Model uncertainty of recycled aggregate concrete beams subjected to bending

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Abstract

This paper investigates whether the model uncertainty of reinforced recycled aggregate concrete (RAC) beams subjected to bending differs from that of reinforced natural aggregate concrete (NAC) beams.
An introductory remark concerning the importance of the codification of RAC structural design is made and notions concerning model uncertainties and their role on structural codification are given. Afterwards, the criteria used in the construction of a database of RAC and NAC beams are referred before presenting the key findings of an analysis on the model uncertainty of the cracking, yielding and ultimate moments of beams subjected to four-point bending tests. The analytical moments were calculated following Eurocode 2 provisions. Probabilistic models for model uncertainties are proposed. Negligible differences in the model uncertainty of NAC and RAC beams are reported.

Keywords: sustainability; CDW; structural concrete; model uncertainty; reliability.

Preliminary remarks

The state-of-the-art on RAC supports its use as a structural material. However, most RAC studies concern expected performance, neglecting variability and uncertainty. A structural code providing specifications for the structural design of RAC would be a decisive step towards the widespread design of RAC, contributing to the compliance with EU Directive 2008/98/EC on waste. The most pragmatic way to provide such code is the adaptation of Eurocode 2 to the variability and uncertainty of RAC. NAC is also a fairly variable material and the definition of deterministic sets of verifications that indirectly account for this variability allows reliable designs. This indirect consideration of variability is made by resorting to partial safety factors that are calibrated based on the probabilistic distributions of the several parameters that are uncertain and relevant to structural design, such as material properties, geometry, and loads. The model uncertainty (θ) is one of these parameters and represents the deviations from the expected structural response and the actual response:

$$\theta = {}^{Actual\ response}/_{Analytical\ prediction} \quad (1)$$

If θ is estimated from several samples, a probabilistic distribution of a random variable (RV) can be inferred and incorporated in reliability models. This document investigates the model uncertainty of the cracking moment (θ_{Mcr}), yielding moment (θ_{My}) and ultimate moment resistance (θ_{Mrd}) of NAC and RAC as calculated when Eurocode 2 assumptions and formulae are followed, with the aim of providing θ distributions for partial safety factor calibration. The primary focus of the paper is the analysis of NAC and RAC beams with the incorporation of recycled aggregates sourced from concrete.

Database construction

The first step of this work consisted in the appraisal of all studies concerning the behaviour of RAC beams subject to bending. All test setups found by the authors were of the four-point bending type. Afterwards, part of the studies appraised were rejected whenever material and geometric properties considered relevant were missing. When the Young's modulus of the reinforcement steel was not reported, it was assumed as 200 GPa. 28-day concrete splitting tensile strength tests were converted to uniaxial tensile strength as recommended in Model Code 2010 [10], and the uniaxial tensile strength was converted to flexural tensile strength after Eurocode 2 provisions.
All beams were checked against reinforcement/concrete bond failure following conservative Eurocode 2 design values and it was assumed that shear failures did not occur unless reported in the respective studies. No beams failed due to insufficient bond and the beams that failed with shear interaction were removed from the database.

Analytical calculations

The cracking moment was calculated considering the reinforcement steel. The ultimate moment resistance was estimated using a simplified stress-block neglecting compression reinforcement (M_{Rd1} - Equation 2) and a parabola rectangle stress-block where compression reinforcement was accounted for (M_{Rd2}).

$$M_{Rd1} = A_s f_{sy1} \frac{d_1 - 0.5 A_s f_{sy1}}{b f_c} \quad (2)$$

With A_{s1}, f_{sy1}, and d_1 standing for tensile reinforcement area, yield strength, and effective depth, b the cross-section width, and f_c the 28-day cylinder compressive strength.

In M_{Rd2} calculations, the Bernoulli hypothesis and the stress-strain constitutive parabola rectangle model of Eurocode 2 were used. It was assumed that the most compressed fibre had a strain equal to ε_{cu} and by integrating over the length of the compression zone of the cross-sections (after iterating the depth of the neutral axis), M_{Rd2} was calculated, based on the strains and stress-strain models of the concrete, compression, and tensile reinforcements. The maximum tensile strain of the reinforcement was of 4.15%, well below the strain rupture of current steels. Despite Ignjatović et al. [1] reporting that the reinforcement of some of their beams did not yield, the parabola-rectangle calculations reported yielding for all cases and those results were not removed from the database, since such deviations from analytical models to actual phenomena could also happen in a structural design.

Table 2. Proposed lognormal distributions of θ

	θMcr	θ My	θM_{rd1}	θM_{rd2}	θMrd [8]	θMrd [13]	θMrd [14]	θMrd [15]	θMrd [16]
Average	1.13	1.03	1.16	1.12	1.2	1.08	1.11	1.1	1.02
CoV (%)	36.2%	6.7%	8.6%	9.0%	15.0%	9%	12%	10%	6.0%

Whilst M_{Rd2} is a more accurate estimative, the approach of Equation (2) is a simplified calculation procedure seen as conservative, but that has some assumptions that may not be respected: the tensile reinforcement is assumed as yielding and it is assumed that the concrete under compression is strained to such an extent that the equivalent rectangle distribution is

suitable.
The yielding moment was calculated using the parabola-rectangle stress-block, assuming tensile yield strain. The midspan load-effect caused by self-weight was calculated and subtracted from the analytical moments in all cases. After cracking, the tensile strength of concrete was neglected. Reinforcement hardening was not considered.

Database analysis and NAC/RAC comparison

Table 1 shows the number of beams of different RA incorporations per paper. Different statistical descriptors of the θ values were tested for different sub-databases defined by RA incorporation. The first and second moment descriptors of some of these sub-databases are shown in Figure 1. The effect of RA incorporation on the descriptors was marginal. The same claim is valid for the skewness and kurtosis of the databases; thus it was decided to perform goodness-of-fit tests on probabilistic distributions only for the database with all beams. Correlation assessments were made by plotting and Pearson's coefficients - no correlation between θ and any parameter, including RA incorporation, was found.
All θ passed lognormal goodness-of-fit tests (α=0.05), except about both tails of θ_{My}. Since other RVs have a more significant effect on reliability and the differences between distributions are reduced, the parameters proposed for "all beams" (Table 2) are recommended irrespective of RA incorporation. θ_{MRd} is similar to the models of several partial safety factor calibration recommendations concerning NAC beams [8, 13-16].

Table 1. Number of beams of each paper

Paper	*NAC*	*RCAC50*	*RCAC100*	*RCAC*	*RFAC*	*RCARFA*	*All beams*
[1]	3	3	3	6	0	0	9
[2]	16	0	16	16	0	16	48
[3]	4	0	4	4	0	0	8
[4]	4	4	4	8	0	0	12
[5]	4	0	0	8	0	0	12
[6]	2	0	0	0	8	0	10
[7]	8	4	0	20	0	0	28
[9]	3	0	0	1	2	2	8
[11]	1	0	3	3	0	0	4
[12]	11	0	16	16	2	7	36
Total	56	11	46	82	12	25	175

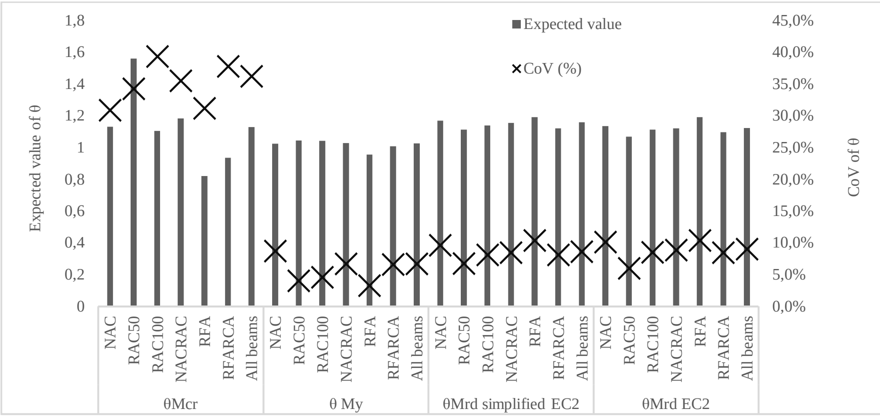

Figure 17. Statistical descriptors of the sub-databases

Conclusion

The model uncertainty of the cracking, yielding and ultimate moment of beams subjected to bending was analysed statistically and probabilistically. Lognormal distributions fitted the data well and statistical and correlation analyses showed that the effects of RA incorporation are marginal. Probabilistic distributions for the model uncertainty were proposed and benchmarked with recommendations for NAC design. The influence of RA on the model uncertainty of the bending strength of reinforced concrete beams is limited and models previously used in NAC calibration are conservative and adequate for RAC.

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