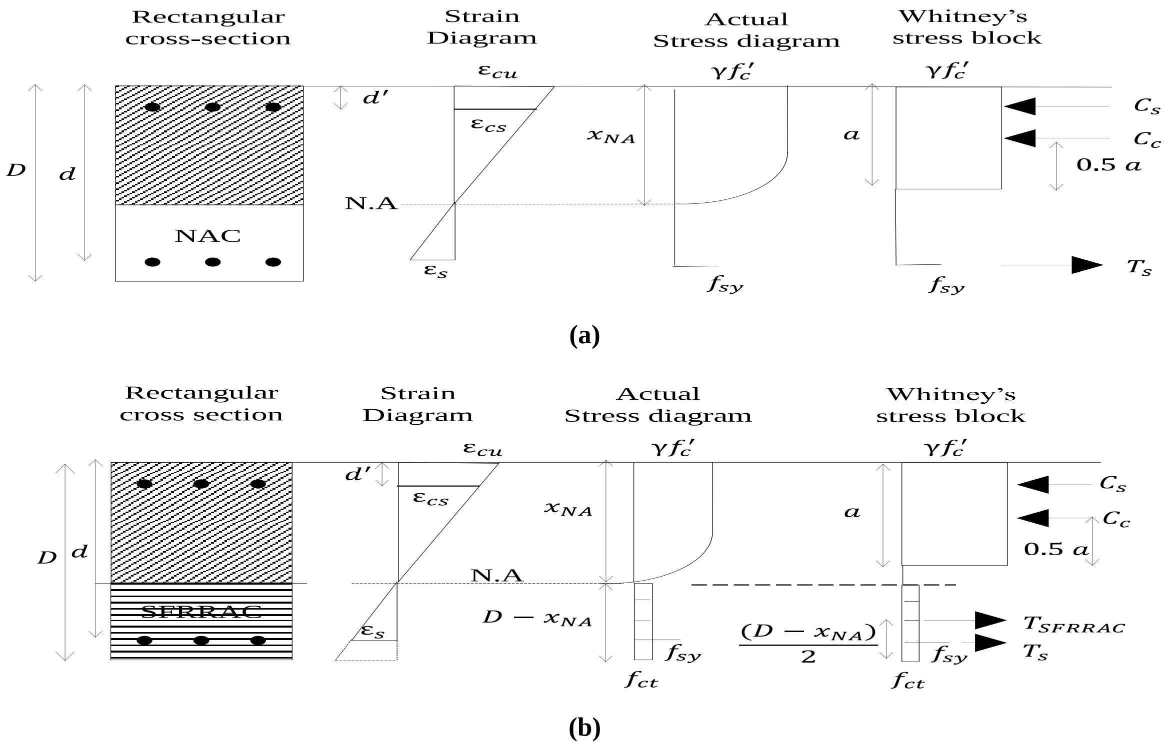

Figure 1. Stress and strain diagrams of doubly reinforced (a) NAC and (b) SFRRAC beams with rectangular cross sections

4. RELIABILITY ANALYSIS

To calibrate the safety factors for the flexural capacity prediction of SFRRAC, the reliability analysis method provided in Annex D of Eurocode (2002) and ISO 2394 (1998) is extensively used in this study. The numerical value of the target reliability index (*β*) adopted in this study when considering resistance separately is 3.04. The safety factor for each beam (ϕ_i) is calculated using the following equation:

$$\phi_i = r_{di}/r_{ki} \tag{3}$$

where r_{di} and r_{ki} are obtained from the calculation procedure provided in the following sub sections.

4.1. Calculation of design capacity (r_d)

The design moment capacity of the i^th SFRRAC beam out of the nine beams tested by Mirza et al. (2017) (r_{di}) can be theoretically estimated using the prediction model provided in the previous section, which considers the flexural tensile strength of SFRRAC using Equation 2.

$$r_{di} = \overline{b} \times r_{ti} \times \exp(-k_i \times Q_i - 0.5 \times Q_i^2) \tag{4}$$

where r_{ti} is the theoretically estimated moment carrying capacity of the i^th beam; $\overline{b}$ is the bias correction factor estimated using the following equation, and k_i and Q_i are coefficients estimated using Equations 7 and 8, respectively as stated below.

$$\overline{b} = (\textstyle\sum_i^n r_{ei} \times r_{ti})/\sum_i^n r_{ti}^2 \tag{5}$$

where r_{ei} and r_{ti} are the experimental and theoretical moment carrying capacities of the i^th beam obtained experimentally, respectively. The prediction error in the model for i^th value is calculated as:

$$\delta_i = r_{ei}/(\bar{b}r_{ti}) \tag{6}$$

The modelling error of the theoretical prediction model proposed in Section 2 is denoted by V_δ^2, and is found to be 0.0029. To account for the error due to finite number of data, design fractile factor k_d is applied.

$$k_i = (k_d \times V_\delta^2 + \beta \times V_{rti}^2)/V_{ri}^2 \tag{7}$$

where k_d is obtained from Table D2 in Annex D of Eurocode (2002), β = 3.04 is the target reliability index, V_{rti}^2 represents the total parametric uncertainty in the ith beam, and V_{ri}^2 represents the combined modelling and parametric uncertainty in the ith beam. Q_i in Equation 4 is estimated as follows:

$$Q_i = \sqrt{\ln(1 + V_{ri}^2)} \tag{8}$$

4.2. Calculation of characteristic capacity (r_k)

The characteristic design moment capacity value r_{ki} is used when the nominal design moment capacity value r_{ni} for each beam is not available. r_{ki} is calculated by plugging in the characteristic values of material strengths obtained from Equations 9 and 10, in the equations for calculating ultimate moment capacity. The characteristic values of the compressive strength of NAC (f_{cki}) and the yield strength of the steel reinforcement bars in the ith beam (f_{syki}), respectively, at 5% significance are given by the following equations:

$$f_{cki} = f_{c_i} \times \exp(-1.64 \times \sigma_{lnf_{c_i}} - 0.5 \times \sigma_{lnf_{c_i}}^2) \tag{9}$$

where, f_{c_i} is the nominal value of the compressive strength of concrete for the ith beam, and $\sigma_{lnf_{c_i'}}$ = 0.15 is the c.o.v of the compressive strength of concrete obtained from Johnson and Huang (1994), similar to the calculations in Eurocode (2002).

$$f_{syki} = f_{syi} \exp(-1.64 \times \sigma_{lnf_{syi}} - 0.5 \times \sigma_{lnf_{syi}}^2) \tag{10}$$

where f_{syi} is the nominal value of the yield strength of the steel reinforcement bars for the ith beam, $\sigma_{lnf_{syi}}$ = 0.07 is the c.o.v of yield strength of steel reinforcement bars (JCSS, 2001).

5. RESULTS AND DISCUSSION

5.1. Safety factors and reliability indices for a NAC beam

The safety factors for flexural action (ϕ) for Beam 1 (NAC) corresponding to the reliability index β = 3.04 are 0.8878, 0.8874 and 0.8824 when AS 3600 (2009), ACI 318-11 (2011), and Eurocode 2 (2004) are used, respectively. The safety factors are estimated using Equation 3, in which the design and characteristic moment carrying capacities (r_{di}, r_{ki}) of Beam 1 (NAC) are found using the flexural moment capacity calculations provided in Eurocode 2 (2004), AS 3600 (2009), and ACI 318-11 (2011). The values of these safety factors are approximately 0.885 for all the three international standards. For this calculation, the design fractile factor (k_d) was obtained from Table D2 in Annex D of Eurocode (2002). The adopted value corresponds to the number of test data available (n = 9). If further data are collected, the design fractile factor will decrease, and accordingly, the safety factor of NAC will increase. The current safety factor values used in the national standards are 0.8 (capacity factor) in AS 3600 (2009) and 0.9 (strength reduction factor) in ACI 318-11 (2011). The equivalent safety factor for flexural moment capacity derived from the material partial safety factors used in Eurocode 2 (2004) is 0.86. For NAC, the reliability indices that correspond to these safety factors are inversely calculated as shown in Fig. 2. From Fig. 2, it can be seen that the reliability indices are 4.57, 2.83 and 3.42 for the current safety factor values used in AS 3600 (2009), ACI 318-11 (2011) and Eurocode 2 (2004), respectively. These target reliability indices are greater than or around the target reliability index value of 3.04 according to Eurocode (2002) and ISO 2394 (1998).

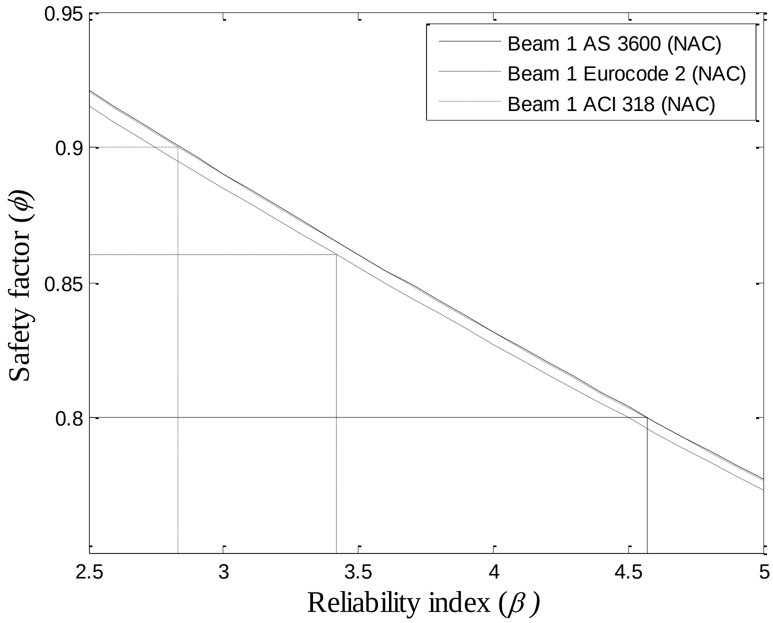

Figure 2. Target reliability indices for NAC corresponding to the existing safety factors in AS 3600 (2009), ACI 318-11 (2011) and Eurocode 2 (2004)

5.2. Reliability index ratios

Table 2 lists the reliability indices of the nine beams normalised by that of Beam 1 (NAC beam). The meaning of these normalised reliability indices is that if the value is close to 1, the SFRRAC beam is equivalent to a normal NAC beam.

Table 2. Reliability index ratio for the SFRRAC mixes with respect to the NAC mix

RA (%) -SF (%)	0-0	30-0	100-0	0-0.3	30-0.3	100-0.3	0-0.6	30-0.6	100-0.6
	1	0.981	0.975	1.593	1.569	1.561	2.029	2.027	2.020
	1	0.967	0.957	1.846	1.807	1.793	2.475	2.471	2.457
	1	0.970	0.960	1.732	1.696	1.683	2.275	2.272	2.262

6. CONCLUSION

This paper proposed a reliability analysis framework for the structural design of SFRRAC beams that includes the contribution of SF to the tensile strength of the beams., based on the method discussed in Eurocode (2002) and ISO 2394 (1998). The reliability indices decreased as the RA content increased, when the safety factor was fixed. The safety factors for NAC corresponding to the values of the reliability indices currently used in the design standards (Eurocode 2 (2004), AS 3600 (2009), and ACI 318-11 (2011)) were around 0.885.

REFERENCES

ACI (American Concrete Institute) (2011). ACI 318-11, Building Code Requirements for Structural Concrete and Commentary.

Bandyopadhyay JN (2008). Design of concrete structures, Prentice Hall of India Learning Pty. Ltd.

Bhikshma V, Manipal K (2012). Study on mechanical properties of recycled aggregate concrete containing steel fibers, Asian Journal of Civil Engineering (Building and Housing), 13, 155–164.

BSI (2002). BS EN 1992:2002, Eurocode Basis of structural design.

BSI (2004). BS EN 1992-1-1:2004 Eurocode 2, Design of concrete structures, Part 1-1: General rules and rules for buildings.

Erdem S, Dawson AR, Thom NH (2011). Microstructure-linked strength properties and impact response of conventional and recycled concrete reinforced with steel and synthetic macro fibres, Construction and Building Materials 25, 4025–4036.

Etxeberria M, Vázquez E, Marí A, Barra M (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cement and Concrete Research 37, 735–742.

International Organization for Standardization (1998). ISO 2394-1998, General principles on reliability for structures.

JCSS (Joint Committee on Structural Safety) (2001). JCSS Probabilistic model code Part 3: Material Properties.

Johnson RP, Huang D (1994). Calibration of safety factors $\gamma_M$for composite steel and concrete beams in bending, In: Proceedings of the Institution of Civil Engineers – Structures and Buildings, 104, 193–203.

Mirza O, Wigg D, Kang W-H, Ramesh RB, Senaratne S, Tam VWY (2017). Flexural behaviour of reinforced concrete beams with recycled aggregates and steel fibres. KSCE Journal of Civil Engineering, Submitted for review.

Song PS, Hwang S (2004). Mechanical properties of high-strength steel fiber-reinforced concrete, Construction and Building Materials, 18, 669–673.

Standards Australia (2009). AS 3600-2009, Australian Standard Concrete structures.

Kang, WH, Ramesh RB, Mirza O, Senaratne S, Tam V, Wigg D (2017). Reliability Based Design of RC Beams With Recycled Aggregate and Steel Fibres, Structures, 11, 135-145.

Vaishali GG, Rao HS (2012). Strength and permeability characteristics of fiber reinforced high performance concrete with recycled aggregates, Asian Journal of Civil Engineering, 13, 55–77.